Effect Of Larger Sized Coarse Aggregates And Of Microsilica On Environmental Properties Of Portland Cement Concrete Pavements And Structures

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16. Abstract

Addition of microsilica to a concrete mix usually results in significant improvements in strength, durability and permeability. Densified microsilica samples submitted to ODOT, however, sometimes exhibit densification. At the other extreme of the concrete mix design gradation spectrum, the use of larger sized coarse aggregates may be useful in limiting cement content, yet larger sized coarse aggregates may also decrease concrete strength by weakening the aggregate-cement paste bond. This study examines whether the addition of microsilica, or the use of aggregates with maximum size above 1.5 in., in concrete mixes can have adverse effects on the durability properties of such structures. The behavior of several series of concrete specimens has been monitored over a period exceeding a year. Different coarse aggregate gradations did not impact significantly the environmental properties of concrete examined. Differences observed were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. It is, therefore, concluded that coarse aggregate gradation had little effect on the environmental properties of concrete. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the environmental properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes. It was found earlier that the compressive and flexural strengths of abused microsilica did not differ much from that of densified microsilica. The abused microsilica was intended to represent the worst possible situation that might arise in the field. This conclusion is brought into question by the rapid chloride permeability results obtained. Nonetheless, all values obtained are within the limits termed as low or moderate by the prevailing specifications. The suitability of microsilica types, other than the undensified, must be explored by a larger series of tests focusing exclusively on the environmental properties of concrete mixes containing these materials.

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Effect of Larger Sized Coarse Aggregates and of Microsilica on Environmental Properties of Portland Cement Concrete Pavements and Structures

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FINAL REPORT

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by

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DISCLAIMER

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.

FOREWORD

The investigation described in this Report was sponsored by the Ohio Department of Transportation (ODOT) and by the Federal Highway Administration (FHWA) as Ohio State Job No.: 14803(0); PID No.: 11494, under project "Larger Sized Coarse Aggregates in Portland Cement Concrete Pavements and Structures," and as Ohio State Job No.: 14800(0); PID No.: 11340, under project "Fineness of Densified Microsilica and Dispersion in Concrete Mixes." The Principal The Principal Investigators were Drs Anastasios M. Ioannides and Richard A. Miller, Department of Civil and Environmental Engineering, University of Cincinnati. The ODOT Technical Liaison was Mr Bryan Struble, the Research Manager was Mr Lloyd Welker, the Administrator for the Office of Research and Development at ODOT was Ms Monique Evans, and the FHWA liaison in Columbus, OH was Mr Herman Rodrigo. The assistance, cooperation and friendship of these individuals was a major contributor to the success of the study, and their support is gratefully acknowledged. The sand and both kinds of coarse aggregates were supplied free of charge by *Martin Marietta Materials*, through Mr Jim Martin. The cement was donated by *CEMEX*, through Mr Steve Reibold. The admixture was contributed at no cost by *Master Builders, Inc.*, through Mr Greg Wirthlin. The authors also acknowledge the contributions to the project of graduate students Jeff C. Mills and Amarendranath Deshini. This Report will be submitted by Kristy M. Walsh to the Division of Research and Advanced Studies of the University of Cincinnati in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil and Environmental Engineering, in December 2007.

ABSTRACT

This project examines whether the addition of microsilica, or the use of aggregates with maximum size above 1.5 in., in concrete mixes prepared by the Ohio Department of Transportation (ODOT) for bridge decks and highway pavements can have adverse effects on the durability properties of such structures. The behavior of several series of concrete specimens has been monitored over a period exceeding a year, and numerous measurements have been recorded. Such data are evaluated to determine if altering the standard ODOT concrete mix design on either end of the gradation spectrum can indeed lower the cement content and increase its cost effectiveness and efficiency. It was found that different coarse aggregate gradations did not impact significantly the environmental properties of concrete examined. Differences observed were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the environmental properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes. It was found earlier that the compressive and flexural strengths of abused microsilica did not differ much from that of densified microsilica. This conclusion is brought into question, at least in the case of abused microsilica, by the rapid chloride permeability results obtained. Nonetheless, all values obtained are within the limits termed as low or moderate by the prevailing specifications.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C: degree Celcius

°F: degree Fahrenheit

AASHTO: American Association of State Highway and Transportation Officials

AC: abused microsilica concrete with crushed aggregate

AN: abused microsilica concrete with crushed aggregate

ASTM: American Society for Testing and Materials

DC: densified microsilica with crushed aggregate

DN: densified microsilica with crushed aggregate

in.: inch

NCHRP: National Cooperative Highway Research Program

ODOT: Ohio Department of Transportation

PCC: Portland Cement Concrete

UC: undensified microsilica with crushed aggregate

UN: undensified microsilica with natural aggregate

US: United States of America

ε: strain

μ: micro

No.: number

%: percentage

LIST OF SPECIFICATIONS CITED

ASTM C 1240 – 01 *Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar and Grout*

ASTM C 157 – 93 *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*

AASHTO T 160 – 97 (2001) *Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete*

ASTM C 512 – 87 (Reapproved 1994) *Standard Test Method for Creep of Concrete in Compression*.

ASTM C 666 – 97 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*

AASHTO T 161 – 00 *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*

ASTM C 33 – 93 *Standard Specification for Concrete Aggregates*

ASTM C 944 – 99 *Standard Test Method Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*

ASTM C 1202 – 97 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*

AASHTO T 277 – 96 *Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*

Virginia Test Method - 112 *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, July 1, 2001

ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

1 INTRODUCTION

1.1 Problem Statement

When microsilica is present in a Portland cement concrete (PCC) mix, it may lead to increased compressive strengths, as well as greater resistance to chemical attack on account of its chemical properties. Moreover, filling of voids in the concrete matrix with microsilica leads to a denser pore structure, and this may reduce the number and size of capillaries available to contaminants potentially infiltrating the material. Microsilica concretes can also exhibit very good freeze-thaw durability provided the air entrained is controlled. Reduction in the alkalinity of the pore solution and in the diffusion of alkali ions and water may lead to a decrease in alkali-aggregate reactivity. High early strengths and resistance to abrasion have been found to be additional benefits (Mehta and Monteiro, 1993).

At the other extreme of the concrete mix design gradation spectrum, increasing the maximum size of aggregate in a concrete mix can lower the water content for any required desired level of workability and may lead to increased strength. There is a concern, however, that increasing aggregate size above a maximum of approximately 1.5 in., can lead to a decrease in the bond area between the cement paste and the aggregate, and an increase in crack probability, favoring particularly the development of D-cracks (Bartos, 1998).

This study examines whether the addition of microsilica, or the use of aggregates with maximum size above 1.5 in., in concrete mixes prepared by the Ohio Department of

Transportation (ODOT) for bridge decks and highway pavements can have adverse effects on the durability properties of such structures. The behavior of several series of concrete specimens has been monitored over a period exceeding a year, and numerous measurements have been recorded. Such data are evaluated to determine if altering the standard ODOT concrete mix design on either end of the gradation spectrum can indeed lower the cement content and increase its cost effectiveness and efficiency. It is anticipated that the results obtained from this investigation will be useful to ODOT personnel as they proceed to optimize their concrete mix design procedures.

1.2 Project Context

This research is conducted in association with two projects executed at the University of Cincinnati, which seek to determine whether the cement efficiency of standard ODOT concrete mixes can be improved by the use of microsilica or of larger sized coarse aggregates. For the first project, three forms of microsilica are used, viz., undensified, densified, and abused microsilica (Ioannides and Deshini, 2006). Undensified microsilica concrete provides a benchmark for assessing the engineering repercussions of using material that may not meet the requirement in American Society for Testing and Materials (ASTM) C 1240 – 01 *Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar and Grout* that wet-sieved microsilica pass a No. 325 sieve with no more than 10% retained. The process followed in preparing the abused microsilica can provide information on the effectiveness of mechanical mixing in breaking up densified particles. Coarse aggregate employed is of two kinds, both in the No. 8 gradation with a nominal maximum aggregate size of 3/8 in.: natural river gravel, or crushed limestone. A total of six mixes of concrete are made, named as follows: Densified Natural (DN), Densified Crushed (DC), Undensified Natural (UN), Undensified Crushed (UC), Abused Natural (AN), and Abused Crushed (AC). For each mix, rapid chloride permeability testing has been performed.

For the second ODOT project on the effects of larger sized coarse aggregates, the two aggregate types (natural and crushed) are combined with three gradations (No. 57, No. 467, and No. 357, with maximum sizes of 1, 1.5, and 2.0 in., respectively) (Ioannides and Mills, 2006). This gives rise to six distinct mixes, designated as follows: N057, N467, N357, C057, C467, and C357. The No. 57 gradation is currently used for most ODOT designs. For each mix produced, the following environmental tests have been performed: shrinkage, creep, freeze-thaw durability, abrasion resistance, and rapid chloride permeability. All tests conform to the pertinent specifications of ASTM and of the American Association of State Highway and Transportation Officials (AASHTO).

1.3 Research Objectives

Given that the efficiency of an optimum concrete mix is controlled by the amount of cement employed and that the paste is usually responsible for most of the durability and cracking problems encountered, the goal of this research is to see if the cement efficiency of standard ODOT mixes can be improved through the use of larger aggregate on the one end of the aggregate size spectrum and microsilica on the other. The investigation seeks to assess and quantify the influence of aggregate size on strength, chloride resistance, abrasion resistance, freeze-thaw durability, creep and shrinkage.

Such observatios impact directly the behavior of pavement slabs under curling, warping, cracking and load transfer considtions. The repecussions on environmental properties of pavement concrete if densified silica fume fails the sieve test are also examined.

1.4 Report Organization

This report is divided into six chapters. The first chapter introduces the reader to the research topic, and outlines the context of the investigations in association with two ODOT projects executed at the University of Cincinnati. The second chapter presents the findings of a literature survey conducted concerning the effect of larger sized coarse aggregates and microsilica on the durability of concrete. The testing procedures employed in this study are discussed in Chapter 3, while the results obtained are presented in Chapter 4. The data are analyzed in the fifth chapter, and interpretations are discussed pertaining to the environmental properties of the mixes tested. Finally, the sixth chapter summarizes the findings of the investigation, and lists a number of recommendations formulated for the implementation of the results in future ODOT concrete mix designs.

2 LITERATURE SURVEY

2.1 Introduction

This chapter presents a summary of the literature pertaining to the effect of larger sized coarse aggregates and of microsilica on the durability of concrete. The scope of the chapter is first delimited through a series of definitions of terms commonly employed in discussions in this subject area. The emphasis of the information presented is on the various experimental methods of assessing the environmental properties of concrete mixes, many of which are used subsequently in this project. All testing procedures conform to the specifications of the American Association of State Highway and Transportation Officials (AASHTO), of the American Society for Testing and Materials (ASTM), and of the Ohio Department of Transportation (ODOT). The bibliography examined covers primarily the period between 1990 and the present.

2.2 Definitions

Soundness: Soundness refers to the ability of hardened cement paste to retain its volume after setting. Soundness is often an unclear and misunderstood property related to the weatherability of aggregate. Weatherability can be easily defined as the aggregate's resistance to the effects of weathering. It has been found that soundness refers to a material that is free from damage and resistant to the effects of weather.

Abradability: Abradability is another term used to define the weatherability of the aggregate. It refers to failure that may occur in the aggregate particle due to wear and tear, or in the case of pavement, the wear due to the impact of tires on the aggregate. As loads are applied to the pavement surface the aggregates wear down and break over time. This is sometimes a concern for coarse aggregates due to the fact that they have a large surface area.

Durability: Durability is the resistance of the aggregate to failure during the life cycle of the structure in which it is used. This means that the aggregate will not break down due to excessive loading, weather, or exposure to harmful chemicals. Usually aggregates with a low porosity, i.e. a small amount of void space, are highly durable.

Shrinkage: Shrinkage refers to length changes of a hardened concrete specimen due to factors other than externally applied forces and temperature changes. The monitoring of such changes can aid the assessment of the potential for in-service volumetric changes.

Creep: The creep of concrete is the load-induced time-dependent strain at any age under sustained longitudinal compressive load.

Freeze-Thaw Durability: The freeze-thaw durability of concrete reflects its resistance to repeated cycles of freezing and thawing.

Abrasion Resistance: The abrasion of concrete is the relative wear resistance to abrasion.

Rapid Chloride Permeability: The rapid chloride permeability of concrete is its resistance to the penetration of chloride ions, determined by measuring its electrical conductance. Such measurements can be used to evaluate the desirability of the concrete mix design adopted.

2.3 Effect of Larger Sized Coarse Aggregates and Microsilica on the Durability of Concrete

2.3.1 Effect of Shrinkage on the Durability of Concrete

Shrinkage is known to cause damage to concrete structures and is, therefore, an important factor to investigate when determining the effect of larger sized coarse aggregates and microsilica on the durability of concrete. Shrinkage controls the time dependent strain of a non-loaded, plain structural concrete member exposed to a dry or moist environment after curing (Muller, 1992). Shrinkage consists of four different mechanisms that act in conjunction with one another to calculate the contraction of the concrete member. The shrinkage mechanisms are known as plastic shrinkage, drying shrinkage, autogenous shrinkage, and carbonation. Plastic shrinkage is caused by the rate of evaporation of surface water exceeding the rate of bleed water production. Drying shrinkage is caused by the loss of capillary water by evaporation to the outside of the concrete. The evaporation of capillary water is a result of excess water that is not consumed during hydration being diffused into the surrounding environment, resulting in a net volume loss. Autogenous shrinkage is the water loss due to the heat of hydration in the cement. Carbonation shrinkage is the process by which CO_2 in the atmosphere reacts with $Ca(OH)_2$ in the cement paste, in the presence of moisture, producing $CaCO_3$.

Shrinkage is usually measured by the ASTM C 157 – 93 *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* procedure. This method measures the change of length in the specimen which allows for the potential for volumetric expansion or contraction of concrete due to causes other than applied force or temperature change due to the fact that the procedure is conducted in a controlled environment. Shrinkage is just one component that is used to calculate the total strain of a concrete specimen. The total strain of a concrete specimen is the sum of elastic, creep, and shrinkage strains. The processes of creep and shrinkage affect each other, but for analysis and testing purposes they are treated as additive, independent processes and can have a significant effect on the performance of certain types of structures (Neville, 1992).

Mixes with a low water/cement ratio can decrease creep and shrinkage. Since the primary goal of effective concrete mixes is to limit the amount of water needed, it is very important to ensure that enough water remains available for the hydration process. If the hydration process is not allowed to be carried out to completion there would not be a decrease in either creep or shrinkage. Therefore, it is essential that wet curing be done as early as possible, and continue until the tensile strength is high enough to resist internal cracking (www.engr.psu.edu/ce/concrete_clinic/virtualclass/HPC/Testing/Testing%20 HPC.htm; accessed: 10/26/05).

2.3.2 Effect of Creep on the Durability of Concrete

Creep of concrete is also known to cause damage to concrete structures and is therefore an important factor to investigate when determining the effect of larger sized coarse aggregates and microsilica on the durability of concrete. Concrete undergoes immediate elastic deformations as well as time-dependent deformations that must be considered in design. Those time-dependent deformations that are a result of sustained stress can be defined as creep. ASTM C 512 – 87 (Reapproved 1994) *Standard Test Method for Creep of Concrete in Compression* is used to determine the creep of molded concrete cylinders subjected to a sustained longitudinal compressive load. Creep strain can be calculated by subtracting the initial elastic strain of the loaded creep specimen and the shrinkage strain of the companion specimen from the total strain of the loaded creep specimen. Creep may be further explained by separating it into two components: basic creep and drying creep. Basic creep occurs in a sealed condition, without any exchange of water between the concrete and its surroundings. The creep that is experienced by the innermost region of a large concrete member is predominately basic creep, since very little water is lost to the outside environment. Drying creep involves more water movement to the surrounding environment (Shah, 1994). Movement of water due to basic and drying creep brings the formation of microcracks at the interface between the aggregate and the cement paste. Although the amount of creep that actually occurs is typically relatively small, it could affect the performance of structures. For example, in simply supported beams (such as in bridge girders), creep increases the stress in steel and causes unforeseen prestress in prestressed concrete structures.

There is a possible benefit to creep, since it is possible that creep can improve the distribution of stresses within a member. Even in the event of a simply supported beam, the load is distributed across the entirety of the beam because of the effect of creep. The effect of age at loading is also a determining factor in the effect of duration of creep (Muller, 1992). It has been found that the partial replacement of cement by either fly ash or blast furnace slag can lead to reduced creep except for at early age loading. Current data that is available on the use of microsilica as a partial replacement for cement however suggests that it increases creep (Brooks and Neville, 1996). Aggregate characteristics can also have a factor in influencing the effect of creep. Aggregate characteristics that have been found to influence creep include stiffness, size, absorption, and surface roughness (Alexander, 1993). For example, in a study conducted by Collins (1992), it was found that mixtures with a maximum size of 1½ in. experienced 15% less creep after 90 days than those with a ¾ in. maximum size. It is important to reduce the effect of creep on hardened concrete due to its ability to form microcracks within the concrete structure.

2.3.3 Effect of Freeze-Thaw Damage on the Durability of Concrete

It has long been known that exposing concrete to freezing temperatures causes damage to the concrete so it is important to investigate the phenomena when determining the effect of larger sized coarse aggregates and microsilica on the durability of concrete. Many areas in the United States (US) are particularly susceptible to freeze-thaw damage because the temperature fluctuates above and below 0^{o}C many times a year. When the water contained in concrete begins to freeze, it expands by up to 10%. This expansion can cause stress on both the aggregate and the cement paste, causing them to fail. Internal stresses in the concrete can reduce its durability. If these stresses exceed the tensile strength of the aggregate or cement paste, the cavities will rupture. To resist the effects of freezing and thawing, entrained air is added to concrete. Entrained air acts as empty chambers in the paste for the freezing and migrating water to enter. When moisture in concrete freezes, air bubbles relieve internal stresses, by providing microscopic chambers for expansion. The spacing and size of air voids are important factors contributing to the effectiveness of air entrainment in concrete. The air bubbles must have a minimum diameter of 0.1 to 1.0 mm, a spacing factor of less than 0.20 mm and the spacing must not be interconnected (www.engr.psu.edu/ce/concrete_clinic/virtual class/HPC/Testing/Testing%20HPC.htm; accessed: 10/26/05).

Freeze-thaw durability is measured using ASTM C 666 – 97 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)* and AASHTO T 161 – 00 *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*. This method measures the resistance in terms of dynamic modulus of elasticity after 300 cycles of freeze and thaw. Repeated cycles of freezing and thawing causes concrete to fail many times, producing larger cracks. This distress is known as D-cracking. Because D-cracking is such a serious problem in the US, the durability of concrete is determined by its freeze-thaw durability. D-cracking starts by absorbing moisture at the bottom of the concrete slab due to the absence of dryness. Such moisture penetrates small pores of the coarse aggregates and gets trapped, forming ice when frozen. D-cracking is generally found initially at the longitudinal and transverse joint intersections and subsequently at transverse cracks. The deterioration starts in the corners and progresses along the joints, with transverse joints usually exhibiting the most rapid damage (O'Doherty, 1987).

Factors that affect freeze-thaw durability include the water-cement ratio, the strength of the concrete, the air entrainment, the quality of the aggregate, and the size of the aggregate. A decrease in the water-cement ratio usually results in improved resistance to freezing, and hence increases the durability of the concrete. This effect is more significant when the water cement is less than 0.45. For this reason, a maximum water cement ratio of 0.45 is generally recommended in concrete which could be susceptible to frost action (Soroka, 1979). A strong concrete is usually expected to have greater freeze-thaw durability than a weaker one. In the early stages of development, concrete is more susceptible to frost action due to its low strength. Therefore, it is advisable to delay the time of exposure to frost action so that the concrete will gain strength with time. Air entrainment usually increases the freeze-thaw durability of the concrete. Therefore, the presence of air voids is always advisable in concrete to decrease the effect of freeze thawing.

The quality of the aggregate and the size of the aggregate also influence the freeze-thaw durability of concrete. Highly saturated aggregate particles, from certain sources, and subjected to very low or freezing temperatures, cause expansion in the concrete and eventually tend to disintegrate. This may be in the form of discrete pop outs or pits. In research conducted by Gaynor and Meininger (1967), fifty-six aggregates were tested to find out the effect of the aggregate size on the freezing and thawing of the aggregates. ASTM C 33 – 93 *Standard Specification for Concrete Aggregates* limits the loss after five cycles of the soundness test. The limit for sodium sulphate is 10%, while the limit for magnesium sulphate is 15%. Of the aggregates tested, twelve had exceeded the limit for sodium sulphate, and seven had exceeded the limit for magnesium sulphate. Although there is no evidence that the soundness tests can be used to detect the effect on freezing and thawing durability, few aggregates with high soundness loss were found to be highly durable. The presence of even a very small percentage of these types of materials may have considerable influence on the durability of aggregate subjected to freezing and thawing. The way that frost action in the aggregate causes damage to the concrete depends heavily on the properties of the aggregate.

2.3.4 Effect of Abrasion Resistance on the Durability of Concrete

The abrasion resistance of concrete is of particular interest to transportation structures because of the constant wear and tear on the concrete due to traffic so it is important to investigate it when determining the effect of larger sized coarse aggregates and microsilica on the durability of concrete. The abrasion resistance of concrete is directly related to its strength so the compressive strength of the concrete is important to determining the abrasion resistance. The increase in resistance is principally due to an increase in cement content and reduction of water content that is associated with higher strength concrete. The quality of the cement paste is the most important factor. In fact the hardness of the coarse aggregate only becomes significant under exceptionally abrasive conditions, i.e., when the surface of the concrete has already been worn away. The abrasion resistance of concrete is enhanced by the addition of silica fume. This is due to the increased hardness of the cement paste itself and the enhanced bonding between the cement paste and the aggregates. The latter factor reduces the tendency of coarse aggregates to be pulled from the cement paste by abrasive actions.

Abrasion resistance is tested in order to improve concrete surfaces subjected to acceleration and deceleration of heavy vehicles, chains, tire studs, and hydraulic scour which can cause erosion of the concrete surface. Abrasion problems are associated with soft aggregates, low strength, and weakened surfaces from inadequate curing and finishing. Since it has been shown that abrasion resistance is proportional to the compressive strength of concrete, the higher the compressive strength the greater the abrasion resistance. Higher compressive strength can be achieved by lowering the water cement ratio, providing adequate curing conditions and harder aggregate.

Abrasion resistance is measured using the ASTM C 944 – 99 *Standard Test Method Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method* procedure. This method tests the abrasion resistance of concrete by applying a 196 N shear force, and measuring the wear depth of the concrete. After the wear depth in the concrete specimen is measured, a grade can be determined that is inversely proportional to the wear depth (www.engr.psu.edu/ce/concrete_clinic/virtual class/HPC/Testing/Testing%20HPC.htm; accessed: 10/26/05).

Apart from the direct relationship between abrasion resistance and concrete compressive strength, other factors also have been found to have a major effect on abrasion resistance. Work carried out by the University of Aston and the Cement and Concrete Association of New Zealand indicates that the methods of construction such as the finishing process can have an influence on abrasion resistance (www.cca.org.nz/ach_des/abrasion.htm; accessed: 10/26/05). For example, an unfinished surface will be less resistant to abrasion because it is susceptible to scouring. Curing and the type of surface treatment are other important factors because without proper curing the concrete will be more vulnerable to spalling and other typical pavement distresses.

2.3.5 Effect of Rapid Chloride Permeability on the Durability of Concrete

The permeability of concrete may be the most relevant concrete property affecting its durability because it relates the problems associated with long-term exposure to an aggressive environment so it is also important to investigate it when determining the effect of larger sized coarse aggregates and microsilica on the durability of concrete. The rapid chloride permeability test is conducted in order to determine the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. The results of this test can be used to evaluate material and material proportions that are used in the mix design process. Resistance of chloride ions is important to concrete structures because chloride ions promote corrosion of reinforcement steel. They may also affect freeze-thaw durability. The loss of bond between the cement paste and the aggregates leads to the break down of the concrete. Pot holes, spalling, and other pavement distresses are likely to occur as a result of chloride ions. As a result, permeability is an aspect of concrete performance that should be designed for and monitored throughout the production of concrete. This is especially true in the case of transportation structures such as a bridge deck subjected to deicing salt, a parking garage, a pavement overlay, or even a building structure where durability and life cycle costs are a critical issue.

The addition of microsilica has been found to significantly reduce the rapid chloride permeability of concrete specimens and reduces the porosity of the transition zone between the cement paste and the aggregates because the chloride ions bounce off of the pozzolan particles. In their five-year exposure test, Sasatani, et al. (1995) found that microsilica concrete showed the lowest chloride permeability when compared to ordinary Portland cement concrete and concretes containing other admixtures. This phenomenon is indicated in some of our results that were obtained early on in this investigation. In the case of larger sized coarse aggregate, it is possible that due to the distance that is present between the larger aggregate, therefore leaving a greater area for the cement paste, that permeability will be increased. Permeability to chloride ions is critical in reinforced concretes exposed to seawater and de-icing salts. The chloride ions destroy the iron oxide layer over the reinforcement, therefore making it vulnerable to corrosion. The addition of microsilica decreases the volume of pores within the concrete, thereby reducing the penetration of chloride ions into the concrete and preventing corrosion (Malhotra, 1996).

3 MATERIALS AND PROCEDURES

3.1 Introduction

To begin with, this chapter enumerates the materials employed in each of the two projects for the Ohio Department of Transportation (ODOT) considered in this report, which seek to determine whether the cement efficiency of standard ODOT concrete mixes can be improved by the use of microsilica or larger sized coarse aggregates. Subsequently, the testing procedures adopted for the purpose of assessing the environmental properties of the concrete mixes prepared are described, illustrating adherence to the specifications of ODOT, of the American Association of State Highway and Transportation Officials (AASHTO), and of the American Society for Testing and Materials (ASTM). The methodology leading to the concrete mix designs implemented, the testing protocols followed for the fine and coarse aggregates, as well as the arduous mixing, casting and curing processes, have been described in the corresponding volumes for each of the two ODOT projects that describe the mechanical properties of the test specimens.

3.2 Materials Used

Materials used in both the microsilica and the larger sized coarse aggregates projects were sand, coarse aggregate, Type I-II Portland cement, water (www.cincinnati-oh.gov/water; accessed: 07/22/05) from greater Cincinnati water works, and air entrainer. The sand and coarse aggregate were supplied free of charge by *Martin Marietta*

Materials, a leading supplier in the Cincinnati area. The sand was natural and came from their sand and gravel facility in Ross, OH. Coarse aggregate was of two kinds, natural river gravel, or crushed limestone. Natural No. 8, and No. 57 aggregates came from their plant in Fairfield, OH, while natural No. 4 aggregates came from their E-Town plant in North Bend, OH. Finally, all crushed coarse aggregates, including No. 8, No. 57, No. 4, and No. 2, were provided from the Phillipsburg quarry in Brookville, OH (Jim R. Martin: personal communication, 10/14/02; www.martinmarietta.com; accessed: 12/02/02).

The Portland cement Type I-II was donated by *CEMEX* from their operation in Fairborn, OH (Steve Reibold: personal communication, 09/11/02; www.cemexusa.com; accessed: 08/14/02). The air entrainer MB-AE 90 was supplied at no cost by *Master Builders, Inc*. (Greg Wirthlin: personal communication, 08/07/02; www.masterbuilders.com; accessed: 07/24/02).

In addition to these materials, the microsilica project employed microsilica by *ELKEM Materials* from their location in Alloy, WV (Tony N. Kojundic: personal communication, 08/07/02; www.materials.elkem.com; accessed: 07/24/02), as well as *Rheobuild 1000* superplasticizer from *Master Builders, Inc*. The research laboratory facilities on the University of Cincinnati campus were used, except as noted.

3.3 Tests of Environmental Durability

3.3.1 Shrinkage Test

This test was conducted in accordance with ASTM C 157 – 93 *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* and AASHTO T

160 – 97 (2001) *Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete*. Specimens were cast as either 4 × 4 × 11.25 in. prisms molds (per AASHTO T 160, for mixes in which the nominal aggregate size was less than 1 in.), or as 6 × 6 × 21 in. beams (for those mixes whose maximum aggregate size was greater than 1 in.). It is noted that ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* requires that the smallest dimension of the specimen be at least 3 aggregate sizes. For 2-in. aggregate, this would be 6 in., minimum. ASTM C 192 also indicates that when the aggregate is too large for the standard specimen, the oversized aggregate should be removed. Obviously, this defeats the purpose of using the large aggregate. For this reason, the transverse size of the shrinkage specimen was increased to 6 in., since this is 3 times the maximum aggregate size of the largest aggregate (2 in.). Since standard 6 × 6 × 21 in. modulus of rupture molds were available, these were used for the shrinkage specimens for those mixes whose maximum aggregate size was between 1 and 2 in.. A 6-in. shrinkage gage (*Geokon Model VCE-4200*) with a 3,000 με range was embedded in the upper one-third of each specimen. Upon demolding, this gage was connected to multiplexer and datalogger unit that began recording, 24 to 36 hours after casting. The specimens remained in the University of Cincinnati environmental chamber, in which the temperature is maintained 73.4 ± 3.0ºF and the relative humidity at 50 ± 4%. A lime-saturated water solution was used for curing during the first 28 days, after which the samples were cured in air, placed on risers. The latter were elevated to at least 1 in. so that air could circulate all around the prisms and beams. Strain data was collected for a period of one year, using data acquisition software. According to the specification, the

total length change of the specimen at any time is calculated as the difference between the comparator reading of the specimen and the reference bar at the same age divided by the length of the gage. With ODOT's consent, the embedded vibrating wire gage was used for this purpose during this project, instead. The length change of the specimen at any age is expressed as a percentage.

3.3.2 Creep Test

The pertinent specification is ASTM C 512 – 87 (Reapproved 1994) *Standard Test Method for Creep of Concrete in Compression*. This requires a 6-in. in diameter. cylindrical specimen, which is already 3 time the maximum size of aggregate in this study (2 in.). Consequently, clindrical 6 x12 in. specimens were prepared and cured in a lime-water bath for 28-days. Each specimen was then allowed to dry in air for a 24 hour period. Two 6-in. long strain gages (*Geokon Model VSM-4000*) with a 3000 $\mu\varepsilon$ range were epoxy glued longitudinally to the cylinder, so that they formed a single plane that also included the sample's diameter. The specimen was then placed a spring-loaded frame capable of applying and maintaining a specified load. Fabricated for this purpose at the University of Cincinnati, the frame consists of a lower and upper load plate, springs, and a group of loading bars that work in tandem during the test, which is conducted in the University of Cincinnati environmental chamber. The concrete cylinder specimen is loaded at an intensity of not more than 40% of the compressive strength at 28 days, the latter determined prior to testing. Load and strain readings are then taken as follows: immediately before and after loading; at 6 hours; daily for a period of a week; weekly for the period of a month; and monthly until the period of one year has elapsed.

The load was adjusted if it varied more than 2% from the prescribed value. The data is collected and translated using a multiplexer/datalogger unit with the help of data acquisition software. The total load-induced strain per unit pressure at any time is calculated as the difference between the average strain values of the loaded and control specimens divided by the average stress.

3.3.3 Freeze-Thaw Durability Test

The specifications provided in ASTM C 666 – 97 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*, and in AASHTO T 161 – 00 *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)* were adhered to in this case. Concrete beams, 6 × 6 × 21 in., were cured in a lime-water bath until for 14 days, at which point test specimens were cut out of them. Like the shrinkage test specification, ASTM C 666 calls for 4 × 4 × 11.25-in. specimens, and as noted earlier, such specimens are too small for concrete containing aggregate larger than 1-3/8 in. Consequently, 6 × 6 × 21 in. beams replaced the standard specimens, to ensure that the least dimension of the specimen is at least 3 times the maximum aggregate size. Each specimen was then completely surrounded by not less than 1/32 in. nor by more than 1/8 in. of water at all times, while being subjected to freezing and thawing cycles. Initially the specimen was brought to a temperature between -2 and +4ºF of the target thaw temperature that will be used in the freeze-thaw cycle. The initial specimen dimensions and length are recorded at this time also. The nominal freezing and thawing cycle consists of lowering the temperature of the specimen from 40 to 0ºF and raising it from 0 to 40ºF in not less than 2 hours nor more than 4 hours. The freezing and thawing cycles are continued at intervals of not more than 36 cycles of exposures, measuring the dimensions, length, and mass of the specimen at the end of each interval. Testing should be continued until the relative dynamic modulus of elasticity reaches 60 percent of the initial modulus or 0.10 percent expansion. Any defects or deformities seen in the specimen throughout any portion of the test should be noted. The relative dynamic modulus of elasticity and the percentage of weight change were recorded throughout the length of the test. The former can be found by dividing the fundamental transverse frequency after c cycles of freezing and thawing by the fundamental transverse frequency at 0 cycles of freezing and thawing and expressing it as a percentage. The latter can be determined by multiplying the relative dynamic modulus of elasticity at N cycles by the number of cycles at which it reaches the specified minimum value and dividing the quantity by the specified number of cycles at which the exposure is to be terminated.

3.3.4 Abrasion

The procedure followed was conducted in accordance with ASTM C 944 – 99 *Standard Test Method Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*, using 6 × 12 in. cylinders, cast for this purpose. The ASTM specification requires that after 14 days of curing, a specimen of any size and shape should be cut from such a cylinder, and that the surface to be tested should be either formed or finished. Therefore, 1-in. thick discs were cut from both the top and the bottom of each cylinder after 90 days of curing, resulting in one finished and one formed surface, respectively. Before testing began, the mass of each disc was determined to the nearest 0.1g. The specimen was then fastened securely onto the abrasion device so that the test surface is normal to the shaft. A rotating cutter revolving at a speed of 200 revolutions per minute was gently applied to the surface of the specimen under a load of 22 ± 0.2 lb. This procedure was continued for two minutes and then the rotating cutter was removed. The specimen was then removed from the device and the surface was cleaned with a soft brush in order to remove any remaining debris. The mass of the specimen was again determined to the nearest 0.1 g. This process was repeated an additional two more times. The difference between the weight before cutting and the weight after cutting is an indication of how much material was abraded away.

3.3.5 Rapid Chloride Permeability

The procedures prescribed in ASTM C 1202 – 97 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* and in AASHTO T 277 – 96 *Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* were followed in this case. A 4 × 8 in. concrete cylinder was cured in a lime saturated water solution for 28 days in warm water (per the Virginia Test Method - 112 *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, July 1, 2001, found at www.virginiadot.org/business/materials-download-docs.asp; accessed: 03/17/03), or for 90 days in water at room temperature. On the day of the test, the cylinder was allowed to dry in air for an hour, before a 2-in. thick specimen was cut from its middle third. The specimen was coated with a rapid setting epoxy on its curved surface, and allowed to cure until the coating no longer appeared to be sticky. It was then placed in a vacuum desiccator in such a way that the two ends of the sample were exposed to water infiltration. The desiccator was sealed and the vacuum was maintained for a minimum period of 3 hours. The specimen was then soaked in a warm water bath for 18 ± 2 hour, after which it was securely placed between two voltage cells. The negative end of sample was inundated with a 3% sodium chloride solution and the positive end was filled with a 0.3 N sodium hydroxide solution. The lead wires from the voltage cell were attached to a power supply set to 60 ± 0.1 V, which was then turned on, and the initial reading was recorded. Thereafter, the readings were taken at 30-minute intervals. Care was taken to maintain the solutions on the two sides of the cell at the appropriate levels. Readings were taken at least every 30 minutes until the test was terminated six hours later, and the specimen was removed from the voltage cells. The information that was obtained from the test was used to plot a graph of current (in Amp) versus time (in s). The area under the curve was integrated to obtain the number of coulombs (C) of charge passed through the specimen, which is the measure of the electrical conductance of the concrete during the period of the test.

4 TEST RESULTS

4.1 Introduction

This chapter presents the data recorded during the environmental tests conducted, expressed in most instances as mean values. For the first of the Ohio Department of Transportation (ODOT) projects, concrete mixes are named after the microsilica type and the nature of the coarse aggregate used, as Densified Natural (DN), Densified Crushed (DC), Undensified Natural (UN), Undensified Crushed (UC), Abused Natural (AN), and Abused Crushed (AC). For the other project, each mix is assigned a four-character alphanumeric code identifying the type of the coarse aggregate used (natural, N, or crushed, C), and the coarse aggregate gradation number (No. 57, No. 467, or No. 357), with maximum sizes of 1, 1.5, and 2.0 in., respectively. Thus, six distinct mixes were considered, as follows: N057, N467, N357, C057, C467, and C357. This information will constitute the database to be used in the next chapter for the purpose of comparing the different mixes.

4.2 Environmental Properties of Microsilica Concrete Specimens

The only environmental test performed on these specimens was that prescribed in ASTM C 1202 – 97 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* and in AASHTO T 277 – 96 *Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. These tests require 90-day cure in water at room temperature. In addition, 28-day accelerated cure in warm water was adopted for the specimens in the microsilica project, in accordance with the Virginia Test Method - 112 *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, July 1, 2001 (www.virginiadot.org/business/materials-download-docs.asp; accessed: 03/17/03).

4.2.1 Rapid Chloride Permeabilty

Results obtained are presented in Tables 4.1 and 4.2, respectively.

4.3 Environmental Properties of Coarse Aggregate Concrete Specimens

Specimens from these mixes were subjected to the following environmental tests: ASTM C 157 – 93 *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* and AASHTO T 160 – 97 (2001) *Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete*; ASTM C 512 – 87 (Reapproved 1994) *Standard Test Method for Creep of Concrete in Compression*; ASTM C 666 – 97 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*, and in AASHTO T 161 – 00 *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A, Rapid Freezing and Thawing in Water)*; ASTM C 944 – 99 *Standard Test Method Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*; and ASTM C 1202 – 97 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* and in AASHTO T

277 – 96 *Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*.

4.3.1 Shrinkage

The total length change of the specimens at any time obtained during the testing period are recorded in Figures 4.1 through 4.4.

4.3.2 Creep

The total load-induced strain per unit pressure of the specimens are recorded in Figures 4.5 through 4.8.

4.3.3 Freeze-Thaw Durability

The percentage of weight change and the durability factor (the relative dynamic modulus of elasticity at the end of 300 cycles) obtained at the completion of testing for each of the tests conducted on the concrete specimens are recorded in Table 4.3 and Figures 4.9 and 4.10.

4.3.4 Abrasion Resistance

The average loss of weight of each specimen and the associated coefficient of variation are presented in Table 4.4 and Figure 4.11.

4.3.5 Rapid Chloride Permeability

The electrical conductance of concrete to provide an indication of its resistance to the penetration of chloride ions is presented in Table 4.5.

Table 4.1: Rapid Chloride Permeability Results from Microsilica Concrete Specimens at 28 Days (Warm Curing)

	Permeability (coulomb)		
Mix	**Sample A**	**Sample B**	**Average**
ND	1361.541	894.8799	1128.21
NU	606.26653	609.39422	607.83
NA	1418.8394	1222.2161	1320.53
CD	1324.9793	1111.9001	1218.44
CU	484.75324	500.02842	492.39
CA	2307.6666	2126.527	2217.10

Table 4.2: Rapid Chloride Permeability Results from Microsilica Concrete Specimens at 90 Days (Conventional Curing)

	Permeability (Coulombs)		
Mix	**Sample A**	**Sample B**	**Average**
ND	716.56868	889.19989	802.88
NU	796.46201	759.94609	778.20
NA	1165.66	958.19825	1061.93
CD	1440.943	743.6172	1092.28
CU	681.22514	746.81342	714.02
CA	1646.3156	809.4506	1227.88

Table 4.3: Freeze-Thaw Durability Results from Coarse Aggregate Concrete Specimens After 300 Cycles

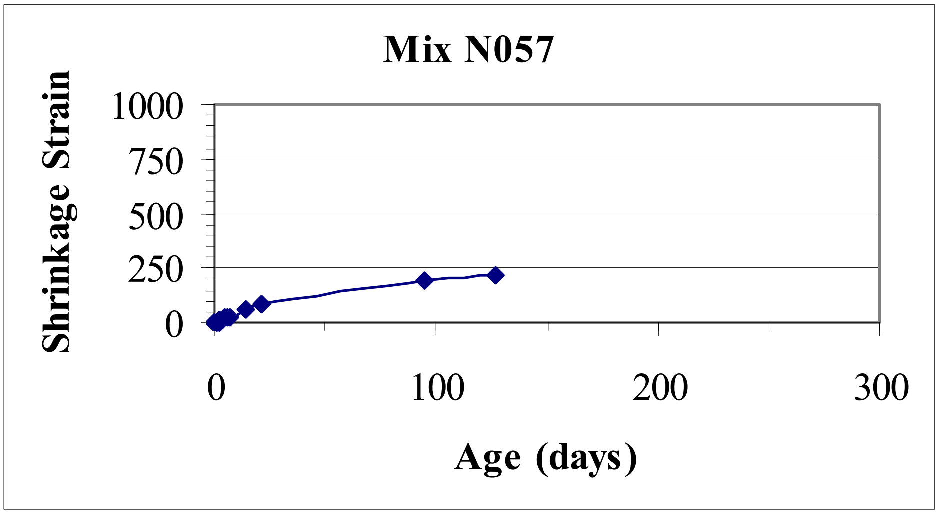
Mix	% of Weight Change	Durability Factor
N057	99.0	96
N467	99.6	94
N357	98.8	97
C057	97.2	87
C467	99.6	86
C357	96.5	91

Table 4.4: Abrasion Resistance Results from Coarse Aggregate Concrete Specimens

Specimen Name	Average Loss (g)		COV (%)	
	Top	Bottom	Top	Bottom
N057	3.90	1.20	2.41	0.16
N467	6.80	3.70	3.14	0.77
N357	11.10	4.80	4.10	1.97
C057	3.00	1.80	1.10	0.24
C467	7.90	12.30	3.07	5.46
C357	7.90	6.00	2.81	2.65

Table 4.5: Rapid Chloride Permeability Results from Coarse Aggregate Concrete Specimens at 90 Days (Conventional Curing)

	Permeability (coulomb)		
Mix	**Sample A**	**Sample B**	**Average**
N057	3027.9573	951.83054	1989.89
N467	3555.0535	4440.0099	3997.53
N357	1383.6723	3505.7283	2444.70
C057	2502.1805	1048.2854	1775.23
C467	3821.329	1040.3863	2430.86
C357	3399.4158	4254.8149	3827.12



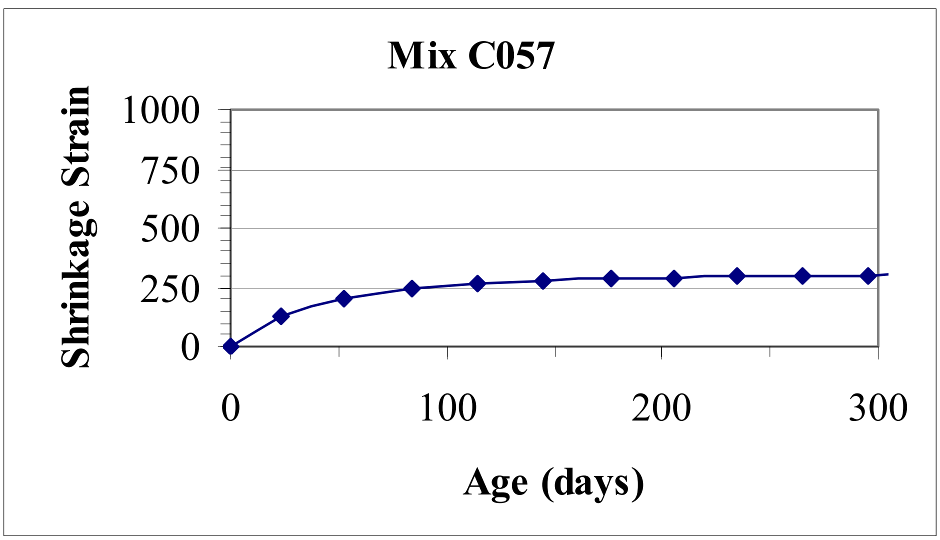
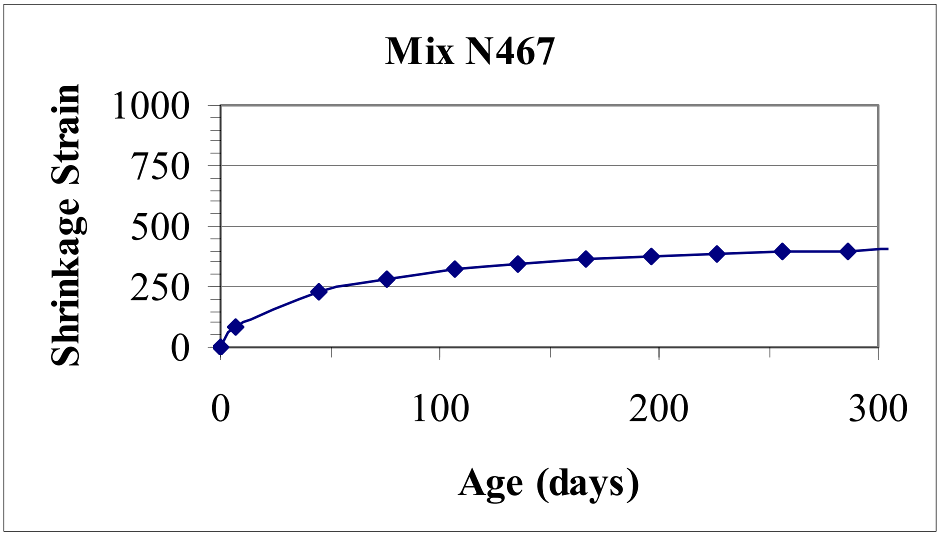


Figure 4.1: Shrinkage Test Results on Specimens with No. 57 Aggregate



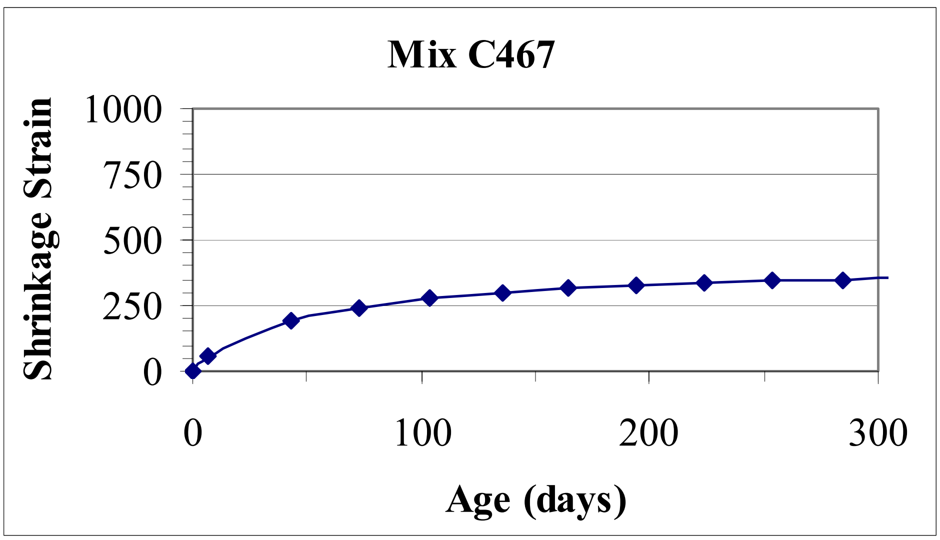


Figure 4.2: Shrinkage Test Results on Specimens with No. 467 Aggregate

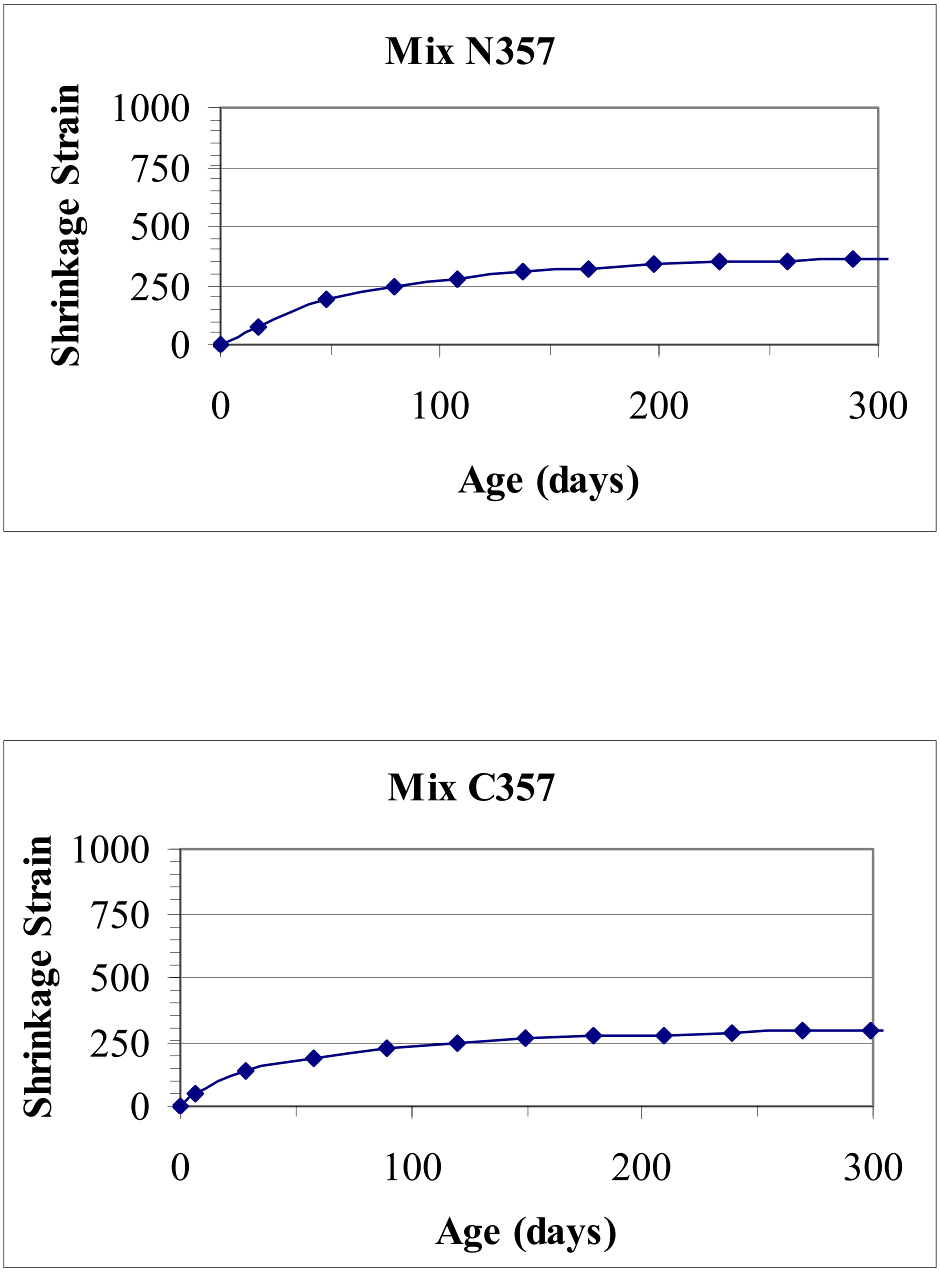


Figure 4.3: Shrinkage Test Results on Specimens with No. 357 Aggregate

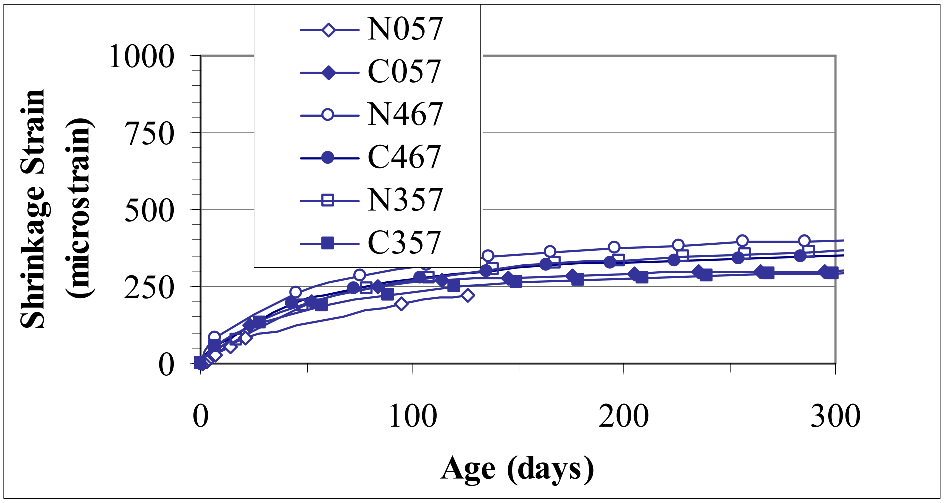
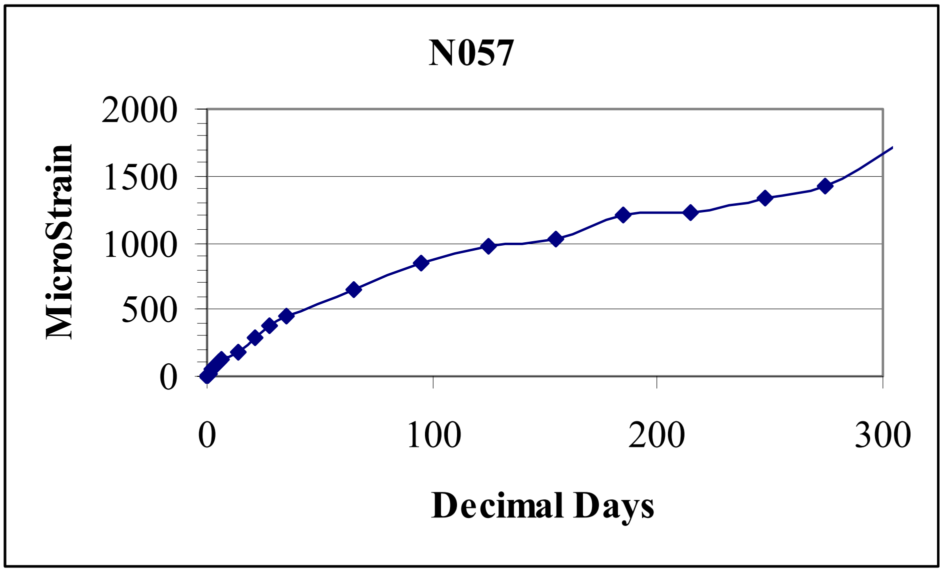


Figure 4.4: Shrinkage Test Results



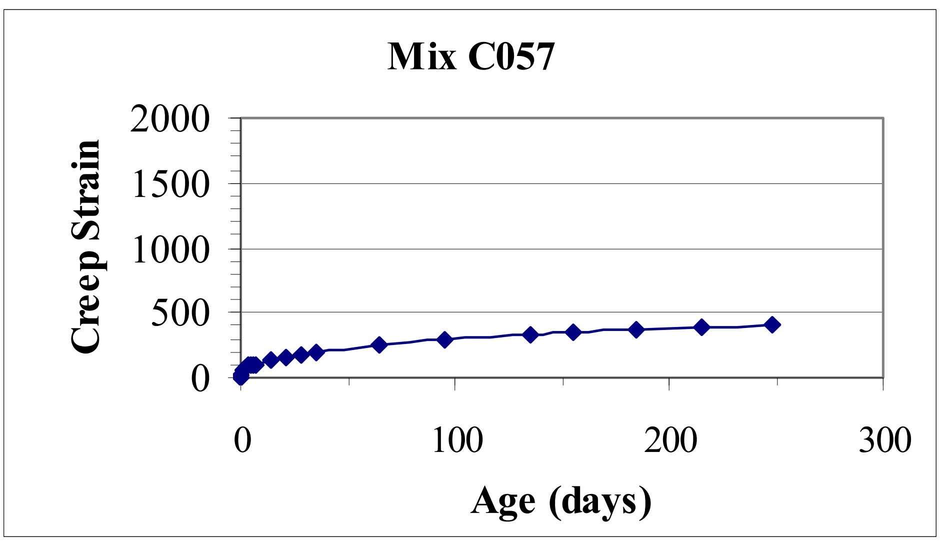
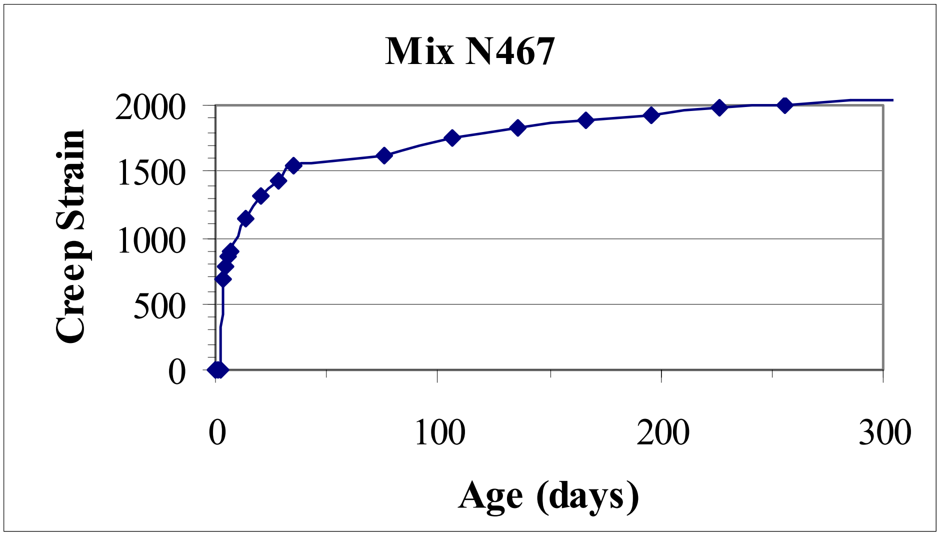


Figure 4.5: Creep Test Results on Specimens with No. 57 Aggregate



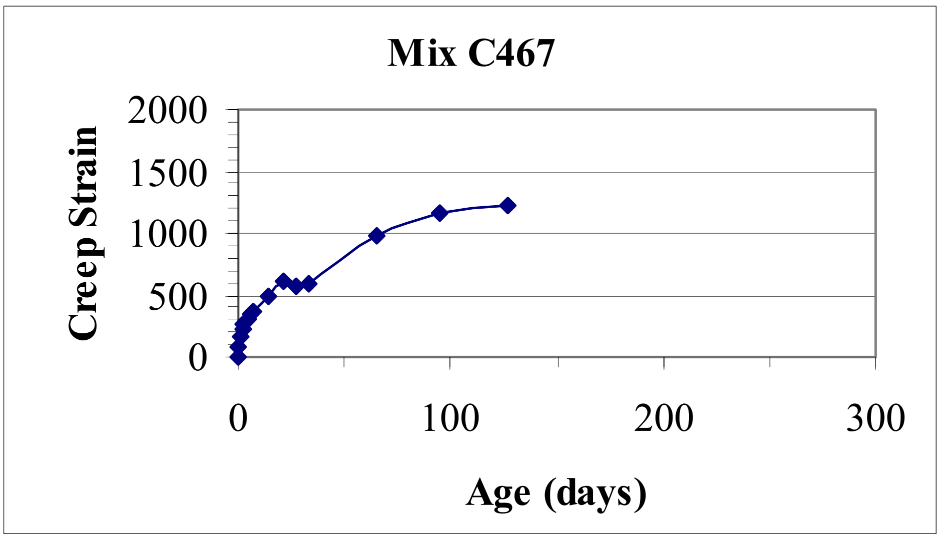
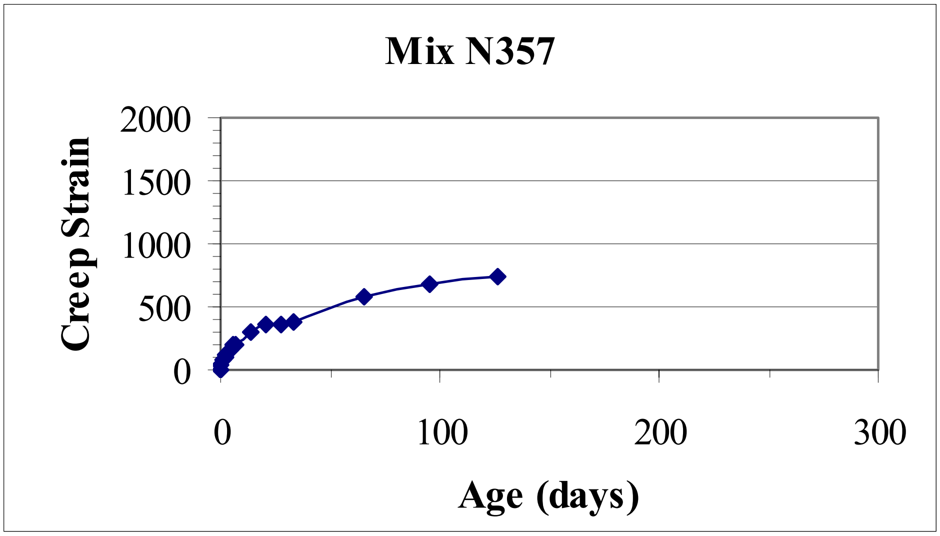


Figure 4.6: Creep Test Results on Specimens with No. 467 Aggregate



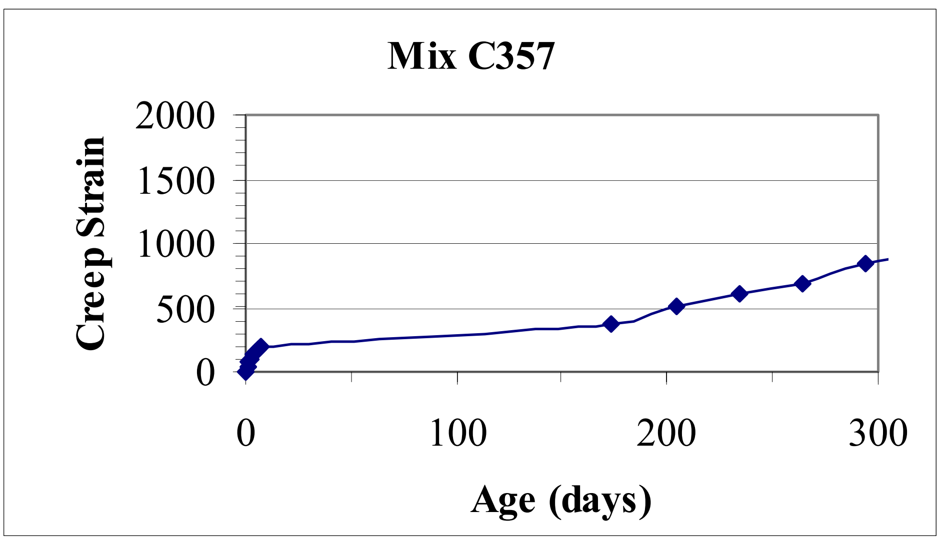


Figure 4.7: Creep Test Results on Specimens with No. 357 Aggregate

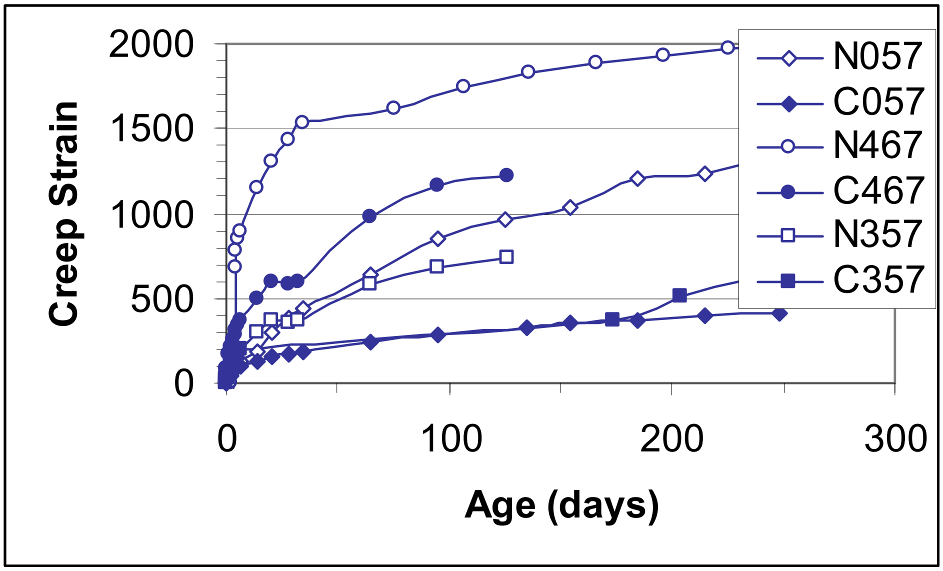


Figure 4.8: Creep Test Results

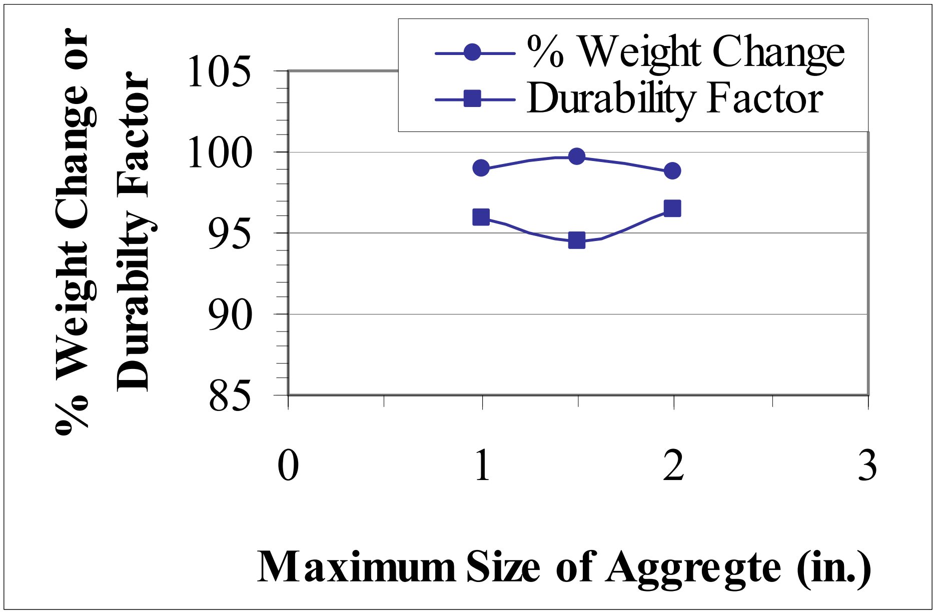


Figure 4.9: Freeze-Thaw Durability from Specimens with Natural Aggregate

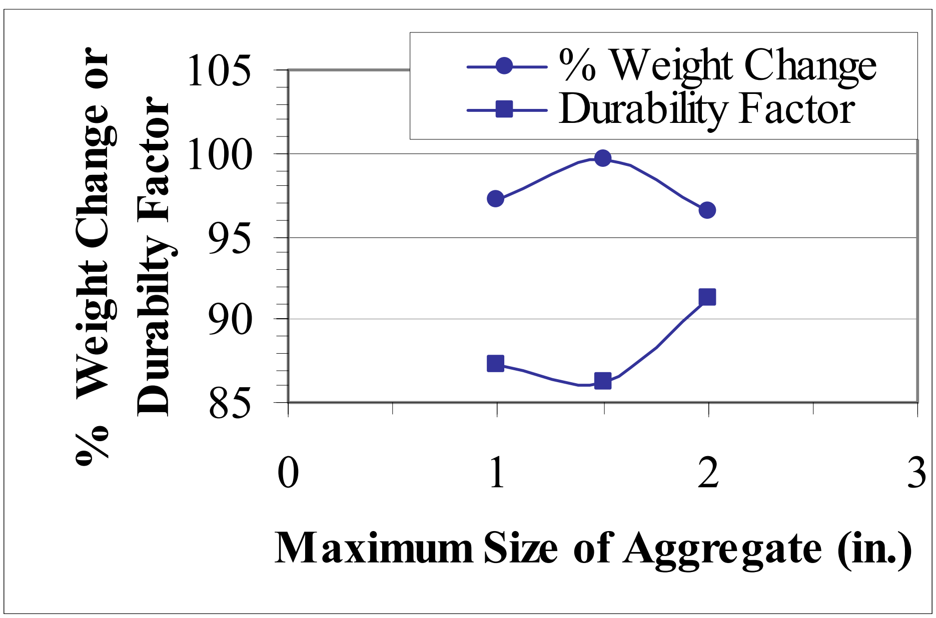


Figure 4.10: Freeze-Thaw Durability from Specimens with Crushed Aggregate

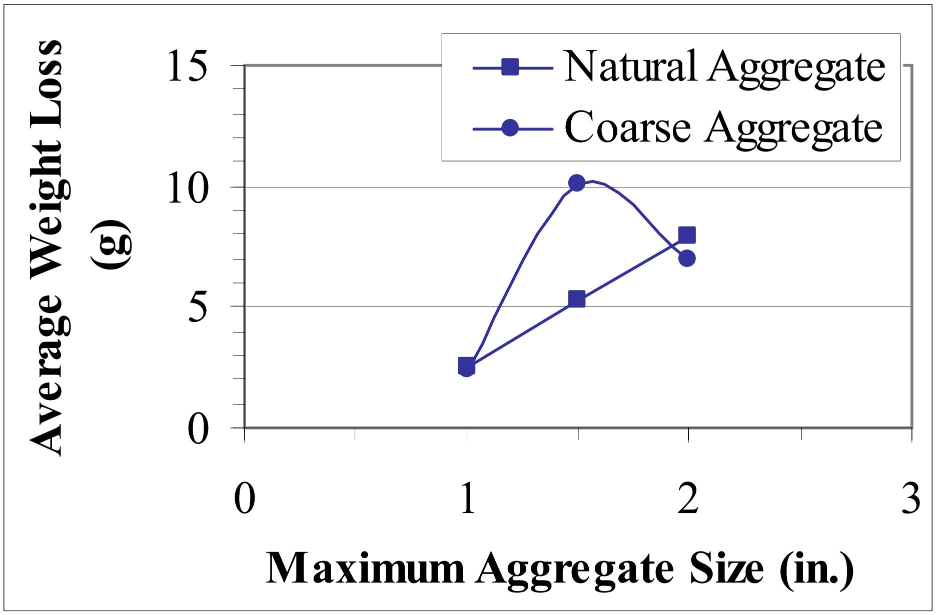


Figure 4.11: Abrasion Test Results

5 DISCUSSION OF TEST RESULTS

5.1 Introduction

This chapter presents comparisons among the test results compiled in order to identify trends observed and assess the effects of various factors. Two different types of aggregates (natural and crushed) were used in the mix designs for both the microsilica and the larger size coarse aggregate projects. The microsilica type (undensified, densified and abused) was considered in the first project, giving rise to a total of six mixes of concrete, named as follows: Densified Natural (DN), Densified Crushed (DC), Undensified Natural (UN), Undensified Crushed (UC), Abused Natural (AN), and Abused Crushed (AC). On the other hand, the larger size coarse aggregate gradation was examined in the second project (No. 57, No. 467, and No. 357, with maximum sizes of 1, 1.5, and 2.0 in., respectively), resulting in six distinct mixes, designated as follows: N057, N467, N357, C057, C467, and C357.

5.2 Effect of Aggregate Type on Environmental Properties of Concrete

5.2.1 Shrinkage

There was no significant difference between the shrinkage responses of mixes representing the two aggregate types, crushed and natural. In general, it was found that the mixes that contained natural aggregates underwent a somewhat larger amount of shrinkage. Mix N467 had a shrinkage rate that was 46.8 $\mu\varepsilon$ higher than mix C467. Mix

N357 had a shrinkage rate that was 9.8 με higher than mix C357. Finally, data pertaining to mix N057 are not considered reliable due to a problem with the strain gauge. In the context of the natural variability of the test results, however, such distinctions are not considered significant.

5.2.2 Creep

In general, it was found that the mixes that contained natural aggregates had a larger rate of creep than the mixes that contained crushed aggregates, an observation that may be ascribed to the improved frictional properties of crushed aggregate, and possibly to mineralogical and hardness differences among the aggregates used. Mix N057 had a creep rate that was 764 με higher than mix C057. Mix N467 had a creep rate that was 898 με higher than mix C467. Finally, mix N357 had a creep rate that was 8 με higher than mix C357.

5.2.3 Freeze-Thaw Durability

Trends observed in these tests are consistent with conventional expectations. In general, it was found that the relative dynamic modulus of elasticity and the percentage of weight change recorded for most of the concrete specimens decreased as the number of cycles increased. The percentage of weight change recorded during testing for the specimens from mixes N057, N467 and C467 remained essentially the same throughout the duration of testing. The relative dynamic modulus of elasticity recorded during testing for the specimen from mix C057 decreased at a faster rate than the other specimens. In all cases, the concrete containing natural aggregates was somewhat more durable than the concrete containing crushed aggregate. This small difference may be the result of differences in aggregate porosity and mineralogy.

5.2.4 Abrasion Resistance

Most of the specimens indicated that the finished surface was less resistive to abrasion than the formed surface. The exception was mix C467, for which the finished surface was more resistive to abrasion than the formed surface. This, however, is attributable to the fact that during testing of the formed surface, the rod bent and the specimen jammed the motor. The mixes that included natural materials were found to be less resistive to abrasion than the mixes that contained crushed materials.

5.2.5 Rapid Chloride Permeability

In most cases, it was found that the rapid chloride permeability of the cast specimens that contained natural aggregates was greater than the mixes that contained crushed aggregates. For example, mix N057 had an average permeability of 215 C more than mix C057. Mix N467 had an average permeability of 1567 C more than mix C467. The exception to this trend was mix N357, which had an average permeability of 1382 C less than mix C357.

5.3 Effect of Aggregate Size on Environmental Properties of Concrete

5.3.1 Shrinkage

As already noted, no significant differences are observed among these data, when considered within the context of the natural material variability. For mixes containing natural aggregate, the rate of shrinkage decreased somewhat as the size of the aggregate increased, whereas this trend is not exhibited by mixes with crushed aggregate. Mix C057 had the largest shrinkage rate of the three crushed aggregate mixes, while mix C467 had the smallest. Thus, the small differences observed are not correlated with the maximum size of aggregate in each gradation.

5.3.2 Creep

Mixes containing the smallest sized aggregates, N057 and C057, had the largest rate of creep, possibly because of the more important role played by the cement paste in these cases. The rates of creep of these mixes were 342 to 476 με greater than those pertaining to mixes N467 and C467. Finally, the rate of creep of mixes N057 and C057 were 514 to 1269 με greater than those of mixes N357 and C357. The trend of the mixes with the smallest sized aggregates having the largest rate of creep was consistent in both the concrete mixes consisting of natural and crushed aggregate.

5.3.3 Freeze-Thaw Durability

The same trend was apparent in both the concrete mixes containing natural aggregates and the concrete mixes containing crushed aggregates for the freeze-thaw durability specimens. The mixes containing the largest sized aggregates, mix N357 and mix C357, were the most durable of all of the mixes. The durability of these mixes was 1% to 4% greater than mix N057 and mix C057. The durability of mix N357 and mix C357 were also 3% to 5% greater than mix N467 and mix C467. The trend of the mixes with the largest sized aggregates being the most durable was consistent in both the concrete mixes consisting of natural and crushed aggregate. It is concluded that the use of 2-in. maximum size aggregate does not appear to create any concerns with regard to freeze-thaw durability, even as additional experimentation within the standard gradations may be desirable.

5.3.4 Abrasion Resistance

The same trend was apparent in both the concrete mixes containing natural aggregates and the concrete mixes containing crushed aggregates for the abrasion resistance specimens. The mixes containing the largest sized aggregates, mix N357 and mix C357, were less resistant to abrasion on the finished surfaces than the mixes containing smaller sized aggregates. The average losses of weight of these mixes were 4.9 grams to 7.2 grams greater than mix N057 and mix C057. The average losses of weight of mix N357 and mix C357 were also 0.0 grams to 4.3 grams greater than mix N467 and mix C467. It should be noted that the average loss of weight of the formed surfaces of the mixes did not follow this trend or any other obvious trend. It is concluded that no disconcerting trends are evident in these test results, whose variability reflects the limitations of the standard test procedure when larger size coarse aggregate mixes are investigated. It is recalled that the test discs for such mixes are cored out of larger specimens.

5.3.5 Rapid Chloride Permeability

In the case of the crushed aggregate mixes, it was found that the rapid chloride permeability of the cast specimens increased as the size of the aggregate increased. For example, the mix containing the largest sized aggregates, mix C357, had the largest permeability rate among the crushed aggregate mixes. The average permeability of mix C357 was 1396 and 2052 coulomb greater than those of mixes C467 and mix C057, respectively. No trend was apparent for the mixes containing natural aggregates. As in the case of the abrasion test, it is concluded that rapid chloride permeability results raise no concerns regarding the use of larger size coarse aggregates, since all values obtained are within the limits termed as low or moderate by the prevailing specifications. It is reiterated that the variability in the test results reflect the limitations of the standard test procedure when larger size coarse aggregate mixes are investigated, since the test discs for such mixes are cored out of larger specimens.

5.4 Effect of Microsilica on Environmental Properties of Concrete

5.4.1 Rapid Chloride Permeability

The results of the rapid chloride permeability tests were compared in order to assess the effect of microsilica type. It was found that most of the mixes that contained crushed aggregates had a larger permeability rate than the mixes that included natural aggregates. The exception was mix NU, which was made with natural undensified microsilica. The rate of permeability of mix NU was larger than mix CU, which consisted of crushed undensified microsilica.

The most significant trend found in the mixes that contained microsilica was that the abused microsilica had the largest rate of permeability. Mix NA, which consisted of natural aggregate and abused microsilica, and mix CA, which consisted of crushed aggregate and abused microsilica, had a larger rate of permeability than both the densified microsilica and the undensified microsilica mixes. The mixes that contained the abused microsilica had an average rate of permeability of 397 C greater than the mixes that contained the densified microsilica and 809 C greater than the mixes that contained the undensified microsilica. The mixes that contained the undensified microsilica were found to have the lowest rate of permeability.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This project examines whether the addition of microsilica, or the use of aggregates with maximum size above 1.5 in., in concrete mixes prepared by the Ohio Department of Transportation (ODOT) for bridge decks and highway pavements can have adverse effects on the durability properties of such structures. The behavior of several series of concrete specimens has been monitored over a period exceeding a year, and numerous measurements have been recorded. Such data are evaluated to determine if altering the standard ODOT concrete mix design on either end of the gradation spectrum can indeed lower the cement content and increase its cost effectiveness and efficiency. This research is conducted in association with two projects executed at the University of Cincinnati, which seek to determine whether the cement efficiency of standard ODOT concrete mixes can be improved by the use of microsilica or of larger sized coarse aggregates.

Of the various kinds of microsilica that are commercially available in the market, only two were considered by the research team: undensified microsilica and densified microsilica. A third type of microsilica, viz., abused microsilica, was also explored. This was prepared by soaking the densified material in water and drying it, thereby encouraging the formation of clumps. Abused microsilica was prepared by the research team in University of Cincinnati concrete laboratory, while densified and undensified microsilica were obtained free of charge from *ELKEM* chemicals.

Larger sized coarse aggregates are often used to improve cement efficiency, as they take up a large volume and have a smaller surface area than smaller coarse aggregates. It is, however, possible that larger sized coarse aggregates can reduce overall concrete strength, making it important to assess what effects, if any, can be attributed to their use. Three different coarse aggregate gradations (No. 57, No. 467, and No. 357) were studied, as well as two different aggregate types (crushed and natural), all obtained free of charge from *Martin Marietta Aggregates*.

The methodology leading to the concrete mix designs implemented, the testing protocols followed for the fine and coarse aggregates, as well as the arduous mixing, casting and curing processes, have been described in the corresponding volumes for each of the two ODOT projects that describe the mechanical properties of the test specimens. This report focuses on a series of tests termed herein as environmental and includes the following procedures: shrinkage, creep, freeze-thaw durability, abrasion resistance, and rapid chloride permeability. All tests conform to the pertinent specifications of ASTM and of the American Association of State Highway and Transportation Officials (AASHTO).

6.2 Major Findings

6.2.1 Shrinkage

There was no significant difference between the shrinkage responses of mixes representing the two aggregate types, crushed and natural, or between those pertaining to the three larger sized coarse aggregate gradations, when such differences are considered within the context of the natural material variability. The small differences observed were not correlated with the maximum size of aggregate in each gradation, but mixes that contained natural aggregates underwent a somewhat larger amount of shrinkage.

6.2.2 Creep

In general, it was found that the mixes that contained natural aggregates had a larger rate of creep than the mixes that contained crushed aggregates, an observation that may be ascribed to the improved frictional properties of crushed aggregate, and possibly to mineralogical and hardness differences among the aggregates used. Mixes with the smallest size aggregates had the largest rate of creep, possibly because of the more important role played by the cement paste in these cases.

6.2.3 Freeze-Thaw Durability

Trends observed in these tests are consistent with conventional expectations. In all cases, the concrete containing natural aggregates was somewhat more durable than the concrete containing crushed aggregate. This small difference may be the result of differences in aggregate porosity and mineralogy. Mixes containing the largest size aggregates were the most durable of all of the mixes. It is concluded that the use of 2-in. maximum size aggregate does not appear to create any concerns with regard to freeze-thaw durability, even as additional experimentation within the standard gradations may be desirable.

6.2.4 Abrasion Resistance

Most of the specimens indicated that the finished surface was less resistive to abrasion than the formed surface. Mixes that included natural materials were found to be less resistive to abrasion than mixes that contained crushed materials. The mixes containing the largest size aggregates were less resistant to abrasion on the finished surfaces than the mixes containing smaller sized aggregates. The average weight loss of the formed surfaces did not follow any obvious trend. It is concluded that no disconcerting trends are evident in these test results, whose variability reflects the limitations of the standard test procedure when larger size coarse aggregate mixes are investigated. It is recalled that the test discs for such mixes are cored out of larger specimens.

6.2.5 Rapid Chloride Permeability

In most cases, it was found that the rapid chloride permeability of the cast specimens that contained natural aggregates was greater than the mixes that contained crushed aggregates. In the case of the crushed aggregate mixes, it was found that the rapid chloride permeability of the cast specimens increased as the size of the aggregate increased. No trend was apparent for the mixes containing natural aggregates. As in the case of the abrasion test, it is concluded that rapid chloride permeability results raise no concerns regarding the use of larger size coarse aggregates, since all values obtained are within the limits termed as low or moderate by the prevailing specifications. It is reiterated that the variability in the test results reflect the limitations of the standard test procedure when larger size coarse aggregate mixes are investigated, since the test discs for such mixes are cored out of larger specimens.

It was also found that most of the mixes cast with microsilica and crushed aggregates had a larger permeability rate than the corresponding mixes that included natural aggregates. The most significant trend observed was that mixes containing abused microsilica had the highest rate of permeability, whereas mixes including undensified microsilica the lowest.

6.3 Practical Significance of Findings

For the most part, different coarse aggregate gradations did not impact significantly the environmental properties of concrete examined. Differences observed were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. It is, therefore, concluded that coarse aggregate gradation had little effect on the environmental properties of concrete. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the environmental properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes.

It was found earlier that the compressive and flexural strengths of abused microsilica did not differ much from that of densified microsilica. The abused microsilica was intended to represent the worst possible situation that might arise in the field. The clumps formed during the abusing process were evidently broken using a trowel; therefore, it was concluded that the clusters of microsilica that are formed in the field due to moisture can easily be broken during the mixing process. This conclusion is brought into question, at least in the case of abused microsilica, by the rapid chloride permeability results obtained. Nonetheless, all values obtained are within the limits termed as low or moderate by the prevailing specifications. It is recommended that the microsilica should be stored for limited time only, in areas of low humidity at room temperatures, and that the mixing process should be careful and thorough, to limit the amount of densification at mixing, and to permit any bonds to be broken.

6.4 Recommendations for Further Research

In view of the natural variability of concrete test results, further research is highly desirable. It is recommended that the number of specimens tested be increased in order to improve the confidence level. The blends conforming to the No. 467 and the No. 357 gradations can be refined further through experimentation. The mineralogical characteristics of the aggregates should be examined using appropriate procedures that were beyond the scope of this project, and should be controlled by exploring the most suitable sources of aggregates. The suitability of microsilica types, other than the undensified, must be explored by a larger series of tests focusing exclusively on the environmental properties of concrete mixes containing these materials.

6.5 Implementation Plan

IMPLEMENTATION STEPS & TIME FRAME: The recommendations above can be implemented immediately by any ODOT District including microsilica or larger sized aggregates in its concrete mix design.

EXPECTED BENEFITS: The main benefits from this research will derive from the use of densified microsilica from respected manufacturers in pavement and bridge construction, as well as the increased cement efficiency and economy expected to be associated with the use of larger sized aggregates, of appropriate mineralogical composition, provided such practices are also justified based on the results from other, more specific and extensive, studies.

EXPECTED RISKS, OBSTACLES, & STRATEGIES TO OVERCOME THEM: It is anticipated that there may be a hesitation to abandon what may currently be the only test conducted at the ODOT laboratory in order to assure the quality of densified microsilica, or to innovate by using larger sized aggregates in pavement and bridge construction. It is suggested that ODOT make more stringent its microsilica procurement process, in order to ensure that material is obtained from reliable manufacturers alone, whose declarations of suitability may be accepted with confidence. It is also suggested that ODOT make more stringent its mineralogical composition requirements when envisaging the use of larger size aggregates. The possibility of bonding the manufacturer to the performance of the pavement or bridge concerned may also be considered.

OTHER ODOT OFFICES AFFECTED BY THE CHANGE: Any ODOT District including microsilica or larger sized aggregates in its concrete mix design.

PROGRESS REPORTING & TIME FRAME: To be determined by ODOT.

TECHNOLOGY TRANSFER METHODS TO BE USED: The Final Report from this study will be made available to interested parties, either in hard copy, or in electronic form, the latter to include either Word .doc format or pdf. At least one refereed journal paper documenting this investigation will be prepared within a year from the completion of this contract.

IMPLEMENTATION COST & SOURCE OF FUNDING: There are no costs associated with implementing the findings of this study.

REFERENCES

Bartos, P. (1992), "Fresh Concrete: Properties and Tests," Elsevier Science Publishers, Amsterdam, Netherlands.

Gaynor, R. and Meininger, R. (1967), "Investigation of Aggregate Durability in Concrete," Highway Research Record 196, Highway Research Board, Washington, D.C., pp 25- 40.

Ioannides, A.M. and Deshini, A. (2006), "Fineness of Densified Microsilica and Dispersion in Concrete Mixes," Report No. FHWA/OH-2006/17, Ohio Department of Transportation, Columbus, OH.

Ioannides, A.M. and Mills, J.C. (2006), "Larger Sized Coarse Aggregates in Portland Cement Concrete Pavement and Structures," Report No. FHWA/OH-2006/10A, Ohio Department of Transportation, Columbus, OH.

Malhotra, V.M. and Mehta, P.K. (1996), "Pozzolanic and Cementitious Materials," Gordon and Breach Publishers, Amsterdam, The Netherlands.

Mehta, K. and Monteiro, P. (1993), "Concrete, Structure, Properties and Materials," Prentice-Hall, Englewood Cliffs, NJ, pp. 49-79.

Neville, A.M. (1995), “Properties of Concrete,” Longman Group Limited, Essex, England.

O’Doherty, J. (1987), “Materials and Technology Engineering and Science,” Issue no. 7, Materials and Technology, Michigan Department of Transportation, Michigan.

Sasatani, T., Torii, K. and Kawmura, M. (1995), “Five-Year Exposure Test on Long-Term Properties of Concretes Containing,” in “Fly Ash, Blast-Furnace Slag, and Silica Fume in Concrete,” Proceedings, Fifth International Conference, Milwaukee, WI (Vol. I), Malhotra V.M. (editor), American Concrete Institute, Detroit, MI, pp. 283-296.

Soroka (1980), “Portland Cement Paste and Concrete,” Chemical Publishing Company Inc, New York, NY.