ABRASION-RESISTANT CONCRETE MIX DESIGNS FOR PRECAST BRIDGE DECK PANELS

Final Report

SPR 622

Oregon Department of Transportation

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by

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16. Abstract

The report documents laboratory investigations undertaken to develop high performance concrete (HPC) for precast and pre-stressed bridge deck components that would reduce the life-cycle cost of bridges by improving the studded tire wear (abrasion) resistance and the durability of bridge decks. Phase I of the project involved an initial investigation of candidate mixtures incorporating type I portland cement, supplementary cementitious materials (silica fume, slag, and fly ash), natural aggregate (river gravel), and crushed rock. Three laboratory-curing methods were utilized in this effort including ordinary water curing and two accelerated steam-curing methods. A Pilot Study was undertaken to refine the laboratory steam curing methods as well as to determine if the duration of Oregon Department of Transportation's (ODOT's) field curing requirement for cast-in-place (CIP) bridge decks could be shortened. Phase II of the project utilized the findings from Phase I and the Pilot Study to develop HPC mixtures that had improved abrasion resistance and durability characteristics relative to a newly-specified ODOT bridge deck mixture. The mixtures investigated in Phase II incorporated type III portland cement and the same supplementary cementitious materials and natural aggregate that were used in Phase I. The silica fume content was varied in Phase II (i.e., 4%, 7%, and 10%), but held constant at 4% in Phase I.

Findings from Phase I indicated that mixtures containing a combination of silica fume and slag clearly had superior abrasion resistance, durability characteristics, and compressive strength relative to the mixtures containing a combination of silica fume and fly ash, and that the mixtures with crushed rock clearly outperformed those with river gravel in terms of abrasion resistance and strength characteristics (durability characteristics were essentially unaffected by aggregate type). Findings from the Pilot Study indicated that steam curing followed by application of a curing compound prior to ambient curing provided strength characteristics similar to that of concrete cured continuously in water, and that the 14-day field curing requirement for CIP bridge decks could be shortened to as few as 3 days without sacrificing 28-day strength provided that adequate measures are taken to ensure that the HPC is kept in saturated conditions.

Three HPC mixtures were developed under Phase II of the study that provided better wear resistance, durability characteristics, and strength properties than ODOT's newly specified HPC for bridge decks (fabricated with fly ash at a w/b ratio of 0.30). All contained silica fume and slag and had w/b ratios of 0.30 or less. One did not contain entrained air. Overall, the mixture with the same mix design as ODOT's newly specified HPC, except with slag in lieu of fly ash, provided the best balance between initial costs and enhanced performance.

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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	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	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	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

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	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

Studded tires have been attributed to pervasive pavement and bridge deck wear in the United States and other countries since their introduction in 1960s. Estimates of the impact of studded tires on concrete pavement have been made, and similar impacts on concrete bridge decks are expected. Studded tires cause considerable wear to concrete surfaces, even when the concrete is of good quality. The ruts caused by the studs lead to reduced pavement life and, consequently, increased pavement life cycle costs. The life expectancy of portland cement concrete (PCC) pavements at 120,000 ADT based on a wheel rut depth of 19 mm is less than 10 years (*Brunette and Lundy 1996*).

Pavement wear rate has been increasing with the increased adoption of studded tire use among the populace exposed to snowy and icy driving conditions. Although studded tires do provide increased traction and safety in these conditions, the ruts, after attaining the critical depth, present themselves as a safety hazard by causing an increase in splash-and-spray and hydroplaning during rainy driving conditions. The rehabilitation of highways with ruts attaining critical depth becomes imperative to ensure driving safety. The estimated annual cost for increased pavement wear attributed to use of studded tire in the state of Oregon has increased from $1.1 million in 1974 to $42 million in 1994, and this trend continues (*Brunette and Lundy 1996*).

At present, the debate to ban the use of studded tires at the cost of safety during long winter driving conditions in states like Oregon has not reached any conclusion. The researchers in industry and academia have only one option at present; and that is to explore the possibilities of developing wearing course materials that are more resistant to damage caused by studded tires.

1.2 BACKGROUND

Degradation of the concrete decks from wear due to the studded automobile tires require costly, and often premature, replacement or rehabilitation of bridge decks. The damage caused by studded tires is due to the dynamic impact of the small tungsten carbide tips of the studs, of which there are approximately 100 in each tire (*ACI 2008*). Efforts have been made to study the properties of existing concrete as related to studded tire wear and develop more wear-resistant types of concretes. Although the reported research results show promise, no affordable concrete has yet been developed that will provide the same service life of the pavements exposed to studded tires as compared to pavements made of existing concrete and exposed to un-studded rubber tires.

Polymer cement concrete and polymer-fly ash concrete provide better resistance to wear at the cost of decreased skid resistance. Steel fiber concrete provides better wear resistance, but abraded loose steel fibers can cause additional scour of the concrete pavement, and the exposed fibers can adversely affect the tire wear (*ACI 2008*). High performance concrete (HPC) is intended to meet the design engineer's minimum requirements for compressive strength and to enhance the long-term properties of the concrete such as durability, abrasion resistance, low permeability to protect against corrosive-ion attack on reinforcing steel, and cracking resistance.

It is well known that adding approximately 7% silica fume to the concrete significantly increases the strength and reduces the permeability of the concrete. However, real-life experiences reveal that this improvement often comes with an increased propensity for early-age cracking in the cast-in-place (CIP) bridge decks that essentially negates the benefits of lower permeability and high strength. In fact, the Oregon Department of Transportation (ODOT) has changed its bridge deck concrete specifications to limit the strength of the concrete in order to reduce the level of cracking seen in the field.

Precast components allow bridge elements to be manufactured under controlled factory conditions, which should provide a higher level of quality. Also, prefabricated components can be assembled more quickly at a bridge site without the need to wait for fresh concrete to reach threshold strengths before continuing construction activities. Precast deck panels could allow HPC designed for abrasion resistance to be used for bridge decks while maintaining production controls to minimize cracking.

1.3 OBJECTIVES

The overall objective of this project was to develop one or more materials systems for precast and pre-stressed bridge deck components that would reduce the life-cycle cost of bridges by improving the studded tire wear (abrasion) resistance while maintaining the durability of bridge decks. Specifically, the research objectives were to:

- Develop a hardened concrete mixture that is more resistant to abrasion than the conventional ODOT bridge deck mixture.
- Develop a hardened concrete mixture that passes less than 1,000 coulombs during the rapid chloride permeability test.

1.4 SCOPE

The project was divided into three main parts: 1) Phase I, 2) Pilot Study, and 3) Phase II. A field study was also originally planned, but the research efforts were redirected following Phase I of the project. Hence, the field study was not undertaken as part of this project.

Phase I involved an extensive literature review to investigate past research on HPC with emphasis on abrasion and corrosion resistance followed by a laboratory study to develop such a mixture for Oregon through investigation of factors including: 1) varying combinations of supplementary cementitious materials (i.e., silica fume plus slag versus silica fume plus fly ash); and 2) two different coarse aggregate types (i.e., crushed versus natural aggregate). Mixtures were tested following water curing and steam curing. All the specimens were tested for various response variables (i.e., compressive strength, abrasion resistance, chloride ion penetration resistance, and freeze-thaw durability).

Different curing types were investigated in a Pilot Study to obtain the best curing method that could be adopted in the field and at the same time give results similar to that obtained by water curing.

Phase II focused more on various levels of silica fume and their effect on the properties of HPC. These mixtures were tested for the same response variables as in Phase I except for freeze-thaw durability.

2.0 LITERATURE REVIEW

An extensive literature review was conducted to obtain information pertaining to characteristics of concrete (e.g., mix design, quality and properties of constituent materials, construction practices, etc.) that makes it highly resistant to abrasion. Additionally, information pertaining to costs of materials and construction practices as well as feasibility of construction practices was sought. With the understanding that precast and pre-stressed panels constructed under controlled factory conditions may provide opportunities to use concrete mixes with desirable performance that would otherwise be difficult to use in cast-in-place construction, the literature review paid particular attention to concrete characteristics that have the potential to provide superior performance when combined with precast panel technology.

This section provides a brief synopsis of the findings pertaining to a description of high performance concrete (HPC), a description of constituent materials commonly used in HPC, an overview of previous studies on HPC, and examples of implementation of HPC in bridge projects.

2.1 HIGH PERFORMANCE CONCRETE (HPC)

According to the American Concrete Institute, " High performance concrete (HPC) is defined as a concrete meeting special combination of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices" (*2008*). A normal strength concrete having properties such as high durability and low permeability can be called a HPC. These requirements may involve enhancements of the following:

- Ease of placement and completion without segregation
- Long-term mechanical properties
- Early-age strength
- Toughness
- Volume stability
- Long life in severe environments

According to NCHRP Report 584, compressive strength specified for the precast concrete deck panels at 28 days is 6,200 psi to 6,500 psi *(Badie and Tadros 2008)*. Apart from strength criteria, HPC should have high durability capable of withstanding corrosion of embedded steel and other severe service environments. The other structural characteristics of HPC include high abrasion resistance, volume stability and toughness, and impact resistance. The concrete must be able to withstand the effects of various agents such as heating and cooling, wetting and drying, freezing and thawing, etc. This again differs depending on where the structure is being constructed and the environmental factors affecting it. HPC must be capable of inhibiting bacterial and mold growth. It also needs to be resistant to chemical attack.

2.2 CONSTITUENTS OF HPC

High performance concrete constitutes a combination of various materials including cement, supplementary cementitious materials, both fine and coarse aggregates, and admixtures that reduce water and improve workability. This section provides brief descriptions and benefits of the materials used to fabricate the concrete mixtures investigated in this study.

2.2.1 Cement

The cement used in HPC plays a key role in the abrasion resistance and durability characteristics of the HPC. The rate of early strength development depends, in part, on cement composition and fineness. Cements are manufactured to conform to one of several specifications including ASTM C 150 (Standard Specification for Portland Cement), AASHTO M 85 (Specification for Portland Cement), ASTM C 595 (Specification for Blended Hydraulic Cements), AASHTO M 240 (Specification for Blended Hydraulic Cements), or ASTM C 1157 (Performance Specification for Hydraulic Cements). ASTM C 150 includes eight types of portland cements, AASHTO M 85 includes five types of portland cements, ASTM C 595 and AASHTO M 240 include five primary classes of blended hydraulic cements, and ASTM C 1157 includes six types of hydraulic cements. All portland and blended cements are hydraulic cements.

Selection of the type of cement used for HPC depends on the desired characteristics of the HPC and the environment in which it will be used. For high strength concrete, the cement should be selected such that it attains 7-day mortar-cube strength of approximately 4,350 psi *(Kosmatka, Kerkhoff, and Panarese 2002)*. However, selection of the cement should also be based on performance measures of the hardened concrete such as compressive strength, abrasion resistance, and durability characteristics.

2.2.2 Supplementary Cementitious Materials (SCMs)

The literature revealed that several supplementary cementitious materials (SCMs) have been used to produce high performance concrete, including fly ash, slag, silica fume, and natural pozzolans such as calcined clay and metakaolin. However, the majority of HPCs incorporated fly ash, slag, or silica fume, or combinations of these materials. These are discussed in more detail in the following paragraphs.

2.2.2.1 Fly Ash

Fly ash is the fine material that results from the combustion of pulverized coal in a coal-fired power plant. Fly ash reduces permeability and chloride diffusivity and, hence, increases resistivity to chloride ion attack, making it a beneficial material in concrete that is exposed to chlorides (e.g., bridge decks) *(Masad and James 2001)*. Nasser and Lai *(1992)* found that 20% replacement of cement with Class C fly ash containing 4 to 6% air content improves the resistance to freezing and thawing. However, it was found to decrease when 35-50% of Class C fly ash was used in concrete containing 6% air. For high strength concrete, use of Class C fly ash can lead to higher 28-day and 91-day compressive strengths and higher 7-day and 28-day flexural strengths at lower cementitious contents as compared with concrete containing no fly ash *(Tikalsky et al.*

1988). According to Naik et al. *(1994)*, concrete incorporating Class C fly ash offers more abrasion resistance than Class F fly ash concrete with 35% cement replacement. In another study *(Naik, Singh, and Ramme 2002)*, it was found that concrete abrasion resistance was not greatly influenced by inclusion of Class C fly ash with 40% of total cementitious materials.

In summary, fly ash produces the following properties in concrete as compared with a similar mixture containing no fly ash: 1) equal or greater flexural and compressive strengths; 2) equal or better workability and cohesiveness; 3) equal or greater resistance to abrasion; and 4) improved long term durability to provide serviceability and performance throughout the life of the structure *(Tikalsky et al. 1988)*. It also improves workability, decreases bleeding, reduces heat evolution, decreases permeability, has minimal effect on modulus of elasticity, and has variable effects on creep and shrinkage.

2.2.2.2 Slag

Ground granulated blast-furnace slag (GGBFS), also called slag, is made by rapidly quenching molten blast-furnace slag and grinding the resulting material into a fine powder. Slag has cementitious properties which can be a major factor in increasing strength. Slag also reduces the water demand by 1 to 10%, which makes it possible to reduce the water-cement ratio (w/c) to a lower value *(Kosmatka, Kerkhoff, and Panarese 2002)*.

The performance of concrete, in terms of its physical properties, durability, and ability to place it can be enhanced by the use of slag-blended cements or through addition of ground granulated blast-furnace slag. Properly proportioned and cured slag concretes will control alkali-silica reactions, impart sulphate resistance, and greatly reduce chloride ion penetration and heat of hydration.

2.2.2.3 Silica Fume

Silica fume, also known as condensed silica fume or microsilica, is a very fine pozzolanic material produced as a by-product in the production of silicon or ferro-silicon alloys. The use of silica fume can result in rapid chloride permeability values of less than 500 coulombs when tested in accordance with ASTM C 1202-10 (Rapid Chloride Penetration Test) whereas a maximum value of 1,000 coulombs is often specified (ACI 2008). Whiting and Detwiler observed that increasing the silica fume content up to approximately 6% of the total cementitious materials reduced the chloride diffusivity. However, above approximately 6%, a much greater addition of silica fume was needed to effect the same change *(1998)*. The abrasion resistance of HPC incorporating silica fume is high. This makes silica fume concrete particularly useful for spillways and stilling basins, and for concrete pavements or concrete pavement overlays subjected to heavy or abrasive traffic *(Holland 2005)*. In summary, when used in concrete, silica fume increases durability, abrasion resistance, and reduces bleeding *(Holland 2005)*.

2.2.3 Aggregates

Good aggregates should be selected to ensure proper consolidation of the concrete mix so as to prevent segregation when the mix is subjected to vibration. The compressive strength of very high strength concretes is highly dependent on the type of aggregate used. The best workability can be achieved when larger aggregates are used. However, smaller aggregates provide more bonding area between mortar and aggregate resulting in higher compressive strengths *(Mak and Sanjayan 1990)*. According to the Washington Department of Transportation (WSDOT), smaller coarse aggregates are being used in concrete to increase freeze-thaw resistance and achieve higher compressive strength *(Masad and James 2001)*. In addition, according to Laplante et al, coarse aggregate is the most important factor affecting the concrete abrasion resistance *(1991)*. For high strength concrete according to ACI 211.4R, fine aggregates with a fineness modulus in the range of 2.5 to 3.2 are preferable for high-strength concrete (for 70 MPa or greater). Also, they should be at least 25% siliceous to be abrasion resistant *(Masad and James 2001)*.

HPC has specific aggregate size, shape, surface texture, mineralogy, and cleanliness requirements *(Holland 2005)*. According to Aitcin and Mehta *(1990)*, the mineralogy and the strength of the coarse aggregate control the ultimate strength of the concrete. Lawler and Krauss suggested that aggregates with a low modulus of elasticity, low coefficient of thermal expansion, and high thermal conductivity result in reduced shrinkage and thermal stresses *(2005)*. Higher strengths can also sometimes be achieved through the use of crushed stone aggregate rather than the rounded-gravel aggregate *(Kosmatka, Kerkhoff, and Panarese 2002)*. In general, equi-dimensional, rough textured and harder aggregates are preferred to give high strength.

2.2.4 Previous Studies

Several researchers have investigated high performance concrete. Some of the important findings obtained from these studies are summarized in this section.

WSDOT developed some guidelines for high performance concrete and conducted a laboratory study by comparing seven different mixture designs *(Masad and James 2001)*. The researchers found that including 5 to 6% air entrainment and maintaining a w/c ratio of 0.35 increased freeze-thaw durability. Adding fly ash also increased freeze-thaw durability. Based on the testing results, the researchers concluded that low chloride permeability could be achieved by using a low w/c ratio and including fly ash.

A study was conducted in Montana to come up with the optimum HPC mixture design for bridge decks using locally available raw materials *(Lawler and Krauss 2005)*. In this study they developed 14 mixture designs by varying the quantity of different supplementary cementitious materials. They found that the combination of the slag-blended cement, Class F fly ash, and silica fume gave excellent performance across all the durability tests, standing out particularly for low drying shrinkage.

A four year study was conducted by the researchers at North Carolina State University, the University of Arkansas, and the University of Michigan to evaluate the mechanical behavior of HPC *(Zia et al. 1993)*. The goal of this study was to significantly improve the criteria for HPC in highway applications. The study was broken down into three categories of Very Early

Strength Concrete (VES), High Early Strength Concrete (HES) and Very High Strength Concrete (VHS). Twenty one HPC mixtures incorporating different types of aggregates (marine marl, crushed granite, dense crushed limestone, and washed gravel) were studied in detail. From this study, the authors concluded that high quality aggregates, high quality cement, and air entraining agents were required to produce HPC.

A study was conducted by the members of Structural Engineering Research Centre at Chennai to observe the properties of HPC when the cement was partially replaced by ground granulated blast furnace slag versus a control mixture design *(Rajamane et al. 2001)*. It was concluded from this study that the addition of GGBFS, as a partial replacement of cement, causes a reduction in the compressive strength at early ages, but at the later ages HPCs with GGBFS had nearly the same strength as that of HPC without GGBFS.

In other studies, efforts were taken to study the abrasion resistance properties of HPC in more detail. The primary factors affecting the abrasion resistance of concrete are compressive strength, aggregate properties, finishing methods, use of toppings, and curing *(Naik, Singh, and Hossain 1994)*. Strong concrete has more resistance to abrasion than that of weak concrete *(Atis 2002)*. It has been shown that by carefully selecting aggregates, it is possible to achieve the same abrasion resistance on high strength concrete (on the order of 14,500 - 17,500 psi) as on granite *(Holland 1990)*. According to Liu *(1981)*, concrete of the lowest practical water-cement ratio and the hardest available aggregates should be used for new construction or repair of hydraulic structures where abrasion is of major concern.

Laplante, Aitcin and Vezina *(1991)* studied 12 HPC mixtures and concluded that coarse aggregate is the most important factor affecting concrete abrasion resistance and inclusion of silica fume in the concrete mixture increased the abrasion resistance of concrete. Also, the abrasion resistance of the concrete was strongly influenced by the abrasion resistance of its constituent mortar and coarse aggregate. It was found that a very low water-to-cement ratio of about 0.30 can make the concrete as highly abrasion resistant as that of high performance rocks like trap rock and fine-grained granite.

In a study conducted by Atis, mixtures were designed based on the principle of minimizing the porosity *(2003)*. Atis concluded that an increase in compressive strength and a decrease in porosity yielded a higher abrasion resistance. Additionally, a constant compressive strength and an increase in porosity yielded a decrease in abrasion resistance.

Another study observed the effect of fly ash on the abrasion resistance of concrete *(Naik, Singh, and Hossain 1994)*. Concrete mixtures having 50% cement replacement with Class C fly ash attained sufficient strength required for structural applications. All the concrete mixtures used in this study showed excellent abrasion resistance when tested in accordance with ASTM C-944.

Holland and Gutschow studied the high strength concrete incorporating silica fume used for the repairs on the Kinzua Dam stilling basin and Los Angeles River projects *(1987)*. Some of the observations noted by the authors pertaining to the placement of the concrete with silica fume were: 1) slump control can be very sensitive in hot weather because of the effective life of some high-range water-reducing admixtures; 2) pozzolans enhance the workability of concretes containing silica fume; 3) concrete with silica fume is more plastic and cohesive than conventional concrete and less susceptible to aggregate segregation and bleeding; 4) plastic shrinkage appears more likely than with conventional concrete; and 5) the occurrence of reflection cracking was minimal.

Horszczaruk *(2005)* studied the abrasion resistance of nine different high strength concrete (HSC) mixtures with regards to compression strength, modulus of elasticity, fiber material, and dimensions. The mixtures were made with portland cement and blast furnace cement, silica fume, basalt aggregate, and superplasticizers. A few of the mixtures contained fibers and two of the mixtures were modified with latex. They found that the latex additive did not increase the abrasion resistance of concrete. The HSC with added PVC fibers improved the abrasive resistance of concrete.

A study by Fernandez and Malhotra *(1990)* showed that the abrasion resistance of the concrete containing slag was inferior to that of the concrete made with portland cement alone.

2.2.5 Implementation of HPC

Several State DOTs are becoming attracted to the benefits of using HPC. It has been used extensively in states such as Ohio, Nebraska, New Mexico, Maryland, and Texas. The Georgia Department of Transportation (GDOT) viewed HPC as a concrete having significant applications of providing longer spans and shallower beams for pre-stressed concrete beams for highway bridges in Georgia. The deck concrete was specified to have a compressive strength of 7,000 psi at 56 days and a maximum chloride permeability of 2,000 coulombs at 56 days *(Liles Jr. 2003)*.

Fifteen HPC bridge decks have been placed in Minnesota since 1997. Few of them, though with a specified compressive strength of 4,300 psi at 28 days, have faced the problem of cracking due to improper curing *(Pruski, Cox, and Ralls 2003)*.

The need to potentially extend the service life of bridges and pavements, while reducing maintenance and replacement costs influenced Nebraska Department of Roads to adopt HPC in 1995, when they designed their first bridge incorporating HPC. Their project was aimed at obtaining a specified concrete strength of 8,000 psi at 56-days, while the required design strength was 4,000 psi *(Beacham 1999)*.

HPC bridge projects in other states and the results of various HPC research projects convinced the Texas Department of Transportation (TxDOT) to modify their specification and add supplementary cementitious materials (SCMs) to make concrete more durable. Class S (HPC) concrete for the bridge deck specified by the TxDOT has a minimum compressive strength requirement of 4,000 psi at 28 days and a maximum water-to-cementitious materials ratio of 0.44, and also a provision requiring replacement of 30% of the cement with Class F fly ash. In Lubbock District of Texas, HPC was recommended to replace two deteriorated concrete bridges because of the significant use of deicing chemicals related to the 70 annual freeze-thaw cycles *(Pruski, Cox, and Ralls 2003)*.

Due to several stringent constraints, California Department of Transportation (Caltrans) opted for high performance precast concrete for pre-stressed, post-tensioned, spliced bulb-tee girders to be built across the Sacramento River in Northern California. They used a concrete mix with a water-to-cementitious materials ratio of 0.33 and a high-range water-reducing admixture. The average 10-day and 35-day strengths were approximately 10,000 psi and 11,000 psi, respectively (the highest compressive strength concrete used by Caltrans) *(Alsamman and Darnall 2003)*.

With more and more new projects coming, the trend has changed over the past decade. Not only states, but also small counties aim at decreasing the life cycle costs associated with bridges. Prince George's County in Maryland, with the goal of building 12 bridges in the next three years, would like to design more durable bridges with extended longevity and decreased long-term maintenance and repair costs at the expense of higher initial costs *(Binseel 2000)*.

The purpose of building the Rio Puerco Bridge located on Old Route 66 west of Albuquerque in 2000 was to establish the viability of HPC in New Mexico. They used cement, silica fume, and Class F fly ash as cementitious materials. A 3-day steam curing period was implemented to achieve concrete strength of 7,500 psi and 10,340 psi at release and at 56 days, respectively. Although there was a 10% increase in the overall construction cost of bridge, it was expected to be much cheaper in long run with respect to life cycle costs *(Peterson 2003)*.

In 1997, the Ohio Department of Transportation installed their first HPC precast, pre-stressed concrete bridge as part of the Federal Highway Administration Showcase program. This bridge superstructure consisted of adjacent box girders. Use of HPC with a compressive strength of 10,000 psi enabled the span of the Ohio B42-48 section (42 in. deep by 48 in. wide) to be extended to 116 ft. In Hamilton County, over 20 HPC bridges have been built in the last ten years. Their mix design must have a water-to-cementitious materials ratio less than 0.40, maximum slump of 6 in., minimum compressive strength of 4,500 psi at 28 days, and 2 lb/y^3 of polypropylene fibers not less than 3/4 in. long to minimize plastic shrinkage cracking. It also requires 7% silica fume by weight of cement, either as a replacement or as an addition *(Mary and Miller 2001)*.

3.0 EXPERIMENT DESIGN

The findings from the literature review guided the development of experiment plans for conducting the research work presented in this report. This section describes these plans for the three parts of this study (i.e., Phase I, Pilot Study, and Phase II).

3.1 PHASE I

Preliminary tests were conducted to determine the optimum water-to-binder (w/b) ratio for all of the concrete mixtures under investigation during Phase I of the project. Findings from the literature review indicated that HPC mixtures are predominately manufactured with w/b ratios in the range of 0.20 to 0.45 *(Kosmatka, Kerkhoff, and Panarese 2002)*; hence, w/b ratios of 0.30, 0.35 and 0.40 were utilized to determine the optimum w/b ratio for Phase I. Based on the results obtained from compressive strength and flexural strength tests, a w/b ratio of 0.30 was selected.

Having selected the w/b ratio for the concrete mixtures, the primary factors that were investigated during Phase I included: 1) combination of supplementary cementitious materials (i.e., silica fume plus slag versus silica fume plus fly ash); 2) coarse aggregate type (i.e., crushed rock versus natural aggregate); and 3) methods for curing the concrete mixtures. These factors (treatments) are discussed in more detail in the following sections.

3.1.1 Experimental Matrix

The experiment design for Phase I of the study is provided in Table 3.1. It identifies the tests conducted on the hardened concrete mixtures as well as the number of specimens per test for each mixture investigated. Details of the tests are provided below in Section 4.5.

The first group in the matrix was the control mixture (ODOT Class 4350, 2002 Standard Specifications) *(ODOT 2002)*, a normal-weight concrete consisting of natural aggregate (gravel) for the coarse aggregate fraction, cement, sand, and water, plus an air-entraining agent. The control mixture was divided into three different sub-categories, each pertaining to three different curing regimes, all of which are described briefly in Section 3.1.2.3 and in more detail in Section 4.4.

The experimental mixtures (A, B, C, and D) contained, in addition to cement, sand, water and an air-entraining agent, different combinations of supplementary cementitious materials (SCMs). Descriptions of the SCMs are provided in Section 4.1. Two of the experimental mixtures contained natural aggregate (gravel), while the other two contained crushed rock, as the coarse aggregate fraction.

Table 3.1 - Phase I Experimental Matrix

			Curing Regime / Test Period	Compressive Strength (ASTM C 39; AASHTO T 22)	Chloride Ion Penetration Resistance (ASTM C 1202; AASHTO T 277)	Abrasion Resistance (ASTM C 779)	Freeze-Thaw Resistance (ASTM C 666; AASHTO T 161)	Subtotal Number of Specimens
	Gravel	ODOT Class 4350	Water: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[a]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[b]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
Silica Fume and Slag	Gravel	Experimental Mix A	Water: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[a]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[b]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
	Crushed Rock	Experimental Mix B	Water: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[a]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[b]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
Silica Fume and Fly Ash	Gravel	Experimental Mix C	Water: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[a]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[b]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
	Crushed Rock	Experimental Mix D	Water: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[a]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9
			Steam[b]: 14-day	---	---	---	3	3
			28-day	3	---	---	---	3
			90-day	3	3	3	---	9

Note: the four specimen-count columns are printed under the spanning header "Number of Specimens for:".

NOTES:

[a]Steam cure + water cure to 14 days + ambient cure to 90 days

[b]Steam cure + ambient cure to 90 days

Table 3.1 indicates that the concrete mixtures were tested at differing periods; that is, freeze and thaw at 14 days, compressive strength at 28 and 90 days, and chloride ion penetration resistance and abrasion resistance at 90 days. At 14 days, the concrete has still not attained its maturity and is quite susceptible to damage due to freezing and thawing. Concrete specimens subjected to the very severe conditions during the freeze-thaw test conducted in the laboratory might be considered as a reasonable measure of field performance. The compressive strength test conducted at 28 days is a standard test. It is believed that concrete attains approximately 90 percent of its ultimate strength in 28 days. Compressive strength was also determined at 90 days to obtain a relationship between compressive strength, abrasion resistance, and chloride ion penetration resistance of the concrete. For each mixture, tests were conducted on at least three specimens for each test to obtain an estimate of the variance in the test results.

3.1.2 Treatments

Three different treatments were investigated in Phase I; namely, aggregate type, combination of supplementary cementitious materials, and curing method. Each treatment is described in the following sections, while Section 4.1 provides additional information about the materials.

3.1.2.1 Aggregates

The precast industry in Oregon commonly uses river gravel as coarse aggregate in their precast slabs and members due to abundance and cheap availability of river gravel; Oregon is a state with numerous rivers where naturally occurring gravels are found in abundance. However, findings from the literature review suggested that the abrasion resistance of the concrete is directly proportional to the hardness of the aggregate used in the mixture. It was found in the literature that use of crushed aggregate such as basalt increased the abrasion resistance of concrete several-fold *(Laplante, Aitcin, and Vezina 1991)*. Therefore, in this research effort, it was decided to compare the abrasion resistance obtained by the use of conventional river gravel as coarse aggregate in the HPC concrete to that obtained by the use of crushed rock. It was reasoned that if the use of more costly crushed rock significantly increased the abrasion resistance of the concrete, it may be more economical from a life cycle standpoint to use crushed rock rather than river gravel. Hence, the two treatments regarding aggregate type included river gravel versus a crushed rock.

3.1.2.2 Cementitious Materials

According to the literature, silica fume reduces the permeability of concrete, thus improving the protection of steel imbedded in the concrete against corrosion. It also increases the early-age compressive strength and abrasion resistance of the concrete, and improves certain fresh properties (e.g., reduced bleeding). To satisfy the requirement of the early-age strength (i.e., 1 day) of pre-cast concrete, it was important to incorporate silica fume. Therefore, silica fume was included in the experimental mixtures. Silica fume content in Phase I was held constant at 4%.

In addition, fly ash and slag both play an important role in improving durability of HPC by reducing permeability and by increasing abrasion resistance and freeze-thaw resistance. Slag also helps in mitigating the effect of alkali silica reactivity and sulfate attack. Slag has cementitious properties while fly ash is pozzolanic in nature. Nevertheless, there remains a need to study the effect of supplementary cementitious materials on the abrasion of concrete caused by use of studded tires. Therefore, efforts were taken in Phase I of the study to separately investigate the effects of combinations of silica fume and slag and combinations of silica fume and fly ash.

3.1.2.3 Curing

Curing plays an important role in improving the durability of concrete structures by preventing the internal water of the concrete from evaporating and thus enhancing or aiding the hydration process of the cement in concrete. There are various ways of curing concrete structures, among which water curing is the most effective method. Since manufacturers of pre-cast concrete members (e.g., bridge girders) require high early strength for high production purposes, the manufacturers raise the concrete temperature through steam curing, thereby aiding the cement hydration process. Though by steam curing one can easily attain a compressive strength of nearly 4,500 psi at 1 day, ultimate strength is either the same or less than that obtained by water curing for 28 days.

In this project comparisons were made between three different curing regimes: 1) water curing at 73±3°F (23±2°C) for 28 days and beyond up to 90 days, as required, 2) steam curing followed by water curing for 14 days followed by ambient curing for 28 days and beyond up to 90 days, as required (Steam Curing Method A), and 3) steam curing followed by ambient curing up to 90 days (Steam Curing Method B). Section 4.4 provides additional details of the curing methods utilized in this study.

3.1.3 Response Variables

All of the concrete mixtures were tested for four different properties of hardened concrete. These are categorized under primary and secondary response variables according to research interest.

3.1.3.1 Primary Response Variables

The main aim of the project was to develop a mixture design for HPC with improved abrasion resistance and reduced permeability, thereby increasing the durability of the concrete. Therefore, abrasion resistance and chloride ion penetration resistance (permeability) properties of the concrete mixtures were the primary factors investigated, or the primary response variables, also referred to herein as performance measures.

Abrasion Resistance

According to the American Concrete Institute 2009, abrasion resistance of concrete can be defined as “ability of a surface to resist being worn away by rubbing and friction”. Abrasion, a mechanical property of concrete, is basically a surface phenomenon. The paste at the surface of newly-placed concrete abrades away quickly and exposes the aggregate, which further gets damaged due to impact and abrasion. Abrasion causes surface wear which aggravates various problems like chloride ion diffusivity and corrosion of embedded steel bars, subsequently leading to failure of structures. Abrasion of different concrete structures takes place due to different factors such as damage to dam spillways due to water borne-particles, abrasion of floors due to production operations and rubbing by foot, and abrasion of pavements and bridge deck slabs due to vehicular traffic, particularly by vehicles equipped with studded tires. Some of the factors that affect abrasion are water-to-cement ratio, compressive strength, finishing technique, curing, types of aggregates, among others.

This research effort was mainly focused on the abrasion of concrete bridge deck slabs caused by studded tires. When vehicles travel on bridges and highways, the tires of vehicles cause wear of the concrete surface due to friction between the surface and tire. Abrasion of concrete is more prominent in the late fall, winter, and early spring in areas that allow studded tires on vehicles. In order to reduce abrasion of concrete, efforts were taken to develop high performance concrete that is resistant to such abrasion.

Chloride Ion Penetration Resistance

Permeability is a general word which refers to the amount of water or other substances (e.g., ions, gas, and liquids) that can penetrate a material such as concrete. This research was mainly concerned with chloride ion permeability. Generally, chlorides are introduced into the deck slabs through deicing salts and sea water. Porous concrete allows water containing chloride ions to enter into the concrete and corrode the embedded steel reinforcement, thereby increasing the chance of concrete failure and, hence, considerably reducing the service life of the concrete structure. In other words, the higher the permeability of the concrete, the less durable it tends to be. Permeability of concrete is affected by the size and arrangement of pores, and the interfacial transition zone of concrete, paste quality, and aggregate gradation. Permeability of concrete can be improved by the use supplementary cementitious materials like silica fume, fly ash, and slag.

3.1.3.2 Secondary Response Variables

Two other hardened concrete properties of interest were freeze-thaw resistance and compressive strength. Freeze-thaw resistance is another measure of concrete durability whereas compressive strength has been correlated with abrasion resistance. Hence, these two properties were considered as secondary response variables in Phase I of this study.

Freeze-Thaw Resistance

Freeze-thaw resistance is defined as the ability of concrete to withstand cycles of freezing and thawing. When the concrete is exposed to alternate cycles of freezing and thawing, water inside the concrete pores alternatively expand and contract creating hydraulic pressures which ultimately leads to detorioration of concrete. Some of the factors that affect freeze-thaw resistance are air entrainment, void spacing factor, aggregate durability, and properties of the paste. In Oregon, freeze-thaw cycling is common in the mountainous regions and in the high desert region of central and eastern Oregon.

Compressive Strength

Compressive strength can be defined as, "The maximum resistance that a concrete specimen will sustain when loaded axially in compression in a testing machine at a specified rate" *(ACI 2002)*. It is the basic and most important parameter for assessing the quality of concrete. Historically, high strength was considered as a sign of better concrete. In today's world, higher strength concrete does not necessarily equate to a highly durable concrete. Still, some factors such as abrasion resistance and chloride ion permeability are directly proportional to compressive strength. Compressive strength still plays an important role in practical applications where durability is a significant concern.

3.1.4 Mixture Designs

3.1.4.1 Overview

A total of five mixture designs were developed in accordance with ACI 211.1-91-R, 2002. The first mixture design was developed to meet the requirements of the ODOT 2002 Standard Specifications and served as the control mixture for comparison with the mixture designs for the experimental mixtures. These were developed in an attempt to exceed the performance of the control mixture in terms of abrasion and chloride ion penetration resistance. The mixture designs are described in detail in the following two sections.

3.1.4.2 Mixture Designs for Control Mixture

The required criteria of minimum compressive and flexural strength, air content, cement content, water-to-cement ratio (w/c ratio), etc. for the control mixture were set according to the ODOT 2002 Standard Specifications for an ODOT Class 4350 concrete mixture for bridge deck panels. Several trials were required to determine the optimum w/c ratio that would provide the highest compressive strength and satisfy the requirement for flexure strength.

The final concrete mixture design for the control mixture was developed after several trials. The nominal maximum size of aggregate for the control mixture was kept at 3/4 inch, slump was targeted at 4 inches, and the entrained air content for severe condition of exposure was determined to be 6%. Several trials were required to determine the optimum dose of air entraining agent to achieve 6% air content. Type I cement and sand with a fineness modulus of 3.0 were used in the mixture. Once the optimum dose of air entraining agent was determined, three mixtures with water-to-cement ratios of 0.30, 0.35, and 0.40 were cast, cured, and tested for fresh and hardened concrete properties. Tests conducted on the fresh concrete included determination of unit weight, air content, slump, density and the temperature of the concrete. Tests conducted on the hardened concrete included determination of compressive strength and flexural strength. A summary of results is given in Table 3.2. Based on the results obtained from the laboratory tests and the requirements of the ODOT specifications, the mixture design with a w/c ratio of 0.30 was selected for the final mixture design for the control mixture as shown in Table 3.3. Appendix A provides details of the mixture design, whereas Appendix B provides details of the test results.

3.1.4.3 Mixture Designs for Experimental Mixtures

The mixture design for experimental mixtures was selected on the basis of high compressive strength through an extensive literature review. The mixture design was similar to that used by the Morse Brothers, Inc. (now Knife River). The basic mixture design was the same for all four experimental mixtures except that slight modifications were made to the base mixture design to account for different specific gravities of the two coarse aggregates used. All mixtures were comprised of 4% silica fume and 30% slag or fly ash. The ratio of the percentage of fine aggregate to coarse aggregate was kept at 40:60. Experimental Mix A was similar to that used by Morse Brothers and contained 30% slag, natural sand, and river gravel. Experimental Mix B had crushed rock instead of gravel along with 30% slag and natural sand. Similarly, Experimental Mixes C and D contained 30% fly ash instead of slag, along with gravel and crushed rock, respectively. Table 3.3 provides a summary of the mixture, while Table 3.4 gives the details of nomenclature used for each individual design.

Table 3.2 - Flexural and Compressive Strength Test Results for the Control Mixture

Materials	Trial		
	1	2	3
w/c ratio	0.3	0.35	0.40
Cement	900	771	675
Coarse aggregate	1648	1648	1648
Fine aggregate	970	1070	1145
Water	270	270	270
Compressive Strength at 28 days, psi	5970	5240	3500
Flexure Strength at 28 days, psi	670	510	510

Table 3.3 - Summary of Mixture Designs for Phase I

Mix Design	Units	Control	Exp A	Exp B	Exp C	Exp D
Max. size of aggregate used	-	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.
Max. w/b ratio	-	0.30	0.30	0.30	0.30	0.30
Total cementitious content	lb	900	800	800	800	800
Cement	lb	900	528	528	528	528
Fly ash	lb	0	0	0	240	240
GGBFS (slag)	lb	0	240	240	0	0
Micro silica (silica fume)	lb	0	32	32	32	32
Water	lb	270	240	240	240	240
Coarse aggregate (3/4-1/2 in.)	lb	1,648	613	1,786	613	1,786
Coarse aggregate (1/2 in. - #4)	lb		1,173		1,173	
Sand (#4-)	lb	929	1,048	1048	1,234	1,234
Aggregate to binder ratio	ratio	2.86	3.54	3.54	3.78	3.78
Fine aggregate (%) to coarse aggregate ratio (%)	ratio	36:64	40:60	40:60	40:60	40:60
Fly ash/GGBFS as a % of total cementitious material	%	0	30	30	30	30
Micro silica as a % of total cementitious material	%	0	4	4	4	4
Air entraining agent dose (ml)	ml	1,037	149	325	108	325
High-range water-reducer dose	ml	0	1,359	1,561	1,350	1,561

Table 3.4 - Nomenclature for Mixture Designs for Phase I

Mixture ID	Description
CW	Control Mix – water cure
CSA	Control Mix – steam cure + water cure to 14 days + ambient cure to 90 days[1]
CSB	Control Mix – steam cure + ambient cure to 90 days[2]
EAW	Experimental Mix A – water cure
EASA	Experimental Mix A – steam cure + water cure to 14 days + ambient cure to 90 days
EASB	Experimental Mix A – steam cure + ambient cure to 90 days
EBW	Experimental Mix B – water cure
EBSA	Experimental Mix B – steam cure + water cure to 14 days + ambient cure to 90 days
EBSB	Experimental Mix B – steam cure + ambient cure to 90 days
ECW	Experimental Mix C – water cure
ECSA	Experimental Mix C – steam cure + water cure to 14 days + ambient cure to 90 days
ECSB	Experimental Mix C – steam cure + ambient cure to 90 days
EDW	Experimental Mix D – water cure
EDSA	Experimental Mix D – steam cure + water cure to 14 days + ambient cure to 90 days
EDSB	Experimental Mix D – steam cure + ambient cure to 90 days
[1]Steam Curing Method A	
[2]Steam Curing Method B	

3.2 PILOT STUDY

Based on the results obtained from Phase I, water curing for 28 days was found to be better than steam curing followed by the ambient curing in terms of compressive strength, abrasion resistance, and chloride ion permeability (see Section 5 for details). However, it is impracticable to apply water curing in the precast industry because it will delay the production process and may result in more costly products. For these reasons, it became important to conduct a Pilot Study to establish the best rapid-curing method that would give results similar to those obtained after 28-day water curing.

3.2.1 Experimental Matrix

Table 3.5 presents a summary of the nine curing methods (i.e., nine different treatments) and the number of specimens of each curing method that were tested for compressive strength at different intervals. As shown in the experimental matrix, tests were conducted at 1, 3, 7, 14, and 28 days to capture strength development over time. To reduce variability, a sufficient amount of the concrete was mixed at a given time to provide enough specimens for up to three treatment conditions.

Table 3.5 - Experimental Matrix for the Pilot Study

Run ID	Curing Method (Treatment)	Compressive Strength (Response Variable) at				
		1 day	3 days	7 days	14 days	28 days
1	Water curing up to 28 days	3	3	3	3	3
2	14 Days water curing + ambient curing	---	---	---	---	3
3	7 Days water curing + ambient curing	---	---	---	3	3
4	14 Days water curing + curing compound + ambient curing	---	---	---	---	3
5	7 Days water curing + curing compound + ambient curing	---	---	---	3	3
6	1 Day water curing + curing compound + ambient curing	---	3	3	3	3
7	3 Days water curing + curing compound + ambient curing	---	---	3	3	3
8	3 Days water curing + ambient curing	---	---	3	3	3
9	1 Day water curing + ambient curing	---	3	3	3	3
10	Steam curing + ambient curing	3	3	3	3	3
11	Steam curing + curing compound + ambient curing	3	3	3	3	3

3.2.2 Treatments

In the Pilot Study, curing method was the only treatment investigated. ODOT was interested in shortening the duration of field curing; therefore, water curing periods of 3, 7, and 14 days were investigated to capture the optimal curing to be followed in the field. Since the Pilot Study was aimed at studying different curing types, 11 different treatments (in terms of 11 different curing methods) were applied to only one mixture composition. The details of the mixture composition are provided in Section 3.2.4.

3.2.3 Response Variable

Compressive strength was the only response variable investigated during the Pilot Study. Since compressive strength of the concrete is directly proportional to abrasion resistance, this test was identified as an indirect measure of abrasion resistance. Hence, it was reasoned that compressive strength would be an adequate way to determine the best curing method to carry forward into Phase II of the project.

3.2.4 Mixture Design

As alluded to earlier, only one mixture design was utilized for the Pilot Study. It incorporated 66% cement, 10% silica fume, and 24% slag for the cementitious ingredients, river gravel for the coarse aggregate, and natural sand for the fine aggregate.

3.3 PHASE II

The principal objective of Phase II was to improve upon the most promising mixture design developed in Phase I. The results from Phase I indicated that the HPC mixtures were more durable than the control mixture (see Section 5). Due to a change in the ODOT Standard Specifications 2008 for bridge deck mixtures, it became necessary to modify the direction of the research to include a new control mixture which constituted an HPC mixture with 66% cement, 4% silica fume, and 30% fly ash. Use of crushed rock showed significant improvement in abrasion resistance and compressive strength, but barely satisfied the maximum chloride ion permeability requirement of 1,000 coulombs set by the new (2008) specification. Locally available river gravel, instead of crushed rock, was used to develop a mixture that would satisfy the objectives of the research without the added expense of the crushed rock. Also, since the chloride ion penetration resistance requirement was so stringent, ODOT requested that the amount of silica fume be varied to observe its effect on chloride ion penetration resistance and abrasion resistance. This gave rise to Phase II of the study.

3.3.1 Experimental Matrix

Table 3.6 summarizes the experiment matrix for Phase II of the study. Mixtures A, B, C, D, and E were the primary mixtures investigated. The tests conducted on the mixtures, along with the number of specimens per test per mixture, is also shown in the experiment matrix. Two more experiment mixtures (S and T) with higher cement contents were also investigated to determine if it was possible to get a highly durable mixture with increased cement content at low to moderate silica fume content. Mixture S was non-air entrained concrete while all others were air entrained concrete.

Table 3.6 - Phase II Experimental Matrix

Mixture ID	**Material Proportion**				**Number of Specimens for**					
					Compressive Strength			**Abrasion Resistance**		**Chloride Ion Penetration**
								OSU	**Alaska DOT&PF**	
	Cement	Slag	Fly Ash	Silica Fume	1-day	28-day	56-day	56-day	56-day	56-day
Control	66%	---	30%	4%	3	3	3	3	3	3
Mix A	66%	27%	---	7%	3	3	3	3	3	3
Mix B	66%	24%	---	10%	3	3	3	3	3	3
Mix C	66%	---	27%	7%	3	3	3	3	3	3
Mix D	66%	---	24%	10%	3	3	3	3	3	3
Mix E	66%	30%	---	4%	3	3	3	3	3	3
Mix S	58%	35%	---	7%	3	3	3	3	3	3
Mix T	58%	38%	---	4%	3	3	3	3	3	3

3.3.2 Treatments

Only two independent treatments were investigated in Phase II. The first treatment was level of silica fume used. Since the new control mixture already contained 4% silica fume, the other two levels included 7 and 10%. The second treatment was type of supplementary cementitious material, either fly ash or slag. The method of curing was based on the results obtained from the Pilot Study (see Section 3.2). All of the specimens were steam-cured after initial set, coated with a curing compound, and were left in the ambient environment of the laboratory for curing until tested.

3.3.2.1 Supplementary Cementitious Materials

Phase I aimed at comparing the effect of different supplementary cementitious materials, fly ash and silica fume versus slag and silica fume, on the abrasion resistance and durability of HPC. Phase II took it one step further by varying the proportions of the supplementary cementitious materials. Section 3.1.2 provided a brief discussion regarding the use of these materials in concrete mixtures.

3.3.2.2 Levels of Silica fume

According to the literature review, an improvement in HPC durability through reduced permeability can be achieved with increased silica fume content. To investigate whether or not increased silica fume content significantly increased the durability of HPC, different percentages of silica fume were used in the mixtures. The basis for comparison was the results from the mixture with 4% silica fume. The other two percentage of silica fume were 7% and 10% as a replacement of cement. The intermediate quantity (i.e., 7%) was chosen since findings from the literature review suggested that this level of silica fume enhances the durability properties of concrete. However, when the level of silica fume is increased beyond 7%, a very high amount of silica fume is required to attain the same properties. Therefore, a level of 10% was chosen as the maximum quantity to be used in the HPC.

3.3.3 Response Variables

All of the concrete mixtures were tested for three different properties of hardened concrete. These were categorized under primary and secondary response variables according to research interest.

3.3.3.1 Primary Response Variables

All of the concrete mixtures developed in the Phase II were tested for abrasion resistance and chloride ion permeability resistance as primary response variables. Section 4.5 provides details of the tests.

3.3.3.2 Secondary Response Variables

Since the worst mixture in Phase I satisfied the freeze-thaw durability requirement of the ODOT Standard Specifications, it was reasoned that all of the concrete mixtures in Phase

II would be more resistant to freeze-thaw cycling and would, therefore, easily satisfy the specified freeze-thaw requirements. Hence, ODOT recommended elimination of freeze-thaw testing in Phase II.

However, compressive strength was retained as a secondary response variable. Section 4.5.4 provides details of this test. Tests were conducted at 1 day to assess early-age strength, at 28 days due to this being an industry standard test period, and 56 days to capture any additional benefits derived from delayed pozzolanic reactions associated with the fly ash supplementary cementitious material.

3.3.4 Mixture Designs

3.3.4.1 Overview

A new control mixture was designed based on the new ODOT specification (ODOT 2008), details of which are provided in the next section. Also, the mixture designs for the experimental mixtures were developed based on the different treatments identified in Section 3.3.2.

3.3.4.2 Mix Designs for Control Mixture

Table 02001-1 in Section 02001.30 of the 2008 ODOT Standard Specifications provided the details of HPC mixtures used for structural concrete deck slabs. It specified a compressive strength of 4,000 psi, a maximum w/c ratio of 0.40, and constituents and criteria as follows:

> *High performance concrete (HPC) mix designs shall either contain cementitious material with 66% portland cement, 30% Fly ash, and 4% Silica fume; or have trial batches performed to demonstrate that the alternate mix design provides a maximum of 1,000 coulombs at 90 days when tested according to AASTHO T 277.*

Additional criteria indicated a maximum slump of 10 inch for pre-cast pre-stressed concrete, use of a high-range water-reducing admixture (Table 02001-3), an air content of 6% (+2%/-1%) for concrete exposed to severe condition, and a nominal maximum aggregate size of 3/4 inch (Table 02001-2). Details of the mixture design are given in Table 3.7.

3.3.4.3 Mix Designs for Experimental Mixtures

Table 3.7 also summarizes the mixture designs for the experimental mixtures. As indicated, the mixture designs had different levels of silica fume, and either slag or fly ash, also at different levels. Mixes A, B, and E contained slag while the control mixture and Mixes C and D contained fly ash. Mix B and D contained 10% silica fume and 24% slag or fly ash, respectively. Similarly, Mixes A and C contained 7% silica fume and 27% slag or fly ash, respectively. The control mixture and Mix E contained 4% silica fume and 30% slag or fly ash, respectively. Mixes S and T contained higher cement contents relative to the other mixtures. Though the percentage of cement in Mixes S and T was less than that of the other mixtures (i.e., 58% instead of 66%), Mixes S and T had

7% and 4% silica fume, respectively. Also, Mix S did not contain an air entraining agent, whereas Mix T did to obtain 6% air. All mixtures, except Mixes S and T, were designed with a w/b ratio of 0.30; Mix S had a w/b ratio of 0.26, and Mix T had a w/b ratio of 0.27.

Table 3.7 - Summary of Mixture Designs for Phase II*

Mix ID	Control	Mix A	Mix B	Mix C	Mix D	Mix E	Mix S	Mix T
Cement-Type III	541	541	541	541	541	541	604	604
Fly Ash	246	0	0	221	197	0	0	0
Slag	0	221	197	0	0	246	365	396
Silica Fume	33	57	82	57	82	33	74	42
Water	245	245	245	245	245	245	269	279
Coarse Aggregate-3/4-1/2	661	661	661	661	661	661	620	624
Sand	928	957	950	925	921	963	1065	1062
w/c ratio	0.30	0.30	0.30	0.30	0.30	0.30	0.26	0.27

*Quantities in lb/ft^3

4.0 MATERIALS AND METHODS

Once the mixture designs were developed on paper, the required materials were procured from different sources. The materials were then mixed, cast, and tested per set standards. This section provides brief descriptions of the materials and tests utilized for this study.

4.1 MATERIALS DESCRIPTIONS

The materials utilized in this study included mineral aggregates, cement, slag, fly ash, silica fume, admixtures, and a curing compound. This section provides brief descriptions of these materials and, where appropriate, properties of the materials.

4.1.1 Aggregates

4.1.1.1 Coarse Aggregate

A nominal maximum aggregate size of 3/4 inch was selected for aggregates. Unwashed gravel with some crushed particles, obtained from Knife River's Corvallis pit, was used as the coarse rock for the control mixtures tested in Phase I and in the Pilot Study. A fully crushed, hard basalt rock obtained from Knife River's Watters quarry was also used as coarse aggregate in Phase I. This aggregate was very dense, dark black in color, and angular in structure. Washed, rounded gravel with some crushed particles used for the experimental mixtures in all phases and the control mixture in Phase II were divided into two fractions; namely, 3/4 in. to 1/2 in. and 1/2 in. to #4. All coarse aggregates were densely graded.

4.1.1.2 Fine Aggregate

Unwashed sand was used for the control mixture in Phase I, while washed sand was used for all of the experimental mixtures in Phase I, the Pilot Study, and Phase II. The source of the sand was the Knife River's Corvallis pit. The sand had a fineness modulus of 3.0.

Physical analyses of both coarse and fine aggregates were conducted in accordance with ASTM C-33. The results of these tests are shown in the Table 4.1.

Table 4.1 - Physical Properties of Coarse and Fine Aggregate

Property	Gravel for Control Mixtures	Gravel for Experimental Mixtures		Crushed Rock	Sand for Control Mixture	Washed Sand (All Exp. Mixtures)
	---	3/4 x 1/2 in.	1/2 in. x # 4	3/4 x 1/2 in.	#4 minus	#4 minus
Specific gravity (SSD)	2.600	2.580	2.580	2.770	2.550	2.540
Specific gravity (Dry)	2.500	2.520	2.500	2.710	2.460	2.460
% water absorption	2.5	2.7	3.0	2.0	3.8	3.4
Fineness Modulus	---	---	---	---	3.0	3.0
			Percent Passing			
Coarse aggregate						
1 in.		100		100	---	---
3/4 in.		88		97	---	---
1/2 in.		16		66	---	---
3/8 in.		5		36	---	---
#4		0.6		1.2	---	---
			Percent Passing			
Fine aggregate						
#4	---	---	---	---	96	96
#8	---	---	---	---	77	77
#16	---	---	---	---	63	63
#30	---	---	---	---	50	50
#40	---	---	---	---	36	36
#50	---	---	---	---	18	18
#100	---	---	---	---	3	3
#200	---	---	---	---	0.8	0.8

4.1.2 Cement

Type I cement was used for the mixtures in Phase I. Test certificates for the cement were not available. The Type III cement used for the Pilot Study and for Phase II met the requirements of ASTM C-150. The cement was supplied by Ash Grove Cement Company, Durkee, Oregon. Test results of physical and chemical analyses of cement are summarized in Table 4.2.

Table 4.2 - Physical and Chemical Analyses of the Ash Grove Type III Cement

Tests	Ash Grove type III cement
Chemical Properties	
Silicon dioxide (SiO_2), %	21
Aluminum oxide ($A1_20_3$), %	3.4
Ferric oxide (Fe_20_3) , %	2.9
Calcium oxide (CaO), %	63.1
Magnesium oxide (MgO), %	1.7
Sulfur trioxide (SO_3), %	2.9
Loss on ignition, %	1.46
Sodium oxide (Na_20), %	0.21
Potassium oxide (K_20), %	0.48
Total equivalent alkali content, %	0.53
Tricalcium silicate, %	62
Dicalcium silicate, %	14
Tricalcium aluminate, %	3
Tetracalcium aluminoferrite, %	9
Insoluble residue, %	0.48
Physical Properties	
Fineness, m^2/Kg	549
Specific Gravity	3.15
Autoclave expansion	0.00%
Time of setting, minutes	
Initial	93
Final	169
Compressive strength, psi	
1 day	3318
3 days	4826
7 days	5943

4.1.3 Slag

NewCem slag, supplied by Lafarge North America Company from their Seattle plant, was used in the study. It met all the requirements of ASTM C 989. Detailed physical and chemical test results of the slag are given in the Table 4.3.

Table 4.3 - Physical and Chemical Analysis of the NewCem Slag

Tests	NewCem Slag
Chemical Properties	
Sulfide sulfur (S), %	0.77
Sulfate Ion (SO_3), %	2.72
Physical Properties	
Fineness, m^2/kg	421
Specific Gravity	2.89
Air Content, %	5.3
Compressive strength, psi	
7 day	4,300
28 days	6,365
Slag Activity Index	
7 day	94
28 days	122

4.1.4 Fly ash

There are two types of fly ash, namely, Class F fly ash and Class C fly ash. Class F fly ash was used in this research study due to the abundant availability of this material in Oregon at the time the study began. This fly ash was supplied by CTL Thompson Materials Engineers, Inc. from their Centralia plant. It met the requirements of ASTM C618-05. Test results of physical and chemical analyses of fly ash are given in Table 4.4.

4.1.5 Silica Fume

Silica fume used in the research project was in the form of dry compacted powder. It was manufactured by Masters Builders and was provided by Knife River. The specific gravity of the silica fume used was 2.2. Silica fume used in the project satisfied all the requirements of ASTM C 1240.

4.1.6 Admixtures

Glenium 3400 NV was used as a high-range water-reducing admixture in the research study. Glenium 3400 NV admixture met the requirements of ASTM C 494/C 494M – 99. As per material data sheet of Glenium 3400 NV *(BASF 2009)*, 8 to 12 fluid ounces per 100 pounds of cement was required for HPC with a slump of around 10”. Actual quantity of admixture required for each mixture design was based on trial and error.

Table 4.4 - Physical and Chemical Analyses of Class F Fly Ash

Tests	Class F fly ash
Chemical Properties	
Silicon dioxide (SiO_2), %	55.3
Aluminum oxide (Al_20_3), %	16.7
Ferric oxide (Fe_20_3) ' %	5.8
Calcium oxide (CaO), %	9.9
Sulfur trioxide (SO_3), %	0.5
Loss on ignition, %	0.1
Sodium oxide (Na_20),%	1.86
Potassium oxide (K_20), %	0.9
Total Silica, Aluminum, Iron, %	77.8
Physical Properties	
Fineness, retained on #325 sieve, %	22.4
Specific Gravity	2.56
Autoclave expansion, %	0.05
Moisture content, %	0
Slag Activity Index	
Ratio to control@ 7 day	81.1
Ratio to control@ 28 day	89.6
Water requirement, % of control	92.6
Drying shrinkage, increase @ 28 days, %	0

Air entraining agent used in this project was MBAE 90. It met the requirements of ASTM C 260. Typical dosage of MBAE 90 is 1/4 to 4 fluid ounces per 100 pounds of cement *(2009)*. Actual quantity was determined through trial and error.

4.1.7 Curing Compound

The curing compound used in this project was 1300 Clear which was a water-based and wax-based concrete curing compound. It was supplied by W. R. Meadows. It satisfied all the requirements set by the ODOT *(2008)*. The curing compound was applied as per manufacturer's data sheet.

4.2 LABORATORY CONCRETE MIXING METHOD

Mixing of concrete in the laboratory was performed in accordance with ASTM C 192 during Phase I of study. Since the silica fume content in the Pilot Study and Phase II was much higher than in Phase I, longer mixing times were required to obtain a homogeneous mixture. For this purpose, the mixing procedure recommended by the Silica Fume Association *(Holland 2005)* was followed. Figure 4.1 provides a flow chart of the mixing process for the concrete with supplementary cementitious materials utilized in this study. All mixing was performed in a concrete mixer with a 2.5 cubic feet capacity.

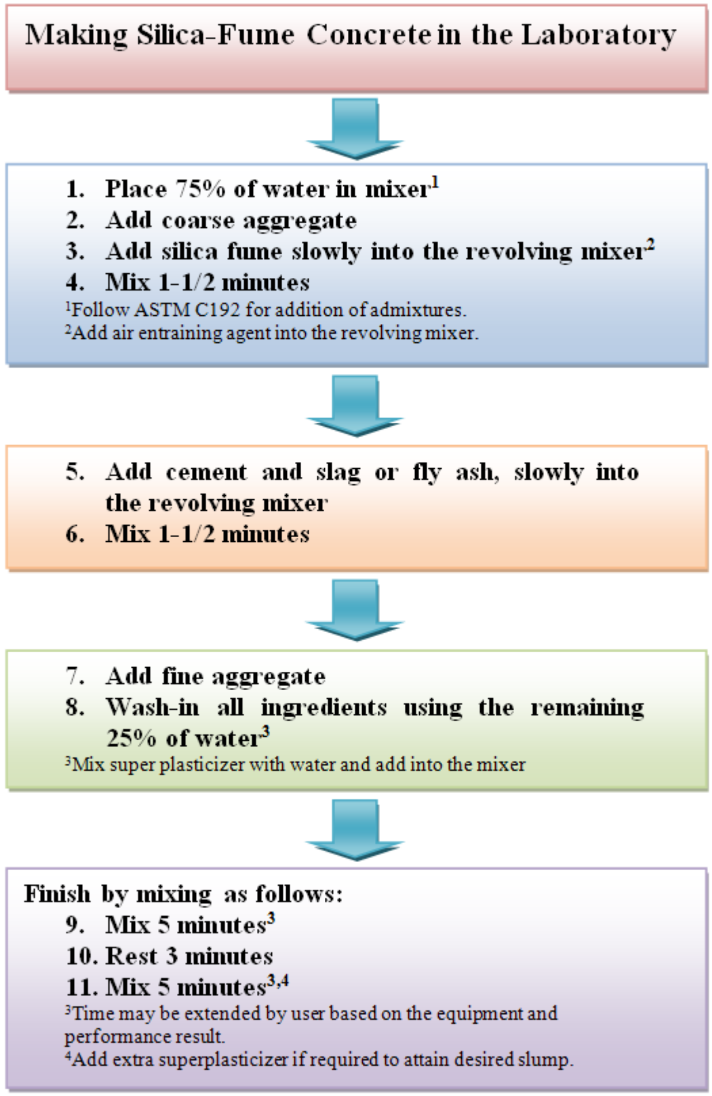

Figure 4.1 - Flow Chart for Mixing Procedure (adapted from 37)

4.3 CASTING

All specimens were cast according to ASTM C 192. All concrete cylinders were cast in 4 × 8 in. plastic molds while the slabs were cast in 12 × 12 × 3 in. steel molds. The freeze and thaw beams were cast in 11 × 3 × 3 in. steel molds. Once the specimens were cast, they were cured according to the predetermined curing method.

4.4 CURING

The method of steam curing was investigated for use to simulate the curing method followed by the precast industry. In general, steam curing is used when it is essential to achieve high early strength. In a study of curing methods on concrete containing 10% silica fume, it was found that the steam curing gave the concrete higher early-age compressive strength compared to air curing and moist curing methods *(Toutanji and Bayasi 1999)*. Additionally, it was found that the use of steam curing decreased the permeability of silica fume concrete as compared to the other methods *(Toutanji and Bayasi 1999)*. Different phases of the research study adopted different curing methods, all of which are described in Section 3.

Water curing involved soaking the specimens in lime-saturated water at a temperature of 23±2°C (73±3°F) for a specified duration of time. Steam curing involved soaking the specimens at ambient temperature until initial setting, followed by increasing the temperature to 140°F in two hours, and again soaking the specimen at 140°F for up to 8 hours, followed by decreasing the temperature to ambient temperature in approximately two hours.

Another curing method involved application of curing compound. Curing compound was sprayed using a manual sprayer after the specimens were stripped from the molds at a coverage rate of approximately 200 sq. ft. / gal (*W.R. Meadows Product Data Sheet Undated*).

Figure 4.2 displays two production steam curing regimes and one laboratory curing regime. The production steam curing regimes were as carried out by Knife River (Harrisburg, Oregon) and Central Pre-Mixture (Spokane, Washington), whereas the laboratory curing regime was as described by Dr. Hooton *(Hooton et al. 1997)*. Given that the production steam curing regimes and the laboratory curing regime were similar with regard to durations and temperature ramping rates, and that Knife River would be fabricating the bridge deck panels for the purposes of the field study, the laboratory curing method which closely resembled that used by Knife River was used for this study.

4.5 TEST METHODS

Tests were conducted on both newly-mixed (fresh) concrete and hardened concrete. This section provides a description of the tests utilized in this study.

4.5.1 Properties of Fresh Concrete

Several tests were conducted on the newly-mixed concrete to determine the properties of the fresh concrete. This section briefly describes these tests.

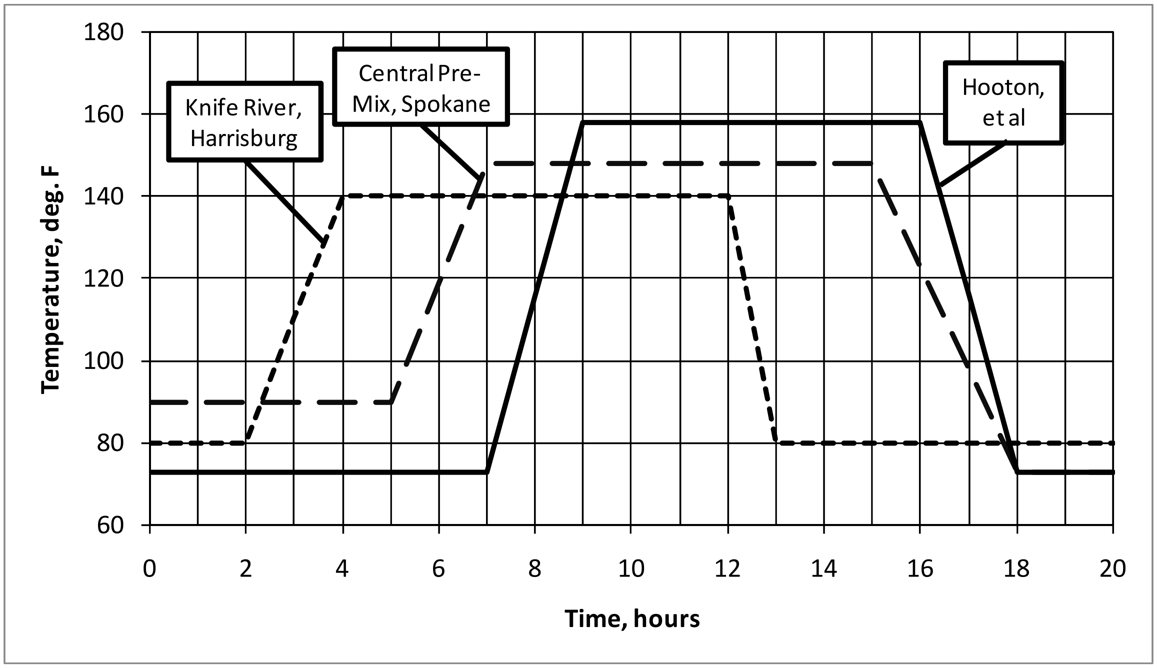

Figure 4.2 - Contractor and Laboratory Steam Curing Regimes

4.5.1.1 Slump

Slump is the measure of workability of concrete. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete. These tests were conducted in accordance with ASTM C 143.

4.5.1.2 Density

The unit weight (density) of concrete varies with the density of the aggregate, the amount of entrapped or entrained air, water content, and the density and content of the cementitious materials. Unit weight of the freshly mixed concrete was determined using the procedure described in ASTM C138.

4.5.1.3 Air content

Air content can have a significant impact on the strength of concrete, with higher air contents resulting in lower strengths. Therefore, careful measures were taken to ensure the mixtures were fabricated with the design entrained air contents. Air contents in the fresh concrete were determined using ASTM C138.

4.5.1.4 Temperature

Temperature of the fresh concrete was determined in accordance with ASTM C1064/C1064M-08.

4.5.2 Properties of Hardened Concrete

Properties of the hardened concrete were evaluated carefully as these were the primary and secondary response variables (performance measures) of interest. This section briefly describes the tests conducted on the hardened concrete test specimens.

4.5.2.1 Abrasion Resistance, OSU

The abrasion resistance tests conducted at OSU were performed on square test specimens that were 12 × 12 in. in plan and 3 in. thick as per ASTM C 779/C 779M. Tests were conducted at 90 days for Phase I and at 56 days for Phase II. The revolving disk method was used with a modification to the disks. Quarter-inch-long tungsten carbide studs with a Rockwell hardness of A92 were used to develop a more aggressive abrasive environment. There were three revolving disks, each equipped with 12 detachable tungsten carbide studs arranged in concentric circles on the disks (see Figure 4.3); hence, a given test utilized a total of 36 studs. These hard studs were sharpened and pointed at the bottom. During Phase I of the study, they were replaced by another set only after they got abraded or studs broke off during a test. During Phase II, the studs were replaced after every third specimen tested.

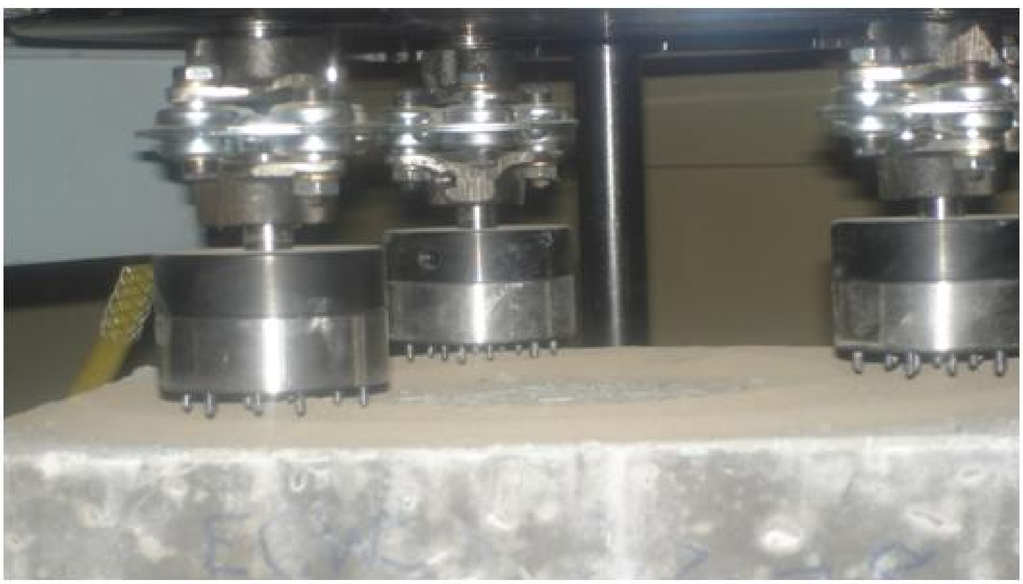

Figure 4.3 - Revolving Disks with Tungsten Carbide Studs

Testing Procedure: Three specimens per experimental mixture were tested at 90 days in Phase I and at 56 days in Phase II. Prior to the start of collecting measurements, the test specimens were preconditioned to remove the surface irregularities and the curing compound, if any, by running the abrasion testing machine for 5 minutes. Following this, measurements were made using a micrometer depth gage (Figure 4.4) that read to an accuracy of 0.001 in. to establish the initial readings. Each test was run for 30 minutes after which the specimen surfaces were cleaned to remove all the dust and loose particles and measurements were taken again. In order to ensure that measurements were made at the same position every time while taking the readings, 24 holes were made in a flat aluminum plate at a diameter of 7.9 inch (200mm) as shown in Figure 4.5. The plate had small fences on two adjacent sides (not shown in Figure 4.5) to facilitate alignment over the concrete specimens.

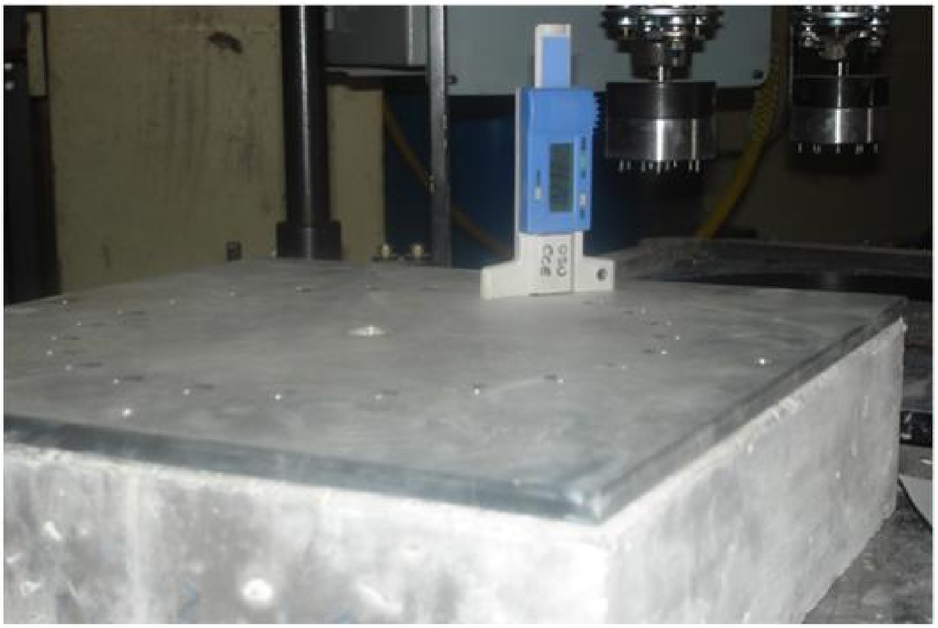

Figure 4.4 - Measurement of Wear Depth using a Depth Micrometer

Figure 4.5 – Arrangement of Holes in Aluminum Plate

Depth of wear was calculated by subtracting the initial reading from the reading taken at 30 minutes and slope or wear rate was obtained by dividing the depth of wear by the corresponding duration of wear. A concrete specimen illustrating the depth of wear after the test is shown in Figure 4.6. In Phase II, the specimens were abraded for an additional 30 minutes to obtain measurements at both 30 minutes and 60 minutes.

Figure 4.6 - Abraded Surface After Test Showing Depth of Abrasion

4.5.2.2 Abrasion Resistance, Prall Test (Alaska DOT&PF)

Three specimens from each of the concrete mixture designs investigated in Phase II and one specimen of the aggregate (river gravel) were sent to the Alaska Department of Transportation & Public Facilities (Alaska DOT&PF) to conduct independent tests for abrasion resistance of the concrete and aggregate. The Prall Test was conducted on the concrete specimens in an attempt to provide some validation of the OSU abrasion tests, while the Nordic Abrasion Test was conducted on the aggregate. Both tests were conducted as a coutesy of Alaska DOT&PF.

4.5.2.3 Prall Test

The Prall Test, generally conducted on asphalt mixture specimens, originated in the USA and is being used in Sweden to predict pavement wear due to studded tires. The test method adopted by Alaska DOT&PF was described in the data sheet provided by the Alaska DOT&PF materials engineer as follows:

> "*The sample to be tested is placed into a small chamber. The chamber is then shaken up and down (950 rpm) together with a number of steel balls for 15 minutes. The steel balls wear the sample surface by bouncing between the chamber walls, ceiling and the test sample. Water is circulated continuously at 5°C, which rinses the worn pavement particles out of the chamber. The Prall value is defined as the volume loss of the material.*"

Figure 4.7a shows the test chamber loaded with an asphalt concrete specimen and the steel balls used during the test while Figure 4.7b shows the chamber loaded in the shaker with hoses attached for circulating the water. Table 4.5 provides an interpretation of the test results.

a) Test Chamber with Specimen b) Test Chamber in Shaker

Figure 4.7 - Prall Test Chamber and Shaker Unit

Table 4.5 - Interpretation of Results from the Prall Test

Prall Value, cm^3	Wear Resistance
< 20	Very Good
20-29	Good
30-39	Satisfactory
40-50	Less Satisfactory
> 50	Poor

Nordic Abrasion Test

The Nordic Abrasion Test (also called the Nordic Ball Mill Test) rotates aggregates in a drum with steel balls and water (Figure 4.8) at 90 revolutions per minute. Degradation of the aggregate is determined as the percentage of material finer than 2 mm lost during the test. A Nordic Abrasion of 7.5 or less is considered good abrasion resistance.

a) Nordic Abrasion Test Drum b) Close-up of Test Drum

Figure 4.8 - Nordic Abrasion Test Apparatus

4.5.3 Permeability

The rapid chloride permeability test (RCPT) was performed in accordance with ASTM C 1202-97 at 90 and 56 days for Phases I and II, respectively. The test specimens consisted of 2 inch thick slices obtained from specimens cast in the 4 × 8 in. cylinder molds.

Test Procedure: Four specimens were tested per mixture design. The circumference of the test specimens was coated with a rapid setting silicone sealant. Pre-conditioning of specimens was accomplished by vacuum saturation of the specimens for 4 hours followed by a soaking period of 18 ±2 hours as shown Figure 4.9.

Figure 4.9 - Setup for Conditioning the Specimen

Following this, the top and bottom surfaces of the specimens were connected to one cell filled with 300 ml of a 3% sodium chloride (NaCl) solution and another cell filled with a 0.3N sodium hydroxide (NaOH) solution. Figure 4.10 shows a photograph of the cells while Figure 4.11 shows the completed test setup. The positive terminal of the power supply was connected to the NaOH cell while the negative terminal was connected to the NaCl cell. A regulated voltage of 60V was applied across the cells and the voltage across a shunt resistor was measured to obtain the current passing through the specimen using the Ohm's Law. Each test lasted for 6 hours.

Readings were taken every 30 minutes and, based on the trapezoidal rule, charge passed through the specimen was calculated using Equation 4.1.

$$\mathbf{Q = 900 * (I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + I_{360})} \qquad \mathbf{(4.1)}$$

Where:

Q = charge passed (coulombs),

I_0 = current (amperes) immediately after voltage is applied, and

I_t = current (amperes) at time t (minutes) after voltage is applied.

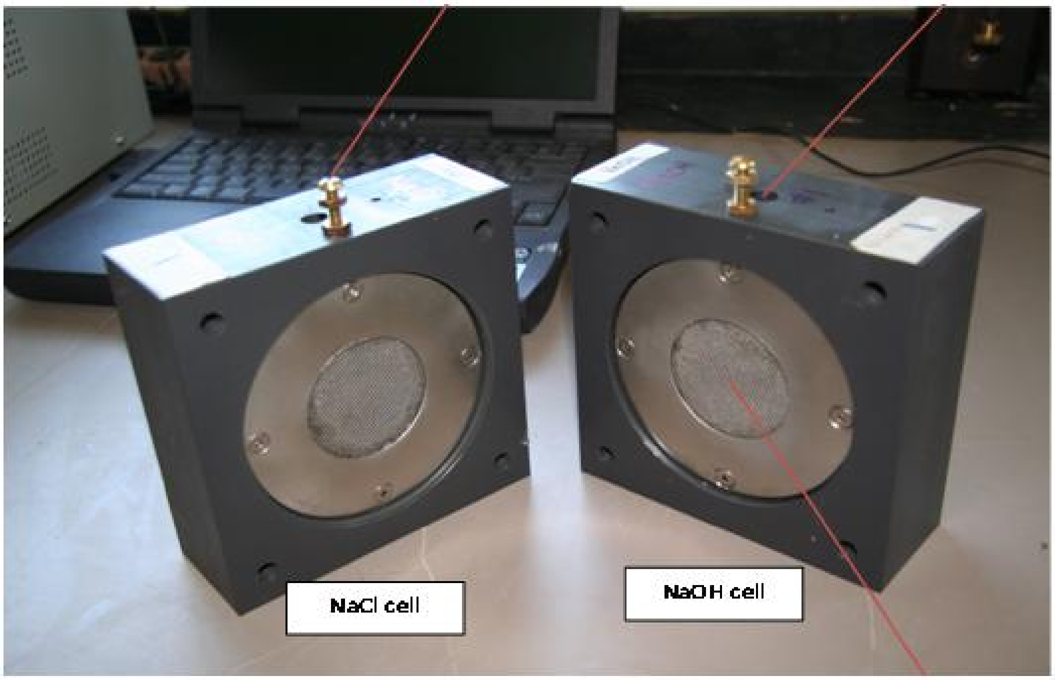

Figure 4.10 - Chloride Ion Permeability Specimen Cell

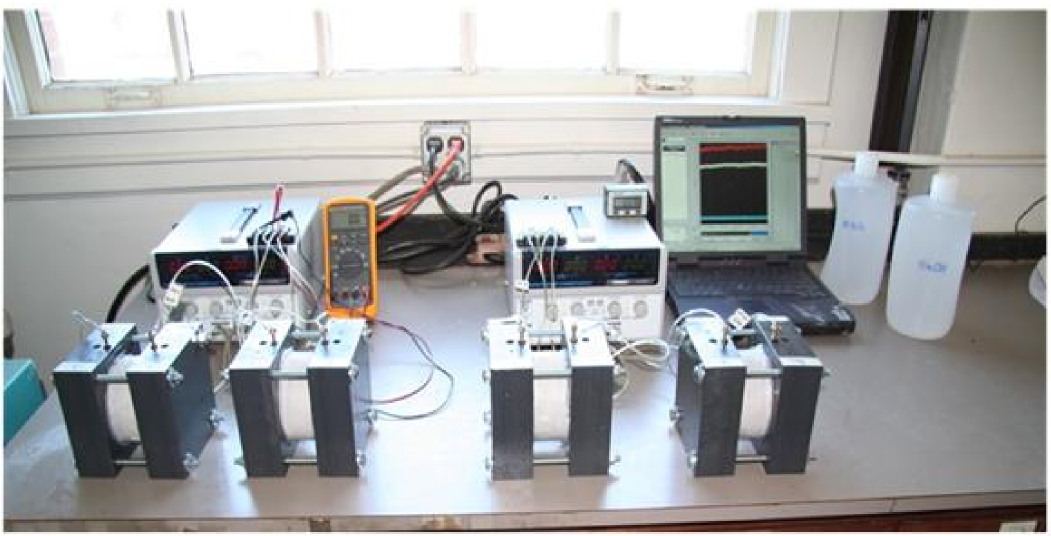
Figure 4.11 - Setup for the Rapid Chloride Penetration Test

4.5.4 Strength

The compressive tests were conducted on 4 × 8 in. cylinders in accordance with ASTM C 39/C 39M at the specified times as described in Section 3.

4.5.5 Freeze-Thaw Resistance

Freeze and thaw tests were conducted on 3 × 3 × 11 in. prisms at 14 days in accordance with ASTM C 666, but with minor modifications.

Test Procedure: Prior to the testing, length, breadth, width, and weight of the specimens were measured and the initial fundamental frequency at zero cycles of freeze and thaw were determined. The minor modification involved wrapping of the specimen in a felt (Figure 4.12) having a thickness neither less than 1/32 in. (1 mm) nor more than 1/8 in. (3 mm). The specimens covered with felt were then immersed in cold water maintained at a temperature of 4°C (Figure 4.13).

After immersion for 1 minute, specimens were taken out of the cold water to allow excess water to drain out, and then specimens were vacuum-sealed in plastic vacuum bags (Figures 4.14 - 4.17) and placed in the freeze and thaw chamber. The temperature of the chamber and a dummy specimen of concrete (with an embedded thermocouple) were recorded using a Lab View Program on a computer. One freeze-thaw cycle involved lowering the core temperature of the concrete from 40°F to 0°F and then raising the temperature from 0°F to 40°F. The duration of one cycle of freeze and thaw was determined to be 3 hours and 56 minutes. Initially, specimens were tested at intervals not exceeding 10 cycles, and then they were tested at intervals not exceeding 36 cycles up to 300 cycles.

After each interval, the specimens were taken out, tested for fundamental transverse frequency (Figure 4.18), measured for weight, again wrapped as described earlier, vacuum-sealed, and returned to the chamber for the next set of freeze and thaw cycles. The specimens were rotated in the chamber in a set pattern to minimize exposure in any particular location that was slightly warmer or slightly cooler than another location.

Figure 4.12 - Specimen Wrapped in Felt

Figure 4.13 - Wrapped Specimen Submerged in Water

Figure 4.14 - Wet Specimen inside Vacuum Seal Bag

Figure 4.15 - Ready for Vacuum Seal Process

Figure 4.16 - Vacuum Seal Process Complete

Figure 4.17 - Ready for the Freeze-Thaw Chamber

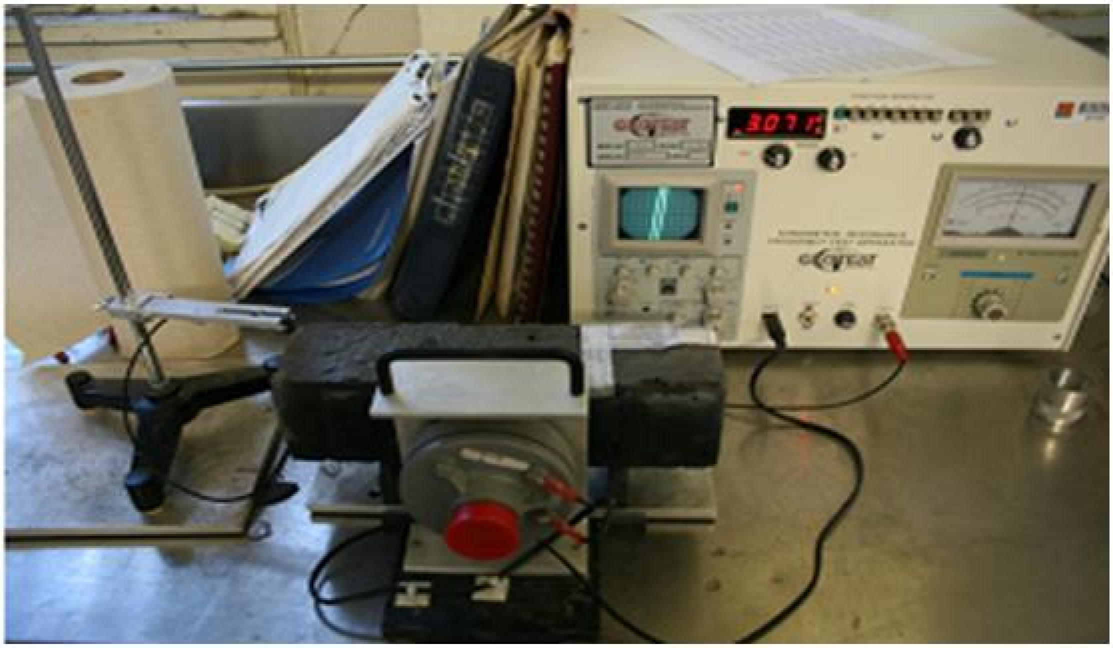

Figure 4.18 - Fundamental Transverse Frequency Measurement

The fundamental transverse frequencies obtained initially (i.e., before freeze-thaw cycling), at intermediate periods throughout the process, and at the end of the 300 freeze-thaw cycles were used to calculate the dynamic modulus of the concrete specimens. The dynamic modulus was monitored to determine if, at any point during freeze-thaw cycling, it fell below 50% of the initial dynamic modulus of the test specimen, signaling failure and termination of the process. If the dynamic modulus did not fall below 50% of the initial dynamic modulus, freeze-thaw cycling continued until it did or until the specimen was subjected to 300 freeze-thaw cycles, at which point the process was discontinued. Once the process was terminated, the durability factor for the specimen was determined as shown in Equation 4.2:

$$DF = \left[{E_n}/{E_0} \right] \times 100 \qquad \textbf{(4.2)}$$

Where:

DF = Durability Factor, percent

E_n = Dynamic modulus after freeze-thaw cycle n, ksi

E_0 = Initial dynamic modulus before freeze-thaw cycling, ksi

5.0 RESULTS AND ANALYSES

This section presents the test results obtained from all phases of this study as well as findings from analyses of the results. These are preceded by a brief description of the analysis methodologies.

5.1 ANALYSIS METHODOLOGY

The experiments were designed to allow statistical comparisons of the test results (see Section 3). The results for most performance measures (e.g., abrasion resistance, permeability, etc.) obtained from Phase I and all performance measures obtained from Phase II were compared using analyses of variance and a multiple comparisons procedure. These techniques were not used for the freeze-thaw resistance tests results obtained from Phase I since only one test per mixture was conducted. The results obtained from the Pilot Study were compared using confidence intervals derived from a separate multiple comparisons procedure. The following sections provide a brief description of the analyses.

5.1.1 Analysis of Variance and Multiple Comparisons

For all performance measures except freeze-thaw resistance, the results obtained from Phase I and Phase II were analyzed using analysis of variance (ANOVA) in a two-step process followed by analyses utilizing a multiple comparisons procedure. All analyses were conducted using the SAS statistical software package (Version 9.2). The following sections provide brief descriptions of the methods.

5.1.1.1 Initial ANOVA

The experiments for both Phase I and Phase II were set up as factorial designs but, in both cases, at least one additional mixture was investigated that did not conveniently fit into the factorial design. Table 5.1 summarizes the factorial designs for both phases and lists the additional mixtures investigated.

Since the additional mixtures were not part of the factorial designs, an initial ANOVA was conducted using only the results fitting into the factorial design to determine if interactions between the factors included in each experiment were significant. That is, for Phase I, the initial ANOVA sought to determine if interaction existed amongst the factors cementitious materials, aggregate type, and curing method. For Phase II, it sought to determine if interaction existed between cementitious materials and silica fume content.

5.1.1.2 Second ANOVA

The second ANOVA included the additional mixtures listed in Table 5.1. For Phase I, this included the control mixture whereas, for Phase II, it included Mixes S and T. In each case, these were included by considering each mixture as a separate treatment, thereby including any interacting factors within the treatment.

Table 5.1 - Summary of Factorial Designs and Additional Mixtures for Phases I and II

	Factorial Design		
Phase	**Factors**	**Levels**	**Additional Mixture(s)**
I	1. Cementitious Material (in addition to portland cement and silica fume)	1. Fly Ash 2. Slag	1. Control Mix: no SCMs (i.e., only portland cement) and only one aggregate type (river gravel)
	2. Aggregate Type	1. River Gravel 2. Crushed Rock	
	3. Curing Method	1. Water Curing 2. Steam Curing Method A 3. Steam Curing Method B	
II	1. Cementitious Material (in addition to portland cement and silica fume)	1. Fly Ash 2. Slag	1. Mix S: high cement content and 7% silica fume 2. Mix T: high cement content and 4% silica fume
	2. Silica Fume Content	1. 4% 2. 7% 3. 10%	

For the Phase I results, the second ANOVA was conducted to determine if there was a significant difference between the means of at least two of the treatments, where each treatment comprised a single combination of cementitious material, coarse aggregate type, and curing method. The second ANOVA was conducted on the Phase II results for the same reason but, in this case, the treatments comprised a single combination of cementitious material and silica fume content. When the ANOVA found significant differences between at least two treatment means, further analysis was undertaken using a multiple comparisons procedure.

5.1.1.3 Multiple Comparisons

Multiple comparison analyses utilized Waller-Duncan k-ratio t-tests to form Waller groupings of the treatments taking into account the differing levels of the various factors. Treatments within a particular Waller group have means that are statistically similar (i.e., not significantly different) for a particular error-seriousness ratio k. Conversely, treatments in different Waller groups have means that are significantly different. Thus, these pair-wise comparisons distinguished differences (or similarities) between means of the response variables (i.e., performance measures of the concrete mixture) for all possible combinations of the different levels of the various factors under investigation.

5.1.1.4 Nomenclature

Several of the following tables contain information (output) obtained directly from the SAS statistical analysis software package. In using the software, abbreviations were used for names of the factors (i.e., variable names) used in the analyses. Table 5.2 provides a list of the variable names used and their corresponding descriptions. For convenience, it also includes descriptions of abbreviations inherent within the output from the software package.

Table 5.2 - Abbreviations used in the SAS Software Package

Abbreviations and Description of Variable Names

Variable Name	Description
CemMat	Combination of cementitious materials
RockType	Coarse aggregate type (Phase I only)
CureType	Curing method (Phase I and Pilot Study only)
SilicaFume	Silica fume content (Phase II only)
TRT	Treatment (single combination of factors, each at a single level)

Description of Abbreviations Inherent Within the Output from SAS

Abbreviation	Description
N	Number of observations
DF	Degrees of freedom
Pr	p-value
F	F statistic
SS	Sum of squares
R-Square	Coefficient of determination (i.e., R^2)
Coeff Var	Coefficient of variation
MSE	Mean square for error

5.1.2 Phase I Freeze-Thaw Resistance Results

Results from the freeze-thaw resistance tests conducted in Phase I were not analyzed using ANOVA since only one specimen per mixture was tested. Instead, the analysis of these results involved comparisons of trends in the data.

5.1.3 Pilot Study

All analyses of the results obtained from the Pilot Study involved calculation of 95% confidence intervals using Bonferroni's multiple comparisons procedure and visually comparing these to determine if the intervals overlapped. Mean values associated with overlapping confidence intervals are not significantly different, while those associated with intervals that do not overlap are significantly different.

5.2 PHASE I

During Phase I of the study, comparisons were made with regard to the types of supplementary cementitious materials (SCMs), types of aggregates, and the types of curing methods. Section 3.1 described the experiment design for this work, Section 4.1 provided a description of the materials, and Section 4.5 described the test methods utilized. The test results and their analyses are presented in this section.

5.2.1 Fresh Properties of Concrete

The fresh properties of concrete monitored during Phase I of this study included temperature, slump, density, and air content. A summary of the results of these tests is presented in Table 5.3. The target slump for the control mixture was 4 inches, while that for the experimental mixtures was 10 inches. It is noted that the slump for Mixture CSB was slightly high, but the slump for all other mixtures were very close to the target values. It is also noted that the temperature for Mixture CW was 77°F and that for Mixture EDW was only 50°F, while the temperatures for all other mixtures were between 61 and 65°F.

Table 5.3 - Summary of Test Results for Fresh Properties of Concrete, Phase I

Mixture ID	Mixture Description	Slump, in.	Temp., °F	Air Content, %
CW	Control – Water Curing	4	77	5
CSA	Control – Steam Curing Method A[1]	5	63	7
CSB	Control – Steam Curing Method B[2]	6	61	6
EAW	Exp A (Gravel, Slag, Silica Fume) – Water Curing	9	64	8
EASA	Exp A (Gravel, Slag, Silica Fume) – Steam Curing Method A	10	63	8
EASB	Exp A (Gravel, Slag, Silica Fume) – Steam Curing Method B	10	65	8
EBW	Exp B (Crushed Rock, Slag, Silica Fume) – Water Curing	9	62	6
EBSA	Exp B (Crushed Rock, Slag, Silica Fume) – Steam Curing Method A	9	63	8
EBSB	Exp B (Crushed Rock, Slag, Silica Fume) – Steam Curing Method B	9	64	8
ECW	Exp C (Gravel, Fly Ash, Silica Fume) – Water Curing	10	63	8
ECSA	Exp C (Gravel, Fly Ash, Silica Fume) – Steam Curing Method A	10	64	7
ECSB	Exp C (Gravel, Fly Ash, Silica Fume) – Steam Curing Method B	10½	64	8
EDW	Exp C (Crushed Rock, Fly Ash, Silica Fume) – Water Curing	10½	50	8
EDSA	Exp C (Crushed Rock, Fly Ash, Silica Fume) – Steam Curing Method A	9½	61	8
EDSB	Exp C (Gravel, Fly Ash, Silica Fume) – Steam Curing Method B	10½	64	8

[1]Steam cure + water cure to 14 days + ambient cure to 90 days
[2]Steam cure + ambient cure to 90 days

5.2.2 Hardened Concrete Properties

Table 5.4 provides a summary of test results for the hardened properties of the concrete mixtures, while Appendix C provides details. Each value in Table 5.4 represents the average of three specimens per mixture design for all the tests except for the Rapid Chloride Ion Penetration Test (RCPT) which is the average of four results, and the freeze-thaw test (only one specimen was tested). The following three sections present findings from statistical analyses of the abrasion resistance, RCPT, and compressive strength results, while the fourth section presents observations of trends in the freeze-thaw resistance test results.

5.2.2.1 Abrasion Resistance, Modified ASTM C 779/C 779M (OSU Test)

Table 5.5 provides the SAS output of an analysis of variance of the data obtained from the experimental mixtures, with wear rate (inches per hour) as the response variable. The results show that the model is highly significant (p-value < 0.0001) providing strong evidence to indicate that at least one of the factors had a strong influence on the wear rate. In addition, the results indicate that the 2-way and 3-way interactions are highly significant (all p-values much less than 0.05). With this being the case, further investigation of the main effects alone is unwarranted.

A second ANOVA was conducted between treatments by considering each treatment as a single combination of cementitious material, coarse aggregate type, and curing method so as to include the results from the control mixture. The results of this analysis, shown in Table 5.6, indicate that the model is significant (p-value < 0.0001), indicating the wear rate was strongly influenced by the treatments, and that the mean values of at least two treatments were significantly different.

The second ANOVA, however, does not provide information to determine differences between specific treatments. Hence, Waller-Duncan k-ratio t-tests were conducted. Table 5.7 displays a summary of the results from this analysis.

Table 5.4 - Summary of Test Results for Properties of Hardened Concrete, Phase I

Mix ID	Mix Description	Abrasion test		RCPT test	Compressive strength test		Freeze-Thaw test
		Wear Depth, inches	Wear Rate, in./hour	Charge Passed, coulombs	28-day Strength, psi	90-day Strength, psi	Durability Factor, %
CW	Control - Water Curing	0.036	0.072	1,791	6,520	7,650	91
CSA	Control - Steam Curing Method A	0.072	0.145	4,474	3,880	3,810	94
CSB	Control - Steam Curing Method B	0.100	0.200	4,635	2,980	2,790	96
EAW	Exp A (Gravel, Slag, Silica Fume) -Water Curing	0.062	0.124	1,176	7,190	8,000	95
EASA	Exp A (Gravel, Slag, Silica Fume) -Steam Curing Method A	0.050	0.100	2,215	5,880	5,360	95
EASB	Exp A (Gravel, Slag, Silica Fume) -Steam Curing Method B	0.072	0.144	2,015	4,570	4,210	97
EBW	Exp B (Crushed Rock, Slag, Silica Fume) - Water Curing	0.025	0.051	1,143	9,450	11,010	93
EBSA	Exp B (Crushed Rock, Slag, Silica Fume) - Steam Curing Method A	0.047	0.094	2,143	7,820	7,510	95
EBSB	Exp B (Crushed Rock, Slag, Silica Fume) - Steam Curing Method B	0.038	0.076	2,426	6,550	6,180	97
ECW	Exp C (Gravel, Fly Ash, Silica Fume) - Water Curing	0.077	0.155	1,000	4,450	5,300	90
ECSA	Exp C (Gravel, Fly Ash, Silica Fume) - Steam Curing Method A	0.073	0.146	3,177	3,630	3,250	91
ECSB	Exp C (Gravel, Fly Ash, Silica Fume) - Steam Curing Method B	0.199	0.397	5,892	2,200	1,750	94
EDW	Exp D (Crushed Rock, Fly Ash, Silica Fume) - Water Curing	0.039	0.079	718	6,530	8,410	93
EDSA	Exp D (Crushed Rock, Fly Ash, Silica Fume) - Steam Curing Method A	0.073	0.147	3,731	4,320	4,200	94
EDSB	Exp D (Crushed Rock, Fly Ash, Silica Fume) - Steam Curing Method B	0.077	0.153	4,422	3,020	2,990	95

Table 5.5 - ANOVA of Wear Rate of Experimental Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.06418733	0.00583521	54.61	<.0001
Error	24	0.00256467	0.00010686		
Corrected Total	35	0.06675200			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.961579	14.62835	0.010337	0.070667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	0.01330178	0.01330178	124.48	<.0001
RockType	1	0.01496544	0.01496544	140.05	<.0001
CureType	2	0.01211150	0.00605575	56.67	<.0001
CemMat*RockType	1	0.00127211	0.00127211	11.90	0.0021
CemMat*CureType	2	0.00905206	0.00452603	42.35	<.0001
RockType*CureType	2	0.00881172	0.00440586	41.23	<.0001
CemMat*RockType*CureType	2	0.00467272	0.00233636	21.86	<.0001

Table 5.6 - ANOVA of Wear Rate of All Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	0.06787111	0.00484794	49.30	<.0001
Error	30	0.00295000	0.00009833		
Corrected Total	44	0.07082111			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.958346	13.87976	0.009916	0.071444

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	14	0.06787111	0.00484794	49.30	<.0001

Table 5.7 - Waller-Duncan k-ratio t-test Results for Wear Rate from Phase I

Waller Grouping	Wear Rate Mean	N	TRT	Description
A	0.198333	3	ECSB	Fly Ash + Gravel + Steam Curing B
B	0.100000	3	CSB	Control Mix + Steam Curing B
C	0.077333	3	ECW	Fly Ash + Gravel + Water Curing
C	0.076667	3	EDSB	Fly Ash + Crushed Rock + Steam Curing B
C	0.075333	3	EAW	Slag + Gravel + Water Curing
C	0.073667	3	EDSA	Fly Ash + Crushed Rock + Steam Curing A
C	0.073000	3	ECSA	Fly Ash + Gravel + Steam Curing A
C	0.072333	3	CSA	Control Mix + Steam Curing A
C	0.072000	3	EASB	Slag + Gravel + Steam Curing B
D	0.051333	3	CW	Control Mix + Water Curing
D	0.050333	3	EASA	Slag + Gravel + Steam Curing A
D	0.047333	3	EBSA	Slag + Crushed Rock + Steam Curing A
D	0.040333	3	EDW	Fly Ash + Crushed Rock + Water Curing
E D	0.038333	3	EBSB	Slag + Crushed Rock + Steam B Curing
E	0.025333	3	EBW	Slag + Crushed Rock + Water Curing

The results indicate that treatment ECSB had the highest wear rate. The wear rates of the mixtures in Waller Grouping C were not significantly different from the wear rate of the control mixture subjected to Steam Curing Method A, but they were significantly different from the wear rate of the control mixture cured in water. Treatment EBW had the lowest wear rate. Its wear rate was not significantly different from treatment EBSB, but it was significantly different from the wear rates of the other treatments in Waller Grouping D.

For the mixtures with gravel, the mixture with slag cured with Steam Curing Method A performed significantly better than the mixture with fly ash cured by either steam curing method. However, there was no difference between the mixtures with slag and fly ash that were cured in water. In addition, the control mixture cured in water performed significantly better than the mixture with fly ash independent of the curing method for the mixture with fly ash.

For the mixtures with crushed rock, the mixture with slag performed significantly better than the mixture with fly ash for a given curing method. The mixture with slag also performed significantly better than the control mixture (with gravel) for a given curing method. However, the control mixture performed better than the mixture with fly ash mixture cured with Steam Curing Method B, but essentially the same for the other curing methods.

5.2.2.2 Permeability

The SAS output of an analysis of variance of the data obtained from the experimental mixtures, with charge passed (in coulombs) as the response variable, is shown in Table 5.8. The results are interpreted in a way such that the higher the charge passed through a concrete specimen, the higher the permeability of the concrete and, hence, the lower the chloride ion penetration resistance.

The results show that the model is highly significant ($p\text{-value} < 0.0001$) indicating that chloride ion penetration resistance of the mixtures was strongly influenced by at least one of the factors. The results also show that cementitious materials and curing method, but not rock type (i.e., river gravel versus crushed rock), significantly affected chloride ion penetration resistance of the mixtures. In addition, the results indicate that the 2-way and 3-way interactions are highly significant. With this being the case, further investigation of the main effects alone is unwarranted.

The results of the second ANOVA, conducted to include the results from the control mixture, is shown in Table 5.9. As indicated, the model is highly significant ($p\text{-value} < 0.0001$) indicating the amount of charge passed was strongly influenced by the treatments and that the mean values of at least two of the treatments were significantly different.

Table 5.8 - ANOVA of Chloride Ion Penetration of Experimental Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	105545009.6	9595000.9	63.81	<.0001
Error	36	5413584.9	150377.4		
Corrected Total	47	110958594.5			

R-Square	Coeff Var	Root MSE	Charge Passed Mean
0.951211	15.43203	387.7852	2512.860

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	19892592.14	19892592.14	132.28	<.0001
RockType	1	209962.62	209962.62	1.40	0.2451
CureType	2	58605517.52	29302758.76	194.86	<.0001
CemMat*RockType	1	855449.58	855449.58	5.69	0.0225
CemMat*CureType	2	21598496.03	10799248.02	71.81	<.0001
RockType*CureType	2	1191009.55	595504.77	3.96	0.0279
CemMat*RockType*CureType	2	3191982.16	1595991.08	10.61	0.0002

Table 5.9 - ANOVA of Chloride Ion Penetration of All Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	138008611.6	987758.0	68.81	<.0001
Error	45	6446269.3	143250.4		
Corrected Total	59	144454880.9			

R-Square	Coeff Var	Root MSE	Charge Passed Mean
0.955375	13.82879	378.4844	2736.931

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	14	138008611.6	9857758.0	68.81	<.0001

Table 5.10 shows the results of Waller-Duncan k-ratio t-tests performed to distinguish differences (or similarities) between the treatments. It indicates that mixture ECSB passed the greatest amount of charge, while mixture EDW passed the least (i.e., had the greatest resistance to chloride ion penetration and, therefore, the lowest permeability). Also note that the mixtures cured in water had lower permeability than those cured with steam; those with fly ash had the lowest permeability, and were the only mixtures that passed less charge than the criterion of 1,000 coulombs as stipulated in the ODOT Standard Specifications *(2008)*. Of those cured with steam, the mixtures with slag had lower permeability. Independent of SCM type or curing method, rock type did not have much influence on chloride ion penetration resistance corroborating the finding shown in Table 5.8.

Table 5.10 - Waller Groupings of Chloride Ion Penetration from Phase I

Waller Grouping	Charge Passed Mean	N	TRT	Description
A	5891.8	4	ECSB	Fly Ash + Gravel+ Steam Curing B
B	4634.8	4	CSB	Control Mix + Steam Curing B
B	4473.9	4	CSA	Control Mix + Steam Curing A
B	4422.1	4	EDSB	Fly Ash + Crushed Rock + Steam Curing B
C	3731.0	4	EDSA	Fly Ash + Crushed Rock + Steam Curing A
D	3177.3	4	ECSA	Fly Ash + Gravel + Steam Curing A
E	2425.6	4	EBSB	Slag + Crushed Rock + Steam B Curing
F E	2214.5	4	EASA	Slag + Gravel + Steam Curing A
F E	2142.9	4	EBSA	Slag + Crushed Rock + Steam Curing A
F E	2014.9	4	EASB	Slag + Gravel + Steam Curing B
F	1791.0	4	CW	Control Mix + Water Curing
G	1240.9	4	EBW	Slag + Crushed Rock + Water Curing
H G	1175.7	4	EAW	Slag + Gravel + Water Curing
H G	999.7	4	ECW	Fly Ash + Gravel + Water Curing
H	717.9	4	EDW	Fly Ash + Crushed Rock + Water Curing

5.2.2.3 Compressive Strength

Table 5.11 displays the results of the analysis of variance of the compressive strength data for the experimental mixtures. It indicates a significant model (p-value < 0.0001) and significance amongst two of the interactions between main effects, both involving rock type. Due to this, further investigation of the main effects alone is unnecessary.

Table 5.11 - ANOVA of Compressive Strength of Experimental Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	150237309.2	13657937.2	142.04	<.0001
Error	24	2307805.7	96158.6		
Corrected Total	35	152545114.9			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.984871	5.672259	310.0945	5466.860

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	75084680.10	75084680.10	780.84	<.0001
RockType	1	23849467.57	23849467.57	248.02	<.0001
CureType	2	47744756.54	23872378.27	248.26	<.0001
CemMat*RockType	1	1675234.06	1675234.06	17.42	0.0003
CemMat*CureType	2	21434.47	10717.24	0.11	0.8950
RockType*CureType	2	1332169.90	666084.95	6.93	0.0042
CemMat*RockType*CureType	2	529566.54	264783.27	2.75	0.0838

Table 5.12 shows the results of the second ANOVA conducted to include the results of the control mixture. As before with the wear rate and permeability results, each combination of cementitious material, rock type, and curing method was considered as a separate treatment in this analysis. The results indicate the model is significant (p-value < 0.0001) meaning that compressive strength was strongly influenced by the treatments, and the mean values of at least two treatments were significantly different.

Table 5.12 - ANOVA of Compressive Strength of All Mixtures from Phase I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	177902568.3	12707326.3	148.19	<.0001
Error	30	2572429.2	85747.6		
Corrected Total	44	180474997.5			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.985746	5.561921	292.8270	5264.853

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	14	177902568.3	12707326.3	148.19	<.0001

To distinguish differences (or similarities) between treatments, Waller-Duncan k-ratio t-tests were conducted. Table 5.13 displays the results of this analysis. It indicates the mixtures with slag had the highest strengths. For the slag mixtures with crushed rock, the mixture cured in water had a significantly higher strength than the mixture cured with Steam Curing Method A which, in turn, had a significantly higher strength than the mixture cured with Steam Curing Method B. The same findings hold true for the slag mixtures with gravel, for the mixtures with fly ash (for both rock types), and for the control mixture (with gravel).

Table 5.13 - Waller-Duncan k-ratio t-test Results for Wear Rate from Phase I

Waller Grouping	Compressive Strength Mean	N	TRT	Description
A	9452.3	3	EBW	Slag + Crushed Rock + Water Curing
B	7817.1	3	EBSA	Slag + Crushed Rock + Steam Curing A
C	7193.4	3	EAW	Slag + Gravel + Water Curing
D	6552.7	3	EBSB	Slag + Crushed Rock + Steam B Curing
D	6524.9	3	EDW	Fly Ash + Crushed Rock + Water Curing
D	6517.3	3	CW	Control Mix + Water Curing
E	5880.0	3	EASA	Slag + Gravel + Steam Curing A
F	4570.8	3	EASB	Slag + Gravel + Steam Curing B
F	4444.8	3	ECW	Fly Ash + Gravel + Water Curing
F	4319.5	3	EDSA	Fly Ash + Crushed Rock + Steam Curing A
G	3876.6	3	CSA	Control Mix + Steam Curing A
G	3632.1	3	ECSA	Fly Ash + Gravel + Steam Curing A
H	3018.2	3	EDSB	Fly Ash + Crushed Rock + Steam Curing B
H	2976.6	3	CSB	Control Mix + Steam Curing B
I	2196.5	3	ECSB	Fly Ash + Gravel+ Steam Curing B

5.2.2.4 Freeze-Thaw Resistance

Results of the freeze-thaw resistance tests were not analyzed using analysis of variance since only one specimen per mixture was tested. Instead, this section presents trends in the data.

Figures 5.1 - 5.4 show photographs of the visual appearance of several specimens taken after freeze-thaw testing. Figures 5.1 and 5.2 show evidence of surface scaling on the control mixture and Figure 5.2 also shows evidence of structural degradation. Scaling was also evident on the mixture with fly ash (Figure 5.3), but not on the mixture with slag (Figure 5.4).

Figure 5.1 - Surface Scaling on the Control Mixture Specimen (CW)

Figure 5.2 - Broken End on Control Mixture Specimen (CSA)

Figure 5.3 - Surface Scaling Evident on Experimental Mixture with Fly Ash (ECW)

Figure 5.4 - Surface Scaling not Evident on Experimental Mixture with Slag (EASB)

Dynamic Moduli

Figures 5.5, 5.6, and 5.7 provide freeze-thaw resistance test results from the mixtures cured in water, with Steam Curing Method A, and Steam Curing Method B, respectively. The results show, for each mixture design, the dynamic modulus of the concrete specimen after freeze-thaw cycling relative to the initial dynamic modulus, expressed in percent. Initial moduli of the specimens were determined before freeze-thaw cycling.

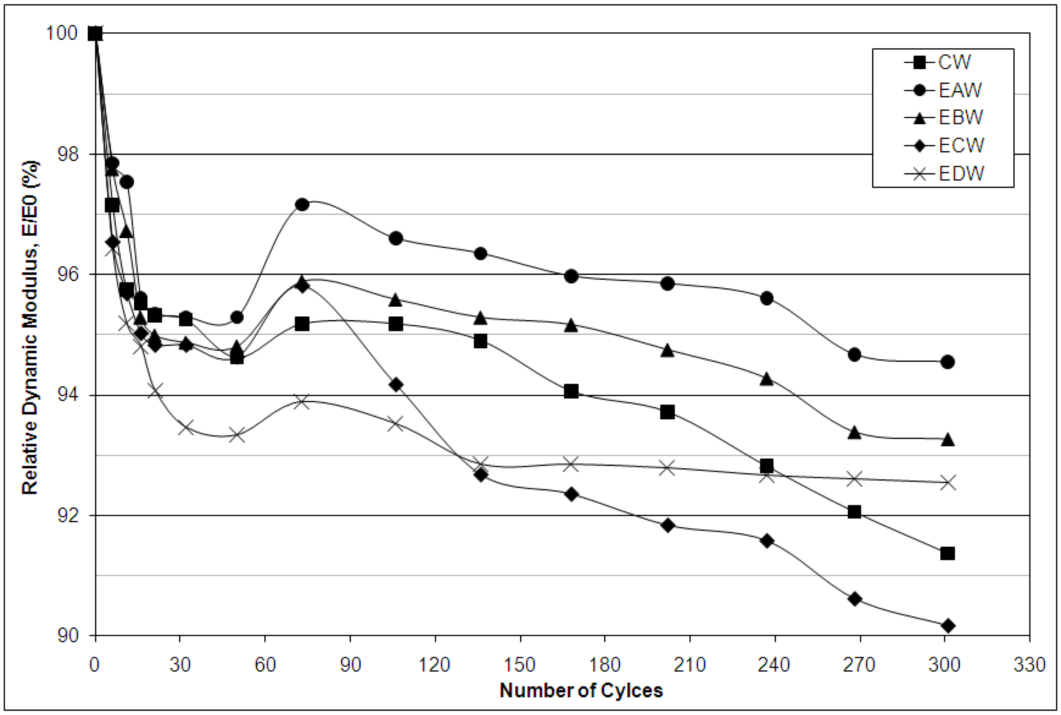

Figure 5.5 - Relative Dynamic Modulus for Mixtures Cured in Water

In all cases, the results indicate a decrease in stiffness (modulus) during the first several freeze-thaw cycles followed by a period of no further decrease. Between about 50 and 75 freeze-thaw cycles the results indicate that the stiffness recovered slightly, after which it once again decreased until the end of freeze-thaw cycling. It is not known if the recoveries shown are true responses; the consistency in the data suggests a systematic error in testing. Nevertheless, comparisons of results remain valid since relative performance is desired, rather than absolute values for performance.

All mixtures retained more than 90% of the initial modulus after 300 freeze-thaw cycles. Assuming that a systematic error during testing caused the apparent recoveries of the specimens between about 50 and 75 freeze-thaw cycles, negating the magnitude of the recoveries would result in most specimens still having relative moduli in excess of 90% of the initial moduli.

Another general observation is that the mixtures cured in water provided similar trends in the results as those cured using Steam Curing Method A. However, the results appeared to also indicate that the mixtures cured using Steam Curing Method B suffered the least overall decrease in stiffness.

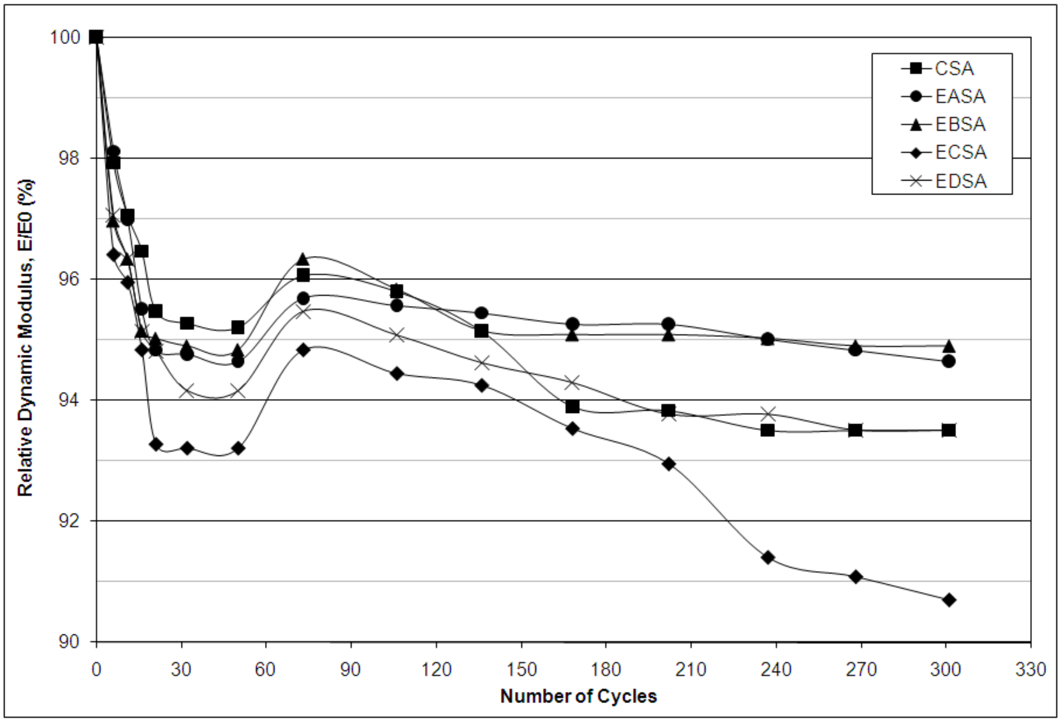

Figure 5.6 - Relative Dynamic Modulus for Mixtures Cured using Steam Curing Method A

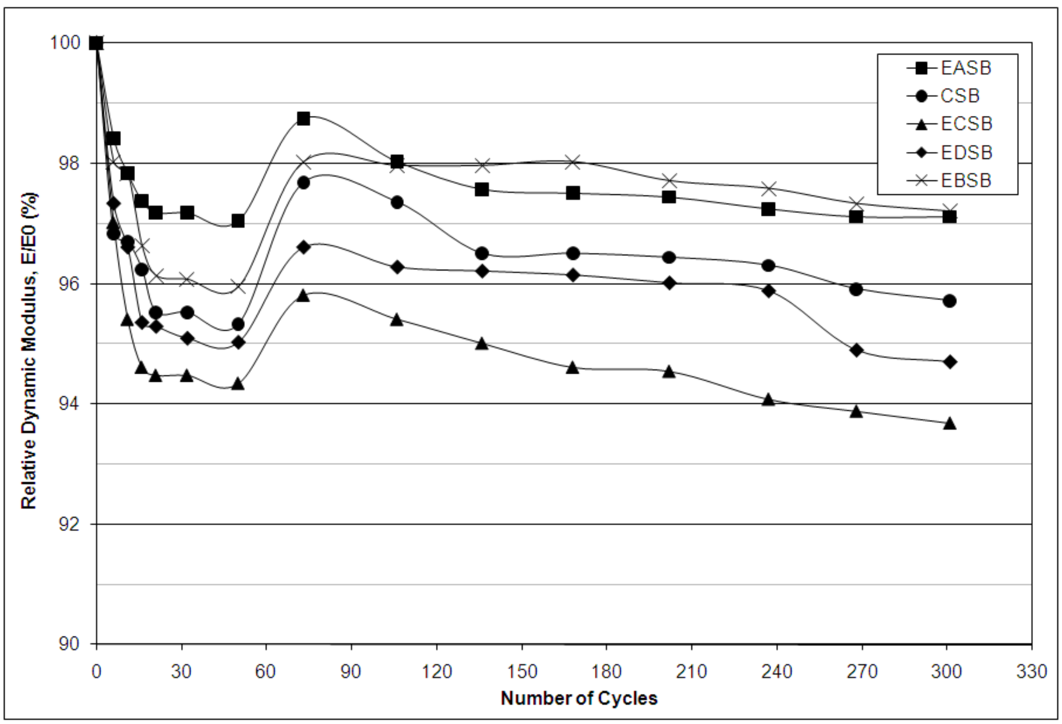

Figure 5.7 - Relative Dynamic Modulus for Mixtures Cured using Steam Curing Method B

Durability Factors

The remainder of this section provides comparisons based on durability factors. Equation 4.2 (Section 4.5.5) was used to calculate the durability factors.

Comparisons between Types of Supplementary Cementitious Materials

The following two figures present the durability factors of the mixtures for each type of rock used in the mixtures. Figure 5.8 shows the results for mixtures containing river gravel and Figure 5.9 shows the results for those containing crushed rock.

The results shown in Figure 5.8 indicate that the durability factors for the mixtures with slag exceeded those of the control mixture, albeit only slightly. Similarly, the durability factors of the control mixture slightly exceeded those of the mixtures with fly ash. Further, the durability factors of the mixtures with slag exceeded those of the mixtures with fly ash by several percent.

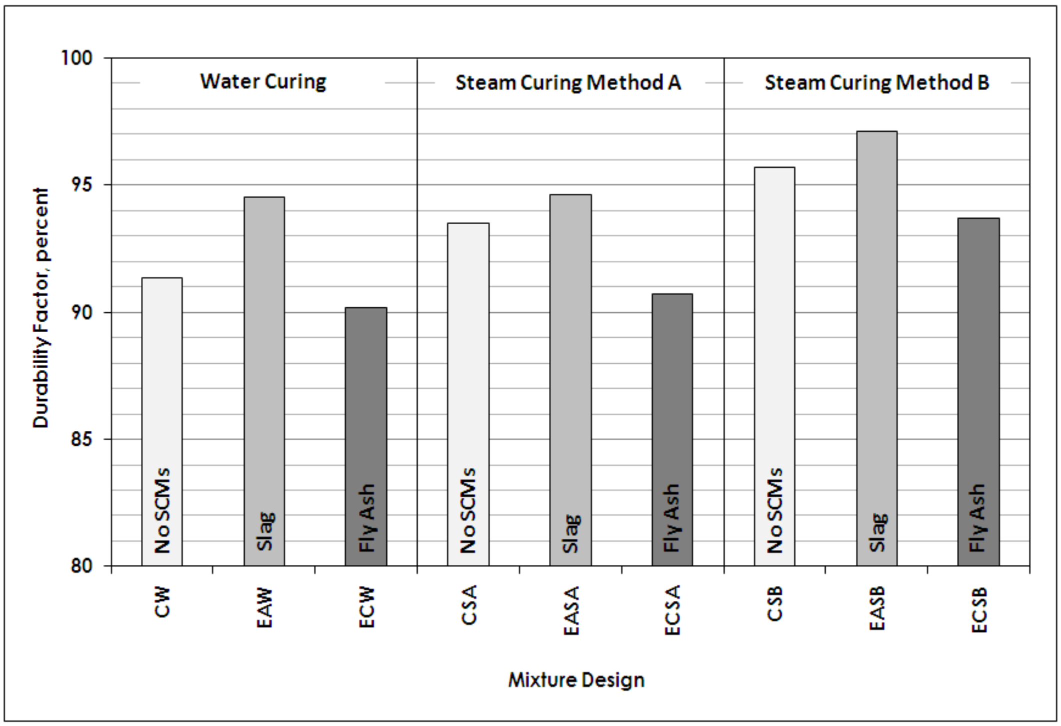

Figure 5.8 - Durability Factors of Mixtures with River Gravel

Figure 5.9 shows similar trends in the results to those shown in Figure 5.8. However, there are two exceptions; the durability factor of the mixture with fly ash exceeded that of the control mixture for the mixtures cured in water, and the magnitude of differences were smaller, particularly between the slag and fly ash mixtures.

Comparison between Types of Aggregates

Figure 5.10 and 5.11 show the durability factors of the mixtures containing slag and fly ash, respectively. The figures exclude the results from the control mixture since it contained neither supplementary cementitious material.

Figure 5.10 shows that there was very little (essentially no) difference between durability factors of mixtures with gravel and mixtures with crushed rock. Figure 5.11, however, shows that the durability factors of the mixtures with crushed rock were slightly higher than those of the mixtures with river gravel.

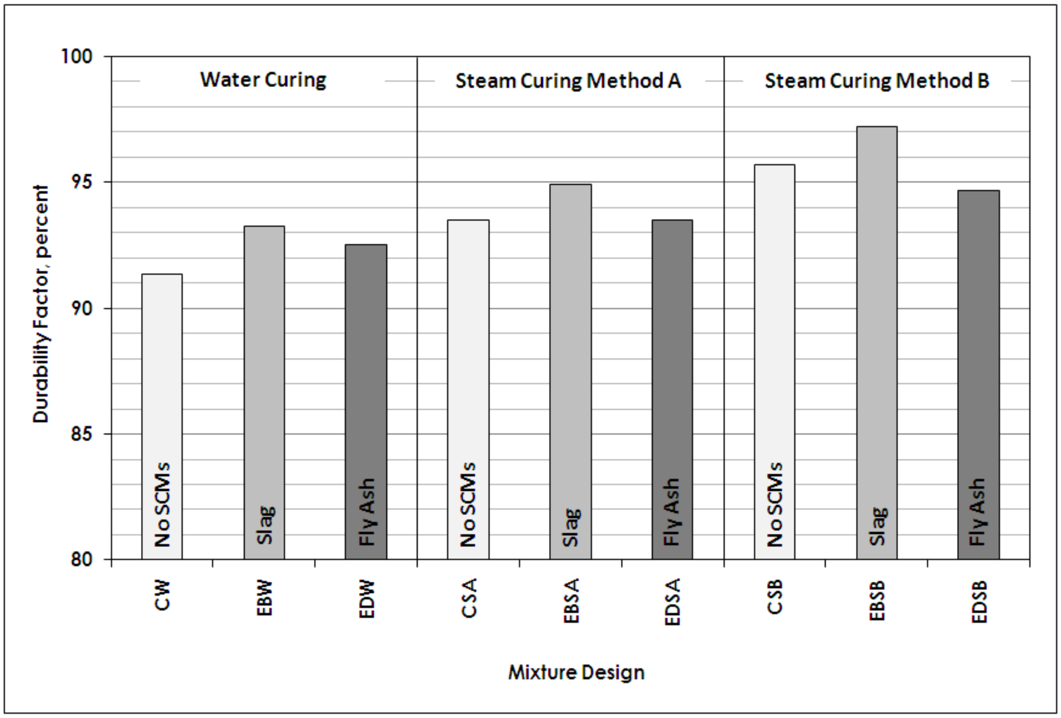

Figure 5.9 - Durability Factors of the Control Mixture and Those with Crushed Rock

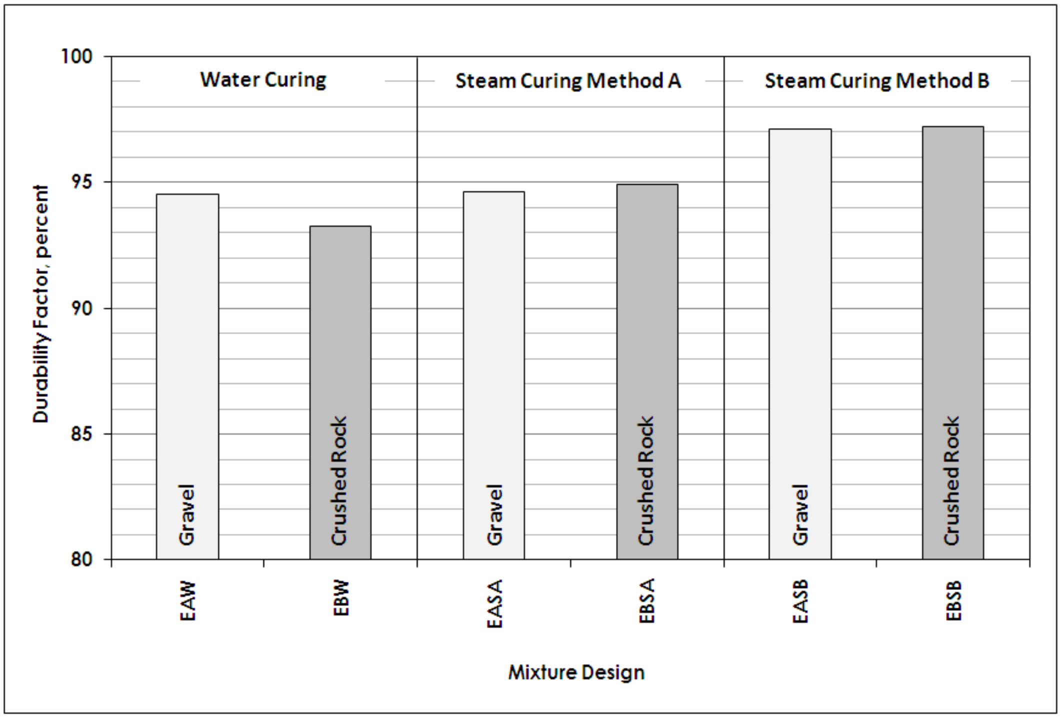

Figure 5.10 - Durability Factors of Mixtures with Slag

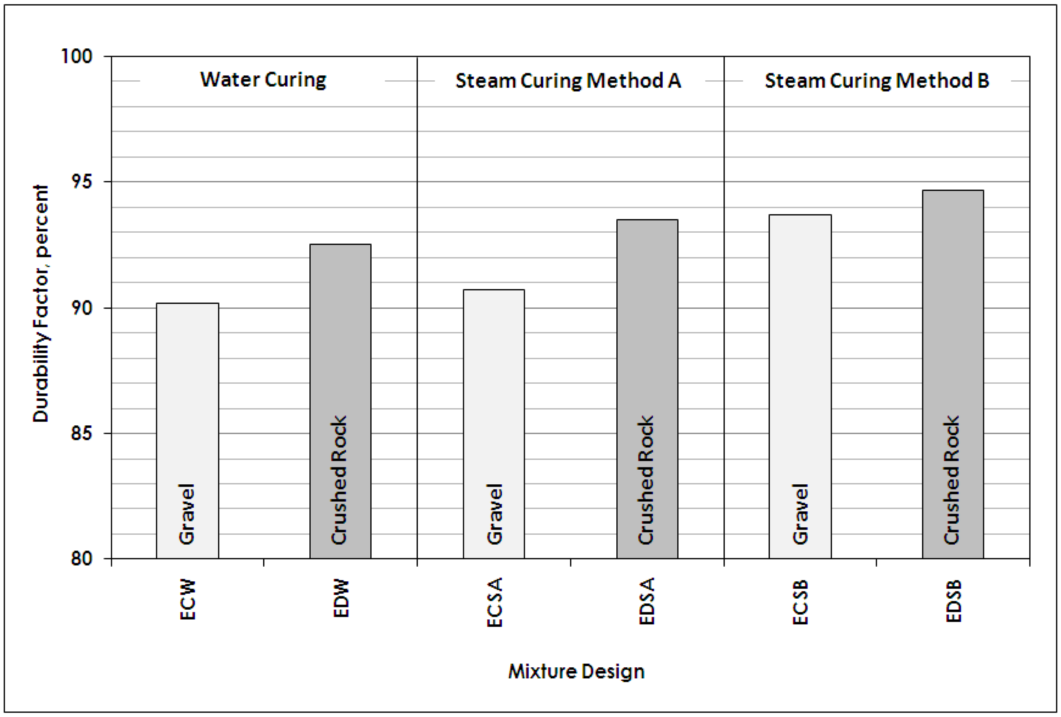

Figure 5.11 - Durability Factors of Mixture with Fly Ash

Comparison between Curing Methods

Figure 5.12 shows the durability factors for all of the mixtures tested in Phase I of the study, organized by mixture design. For each group of mixtures, the left bar provides the results from the specimens cured in water, the middle bar provides those from the specimens cured by Steam Curing Method A, and the right bar provides the results from the specimens cured by Steam Curing Method B.

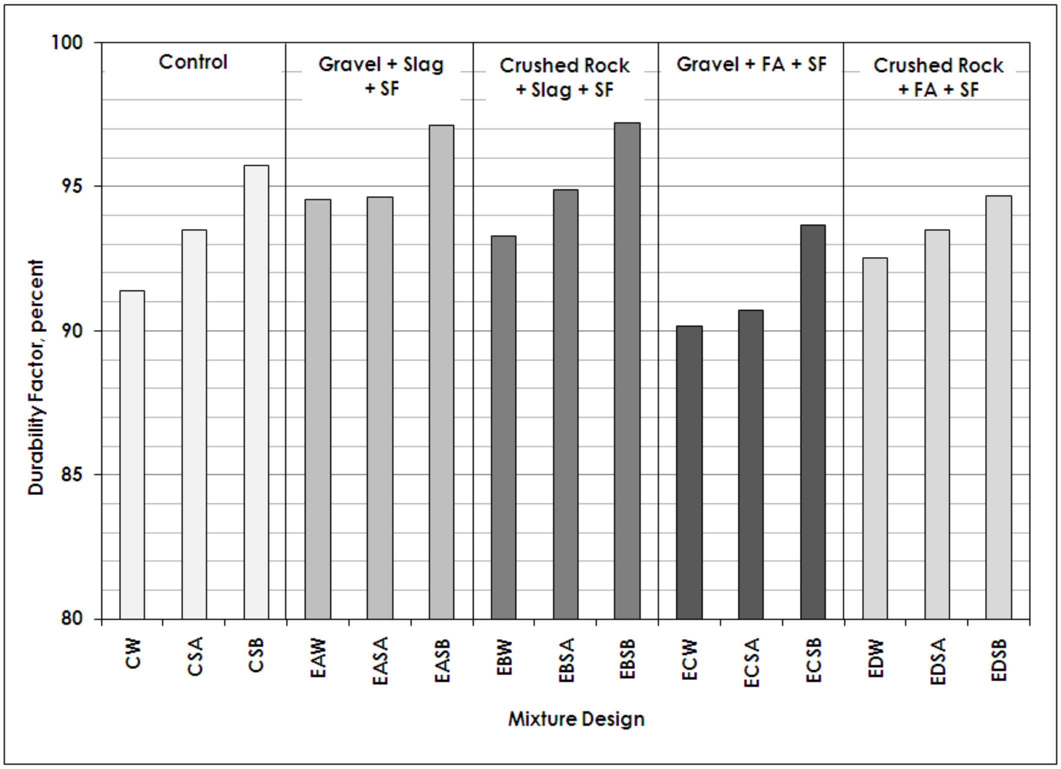

Figure 5.12 - Effect of Curing Method on the Durability Factor of Various Mixtures

The results indicate a clear trend in durability factor as a result of curing method. That is, for all five mixture designs, the mixtures cured in water had the lowest durability factors, the mixtures cured using Steam Curing Method A had the next lowest durability factors, and the mixtures cured using Steam Curing Method B had the highest durability factors. Steam curing clearly improved the resistance to freeze-thaw cycling, and the inclusion of a drying period (as in the case of the mixtures cured using Steam Curing Method B) provided additional benefit.

5.2.3 Summary

Statistical analyses of the data obtained from testing conducted in Phase I revealed that the type of cementitious materials and curing method strongly influenced the wear rate, chloride ion penetration resistance, and compressive strength of the concrete mixtures. Type of rock (crushed rock versus gravel) alone did not have a strong influence on the permeability of the mixtures, but its interactions with cementitious materials and curing method did. Rock type alone, however, strongly influenced wear rate and compressive strength, as did its interactions with cementitious materials and curing method.

Inclusion of slag generally produced concrete with better resistance to wear, lower permeability, and greater strength than concrete with fly ash. However, water-cured fly ash mixtures had lower permeability than slag mixtures.

For a given rock type and combination of cementitious materials, water-cured mixtures provided concrete with the lowest permeability and greatest strength. This was also generally true for wear rate except that the mixtures with SCMs and gravel cured using Steam Curing Method A had greater wear resistance than those cured in water. Considering the two steam curing methods, Method A generally provided concrete with better properties than did Method B. However, it is important to note that, in these inferences regarding curing methods, significant differences did not exist between some methods.

Observations in the trends of the freeze-thaw resistance test results indicate that the slag mixture had better durability than the fly ash and the control mixture, but clear differences between the fly ash and the control mixture are not apparent. Mixtures with crushed rock generally had better durability than those with river gravel, and steam curing produced concrete with better durability than water-cured concrete. Inclusion of a drying period following steam curing (i.e., Steam Curing Method B) provided additional benefit for the durability of the concrete.

5.3 PILOT STUDY

The primary purpose of conducting the Pilot Study was to identify or develop a laboratory curing regime that would provide high early strength and, at the same time, compressive strength comparable to that of specimens cured in water for 28 days. The findings from Phase I confirmed that water curing is the best method of curing, but it would be quite difficult to carry out in the field due to the constraints of cost and construction issues. Therefore, it became important to consider alternative techniques that would be practical for use during plant production as well as produce concrete with properties similar to those cured in water. A secondary objective of the Pilot Study was to investigate whether or not ODOT's 14-day field curing requirement for cast-in-place concrete bridge decks *(ODOT 2008)* could be shortened.

Eleven curing methods combining different curing techniques and different curing periods were investigated (see Section 3.2). Curing techniques included water curing, water curing plus ambient curing with and without a curing compound, and steam curing plus ambient curing with and without a curing compound. Curing durations ranged up to 28 days. Three specimens for each curing method were cast for the Pilot Study providing a total of 33 specimens. Evaluation of the effectiveness of the curing regimes was based solely on the average compressive strength of the specimens. However, the fresh properties of the concrete were also determined. This section presents the results of these tests.

5.3.1 Fresh Concrete Properties

Table 5.14 provides a summary of the fresh properties of the concrete mixture used in the Pilot Study. Although it had a single mixture design (see Section 3.2.4), mixture specimens were produced in five separate batches (due to the capacity of the mixer). Air contents and slump of the batches varied, but were within the specified limit set by the new (*2008*) ODOT specification. Temperature of the concrete varied according to the ambient temperature on the day of casting.

Table 5.14 - Summary of Test Results for Fresh Properties of Concrete, Pilot Study

Run ID	Slump, in.	Air Content, %	Temperature, °F
Run 1	9	6.5	58
Run 2	9	6.5	58
Run 3	9	6.5	58
Run 4	9	6.5	58
Run 5	9¾	7.5	66
Run 6	9¾	7.5	66
Run 7	9¾	7.5	66
Run 8	8½	7.2	64
Run 9	10	7.5	58
Run 10	10	7.5	58
Run 11	8½	6.6	61

5.3.2 Hardened Concrete Properties

Since previous studies suggested that the abrasion resistance of concrete is directly proportional to its compressive strength, the Pilot Study focused on compressive strength at various stages of curing. Table 5.15 provides a summary of the results, while Appendix D provides details.

Figure 5.13 presents the results in graphical format to illustrate the evolution of compressive strength due to the curing regimes investigated. Some general observations indicate that:

- One day of water curing followed by ambient curing (Run 9) did not result in as rapid of strength gain, nor as high of 28-day compressive strength, as the other curing regimes. Peak strength occurred at 14 days.

Table 5.15 - Average Compressive Strength at Various Stages of Curing

Run ID	Curing[1]	Average Compressive Strength[2], psi				
		1-day	3-day	7-day	14-day	28-day
1	28 day WC	4,870	8,070	9,800	10,450	11,260
2	14 days WC + AC	---	---	---	---	11,690
3	7 days WC + AC	---	---	---	10,460	11,190
4	14 days WC + CC + AC	---	---	---	---	11,520
5	7 days WC + CC + AC	---	---	---	9,179	10,130
6	1 day WC + CC + AC	---	6,750	7,660	9,340	9,110
7	3 days WC + CC + AC	---	---	8,920	9,350	9,940
8	3 days WC + AC	---	---	9,990	10,220	11,000
9	1 day WC + AC	---	4,420	5,590	6,410	6,170
10	SC + AC	5,390	6,570	7,210	7,160	6,860
11	SC + CC + AC	8,870	9,810	10,480	10,550	10,930

[1]WC = water curing; AC = ambient curing; CC = curing compound; SC = steam curing
[2]Average of three specimens

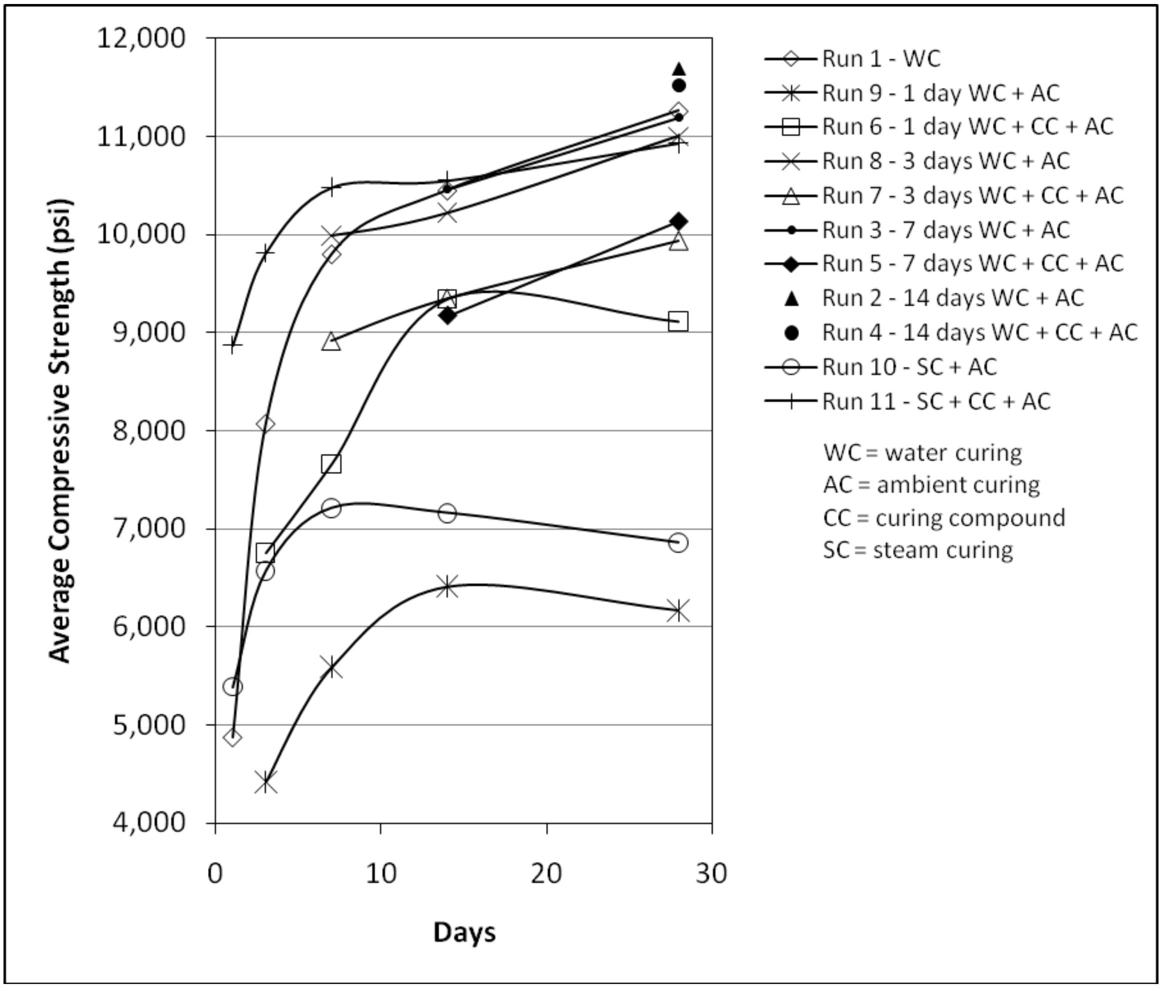

Figure 5.13 - Evolution of Strength due to Curing Regimes Investigated in the Pilot Study

- Application of a curing compound after 1 day of water curing followed by ambient curing (Run 6) resulted in substantial improvement, in terms of rate of strength gain and 28-day strength, relative to 1 day of water curing without application of a curing compound (Run 9). Peak strength occurred at 14 days for both of these mixtures.
- Steam curing followed by ambient curing (Run 10) produced a similar trend in results as that of 1 day of water curing followed by ambient curing (Run 9). However, it resulted in a greater rate of strength gain and a higher 28-day strength. Peak strength for Run 10 occurred at 7 days.
- As little as 3 days of water curing (Runs 7 and 8) resulted in early-age strength gain followed by continued gain through 28 days. Interestingly, application of a curing compound after 3 days of water curing (Run 7) did not result in a marked improvement in 28-day strength relative to the mixture without curing compound (Run 8). Perhaps more importantly, 3 days of water curing produced strengths similar to continuous water curing (Run 1).
- Seven days of water curing (Runs 3 and 5) produced results similar to those found from the specimens cured in water for 3 days (Runs 8 and 7, respectively).

- Fourteen days of water curing (Runs 2 and 4) resulted in 28-day strengths similar to that produced from continuous water curing (Run 1). Application of a curing compound after 14 days of water curing did not appear to have a significant impact on strength gain.
- Steam curing followed by application of a curing compound (Run 11) resulted in a greater rate of early strength gain than that of continuous water curing (Run 1), but strength gain leveled off after 7 days. However, the 28-day strength of the steam-cured mixture with curing compound (Run 11) was very similar to that of the mixture that had been cured continuously in water (Run 1).

The following sections provide statistical comparisons of the results.

5.3.2.1 Water-Cured Mixture

The specimens for Runs 1 - 9 were cured in water for various durations (Table 5.15). Following the water curing period, all specimens except those for Run 1 were cured in ambient conditions. The specimens for Runs 4 - 7 were coated with a curing compound following water curing, but before ambient curing.

The symbols in Figure 5.14 show the average 28-day compressive strength of the specimens (except those for Run 1) resulting from various periods of water curing followed by ambient curing. It also shows the 95% Bonferroni confidence intervals (bars extending above and below the symbols) for each set of results, including the interval for the specimens cured in water for 28 days.

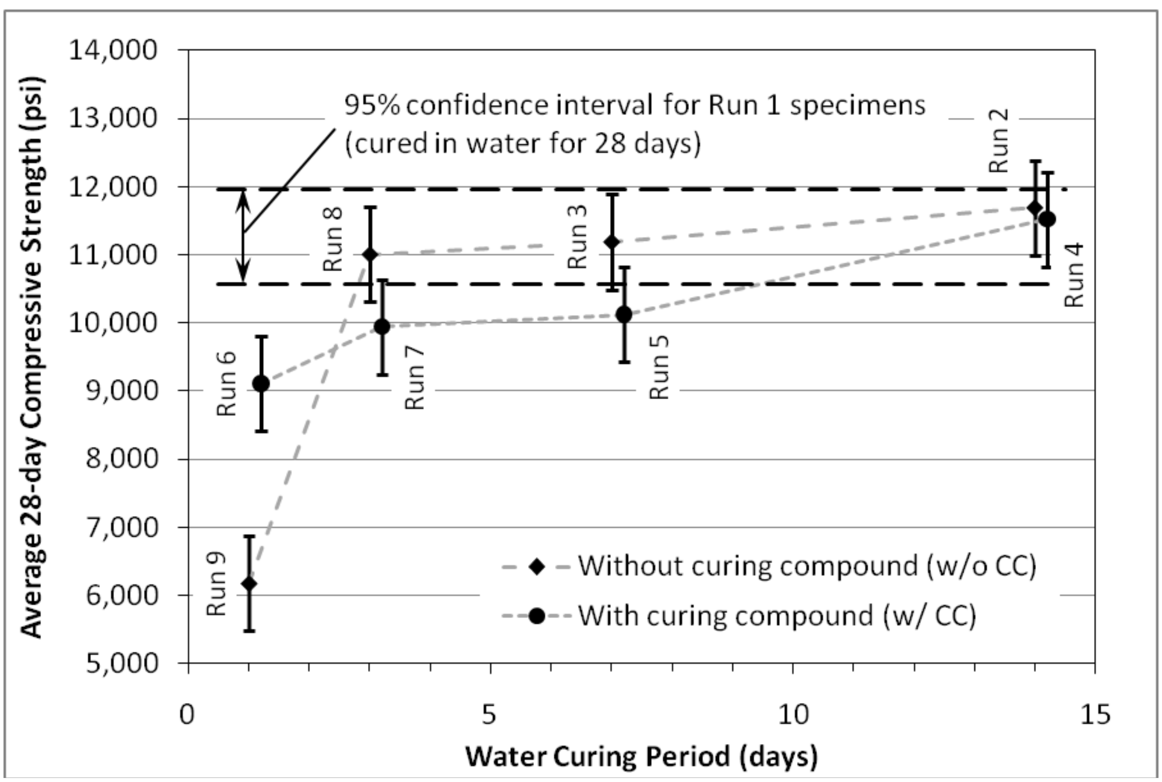

Figure 5.14 - 28-day Strengths of Water-Cured Specimens

The results displayed in the figure indicate the following:

- The average strengths of the specimens cured in water for 3 days or longer (i.e., those for Runs 2, 3, 4, 5, 7, and 8) followed by ambient curing were not significantly different from the average strength of the specimens cured continuously in water for 28 days (Run 1).
- The average strength of the specimens cured in water for 3 days (Run 8) was not significantly different from the average strength of the specimens cured for 14 days (Runs 2 and 4). There was a significant difference, however, between the average strength of the specimens for Run 7 and the average strengths of the specimens for Runs 2 and 4.
- The specimens coated with a curing compound after 1 day of water curing (those for Run 6) had a significantly higher average 28-day compressive strength than those that were not coated with a curing compound (those for Run 9). However, application of curing compound following 3 or more days of water curing had an insignificant influence on the 28-day compressive strength of the concrete.

5.3.2.2 Steam-Cured Mixture

The specimens for Runs 10 and 11 were steam-cured followed by ambient curing. Those for Run 11 were coated with a curing compound prior to ambient curing.

Figure 5.15 displays the evolution of strength gain of the concrete as well as the 95% Bonferroni confidence intervals. Results from the specimens cured continuously in water are also included for comparison purposes.

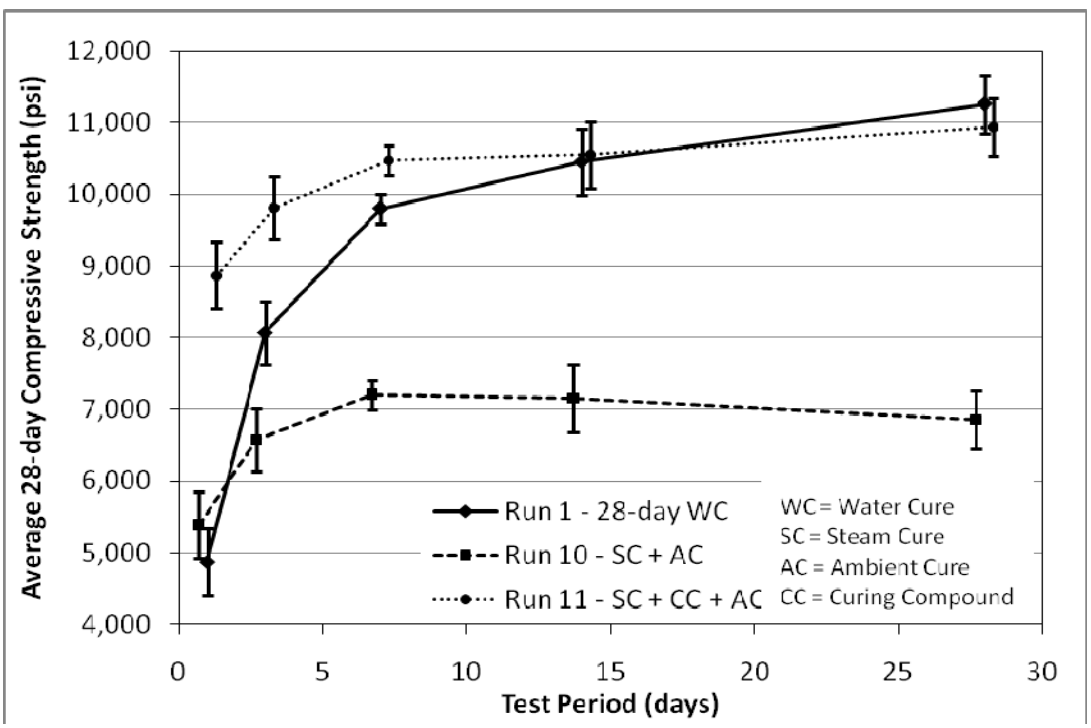

Figure 5.15 - Strength Gain of Steam-Cured and Continuously Water-Cured Specimens

The results displayed in the figure indicate that the average strength of the specimens without a curing compound (Run 10) increased up to the 7-day test period, but then increased no further. Conversely, the average strength of the specimens with a curing compound (Run 11) continued to increase up to the 28-day test period. In addition, the average strength of the specimens with a curing compound (Run 11) was significantly higher than that of the specimens without a curing compound (Run 10) at all test periods.

Figure 5.15 also shows that the specimens with a curing compound (Run 11) had a significantly higher strength than the specimens continuously cured in water up to the 7-day test period. Beyond this, differences in the strengths were insignificant.

5.3.3 Summary

The principal findings from the Pilot Study included the following:

- For the specimens that were not coated with a curing compound, there was no significant difference in 28-day strengths between specimens continuously cured in water for 28 days and those that had been cured in water for at least 3 days (Figure 5.14).
- Application of a curing compound following 1 day of water curing promoted 1-day strength gain (Figure 5.14). However, application of the compound following 3 or more days of water curing did little to improve strength properties of the concrete.
- Application of a curing compound following steam curing resulted in significantly higher strength relative to that of the specimens not coated with a curing compound at all evaluation periods (Figure 5.15). In addition, the steam-cured specimens with a curing compound had significantly higher early-age strength than that of the water-cured specimens, but there was no significant difference in 14-day or 28-day strengths.

5.4 PHASE II

Findings from Phase I indicated that HPC mixtures, particularly those with slag and/or crushed rock, could provide improved abrasion and durability characteristics relative to concrete without supplementary cementitious materials or crushed rock. However, the improvements were not substantive enough to warrant trials of the mixtures in field tests. In addition, changes to the ODOT Standard Specifications occurred that allowed the use of HPC for structural concrete beginning in 2008. Phase II of the study sought to improve upon the mixtures developed under Phase I taking into account the changes made to the specifications as well as the findings from the Pilot Study regarding curing methods.

Several new mixture designs were investigated in Phase II. Section 3.3 provides details of these mixture designs, as well as the experiment plan. In brief, the new mixture designs were all HPC mixtures containing silica fume and fly ash or slag. The new (2008) ODOT Standard Specifications stipulated that HPC shall contain 66% cement, 30% fly ash, and 4% silica fume[1].

[1] The 2008 ODOT Standard Specifications allow the use of other constituents provided that the alternate mixture design provides a mixture that passes a maximum of 1,000 coulombs at 90 days when tested in accordance with AASHTO T 277.

For Phase II, this became the new control mixture. The experimental mixtures were comprised of the same constituent materials but their contents were varied. Section 4.1 provides a description of these materials. All mixtures except Mixes S and T had a water-to-binder (w/b) ratio of 0.30, whereas that for Mix S was 0.26 and that for Mix T was 0.27.

One other item to note is that the findings from Phase I provided convincing evidence that crushed rock could improve the strength and abrasion resistance characteristics (but did little to improve the permeability and freeze-thaw resistance characteristics) of concrete mixtures. However, it was decided to utilize only river gravel in the new mixtures so as to simulate mixtures that would most likely be produced routinely in actual production. That is, it was reasoned that manufacturers would most likely utilize locally available aggregates such as river gravels, rather than importing higher-quality crushed rock, to keep production cost as low as possible.

Although evaluation of the mixtures was based on hardened concrete properties, the properties of the fresh concrete were also determined. Section 4.5 provides a description of the test methods utilized. This section provides a summary of the test results.

5.4.1 Fresh Properties of Concrete

Table 5.16 provides a summary of test results for the freshly-mixed concrete. Slump and air contents were within the specified limits of the 2008 ODOT Standard Specifications for these properties. Mix S did not contain an air-entraining additive, therefore the air content of the mixture was only 2%.

Table 5.16 - Summary of Test Results for Fresh Properties of Concrete, Phase II

Mixture ID	Temperature, °C	Slump, in.	Air Content, %
Control	66	8½	7.5
Mix A	66	10	6.5
Mix B	72	8½	7.5
Mix C	59	9½	7.8
Mix D	66	10	6.9
Mix E	64	9½	5.0
Mix S	61	10	2.0
Mix T	79	10	7.0

5.4.2 Hardened Concrete Properties

Table 5.17 provides a summary of tests results for the hardened concrete, while Appendix E provides details. As indicated, tests included abrasion resistance, the Rapid Chloride Ion Penetration Test (RCPT), and compressive strength. As mentioned previously, freeze-thaw tests were not conducted during Phase II due to the satisfactory performance of the HPC mixtures during Phase I. Each value in Table 5.17 represents the average of three specimens per mixture design for all the tests except for RCPT, which is the average of four results, except as noted. The following sections present findings from the statistical analyses of the results from these tests.

Table 5.17 - Summary of Test Results for Properties of Hardened Concrete, Phase II

Mixture ID	Abrasion test (OSU), in./hr		Prall Test (Alaska DOT&PF), cm^3	RCPT test, coulombs	Compressive strength test, psi		
	30-min	60-min[1]			1-day	28-day	56-day
Control	0.112	0.071	49.1	660	6,610	7,860	7,520
Mix A	0.148	0.100	24.0	320	7,680	9,540	9,260
Mix B	0.121	0.083	---	260[2]	7,700	9,700	9,990
Mix C	0.227	0.103	32.1	550	5,230	5,760	5,750
Mix D	0.113	0.071	36.2	270	7,270	8,820	9,070
Mix E	0.082	0.048	25.2	310	8,200	10,680	10,170
Mix S	0.020	0.016	18.0	230	-	13,600	13,900
Mix T	0.075	0.032	28.5	290	8,870	10,440	11,060

[1]Wear rate of specimens during second portion of test (i.e., between 30 and 60 minutes).
[2]Average of two tests.

5.4.2.1 Abrasion Resistance, Modified ASTM C 779/C 779M (OSU Test)

Even though the studs were made of tungsten carbide and they were replaced with a new set of sharpened studs after every third test (i.e., after each set of three tests on a given mixture), they still unfortunately blunted enough during the tests to have an impact on the wear rate obtained from a given test run. This did not become apparent until several of the mixtures were tested. Hence, to maintain consistency in the test procedure amongst all mixtures, all tests were conducted in like manner.

This, however, affected the analysis of the results in that a blocking variable was included to accommodate the studs becoming blunt. That is, each result was identified by a run number (1, 2, or 3) effectively dividing the results into blocks according to sharpness of the studs, with the first block representing the results derived using the sharpest studs. As a result, the analysis was able to determine if stud sharpness affected the results as well as account for it if it did.

Wear Rate for First 30-minute Portion of Test

Table 5.18 shows the results from the initial ANOVA for the mixtures excluding Mixes S and T, with wear rate (inches per hour) during the first 30 minutes as the response variable. The results indicated that the model was highly significant (p-value < 0.0001) providing strong evidence to show that wear rate was strongly influenced by cementitious material (p-value = 0.0067) and level of silica fume (p-value < 0.0001). In addition, the results indicated that the interaction of these two factors was highly significant with a p-values of 0.0148. The blocking variable was also highly significant (p-value < 0.0001). With the 2-way interaction being significant, further investigation of the main effects alone was unwarranted.

Table 5.18 - ANOVA of 30-Minute Wear Rate Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.06876400	0.00982343	22.18	<.0001
Error	10	0.00442800	0.00044280		
Corrected Total	17	0.07319200			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.939502	15.70359	0.021043	0.134000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	2	0.03041200	0.01520600	34.34	<.0001
CemMat	1	0.00513422	0.00513422	11.59	0.0067
SilicaFume	2	0.02736533	0.01368267	30.90	<.0001
CemMat*SilicaFume	2	0.00585244	0.00292622	6.61	0.0148

Table 5.19 shows the analysis results including those from Mixes S and T. In this case, the analysis considered each mixture (i.e., combination of cementitious material and silica fume content) as a separate treatment (or main effect). The results show that the model is significant (p-value < 0.0001), and that both the blocking variable (accounting for stud sharpness) and the treatment variable (accounting for interaction between cementitious material and silica fume content) are significant (p-values < 0.0001) indicating that both had a strong influence on the wear rate.

Table 5.19 - ANOVA of 30-Minute Wear Rate Including All Mixtures

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	0.10645538	0.01182838	22.83	<.0001
Error	14	0.00725425	0.00051816		
Corrected Total	23	0.11370963			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.936204	20.25641	0.022763	0.112375

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	7	0.07655963	0.01093709	21.11	<.0001
BLOCK	2	0.02989575	0.01494788	28.85	<.0001

Due to the significance of the blocking and treatment variables, further analysis was conducted to determine differences (and similarities) between the treatments. Table 5.20 shows the results of Waller-Duncan k-ratio t-tests where the mean values of the treatments in different Waller groupings (designated by different letters) are significantly different. It shows considerable overlap in Waller groupings indicating insignificant differences in many cases.

Table 5.20 - Waller-Duncan k-ratio t-test Results for 30-Minute Wear Rate from Phase II

Waller Grouping	Mean	N	TRT
A	0.22800	3	Mix C – Fly Ash + 7% Silica Fume
B	0.14800	3	Mix A – Slag + 7% Silica Fume
B	0.12067	3	Mix B – Slag + 10% Silica Fume
C B	0.11267	3	Mix D – Fly Ash + 10% Silica Fume
C B D	0.11200	3	Control – Fly Ash + 4% Silica Fume
C D	0.08267	3	Mix E – Slag + 4% Silica Fume
D	0.07500	3	Mix T* – Slag + 4% Silica Fume
E	0.02000	3	Mix S* – Slag + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

Wear Rate for Second 30-minute Portion of Test

Tables 5.21 and 5.22 show similar outcomes for the wear rate results obtained from the second 30-minute portion of the test as for the first 30-minute portion. Table 5.23, however, shows better distinction (i.e., no overlap) between Waller groupings.

Table 5.21 - ANOVA of 60-Minute Wear Rate Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.01127189	0.00161027	23.50	<.0001
Error	10	0.00068522	0.00006852		
Corrected Total	17	0.01195711			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.942693	10.44885	0.008278	0.079222

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	2	0.00476344	0.00238172	34.76	<.0001
CemMat	1	0.00009800	0.00009800	1.43	**0.2593**
SilicaFume	2	0.00547011	0.00273506	39.91	<.0001
CemMat*SilicaFume	2	0.00094033	0.00047017	6.86	**0.0133**

Table 5.22 - ANOVA of 60-Minute Wear Rate Including All Mixtures

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	0.02531525	0.00281281	35.39	<.0001
Error	14	0.00111275	0.00007948		
Corrected Total	23	0.02642800			

R-Square	Coeff Var	Root MSE	Wear Rate Mean
0.957895	13.61111	0.008915	0.065500

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	7	0.02045000	0.00292143	36.76	<.0001
BLOCK	2	0.00486525	0.00243262	30.61	<.0001

Table 5.23 - Waller-Duncan k-ratio t-test Results for 60-Minute Wear Rate from Phase II

Waller Grouping	Mean	N	TRT
A	0.103333	3	Mix C – Fly Ash + 7% Silica Fume
A	0.100000	3	Mix A – Slag + 7% Silica Fume
B	0.083000	3	Mix B – Slag + 10% Silica Fume
B	0.070667	3	Control – Fly Ash + 4% Silica Fume
B	0.070667	3	Mix D – Fly Ash + 10% Silica Fume
C	0.047667	3	Mix E – Slag + 4% Silica Fume
D	0.032333	3	Mix T* – Slag + 4% Silica Fume
E	0.016333	3	Mix S* – Slag + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

In particular, the table shows that Mix C had the highest wear rate while the Mix S had the lowest. In addition, it shows that the effect of SCMs was not evident in mixtures containing the higher percentages of silica fume (namely, 7% and 10%), but for mixtures containing 4% silica fume, the mixture with slag (Mix E) performed significantly better than control mixture containing fly ash.

Considering only the mixtures with fly ash, the mixture with 4% silica fume had the same wear rate as the mixture with 10% silica fume (Control and Mix D, respectively), whereas the wear rate for the mixture with 7% silica fume (Mix C) was significantly higher. For the slag mixtures with a w/b ratio of 0.30 (i.e., Mixes A, B, and E), the mixture with 4% silica fume (Mix E) had the lowest wear rate, the mixture with 10% silica fume (Mix B) had the next lowest wear rate, and the mixture with 7% silica fume (Mix A) had the highest wear rate, and all were significantly different from one another.

Mixes S and T had higher total cementitious materials contents than all of the other mixtures. The wear rate of Mix S (with 7% silica fume, 35% slag, and a w/b ratio of 0.26) was significantly lower than all of the other slag mixtures independent of silica fume content. Similarly, the wear rate of the Mix T (with 4% silica fume, 38% slag, and a w/b ratio of 0.27) was also significantly lower than all other mixtures, except for Mix S.

The mixtures with 7% silica fume (aside from Mix S) had lower abrasion resistance than the mixtures with 4% and 10% silica fume. At all silica fume contents, the mixtures with slag were about equal to, or better than, the mixtures with fly ash in terms of wear resistance. Although Mix S was clearly the best performer, it might be due to the 2% air content, but the increased cementitious materials content most likely contributed as well.

Comparing only the mixtures with 4% silica fume and a w/b ratio of 0.30 (Control and Mix E), the mixture with slag (Mix E) had a significantly lower wear rate relative to the control mixture (with fly ash). Increasing the total cementitious materials content and at the same time keeping the proportion of silica fume at 4% (Mix T) significantly improved the abrasion resistance of this slag mixture relative to the other mixtures.

Considering only the mixtures with 7% silica fume and a w/b ratio of 0.30 (Mixes A and C), the mixture with slag (Mix A) had essentially the same wear rate as the mixture with fly ash (Mix C). Increasing the total cementitious materials content and at the same time keeping the proportion of silica fume at 7% (Mix S) indicated a substantial improvement, in terms of abrasion resistance, over the mixture with fly ash (Mix C). However, this improvement was more likely due to the increased total cementitious materials content and lower air content of Mix S relative to Mix C.

Only a very small difference can be seen between the wear rates of the two mixtures that had 10% silica fume (Mixes B and D). This possibly could be due to the high amount of silica fume, which likely played a major role in the strength gain and abrasion resistance, thereby negating the effect of the other supplementary cementitious materials.

5.4.2.2 Abrasion Resistance, Prall Test (Alaska DOT&PF)

The Prall test data were analyzed in the same way as described in Section 5.1.1 for the tests conducted at OSU with one exception. Since Mix B was not tested, the cell in the factorial design for slag and 10% silica fume was empty and, hence, an ANOVA to determine if significant interaction existed amongst the factors (see Section 5.1.1.1) was not conducted. Instead, the data were analyzed as described in Sections 5.1.1.2 and 5.1.1.3.

The results of the ANOVA including all mixtures is presented in Table 5.24. It shows that the model was significant (p-value < 0.0001) indicating that the treatments strongly influenced the Prall Value and that the mean values of at least two of the treatments were significantly different.

Table 5.24 - ANOVA of All Mixtures from Phase II Tested by ADOT&PF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	1835.369524	305.894921	19.02	<.0001
Error	14	225.160000	16.082857		
Corrected Total	20	2060.529524			

R-Square	Coeff Var	Root MSE	Prall Value Mean
0.890727	13.16511	4.010344	30.46190

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	6	1835.369524	305.894921	19.02	<.0001

Table 5.25 shows the results of Waller-Duncan k-ratio t-tests performed to distinguish differences (or similarities) between the treatments. The results indicated that, in general, the mixtures with slag were significantly more resistant to wear than the mixtures with fly ash (although there was not a significant difference between means for Mixes C and T). In addition and generally contrary to the findings from the OSU abrasion tests, the results in Table 5.25 show that the mixtures with 7% silica fume were more resistant to wear than mixtures with 4% silica fume based on mean values, but there was not a significant difference between means of the mixtures with slag (Mixes A and E). However, the Prall Test conducted at Alaska DOT&PF showed that Mixes E, S, and T performed well relative to the other mixtures (except Mix A) and, in particular, relative to the control mixture; thus, providing some validation of the OSU abrasion tests. Significant

differences in the test procedures (see Section 4.5.2) may have accounted for these discrepancies.

Table 5.25 - Waller-Duncan k-ratio t-test Results for Prall Value

Waller Grouping	Mean	N	TRT
A	49.133	3	Control – Fly Ash + 4% Silica Fume
B	36.233	3	Mix D – Fly Ash + 10% Silica Fume
C B	32.067	3	Mix C – Fly Ash + 7% Silica Fume
C D	28.533	3	Mix T* – Slag + 4% Silica Fume
D	25.233	3	Mix E – Slag + 4% Silica Fume
E D	24.000	3	Mix A – Slag + 7% Silica Fume
E	18.033	3	Mix S* – Slag + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

5.4.2.3 Nordic Abrasion of Aggregate

The Nordic Abrasion Test was conducted by Alaska DOT&PF on a sample of river gravel fractionated to 3/4”×5/8” size (unfortunately, a sample of the basalt was not sent to Alaska DOT&PF for testing). The river gravel had a Nordic Abrasion of 13, whereas a Nordic Abrasion of 7.5 and less was considered to be good. The results suggested that abrasion resistance would likely be improved with a higher quality aggregate such as the basalt used in Phase I of this study.

5.4.2.4 Permeability

Table 5.26 shows the results of the initial ANOVA for the mixtures excluding the results from Mixes S and T. It shows that the model was highly significant (p-value = 0.0013) indicating that cementitous materials and silica fume content had a strong influence on the permeability of the mixtures, but the interaction between these factors was not significant (p-value = 0.0790).

Table 5.27 shows the results of the second ANOVA including the results from Mixes S and T. Due to the model being significant (p-value < 0.0001), there was strong evidence to indicate a significant difference between the means of at least two treatment means.

Table 5.26 - ANOVA of Chloride Ion Penetration Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	525514.2500	105102.8500	6.92	0.0013
Error	16	242985.2500	15186.5781		
Corrected Total	21	768499.5000			

R-Square	Coeff Var	Root MSE	Charge Passed Mean
0.683819	30.31583	123.2338	406.5000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	194120.8500	194120.8500	12.78	0.0025
SilicaFume	2	240683.0719	120341.5359	7.92	0.0041
CemMat*SilicaFume	2	90710.3281	45355.1641	2.99	0.0790

Table 5.27 - ANOVA of Chloride Ion Penetration Including All Mixtures

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	664010.0500	94858.5786	8.46	<.0001
Error	22	246760.2500	11216.3750		
Corrected Total	29	910770.3000			

R-Square	Coeff Var	Root MSE	Charge Passed Mean
0.729064	28.88121	105.9074	366.7000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	7	664010.0500	94858.5786	8.46	<.0001

Table 5.28 shows the results of the Waller-Duncan k-ratio t-tests and indicates only two Waller groupings. The control mixture and Mix C (both with fly ash) were in the same group indicating that the means were not significantly different from one another, but were significantly different from the means of all other mixtures. Aside from this observation, very little can be inferred (with statiscally-based support) from these results except that all mixtures passed less charge than the threshold value of 1,000 coulombs set by the ODOT Standard Specifications *(2008)*.

Table 5.28 - Waller-Duncan k-ratio t-test Results for Chloride Ion Penetration, Phase II

Waller Grouping	Mean	N	TRT
A	658.00	4	Control – Fly Ash + 4% Silica Fume
A	551.25	4	Mix C – Fly Ash + 7% Silica Fume
B	318.75	4	Mix A – Slag + 7% Silica Fume
B	311.75	4	Mix E – Slag + 4% Silica Fume
B	288.50	4	Mix T* – Slag + 4% Silica Fume
B	267.50	4	Mix D – Fly Ash + 10% Silica Fume
B	257.00	2	Mix B – Slag + 10% Silica Fume
B	226.00	4	Mix S* – Slag + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

5.4.2.5 Compressive Strength

Testing for compressive strength of the mixtures was performed at periods of 1 day, 28 days, and 56 days. Figure 5.16 shows the evolution in compressive strength of the mixtures (unfortunately, 1-day strength tests were not conducted on Mix S). It is interesting to note from this chart that the strengths of all of the mixtures with a w/b ratio of 0.30 (i.e., all those except Mixes S and T) and silica fume contents of either 4% or 7% (Control and Mixes A, C, and E) did not continue to increase beyond the 28-day test period. However, those with 10% silica fume (Mixes B and D) did, as did the mixtures with the higher total cementitious materials contents (Mixes S and T). The following sections provide a summary of the statistical analyses conducted on the results of these tests.

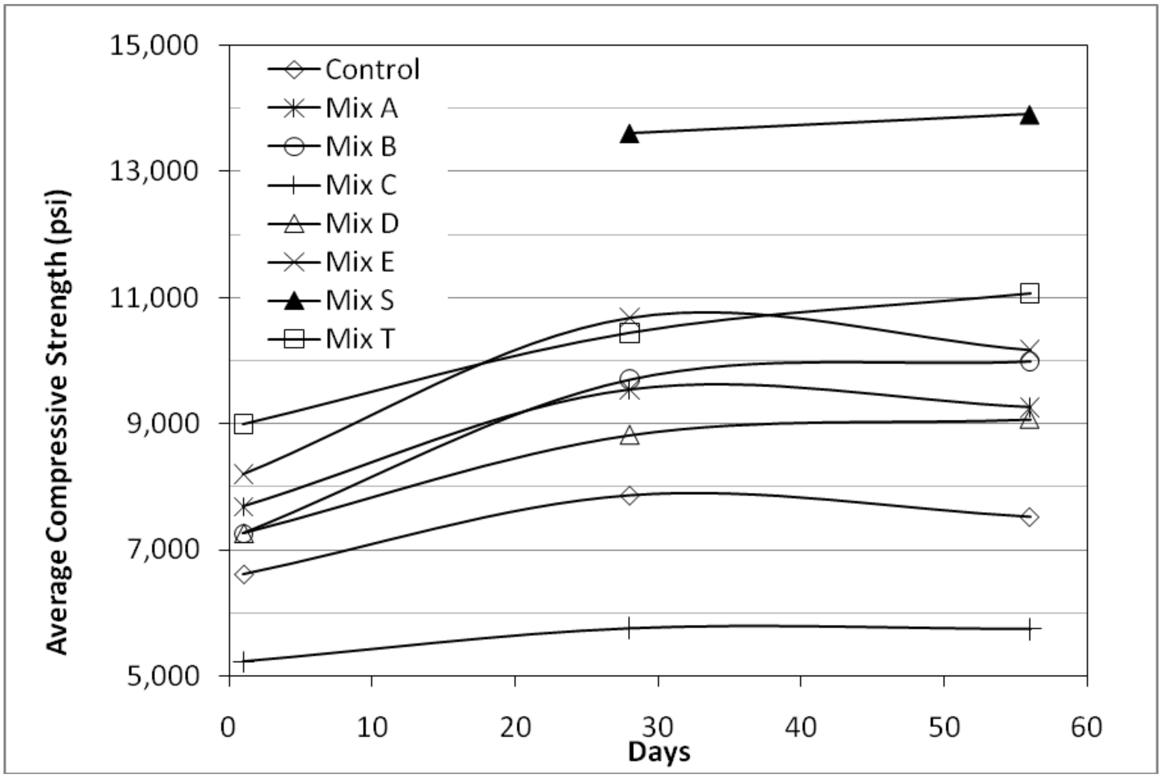

Figure 5.16 - Evolution of Compressive Strength of the Mixtures Tested in Phase II

Compressive Strength at 1 Day

Table 5.29 shows the results from the initial ANOVA of the 1-day strength data excluding that for Mix T. As shown, the model was highly significant as were both factors (p-values < 0.0001) indicating that early-age strength of the concrete was strongly affected by cementitious material and silica fume content. The table also indicates that the interaction between the two factors was significant (p-value < 0.0001).

Table 5.29 - ANOVA of 1-Day Compressive Strength Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	17081709.11	3416341.82	80.09	<.0001
Error	12	511872.00	42656.00		
Corrected Total	17	17593581.11			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.970906	2.903286	206.5333	7113.778

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	10047150.22	10047150.22	235.54	<.0001
SilicaFume	2	3924076.78	1962038.39	46.00	<.0001
CemMat*SilicaFume	2	3110482.11	1555241.06	36.46	<.0001

Table 5.30 shows the results from the second ANOVA including the results from Mix T. These results also indicate that the model was significant meaning that a significant difference existed between at least two of the treatment means.

Table 5.30 - ANOVA of 1-Day Compressive Strength Including All Mixtures Except Mix S

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	24991748.00	4165291.33	64.72	<.0001
Error	14	901052.67	64360.90		
Corrected Total	20	25892800.67			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.965201	3.444908	253.6945	7364.333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	6	24991748.00	4165291.33	64.72	<.0001

Table 5.31 shows the Waller groupings of the 1-day strength results and indicates that nearly all mixtures are in a separate group. The results indicate that Mix T had the greatest strength, those with slag had significantly greater strengths than those with fly ash, and that only one mixture (Mix C with fly ash) had a significantly lower strength than the control mixture (also with fly ash). In addition, aside from the control mixture, those with 4% silica fume had significantly greater strengths than the mixtures with 7% and 10% silica fume.

Perhaps the most significant finding from these results, with respect to production activities, was that all of the mixtures attained sufficient strength in 1 day to satisfy the minimum strength requirement of 5,000 psi for the purposes of removing precast elements from the casting bed. However, the results presented in Table 5.31 did not provide evidence concerning the longer-term properties of the mixtures.

Table 5.31 - Waller-Duncan k-ratio t-test Results for 1-Day Compressive Strength, Phase II

Waller Grouping	Mean	N	TRT
A	8867.7	3	Mix T* – Slag + 4% Silica Fume
B	8204.0	3	Mix E – Slag + 4% Silica Fume
C	7694.7	3	Mix B – Slag + 10% Silica Fume
C	7684.0	3	Mix A – Slag + 7% Silica Fume
D	7265.3	3	Mix D – Fly Ash + 10% Silica Fume
E	6609.0	3	Control – Fly Ash + 4% Silica Fume
F	5225.7	3	Mix C – Fly Ash + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

Compressive Strength at 28 Days

The results from the initial ANOVA presented in Table 5.32 for the 28-day strengths of the concrete mixtures reflected the findings for the 1-day strengths, as did the results from the second ANOVA for the 28-day strengths presented in Table 5.33. In the second ANOVA, however, the results for Mix S were included in the analysis.

Table 5.32 - ANOVA of 28-Day Compressive Strength Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	45107078.67	9021415.73	59.21	<.0001
Error	12	1828211.33	152350.94		
Corrected Total	17	46935290.00			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.961048	4.472404	390.3216	8727.333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	28040064.22	28040064.22	184.05	<.0001
SilicaFume	2	10494577.00	5247288.50	34.44	<.0001
CemMat*SilicaFume	2	6572437.44	3286218.72	21.57	0.0001

Table 5.33 - ANOVA of 28-Day Compressive Strength Including All Mixtures

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	108758003.8	15536857.7	126.98	<.0001
Error	16	1957746.0	122359.1		
Corrected Total	23	110715749.8			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.982317	3.662973	349.7987	9549.583

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	7	108758003.8	15536857.7	126.98	<.0001

Table 5.34 presents the results of the Waller-Duncan k-ratio t-tests for the 28-day strength data. The findings were very similar to those for the 1-day strength results except that the strengths of Mixes E and T were not significantly different for the 28-day strength data and that Mix S was included (and had the greatest strength). As with the 1-day results, the mixtures with slag had significantly greater strengths than those with fly ash, only one mixture (Mix C with fly ash) had a significantly lower strength than the control mixture (also with fly ash), and those with 7% silica fume (except Mix S) and 10% silica fume had significantly lower strengths than those with 4% silica fume.

Table 5.34 - Waller-Duncan k-ratio t-test Results, 28-Day Compressive Strength, Phase II

Waller Grouping	Mean	N	TRT
A	13596.0	3	Mix S* – Slag + 7% Silica Fume
B	10683.0	3	Mix E – Slag + 4% Silica Fume
B	10436.7	3	Mix T* – Slag + 4% Silica Fume
C	9703.0	3	Mix B – Slag + 10% Silica Fume
C	9540.3	3	Mix A – Slag + 7% Silica Fume
D	8823.0	3	Mix D – Fly Ash + 10% Silica Fume
E	7860.0	3	Control – Fly Ash + 4% Silica Fume
F	5754.7	3	Mix C – Fly Ash + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

Compressive Strength at 56 Days

Table 5.35 shows the initial ANOVA results for the 56-day strength data but excluding the results for Mixes S and T, and Table 5.36 shows the results from the second ANOVA that included the results from all mixtures. The same outcomes were inferred from these two analyses as were inferred from those for the 1-day and 28-day strength data.

Table 5.35 - ANOVA of 56-Day Compressive Strength Excluding Mixes S and T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	42180240.28	8436048.06	116.82	<.0001
Error	12	866599.33	72216.61		
Corrected Total	17	43046839.61			

R-Square	Coeff Var	Root MSE	Compressive Strength Mean
0.979868	3.121417	268.7315	8609.278

Source	DF	Type I SS	Mean Square	F Value	Pr > F
CemMat	1	24423060.50	24423060.50	338.19	<.0001
SilicaFume	2	12162255.44	6081127.72	84.21	<.0001
CemMat*SilicaFume	2	5594924.33	2797462.17	38.74	<.0001

Table 5.36 - ANOVA of 56-Day Compressive Strength Including All Mixtures

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	124922132.6	17846018.9	265.17	<.0001
Error	16	1076799.3	67300.0		
Corrected Total	23	125998932.0			

R-Square	Coeff Var	Root MSE	CompStrength Mean
0.991454	2.697200	259.4224	9618.208

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	7	124922132.6	17846018.9	265.17	<.0001

Table 5.37 shows the Waller groupings for the 56-day strength data. The groupings were similar to those of the 1-day and 28-day groupings, with a few exceptions. Mix S was not included in the 1-day results, but for the 56-day data, it had a significantly higher strength than any other mixture, consistent with the findings from the 28-day data. Mixtures with slag had significantly higher strengths than those with fly ash, except that the strengths of Mixes A and D were not significantly different. The strength of the slag mixtures with 4% silica fume was not significantly different from that of the slag mixture with 10%, but both were significantly higher than that of the slag mixture with 7% silica fume. For those with fly ash, the strength of the mixture with 10% silica fume was significantly greater than that of the mixture with 4% silica fume which, in turn, was significantly greater than the mixture with 7% silica fume, identical findings to those for the 1-day and 28-day strength data.

Table 5.37 - Waller-Duncan k-ratio t-test Results, 56-Day Compressive Strength, Phase II

Waller Grouping	Mean	N	TRT
A	13900.0	3	Mix S* – Slag + 7% Silica Fume
B	11390.0	3	Mix T* – Slag + 4% Silica Fume
C	10166.7	3	Mix E – Slag + 4% Silica Fume
C	9895.7	3	Mix B – Slag + 10% Silica Fume
D	9260.0	3	Mix A – Slag + 7% Silica Fume
D	9063.3	3	Mix D – Fly Ash + 10% Silica Fume
E	7516.7	3	Control – Fly Ash + 4% Silica Fume
F	5753.3	3	Mix C – Fly Ash + 7% Silica Fume

*Mixes S and T had higher total cementitious materials content

5.4.3 Summary

Statistical analyses of the data obtained from testing conducted in Phase II revealed that silica fume content strongly influenced the wear rate, chloride ion penetration resistance, and compressive strength (at all test periods) of the concrete mixtures. Type of cementitious material (i.e., fly ash versus slag) also strongly influenced the 30-minute wear rate, but not the 60-minute wear rate, and it strongly influenced chloride ion penetration resistance and compressive strength (at all test periods). Interaction between silica fume content and fly ash or slag was also found to be significant for wear rate (for both durations) and compressive strength, but not for chloride ion penetration resistance.

With regard to the abrasion resistance tests conducted at OSU, the two mixtures with the higher total cementitious materials content (Mixes S and T) had the greatest resistance to abrasion, with that of Mix S being significantly greater than that of Mix T. Of the mixtures with a w/b ratio of 0.30, Mix E (slag + 4% silica fume) had a significantly higher resistance to abrasion relative to the control mixture as well as to those with a higher silica fume content. The Prall Test conducted at Alaska DOT&PF also showed that Mixes E, S, and T performed well. The effects of slag and fly ash in combination with silica fume contents of 7% and 10% were not clear from the OSU abrasion test results, but the Prall Test showed that the mixtures with 7% silica fume generally outperformed those with 4% silica fume.

With regard to chloride ion penetration resistance, all mixtures passed far less charge than the 1,000-coulomb criterion stipulated in the ODOT Standard Specifications *(2008)*, possibly confounding detection of significant differences between mixtures. Nevertheless, all slag mixtures and the fly ash mixture with 10% silica fume (Mix D) had significantly lower permeability than fly ash mixtures with 4% and 7% silica fume, (Control and Mix C, respectively). Mix S had the lowest permeability, but not significantly different from most of the other mixtures.

With regard to compressive strength, Mixes E, S, and T consistently had significantly higher strengths than all other mixtures. Of these three mixtures, Mix S consistently had a significantly higher strength, while Mix T generally had a significantly higher strength than Mix E. In addition, mixtures with slag consistently had significantly higher strengths than mixtures with fly ash.

5.5 SELECTION OF THE BEST MIXTURE DESIGN

With the objective of developing a concrete mixture design that would perform better in terms of abrasion resistance and durability than the conventional ODOT bridge deck mixture, it is useful to compare the performance of the experimental mixtures to that of the conventional ODOT bridge deck mixture using a combined measure that incorporates both performance attributes. Figure 5.17 was prepared in an attempt to accomplish this. It shows normalized wear rates obtained from the OSU abrasion tests plotted against normalized chloride ion permeability for all of the mixtures evaluated in Phase II of the study. The data were normalized by dividing the results obtained from the experimental mixtures by the results obtained from the control mixture, where the control mixture represents the conventional ODOT bridge deck mixture. Only the average values were used in the normalization process. Note that the results from the control mixture were also normalized providing a value of unity for both performance measures.

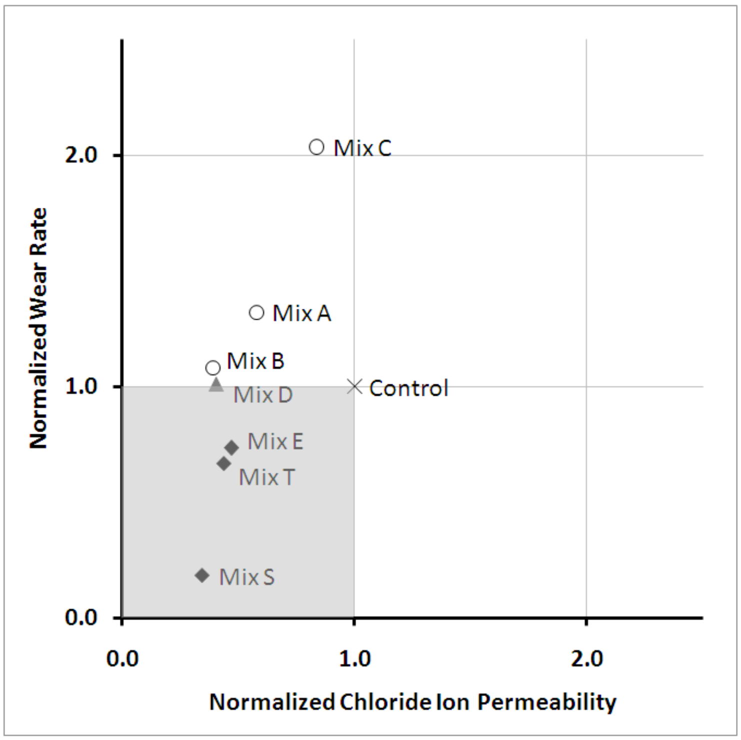

Figure 5.17 - Mixture Selection Chart based on Relative Performance

For improved abrasion resistance of a particular experimental mixture relative to the control mixture, values less than unity are desired for the normalized wear rate. Similarly, for improved chloride ion penetration resistance (improved durability), values less than unity are desired for the normalized chloride ion penetration. Thus, points falling inside the square adjacent to the origin of the chart (i.e., the shaded region) indicate improved characteristics relative to the control mixture. In addition, points closer to the origin indicate improved characteristics relative to points further from the origin.

Figure 5.17 shows that Mixes E, S, and T fall in the shaded region indicating improved performance relative to the control mixture. Further, Mix S is closest to the origin indicating the best relative performance, followed by Mix T, and finally Mix E. Hence, based solely on performance measures, any of the three mixtures would satisfy the principal objective of the study.

However, costs must also be considered since it is also desired to minimize the life cycle costs of bridge decks. Manufacturing bridge deck slabs using either Mix S or Mix T would certainly result in increased initial costs relative to using Mix E (or the control mixture) since both Mixes S and T contain higher total cementitious materials contents (see Table 3.7 in Section 3.3.4). However, it is not known if use of either Mix S or Mix T would result in lower life cycle costs relative to Mix E since in-service performance data are not available at this time.

Another issue with Mix S is that it did not contain entrained air, which is currently required by the ODOT Standard Specifications *(2008)*. There is some debate about the requirement of entrained air in HPC. According to Jacobsen *(2005)*, HPC with a low water-to-binder ratio can be very durable without entrained air, even after very severe freeze/thaw exposure in the presence of deicing salt. Also, according to Kerkhoff *(2002)*, certain high strength concretes do not need as much air as conventional strength concretes to be frost resistant due to the reduced porosity and less freezable water within the high strength concrete. However, Hewlett *(2003)* indicated that air entrainment is required, even at a water-to-cement ratio of 0.30, if freeze-thaw damage is to be avoided.

Considering, together, performance and initial costs (not life cycle costs), Mix E performed better than the control mixture, but its initial costs would be less than those of either Mix S or Mix T. Mix E had a mixture design essentially the same as the control mixture except that it contained slag instead of fly ash.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The report documents laboratory investigations of high performance concrete (HPC) mixtures undertaken to develop one or more materials systems for precast and pre-stressed bridge deck components that would reduce the life-cycle cost of bridges by improving the studded tire wear (abrasion) resistance and the durability of bridge decks. This work was carried out in three parts; namely, Phase I, Pilot Study, and Phase II.

Phase I of the project involved an initial investigation of candidate mixtures incorporating type I portland cement, supplementary cementitious materials (silica fume, slag, and fly ash), natural aggregate (river gravel), and crushed rock. The proportions of SCMs were held constant in this part of the study. This effort also utilized three laboratory curing methods including ordinary water curing and two accelerated steam curing methods.

A Pilot Study was undertaken to refine the laboratory steam curing methods initially investigated in Phase I of the study. It also sought to determine if the duration of ODOT's field curing requirement for cast-in-place bridge decks could be shortened.

Phase II of the project utilized the findings from Phase I and the Pilot Study to develop HPC mixtures that had improved abrasion resistance and durability characteristics relative to a newly-specified ODOT bridge deck mixture. The mixtures investigated in Phase II incorporated type III portland cement and the same supplementary cementitious materials and natural aggregate that were used in Phase I. The silica fume content was varied in Phase II to include proportions of 4%, 7%, and 10% requiring commensurate adjustment of the slag and fly ash proportions to maintain a constant percentage of cement replacement. However, two additional mixtures were investigated that had higher total cementitious materials content.

6.1.1 Phase I Results

The experimental work for Phase I was designed to investigate differences in concrete performance due to two different combinations of supplementary cementitious materials, together with two aggregate types, and subjected to three curing regimes. A control mixture containing no SCMs, one of the two types of aggregates, and subjected to the same curing regimes was also investigated. Concrete performance was assessed using laboratory test methods for abrasion resistance, chloride ion penetration resistance, freeze-thaw resistance, and compressive strength. Statistical analyses were conducted on all results except those from the freeze-thaw resistance tests to determine if significant differences existed between the results. The principal conclusions that can be drawn from these efforts are as follows:

- The type of cementitious materials and curing method strongly influenced the abrasion resistance, chloride ion penetration resistance, and compressive strength of the concrete

- The mixtures containing a combination of silica fume and slag had superior abrasion resistance, durability characteristics, and compressive strength properties relative to the mixtures containing a combination of silica fume and fly ash.
- The mixtures with crushed rock outperformed the mixtures with the river gravel in terms of abrasion resistance and compressive strength characteristics. Durability characteristics were essentially unaffected by aggregate type.
- The conventional water curing method was significantly better than the two steam curing methods in producing concrete with desirable abrasion resistance and durability characteristics.
- Steam curing followed by curing in the ambient conditions in the laboratory (Steam Curing Method B) was better than steam curing followed by water curing (Steam Curing Method A) in producing concrete with desirable durability characteristics. In terms of abrasion resistance characteristics and compressive strength properties, Steam Curing Method A was generally better.

6.1.2 Pilot Study Results

The primary purpose of conducting the Pilot Study was to identify or develop a laboratory curing regime that would provide high early strength and, at the same time, compressive strength comparable to that of specimens cured in water for 28 days. A secondary objective of the Pilot Study was to investigate whether or not ODOT's 14-day field curing requirement for cast-in-place concrete bridge decks could be shortened. Eleven curing methods combining different curing techniques and different curing periods up to 28 days were investigated. The principal conclusions from this part of the study are as follows:

- Applying a curing compound to the water-cured specimens, but before they were left to cure in the ambient conditions of the laboratory, resulted in improved compressive strength properties only when the water curing period was less than 3 days. After this, no additional improvement was realized.

- A water curing period of 3 days resulted in a 28-day compressive strength of the HPC similar to that obtained by water curing for 28 days (i.e., their respective 28-day strengths were not significantly different at a 95% confidence level). This result is significant in that, from a strength-development standpoint, it suggests that ODOT's 14-day field curing requirement for cast-in-place concrete can be shortened to 3 days.

- The findings provided strong evidence to suggest that application of a curing compound immediately following steam curing not only provided concrete with sufficient compressive strength for the purposes of de-molding concrete elements from casting beds (i.e., greater than 5,000 psi in 1 day), but also longer-term, 28-day compressive strength that was not significantly different from that of concrete cured continuously in water.

6.1.3 Phase II Results

Phase II was undertaken to improve upon the mixtures developed under Phase I taking into account the laboratory curing method developed in the Pilot Study and the changes made to the ODOT Standard Specifications regarding use of HPC for bridge decks. Conclusions that can be drawn from this phase of the project are as follows:

- Silica fume content strongly influenced the abrasion resistance, chloride ion penetration resistance, and compressive strength of the concrete mixtures.
- Type of cementitious material (i.e., fly ash versus slag) strongly influenced the 30-minute wear rate, but not the 60-minute wear rate, and it strongly influenced chloride ion penetration resistance and compressive strength.
- Silica fume content interacted with fly ash or slag to strongly influence abrasion resistance and compressive strength, but not chloride ion penetration resistance.
- Regarding abrasion resistance, the two mixtures with the higher total cementitious materials content (Mixes S and T) performed the best. Of the mixtures with the lower cementitious materials content, the mixture with 4% silica fume and slag (Mix E) had a significantly higher resistance to abrasion relative to the control mixture as well as to those with a higher silica fume content. That is, increasing the silica fume beyond 4% did not result in additional abrasion resistance based on the modified ASTM C 779/C 779M method. However, based on the Prall Test, there is some evidence to suggest that mixtures with 7% silica fume had slightly better abrasion resistance than those with 4% silica fume.
- All mixtures passed far less charge in the chloride ion penetration test than the 1,000-coulomb criterion stipulated in the ODOT Standard Specifications. Consequently, the results from most of the mixtures were not significantly different from one another; however, most results were significantly different (lower) than that of the control mixture (the ODOT standard mixture for bridge decks).
- With regard to compressive strength, the two mixtures with the higher total cementitious materials content (Mixes S and T) had significantly higher strengths than all other mixtures, and the strength of Mix S (with 7% silica fume) was significantly higher than that of Mix T (with 4% silica fume). Of the mixtures with the lower cementitious materials content, the mixture with 4% silica fume and slag (Mix E) had a significantly higher strength than the control mixture and most of the other mixtures.
- Regarding comparisons between fly ash mixtures and slag mixtures, those with slag, in most cases, had better abrasion resistance, greater chloride ion penetration resistance, and higher strengths. These findings support those found in Phase I of the study.
- Overall, Mixes E, S, and T performed significantly better than the control mixture (i.e., ODOT's new HPC mixture for bridge decks with 4% silica fume, 30% fly ash, and 66% cement that was fabricated with type III portland cement at a w/b ratio of 0.30 for the purposes of this study). Mix S with 7% silica fume, 35% slag, 58% type III portland cement, and a w/b ratio of 0.26 provided the best results, but it did not contain entrained air. Mix T with 7% entrained air, 4% silica fume, 38% slag, 58% type III portland

- Independent tests for abrasion conducted by the Alaska DOT&PF confirmed that Mixes E, S, and T performed well relative to the other mixtures and, in particular, relative to the control mixture; thus, providing some validation of the findings of this study.

6.2 RECOMMENDATIONS

This research effort revealed that the aggregate had a significant effect on the abrasion resistance characteristic of the concrete; hence, it would be worthwhile to conduct further studies using different aggregate types and from different sources. It is also recommended to investigate if smaller nominal maximum aggregate sizes than those used in this study would improve the durability characteristics of the concrete.

The abrasion of concrete is a surface phenomenon, so further investigation should be made to explore the possibilities of improving the surface properties of the concrete. Previous studies report that concrete made from calcium aluminate cement has improved abrasion resistance; hence, it would be beneficial to conduct further investigations using different combinations of SCMs together with calcium aluminate cement to study the combined effects on studded tire wear resistance.

Apart from investigating the abrasion resistance and resistance to chloride ion penetration properties of the concrete, other durability factors like alkali silica reactivity and sulfate attack should also be investigated for HPC mixtures. Further investigation is also recommended to study the durability and strength characteristics of HPC without air entraining admixtures.

Steam curing followed by application of a curing compound was found to be the best alternative to the water curing technique, and significantly better than without the use of a curing compound. This result is significant in that it provides strong evidence that the use of a curing compound in the production of HPC at the pre-cast yard will provide better characteristics of the concrete than that obtained without use of a curing compound. Hence, evaluation of the practicality and economic impacts of use of a curing compound on pre-cast HPC products manufactured during real-world production activities should be undertaken.

The results of the research were based solely on laboratory testing. This approach did simplify the study, but it merely simulated in-service conditions. Therefore, a field study that includes the combined effects of studded tire wear and the environment is essential to validate laboratory results. A field study can also provide cost and performance data essential for conducting life cycle cost analyses. Appendix F provides recommendations for conducting such a study and to gather requisite information for conducting cost analyses.

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APPENDIX A:
PHASE I MIX DESIGNS

<u>Concrete Mix Design – Control Mixture (ODOT Class 5000 – 3/4 inch)</u>

1. **Required Strength**
   - Specified strength: f'_c = 5,000 psi
   - New mix design – standard deviation of strength unknown
   - Required strength, f'_{cr} (02001.43 option a):
     - $f'_{cr} = f'_c \times 1.20$ = <u>5,000 x 1.20 = 6,000 psi</u>
2. **Select w/c Ratio**
   - Historical records unavailable
   - Trial batches based on Table 9-3 [4] and Morse Bros. Mix Design No. MB 031-50N17000
   - Air-entrained: w/c = <u>0.30, 0.35, and 0.40</u>
   - Check w/c limits based on exposure conditions: Tables 9-1 and 9-2
3. **Air Content**
   - Maximum aggregate size for coarse aggregate = 3/4 in.
   - Target slump = 4 in.
   - Table 9-5 [4]
   - Target air content: <u>5%</u>
4. **Target Slump**
   - Morse Bros. mix design: <u>4 in.</u>
5. **Water Content**
   - Maximum coarse aggregate size: <u>3/4 in.</u>
   - Desired slump: <u>4 in.</u>
   - Aggregate shape: <u>Crushed with some fractured faces</u>
   - Table 9-5 [4]
   - Water Content: <u>305 - 35 = 270 pounds per cubic yard</u>
   - Note: <u>Water content reduced by 35 lb for gravel with some crushed faces</u>
6. **Cement Content**
   - Based on the w/c ratio and the water content
   - Minimums for:
     - Severe freeze-thaw, deicer, and sulfate exposure
     - Placing concrete under water
     - Flatwork
   - Cement content:
     - For w/c = 0.30: <u>900 pounds per cubic yard</u>
     - For w/c = 0.35: <u>771 pounds per cubic yard</u>
     - For w/c = 0.40: <u>675 pounds per cubic yard</u>
   - Minimum required for flatwork (Table 9-7): 540 lb/cy → okay

7. **Bulk Volume of Coarse Aggregate**
   - Maximum coarse aggregate size: 3/4 in.
   - Fineness modulus of sand: 3.05
   - Dry rodded unit weight of coarse aggregate: 101.7 pcf
   - Table 9.4: 0.60 [4]
   - Weight of CA: 0.60 x 101.7 lb/ft^3 x 27 ft^3/yd^3 = 1648 lb/yd^3

8. **Admixture Requirements**
   - Air entraining agent: WR Grace/Daravair-1000

9. **Fine Aggregate Content**
   - Volumes of other ingredient:
     - Water: 270 lb / (1 x 62.4 lb/ft^3) = 4.327 ft^3
     - Cement:
       - For w/c = 0.30: 900 lb / (3.15 x 62.4 lb/ft^3) = 4.579 ft^3
       - For w/c = 0.35: 771 lb / (3.15 x 62.4 lb/ft^3) = 3.922 ft^3
       - For w/c = 0.40: 675 lb / (3.15 x 62.4 lb/ft^3) = 3.434 ft^3
     - Air: (5 / 100) x 27 ft^3) = 1.35 ft^3
     - Coarse Aggregate: 1,648 lb / (2.532 x 62.4 lb/ft^3) = 10.430 ft^3
     - Totals:
       - For w/c = 0.30: 20.686 ft^3
       - For w/c = 0.35: 20.029 ft^3
       - For w/c = 0.40: 19.541 ft^3
   - **FA Content**
     - For w/c = 0.30: 6.413 ft^3 x 2.461 x 62.4 lb/ft^3 = 970 lb
     - For w/c = 0.35: 6.971 ft^3 x 2.461 x 62.4 lb/ft^3 = 1,070 lb
     - For w/c = 0.40: 7.459 ft^3 x 2.461 x 62.4 lb/ft^3 = 1,145 lb

10. **Adjustment for Moisture**
    - Aggregates are dry → no adjustment necessary

Table A.1: Summary of batch weights for one cubic yard of concrete

Ingredient	Batch Weight for One Cubic Yard, lb		
w/c ratio →	0.30	0.35	0.40
Water (to be	270	270	270
Cement	900	771	675
Coarse aggregate	1,648	1,648	1,648
Fine aggregate	970	1,070	1,145
Total			

Table A.2: HPC mixture design spreadsheet

Fraction		Proportion	Sp.Gr	W/A (%)	DRY	Volume	Moisture content	Adjustment for Moisture	Batch Weight (Wet)
			SSD		lb/Cubic yard			lb/cubic Yard	lb/cubic Yard
Cement		-	3.150		528.000	2.686			528.000
Flyash			2.520		0.000	0.000			0.000
Slag			2.890		240.000	1.331			240.000
Microsilica			2.200		32.000	0.233			32.000
Water		-	1.000		240.000	3.846		131.731	108.269
Coarse Aggregate-3/4-1/2		35.79%	2.510	2.42%	613.000	3.914	2.6%	1.103	614.103
Coarse Aggregate-1/2-#4		64.21%	2.500	2.61%	1100.000	7.051	3.39%	8.580	1108.580
Sand			2.460	3.50%	1012.000	6.593	15.56%	122.047	1134.047
W/c Ratio		-	-	-	0.30				
Extra water added		-	-	-	-				-18.900
Total water		-	1	-	221.1				89.369
so modified w/c ratio		-	-	-	0.276375				
Air Entraining Dose, MBAE 90 (ml)		-	-	-	148.5				
BASF?/ Glen. 3400NV	ml				1359.045				
Air %		-	-	-	-	1.35			
Slump	inch.	-	-	-	-				
Totals		-	-	-	3765.000	27.004	-	-	3765.000

APPENDIX B: TEST RESULTS FOR DETERMINING OPTIMUM W/C RATIO FOR CONTROL MIXTURE IN PHASE I

Table B.1: Compressive strength for control mixture (w/c ratio=0.30)

No: ....

Date of Casting:...18 Dec 07.......................................

......Control Mix, w/c ratio= 0.30

Temperature of water:----62.4oF------------

Time of Testing: 9.00 am

Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ in.3)	Density in water , (lb/ in.3)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Type of Fracture	Remarks
15-Jan-08	4	8	12.560	3.8455	2.1736	0.0844	0.0477	69900	5565.286624	5966.8	286.4	4.8	Shear	-
	4.024	8	12.711	3.8612	2.1859	0.0837	0.0474	75200	5916.055502				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
	4.039	8	12.806	3.9129	2.2335	0.0842	0.0481	80000	6247.016081				conical	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
	4.045	8	12.844	3.8606	2.1892	0.0828	0.0470	80000	6228.497269				Shear	-
	4.024	8	12.711	3.8524	2.1843	0.0835	0.0474	72500	5703.643935				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
	4.024	8	12.711	3.9141	2.229	0.0849	0.0483	78050	6140.267712				columnar	Pulling out of aggregate, Mortar Failure, breaking of weathered rock

Table B.2: Compressive strength for control mixture (w/c ratio=0.35)

Lab Identification No: ....

Date of Casting:...20 Dec 07.......................................

Concrete Grade: ......Control Mix, w/c ratio= 0.35

Temperature of water:----62.4oF------------

Time of Testing: 4.00 pm

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ in.3)	Density in water , (lb/ in.3)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	Stdev	Co.of Variation	Type of Fracture	Remarks
C1	28	17-Jan-08	4.033	8	12.768	3.9418	2.2662	0.0851	0.0489	65950	5165.218515	5244.56	307.3584	5.86052	Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C2			4.036	8	12.787	3.9529	2.2762	0.0852	0.0491	69300	5419.525483				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C3			4.021	8	12.692	3.9114	2.2353	0.0849	0.0485	65300	5144.881524				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C4			4.032	8	12.762	3.9101	2.235	0.0844	0.0483	60800	4764.231713				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C5			4.027	8	12.730	3.9066	2.2343	0.0846	0.0484	65500	5145.272542				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C6			4.022	8	12.699	3.9296	2.2567	0.0853	0.0490	63800	5024.199656				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C7			4.03	8	12.749	3.9178	2.2445	0.0847	0.0485	72400	5678.829336				Columnar	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
C8			4.025	8	12.717	3.9298	2.2502	0.0852	0.0488	71400	5614.315128				Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock

Table B.3: Compressive strength for control mixture (w/c ratio=0.40)

Lab Identification No: ....

Date of Casting:...21Dec 07.......................................

Concrete Grade: ......Control Mix, w/c ratio= 0.40

Temperature of water:----62.4oF------------

Time of Testing: 12.00 Noon

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ in.3)	Density in water , (lb/ in.3)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Type of Fracture	Remarks
C1	28	18-Jan-08	4.022	8	12.699	3.8304	2.154	0.0831	0.0467	55900	4402.0809	3499.432	503.7275	14.39455	Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
C2			4.035	8	12.781	3.7817	2.1067	0.0815	0.0454	37300	2918.4489				Shear	
C3			4.042	8	12.825	3.8309	2.1544	0.0823	0.0463	50950	3972.6647				Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
C4			4.03	8	12.749	3.8186	2.1379	0.0825	0.0462	45450	3564.9557				Shear	
C5			4.033	8	12.768	3.7666	2.0905	0.0813	0.0451	40400	3164.1369				Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
C6			4.024	8	12.711	3.765	2.0911	0.0816	0.0453	43000	3382.8509				Shear	Pulling out of large aggregate, Mortar Faliure, breaking of
C7			4.05	8	12.876	3.7566	2.0838	0.0804	0.0446	38500	2990.0677				Shear	
C8			4.03	8	12.749	3.7712	2.0951	0.0815	0.0453	45900	3600.2523				Shear	

Table B.4: Flexural strength for control mixture (w/c ratio=0.30)

Lab Identification No: ....

Date of Casting: 18-Dec-07

Concrete Grade: Control Mix, w/c ratio= 0.30

Time of Testing: 9.00 am

Temperature of Water: ...55.9^{0}F......

Specim. No.	Age	Testing date	Weight in Air (Kg)	Weight in Water (Kg)	Average width of the specimen to the nearest 0.05 in.(1mm) at the fracture , b=	Average depth of specimen to the nearest 0.05 in.(1mm) at the fracture, d=	Span length (in.), L=	Avg. dist. between line of fracture & the nearest support measured on the tension surface of the beam , a=	Max. applied load (lbf) , P=	Modulus of Rupture (psi), R=	Avg. Modulus of Rupture (psi)	Stdev	Remarks: Curing history and apparent moisture condition of the specimen at the time of testing	Remarks: If specimen were capped,ground or if leather shims were used	Remarks: Whether sawed or moulded & defects in specimen	Remarks: Any other remark
C1	28	15 Jan 08	28.88	16.273	6	6	18	8	7460	621.666667	671.67	54.14	Moist	Leather shims	None	Two Days after testing Date
C2			28.84	16.332	6	6	18	8	8750	729.166667			Moist	None	None	
C3			29.14	16.582	6	6	18	8	7970	664.166667			Moist	Leather shims	None	Two Days after testing Date

Table B.5: Flexural strength for control mixture (w/c ratio=0.35)

Lab Identification No: ....

Concrete Grade: Control Mix, w/c ratio= 0.35

Date of Casting: 20-Dec-07

Time of Testing: 4.00 pm

Temperature of Water: ...55.9^{0}F......

Specim. No.	Age	Testing date	Weight in Air (Kg)	Weight in Water (Kg)	Average width of the specimen to the nearest 0.05 in.(1mm) at the fracture , b=	Average depth of specimen to the nearest 0.05 in.(1mm) at the fracture, d=	Span length (in.) , L=	Avg. dist. between line of fracture & the nearest support measured on the tension surface of the beam , a=	Max. applied load (lbf) , P=	Modulus of Rupture (psi) , R=	Avg. Modulus of Rupture (psi)		Remarks: Curing history and apparent moisture condition of the specimen at the time of testing	Remarks: If specimen were capped,ground or if leather shims were used	Remarks: Whether sawed or moulded & defects in specimen	Remarks: Any other remark
C1	28	17 Jan 08	29.48	16.717	6	6	18	8.25	6840	570.000	514.21	48.84	Moist	Leather shims	None	
C2			29.28	16.71	6	6	18	5.5	6460	493.472			Moist	Leather shims	None	DIST BETWEEN FRACTURE LESS THAN MIDDLE THIRD, SO FORMULA 2 USED
C3			29.66	16.826	6	6	18	8	5750	479.167			Moist	Leather shims	None	

Table B.6: Flexural strength for control mixture (w/c ratio=0.40)

Lab Identification No: ....

Concrete Grade: Control Mix, w/c ratio= 0.40

Date of Casting: 21-Dec-07

Time of Testing: 12.00 Noon

Temperature of Water: ...55.9^{0}F......

Specim. No.	Age	Testing date	Weight in Air (Kg)	Weight in Water (Kg)	Average width of the specimen to the nearest 0.05 in.(1mm) at the fracture , b=	Average depth of specimen to the nearest 0.05 in.(1mm) at the fracture, d=	Span length (in.) , L=	Avg. dist. between line of fracture & the nearest support measured on the tension surface of the beam , a=	Max. applied load (lbf) , P=	Modulus of Rupture (psi) , R=	Avg. Modulus of Rupture (psi)		Remarks: Curing history and apparent moisture condition of the specimen at the time of testing	Remarks: If specimen were capped,ground or if leather shims were used	Remarks: Whether sawed or moulded & defects in specimen	Remarks: Any other remark
C1	28	18 Jan 08	28.38	15.75	6	6	18	8.5	5640	470.000	510.21	54.14	Moist	Leather shims	None	
C2			28.36	15.661	6	6	18	7.5	5930	494.167			Moist	Leather shims	None	
C3			28.34	15.663	6	6	18	7.5	7080	590.000			Moist	Leather shims	None	
C4			28.34	15.679	6	6	18	7	5840	486.667			Moist	Leather shims	None	

APPENDIX C:
TEST RESULTS FOR PHASE I

Table C.1: Compressive Strength, Mixture CW

Lab Identification No: …Control Mix- Water Curing-CW					Date of Casting:1.3.08………………			
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
CW8	28	29-Mar-08	4.04	12.81	86500	6751.24	6517.30	214.58
CW9	28		4.05	12.88	81500	6329.62		
CW6	28		4.03	12.75	82500	6471.04		
CW2	90	30-May-08	4.02	12.67	96000	7579.70	7648.63	246.42
CW4	90		4.01	12.63	94000	7444.01		
CW5	90		4.02	12.69	100500	7922.17		

Table C.2: Compressive Strength, Mixture CSA

Concrete Grade: CSA, Control Mix, Steam Curing A								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
CSA-2	28	26-Apr-08	4.01	12.598	51700	4103.92	3876.60	247.86
CSA-4	28		4.02	12.706	45900	3612.34		
CSA-9	28		4.01	12.623	49400	3913.53		
CSA-5	90	30-May-08	4.01	12.65	49900	3944.77	3812.68	172.36
CSA-1	90		4.01	12.64	49000	3875.56		
CSA-8	90		4.0115	12.63	45700	3617.70		

Table C.3: Compressive Strength, Mixture CSB

Concrete Grade: CSB, Control Mix, Steam Curing B									
Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
CSB-2	28	26-Apr-08	4.01	7.96	12.639	39400	3117.43	2976.58	157.57
CSB-7	28		4.01	7.94	12.650	35500	2806.40		
CSB-1	28		4.01	8.06	12.642	38000	3005.91		
CSB-5	90	27-Jun-08	4.00	8.08	12.54	34500	2750.94	2790.40	73.37
CSB-8	90		4.01	8.10	12.64	34700	2745.21		
CSB-9	90		4.0215	8.07	12.70	36500	2875.06		

Table C.4: Compressive Strength, Mixture EAW

Concrete Grade: EAW, Exp A, Water Curing								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EAW-3	28	21-Apr-08	4.02633	12.726	85000	6679.28	7193.41	506.49
EAW-2	28		4.032	12.762	92000	7209.03		
EAW-1	28		4.02867	12.741	98000	7691.90		
EAW-6	90	24-Jun-08	4.0305	12.752	102500	8037.78	7994.56	207.82
EAW-5	90		4.03475	12.779	104500	8177.36		
EAW-9	90		4.00875	12.615	98000	7768.52		

Table C.5: Compressive Strength, Mixture EASA

Concrete Grade:EASA, Exp A, Steam Curing A								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EASA-2	28	22-Apr-08	4.03	12.779	77000	6025.68	5880.00	301.38
EASA-6	28		4.03	12.745	77500	6080.87		
EASA-9	28		4.03	12.741	70500	5533.46		
EASA-1	90	25-Jun-08	4.02575	12.722	70300	5525.76	5362.59	249.37
EASA-3	90		4.02575	12.722	69800	5486.46		
EASA-5	90		4.0235	12.708	64500	5075.54		

Table C.6: Compressive Strength, Mixture EASB

Concrete Grade: EASB, Exp A, Steam CuringB								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EASB-6	28	22-Apr-08	4.02	12.707	58000	4564.43	4570.79	199.69
EASB-4	28		4.03	12.779	61000	4773.59		
EASB-3	28		4.04	12.802	56000	4374.36		
EASB-1	90	25-Jun-08	4.0245	12.714	52400	4121.33	4210.55	194.21
EASB-2	90		4.06175	12.951	52800	4076.97		
EASB-9	90		4.02925	12.744	56500	4433.33		

Table C.7: Compressive Strength, Mixture EBW

Concrete Grade:EBW, Exp-B, Water Curing								
Specim. No.	**Age**	**Testing date**	**Dia ,(in.)**	**Area , (in.2)**	**Max. Load , (lbf)**	**Compressive Strength , (psi)**	**Avg. Strength , (psi)**	**STDEV**
EBW-6	28	30-Apr-08	4.02	12.665	118500	9356.19	**9452.26**	**204.73**
EBW-3	28		4.02	12.670	118000	9313.24		
EBW-7	28		4.02	12.697	123000	9687.36		
EBW-9	90	25-Jun-08	4.019	12.680	142000	11199.09	**11005.10**	**179.27**
EBW-5	90		4.0175	12.670	139000	10970.68		
EBW-8	90		4.01875	12.678	137500	10845.54		

Table C.8: Compressive Strength, Mixture EBSA

Concrete Grade:EBSA, Exp B, Steam Curing A								
Specim. No.	**Age**	**Testing date**	**Dia ,(in.)**	**Area , (in.2)**	**Max. Load , (lbf)**	**Compressive Strength , (psi)**	**Avg. Strength , (psi)**	**STDEV**
EBSA-6	28	28-Apr-08	4.03	12.741	101000	7927.04	**7817.13**	**108.21**
EBSA-8	28		4.02	12.670	99000	7813.65		
EBSA-9	28		4.02	12.710	98000	7710.71		
EBSA-1	90	29-Jun-08	4.021	12.692	98500	7760.66	**7512.72**	**228.8**
EBSA-7	90		4.015	12.654	92500	7309.72		
EBSA-2	90		4.015	12.654	94500	7467.77		

Table C.9 Compressive Strength, Mixture EBSB

Concrete Grade:EBSB, Exp B, Steam Curing B								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EBSB-9	28	28-Apr-08	4.02	12.670	85500	6748.15	**6552.70**	**245.09**
EBSB-7	28		4.02	12.664	79500	6277.72		
EBSB-6	28		4.02	12.665	84000	6632.24		
EBSB-8	90	29-Jun-08	4.0095	12.620	81500	6458.14	**6183.71**	**270.2**
EBSB-2	90		4.037	12.793	79000	6175.04		
EBSB-3	90		4.018	12.673	75000	5917.96		

Table C.10: Compressive Strength, Mixture ECW

Concrete Grade:ECW, Exp C, Water Curing								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
ECW-8	28	23-Apr-08	4.06	12.935	53000	4097.29	**4444.80**	**433.25**
ECW-4	28		4.03	12.717	62700	4930.22		
ECW-7	28		4.03	12.770	55000	4306.90		
ECW-2	90	24-Jun-08	4.02425	12.713	66000	5191.64	**5299.31**	**141.92**
ECW-6	90		4.0335	12.771	67000	5246.15		
ECW-9	90		4.01225	12.637	69000	5460.14		

Table C.11: Compressive Strength, Mixture ECSA

Concrete Grade:ECSA, Exp C, Steam Curing A								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
ECSA-4	28	25-Apr-08	4.01	12.650	42400	3351.73	**3632.06**	**244.52**
ECSA-1	28		4.02	12.690	47500	3743.07		
ECSA-7	28		4.02	12.680	48200	3801.38		
ECSA-9	90	28-Jun-08	4.0275	12.733	45100	3541.90	**3251.56**	**338.31**
ECSA-8	90		4.0305	12.752	42500	3332.74		
ECSA-3	90		4.0345	12.778	36800	2880.04		

Table C.12: Compressive Strength, Mixture ECSB

Concrete Grade:ECSB, Exp C, Steam Curing B								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
ECSB-2	28	25-Apr-08	4.03	12.749	36300	2847.26	**2196.50**	**565.61**
ECSB-5	28		4.02	12.670	23100	1823.18		
ECSB-3	28		4.01	12.610	24200	1919.07		
ECSB-9	90	25-Jun-08	4.01325	12.643	20900	1653.04	**1746.93**	**83.283**
ECSB-6	90		4.02125	12.694	23000	1811.91		
ECSB-8	90		4.0175	12.670	22500	1775.83		

Table C.13: Compressive Strength, Mixture EDW

Concrete Grade:EDW, Exp-D, Water Curing								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EDW-1	28	30-Apr-08	4.01	12.646	79800	6310.05	6524.94	213.57
EDW-7	28		4.01	12.617	85000	6737.16		
EDW-3	28		4.01	12.639	82500	6527.61		
EDW-4	90	25-Jun-08	4.018	12.673	106000	8364.04	8406.57	190.45
EDW-5	90		4.02875	12.741	105000	8240.98		
EDW-8	90		4.01475	12.653	109000	8614.69		

Table C.14: Compressive Strength, Mixture EDSA

Concrete Grade:EDSA, Exp-D, Steam Curing A								
Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV
EDSA-7	28	27-Apr-08	4.02	12.697	55400	4363.25	4319.52	55.79
EDSA-1	28		4.03	12.746	55300	4338.64		
EDSA-6	28		4.02	12.686	54000	4256.69		
EDSA-2	90	28-Jun-08	4.026	12.724	53300	4189.00	4196.51	139.28
EDSA-3	90		4.0255	12.721	55200	4339.40		
EDSA-5	90		4.01925	12.681	51500	4061.14		

Table C.15: Compressive Strength, Mixture EDSB

Concrete Grade:EDSB, Exp-D, Steam Curing B								
Specim. No.	**Age**	**Testing date**	**Dia ,(in.)**	**Area , (in.2)**	**Max. Load , (lbf)**	**Compressive Strength , (psi)**	**Avg. Strength , (psi)**	**STDEV**
EDSB-5	28	27-Apr-08	4.02	12.662	41000	3237.97	**3018.18**	**191.93**
EDSB-7	28		4.03	12.762	36800	2883.61		
EDSB-9	28		4.03	12.717	37300	2932.97		
EDSB-2	90	28-Jun-08	4.022	12.699	37000	2913.72	**2994.45**	**185.55**
EDSB-3	90		4.03	12.749	36500	2862.95		
EDSB-6	90		4.021	12.692	40700	3206.69		

Table C.16: Chloride Ion Penetration Test, Control Mixture

Date of Casting		1-Mar-08		Date of Testing		12-Jun-08		Time of Testing		12.20 pm			
Mix Id	Control Mix_Water Curing, CW			Mix Type		Control Mix		Curing Period		103 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
12.20 pm	69.3	60	0.0598	0.059	60	0.0663	0.067	60	0.0723	0.0723	60	0.0718	0.071
12.50 pm	69.3	60	0.0600	0.059	60	0.0642	0.065	60	0.0739	0.0739	60	0.0685	0.068
1.20 pm	69.3	60	0.0618	0.061	60	0.0680	0.069	60	0.0766	0.0766	60	0.0704	0.070
1.50 pm	69.4	60	0.0607	0.060	60	0.0715	0.072	60	0.0795	0.0795	60	0.0740	0.073
2.20 pm	69.4	60	0.0645	0.064	60	0.0746	0.075	60	0.0826	0.0826	60	0.0771	0.076
2.50 pm	69.6	60	0.0658	0.065	60	0.0775	0.078	60	0.0855	0.0855	60	0.0829	0.082
3.20 pm	69.6	60	0.0685	0.068	60	0.0808	0.082	60	0.0887	0.0887	60	0.0844	0.084
3.50 pm	69.6	60	0.0723	0.072	60	0.0828	0.084	60	0.0909	0.0909	60	0.0852	0.084
4.20 pm	69.6	60	0.0718	0.071	60	0.0850	0.086	60	0.0935	0.0935	60	0.0881	0.087
4.50 pm	69.4	60	0.0740	0.073	60	0.0864	0.087	60	0.0960	0.0960	60	0.0907	0.090
5.20 pm	69.6	60	0.0753	0.075	60	0.0880	0.089	60	0.0984	0.0984	60	0.0928	0.092
5.50 pm	70.0	60	0.0720	0.071	60	0.0891	0.090	60	0.1006	0.1006	60	0.0936	0.093
6.20 pm	69.6	60	0.0730	0.072	60	0.0896	0.091	60	0.1022	0.1022	60	0.1004	0.099
Total Charge Passed		Q1=	1449.089	Coulombs	Q2 =	1719.727	Coulombs	Q2 =	1896.21	Coulombs	Q2 =	1771.129	Coulombs
Average Charge Passed, Coulombs									1709.0				

Table C.17: Chloride Ion Penetration Test, Mixture EAW

Date of Casting		24-Mar-08		Date of Testing		28-Jun-08		Time of Testing		10.21am			
Mix Id	Exp A_Water Curing, EAW			Mix Type		Slag+Gravel		Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
10.21 am	77.5	60	0.0409	0.040	60	0.0407	0.041	60	0.0440	0.044	60	0.0466	0.046
10.52 am	77.5	60	0.0406	0.040	60	0.0409	0.041	60	0.0495	0.0495	60	0.0472	0.047
11.21 am	77.5	60	0.0451	0.045	60	0.0430	0.043	60	0.0525	0.0525	60	0.0469	0.046
11.51 am	77.7	60	0.0470	0.047	60	0.0450	0.045	60	0.055	0.055	60	0.0461	0.046
12.21 pm	77.7	60	0.0500	0.050	60	0.0481	0.049	60	0.0571	0.0571	60	0.0492	0.049
12.51 pm	77.7	60	0.0510	0.050	60	0.0490	0.049	60	0.0590	0.059	60	0.0496	0.049
1.21 pm	77.7	60	0.0520	0.051	60	0.0492	0.050	60	0.0611	0.0611	60	0.0505	0.050
1.51 pm	78.1	60	0.0530	0.052	60	0.0510	0.052	60	0.0620	0.062	60	0.0512	0.051
2.21 pm	78.1	60	0.0550	0.054	60	0.0516	0.052	60	0.0644	0.0644	60	0.052	0.051
2.53 pm	78.3	60	0.0522	0.052	60	0.0517	0.052	60	0.0647	0.0647	60	0.0514	0.051
3.21 pm	78.3	60	0.0532	0.053	60	0.0526	0.053	60	0.0653	0.0653	60	0.0549	0.054
3.51 pm	78.3	60	0.0552	0.055	60	0.0533	0.054	60	0.0662	0.0662	60	0.0558	0.055
4.21 pm	78.3	60	0.0541	0.054	60	0.0547	0.055	60	0.0665	0.0665	60	0.0564	0.056
Total Charge Passed		Q1=	1072.515	Coulombs	Q2 =	1060.182	Coulombs	Q2 =	1281.69	Coulombs	Q2 =	1080.535	Coulombs
Average Charge Passed, Coulombs									1123.73				

Table C.18: Chloride Ion Penetration Test, Mixture EASA

Date of Casting		25-Mar-08		Date of Testing		29-Jun-08		Time of Testing		12.20 pm			
Mix Id	Exp A_Steam Curing A, EASA			Mix Type		Slag+Gravel		Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
7.33 am	79.5	60	0.0719	0.071	60	0.0721	0.073	60	0.0882	0.0882	60	0.0729	0.072
8.03 am	79.7	60	0.0712	0.070	60	0.0761	0.077	60	0.0948	0.0948	60	0.0686	0.068
8.33 am	79.9	60	0.0795	0.079	60	0.0779	0.079	60	0.1023	0.1023	60	0.0718	0.071
9.03 am	79.9	60	0.0827	0.082	60	0.0810	0.082	60	0.109	0.109	60	0.0751	0.074
9.33 pm	79.9	60	0.0840	0.083	60	0.0902	0.091	60	0.1148	0.1148	60	0.0807	0.080
10.03 pm	79.9	60	0.0873	0.086	60	0.0908	0.092	60	0.1202	0.1202	60	0.0819	0.081
10.33 am	79.9	60	0.0932	0.092	60	0.1005	0.102	60	0.125	0.125	60	0.0881	0.087
11.03 am	79.9	60	0.0919	0.091	60	0.1035	0.105	60	0.1295	0.1295	60	0.0915	0.091
11.33 am	79.9	60	0.0980	0.097	60	0.1060	0.107	60	0.1332	0.1332	60	0.0884	0.088
12.03 pm	79.9	60	0.0979	0.097	60	0.1045	0.106	60	0.1366	0.1366	60	0.0926	0.092
12.33 pm	79.9	60	0.1028	0.102	60	0.1027	0.104	60	0.1395	0.1395	60	0.0991	0.098
1.03 pm	79.7	60	0.1019	0.101	60	0.1115	0.113	60	0.1418	0.1418	60	0.1014	0.100
1.33 pm	79.9	60	0.1039	0.103	60	0.1073	0.108	60	0.1438	0.1438	60	0.1025	0.101
Total Charge Passed		Q1=	1921.723	Coulombs	Q2 =	2062.545	Coulombs	Q2 =	2632.86	Coulombs	Q2 =	1830.119	Coulombs
Average Charge Passed, Coulombs									2111.81				

Table C.19: Chloride Ion Penetration Test, Mixture EASB

Date of Casting		25-Mar-08		Date of Testing		29-Jun-08		Time of Testing		2.37 pm			
Mix Id	Exp A_Steam Curing B, EASB			Mix Type		Slag+Gravel		Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
2.37 pm	80.2	60	0.0631	0.062	60	0.0744	0.075	60	0.0716	0.0716	60	0.0668	0.066
3.07 pm	80.4	60	0.0601	0.060	60	0.0720	0.073	60	0.0823	0.0823	60	0.0622	0.062
3.37 pm	80.4	60	0.0701	0.069	60	0.0774	0.078	60	0.0895	0.0895	60	0.0636	0.063
4.07 pm	80.4	60	0.0744	0.074	60	0.0817	0.083	60	0.0958	0.0958	60	0.0668	0.066
4.37 pm	80.4	60	0.0785	0.078	60	0.0830	0.084	60	0.1016	0.1016	60	0.0691	0.068
5.07 pm	80.4	60	0.0824	0.082	60	0.0942	0.095	60	0.1068	0.1068	60	0.072	0.071
5.37 pm	80.6	60	0.0871	0.086	60	0.0930	0.094	60	0.1111	0.1111	60	0.0764	0.076
6.07 pm	80.4	60	0.0896	0.089	60	0.0975	0.098	60	0.1157	0.1157	60	0.0771	0.076
6.37 pm	80.4	60	0.0890	0.088	60	0.0980	0.099	60	0.1186	0.1186	60	0.0802	0.079
7.07 pm	80.6	60	0.0922	0.091	60	0.0983	0.099	60	0.1217	0.1217	60	0.0819	0.081
7.37 pm	80.6	60	0.0942	0.093	60	0.1020	0.103	60	0.1245	0.1245	60	0.0831	0.082
8.07 pm	80.4	60	0.0934	0.092	60	0.1081	0.109	60	0.1263	0.1263	60	0.0895	0.089
8.37 pm		60	0.0970	0.096	60	0.1056	0.107	60	0.128	0.128	60	0.0851	0.084
Total Charge Passed		Q1=	1766.228	Coulombs	Q2 =	1991.273	Coulombs	Q2 =	2328.66	Coulombs	Q2 =	1600.129	Coulombs
Average Charge Passed, Coulombs									1921.57				

Table C.20: Chloride Ion Penetration Test, Mixture EBW

Date of Casting		2-Apr-08		Date of Testing			8.02 am			
Mix Id	EBW			Mix Type			95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
3.06 pm	79.5	60	0.0465	0.046	60	0.0468	0.0468	60	0.0473	0.047
3.36 pm	78.8	60	0.0414	0.041	60	0.0511	0.0511	60	0.0447	0.044
4.06 pm	79.5	60	0.0407	0.040	60	0.0515	0.0515	60	0.0435	0.043
4.36 pm	79.3	60	0.0426	0.042	60	0.0507	0.0507	60	0.0482	0.048
5.06 pm	79.5	60	0.0452	0.045	60	0.0485	0.0485	60	0.0486	0.048
5.36 pm	79.3	60	0.0448	0.044	60	0.0496	0.0496	60	0.0503	0.050
6.06 pm	79.9	60	0.0464	0.046	60	0.05	0.05	60	0.0483	0.048
6.36 pm	79.9	60	0.0479	0.047	60	0.0509	0.0509	60	0.0515	0.051
7.06 pm	79.9	60	0.0479	0.047	60	0.051	0.051	60	0.0514	0.051
7.36 pm	79.5	60	0.0493	0.049	60	0.0517	0.0517	60	0.0516	0.051
8.06 pm	79.7	60	0.0488	0.048	60	0.0517	0.0517	60	0.0533	0.053
8.36 pm	79.5	60	0.0490	0.049	60	0.0517	0.0517	60	0.0547	0.054
9.06 pm	80.8	60	0.0498	0.049	60	0.0518	0.0518	60	0.0562	0.056
Total Charge Passed		Q1=	984.0297	Coulombs	Q2 =	1093.86	Coulombs	Q2 =	1065.475	Coulombs
Average Charge Passed, Coulombs						1047.79				

Table C.21: Chloride Ion Penetration Test, Mixture EBSA

Date of Casting				Date of Testing		6-Jul-08		Time of Testing		2.02 pm			
Mix Id	EBSA			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
2.02 pm	79.9	60	0.0747	0.074	60	0.0833	0.084	60	0.0776	0.0776	60	0.0846	0.084
2.32 pm	79.3	60	0.0712	0.070	60	0.0831	0.084	60	0.0746	0.0746	60	0.0774	0.077
3.02 pm	79.2	60	0.0765	0.076	60	0.0870	0.088	60	0.0785	0.0785	60	0.0856	0.085
3.32 pm	79.2	60	0.0845	0.084	60	0.0927	0.094	60	0.082	0.082	60	0.0882	0.087
4.02 pm	79.3	60	0.0840	0.083	60	0.0947	0.096	60	0.0855	0.0855	60	0.0901	0.089
4.32 pm	79.9	60	0.0869	0.086	60	0.1015	0.103	60	0.0893	0.0893	60	0.0933	0.092
5.02 pm	79.2	60	0.0924	0.091	60	0.1016	0.103	60	0.0913	0.0913	60	0.0989	0.098
5.32 pm	80.2	60	0.0973	0.096	60	0.1127	0.114	60	0.0952	0.0952	60	0.0996	0.099
6.02 pm	79.7	60	0.0978	0.097	60	0.1054	0.106	60	0.0967	0.0967	60	0.1044	0.103
6.32 pm	79.5	60	0.1014	0.100	60	0.1095	0.111	60	0.1006	0.1006	60	0.1054	0.104
7.02 pm	79.3	60	0.1014	0.100	60	0.1208	0.122	60	0.1022	0.1022	60	0.1044	0.103
7.32 pm	79.7	60	0.0996	0.099	60	0.1138	0.115	60	0.1037	0.1037	60	0.1109	0.110
8.02 pm	79.7	60	0.1049	0.104	60	0.1198	0.121	60	0.105	0.105	60	0.1088	0.108
Total Charge Passed		Q1=	1929.743	Coulombs	Q2 =	2226.091	Coulombs	Q2 =	1963.62	Coulombs	Q2 =	2058.238	Coulombs
Average Charge Passed, Coulombs									1983.87				

Table C.22: Chloride Ion Penetration Test, Mixture EBSB

Date of Casting				Date of Testing		5-Jul-08		Time of Testing		2.37 pm			
Mix Id	EBSB			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
2.37 pm	80.4	60	0.0863	0.085	60	0.0995	0.101	60	0.0895	0.0895	60	0.0731	0.072
3.07 pm	80.6	60	0.0697	0.069	60	0.0976	0.099	60	0.0927	0.0927	60	0.0668	0.066
3.37 pm	80.4	60	0.0870	0.086	60	0.1121	0.113	60	0.0973	0.0973	60	0.071	0.070
4.07 pm	80.8	60	0.0890	0.088	60	0.1132	0.114	60	0.102	0.102	60	0.0732	0.072
4.37 pm	80.6	60	0.0900	0.089	60	0.1231	0.124	60	0.1072	0.1072	60	0.0793	0.079
5.07 pm	80.6	60	0.1014	0.100	60	0.1308	0.132	60	0.1119	0.1119	60	0.082	0.081
5.37 pm	80.6	60	0.0977	0.097	60	0.1388	0.140	60	0.1153	0.1153	60	0.0875	0.087
6.07 pm	80.6	60	0.1069	0.106	60	0.1375	0.139	60	0.1189	0.1189	60	0.0906	0.090
6.37 pm	80.6	60	0.1128	0.112	60	0.1462	0.148	60	0.1224	0.1224	60	0.0913	0.090
7.07 pm	80.8	60	0.1117	0.111	60	0.1451	0.147	60	0.1292	0.1292	60	0.0933	0.092
7.37 pm	80.6	60	0.1177	0.117	60	0.1468	0.148	60	0.1284	0.1284	60	0.0955	0.095
8.07 pm	80.6	60	0.1158	0.115	60	0.1474	0.149	60	0.1303	0.1303	60	0.0974	0.096
8.37 pm	80.6	60	0.1185	0.117	60	0.1464	0.148	60	0.1325	0.1325	60	0.1034	0.102
Total Charge Passed		Q1=	2142.356	Coulombs	Q2 =	2839.182	Coulombs	Q2 =	2459.88	Coulombs	Q2 =	1810.96	Coulombs
Average Charge Passed, Coulombs									**2313.09**				

Table C.23: Chloride Ion Penetration Test, Mixture ECW

Date of Casting				Date of Testing		30-Jun-08		Time of Testing		11.27 am			
Mix Id	ECW			Mix Type		Flyash + Gravel		Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
		Cell 1			Cell 2			Cell 3			Cell 4		
Time	Temperature	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
11.27 am	80.2	60	0.0377	0.037	60	0.0386	0.039	60	0.0385	0.0385	60	0.0393	0.039
11.57 am	80.2	60	0.0361	0.036	60	0.0368	0.037	60	0.0425	0.0425	60	0.039	0.039
12.27 pm	80.2	60	0.0372	0.037	60	0.0400	0.040	60	0.0448	0.0448	60	0.0387	0.038
12.57 pm	80.4	60	0.0379	0.038	60	0.0419	0.042	60	0.0467	0.0467	60	0.0395	0.039
1.27 pm	80.4	60	0.0382	0.038	60	0.0419	0.042	60	0.0485	0.0485	60	0.0405	0.040
1.57 pm	80.4	60	0.0401	0.040	60	0.0448	0.045	60	0.0499	0.0499	60	0.0429	0.042
2.27 pm	80.6	60	0.0409	0.040	60	0.0434	0.044	60	0.0512	0.0512	60	0.0443	0.044
2.57 pm	80.4	60	0.0410	0.041	60	0.0444	0.045	60	0.0525	0.0525	60	0.0452	0.045
3.27 pm	80.8	60	0.0430	0.043	60	0.0446	0.045	60	0.0535	0.0535	60	0.046	0.046
3.57 pm	80.8	60	0.0439	0.043	60	0.0459	0.046	60	0.0544	0.0544	60	0.0464	0.046
4.27 pm	81	60	0.0444	0.044	60	0.0461	0.047	60	0.055	0.055	60	0.0459	0.045
4.57 pm	80.8	60	0.0451	0.045	60	0.0474	0.048	60	0.0557	0.0557	60	0.0457	0.045
5.27 pm		60	0.0448	0.044	60	0.0477	0.048	60	0.0561	0.0561	60	0.0471	0.047
Total Charge Passed		Q1=	871.5743	Coulombs	Q2 =	946.0909	Coulombs	Q2 =	1083.6	Coulombs	Q2 =	921.9208	Coulombs
Average Charge Passed, Coulombs									**955.80**				

Table C.24: Chloride Ion Penetration Test, Mixture ECSA

Date of Casting				Date of Testing		2-Jul-08		Time of Testing		8.01 am			
Mix Id	ECSA			Mix Type		Flyash + Gravel		Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
8.01 am	79.5	60	0.0975	0.097	60	0.0850	0.086	60	0.0993	0.0993	60	0.1089	0.108
8.31 am	79.7	60	0.1022	0.101	60	0.0854	0.086	60	0.1201	0.1201	60	0.0976	0.097
9.01 am	80.2	60	0.1086	0.108	60	0.0988	0.100	60	0.1333	0.1333	60	0.1099	0.109
9.31 am	79.9	60	0.1240	0.123	60	0.1120	0.113	60	0.146	0.146	60	0.1283	0.127
10.01 am	80.2	60	0.1326	0.131	60	0.1088	0.110	60	0.1542	0.1542	60	0.1366	0.135
10.31 am	79.9	60	0.1447	0.143	60	0.1163	0.117	60	0.1631	0.1631	60	0.1352	0.134
11.01 am	79.9	60	0.1499	0.148	60	0.1263	0.128	60	0.1704	0.1704	60	0.1505	0.149
11.31 am	79.9	60	0.1563	0.155	60	0.1256	0.127	60	0.1771	0.1771	60	0.1488	0.147
12.01 pm	79.9	60	0.1590	0.157	60	0.1309	0.132	60	0.1819	0.1819	60	0.1611	0.160
12.31 pm	80.2	60	0.1675	0.166	60	0.1334	0.135	60	0.1849	0.1849	60	0.1524	0.151
1.01 pm	80.4	60	0.1674	0.166	60	0.1305	0.132	60	0.1871	0.1871	60	0.1529	0.151
1.31 pm	80.4	60	0.1685	0.167	60	0.1386	0.140	60	0.1893	0.1893	60	0.166	0.164
2.01 am	80.4	60	0.1655	0.164	60	0.1291	0.130	60	0.1889	0.1889	60	0.168	0.166
Total Charge Passed		Q1=	3051.446	Coulombs	Q2 =	2570.273	Coulombs	Q2 =	3512.7	Coulombs	Q2 =	2990.05	Coulombs
Average Charge Passed, Coulombs									3031.12				

Table C.25: Chloride Ion Penetration Test, Mixture ECSB

Date of Casting				Date of Testing		2-Jul-08		Time of Testing		3.01 pm			
Mix Id	ECSB			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
3.01 pm	80.6	60	0.1690	0.167	60	0.1741	0.176	60	0.1732	0.1732	60	0.141	0.140
3.31 pm	80.6	60	0.1878	0.186	60	0.2056	0.208	60	0.2244	0.2244	60	0.1513	0.150
4.01 pm	80.8	60	0.2233	0.221	60	0.2352	0.238	60	0.2544	0.2544	60	0.1753	0.174
4.31 pm	80.8	60	0.2560	0.254	60	0.2553	0.258	60	0.274	0.274	60	0.1980	0.196
5.01 pm	80.8	60	0.2807	0.278	60	0.2460	0.248	60	0.2984	0.2984	60	0.2055	0.203
5.31 pm	81	60	0.3032	0.300	60	0.2653	0.268	60	0.3152	0.3152	60	0.212	0.210
6.01 pm	81	60	0.3258	0.323	60	0.2763	0.279	60	0.3188	0.3188	60	0.2421	0.240
6.31 pm	81	60	0.3215	0.318	60	0.2655	0.268	60	0.3159	0.3159	60	0.2295	0.227
7.01 pm	81	60	0.3346	0.331	60	0.2844	0.287	60	0.3155	0.3155	60	0.2351	0.233
7.31 pm	81	60	0.3382	0.335	60	0.2722	0.275	60	0.3062	0.3062	60	0.2363	0.234
8.01 pm	80.8	60	0.3320	0.329	60	0.2755	0.278	60	0.2975	0.2975	60	0.25	0.248
8.31 pm	80.8	60	0.3243	0.321	60	0.2720	0.275	60	0.301	0.301	60	0.2282	0.226
9.01 pm	80.6	60	0.3292	0.326	60	0.2793	0.282	60	0.2976	0.2976	60	0.2226	0.220
Total Charge Passed		Q1=	6195.814	Coulombs	Q2 =	5600	Coulombs	Q2 =	6222.06	Coulombs	Q2 =	4535.822	Coulombs
Average Charge Passed, Coulombs									5638.42				

Table C.26: Chloride Ion Penetration Test, Mixture EDW

Date of Casting		2-Apr-08		Date of Testing		7-Jul-08		Time of Testing		8.02 am			
Mix Id	EDW			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
8.02 am	79.9	60	0.0243	0.024	60	0.0278	0.028	60	0.0315	0.0315	60	0.0323	0.032
8.32 am	79.5	60	0.0255	0.025	60	0.0280	0.028	60	0.0334	0.0334	60	0.0306	0.030
9.02 am	79.7	60	0.0238	0.024	60	0.0282	0.028	60	0.035	0.035	60	0.0294	0.029
9.32 am	79.5	60	0.0245	0.024	60	0.0283	0.029	60	0.0361	0.0361	60	0.0306	0.030
10.02 am	79.5	60	0.0245	0.024	60	0.0300	0.030	60	0.0371	0.0371	60	0.0313	0.031
10.32 am	78.8	60	0.0251	0.025	60	0.0291	0.029	60	0.0381	0.0381	60	0.0331	0.033
11.02 am	78.8	60	0.0267	0.026	60	0.0303	0.031	60	0.039	0.039	60	0.0326	0.032
11.32 am	78.8	60	0.0270	0.027	60	0.0309	0.031	60	0.0396	0.0396	60	0.0343	0.034
12.02 pm	79.3	60	0.0283	0.028	60	0.0302	0.031	60	0.0402	0.0402	60	0.0337	0.033
12.32 pm	79.2	60	0.0269	0.027	60	0.0305	0.031	60	0.0407	0.0407	60	0.0354	0.035
1.02 pm	79.2	60	0.0270	0.027	60	0.0315	0.032	60	0.0413	0.0413	60	0.0355	0.035
1.32 pm	79.2	60	0.0282	0.028	60	0.0328	0.033	60	0.042	0.042	60	0.0353	0.035
2.02pm	79.2	60	0.0293	0.029	60	0.0320	0.032	60	0.0422	0.0422	60	0.0358	0.035
Total Charge Passed		Q1=	560.1386	Coulombs	Q2 =	654	Coulombs	Q2 =	826.83	Coulombs	Q2 =	705.4752	Coulombs
Average Charge Passed, Coulombs									686.61				

Table C.27: Chloride Ion Penetration Test, Mixture EDSA

Date of Casting				Date of Testing		4-Jul-08		Time of Testing		7.48 am			
Mix Id	EDSA			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
7.48 am	79.7	60	0.1111	0.110	60	0.1202	0.121	60	0.1229	0.1229	60	0.1321	0.131
8.18 am	80.4	60	0.1137	0.113	60	0.1292	0.131	60	0.1488	0.1488	60	0.1258	0.125
8.48 am	80.8	60	0.1188	0.118	60	0.1462	0.148	60	0.1646	0.1646	60	0.14	0.139
9.18 am	80.6	60	0.1283	0.127	60	0.1560	0.158	60	0.1769	0.1769	60	0.1518	0.150
9.48 am	80.6	60	0.1351	0.134	60	0.1642	0.166	60	0.1862	0.1862	60	0.1597	0.158
10.18 am	80.4	60	0.1446	0.143	60	0.1750	0.177	60	0.1939	0.1939	60	0.1652	0.164
10.48 am	80.6	60	0.1466	0.145	60	0.1783	0.180	60	0.2005	0.2005	60	0.1689	0.167
11.18 am	80.8	60	0.1498	0.148	60	0.1818	0.184	60	0.2023	0.2023	60	0.173	0.171
11.48 am	80.2	60	0.1592	0.158	60	0.1946	0.197	60	0.203	0.203	60	0.182	0.180
12.18 pm	80.4	60	0.1562	0.155	60	0.1841	0.186	60	0.2023	0.2023	60	0.1765	0.175
12.48 pm	80.6	60	0.1586	0.157	60	0.1866	0.188	60	0.2018	0.2018	60	0.1783	0.177
1.18 pm	80.6	60	0.1569	0.155	60	0.1870	0.189	60	0.1995	0.1995	60	0.18	0.178
1.48 pm	80.8	60	0.1588	0.157	60	0.1860	0.188	60	0.1971	0.1971	60	0.1908	0.189
Total Charge Passed		Q1=	3034.604	Coulombs	Q2 =	3702	Coulombs	Q2 =	4031.64	Coulombs	Q2 =	3497.792	Coulombs
Average Charge Passed, Coulombs									3566.51				

Table C.28: Chloride Ion Penetration Test, Mixture EDSB

Date of Casting				Date of Testing		4-Jul-08		Time of Testing		3.20 pm			
Mix Id	EDSB			Mix Type				Curing Period		95 days			
Resistance		Cell 1	1.01	ohm	Cell 2	0.99	ohm	Cell 3	1.00 ohm		Cell 4	1.01 ohm	
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
3.20 pm	81	60	0.1463	0.145	60	0.1438	0.145	60	0.1221	0.1221	60	0.13	0.129
3.50 pm	81	60	0.1500	0.149	60	0.1580	0.160	60	0.1449	0.1449	60	0.1308	0.130
4.20 pm	81	60	0.1777	0.176	60	0.1710	0.173	60	0.1641	0.1641	60	0.1479	0.146
4.50 pm	80.8	60	0.2037	0.202	60	0.1935	0.195	60	0.1852	0.1852	60	0.1645	0.163
5.20 pm	80.8	60	0.2170	0.215	60	0.2040	0.206	60	0.1914	0.1914	60	0.1846	0.183
5.50 pm	80.6	60	0.2334	0.231	60	0.2115	0.214	60	0.2033	0.2033	60	0.1894	0.188
6.20 pm	81	60	0.2482	0.246	60	0.2245	0.227	60	0.2102	0.2102	60	0.1968	0.195
6.50 pm	80.6	60	0.2450	0.243	60	0.2307	0.233	60	0.2144	0.2144	60	0.2154	0.213
7.20 pm	80.6	60	0.2418	0.239	60	0.2174	0.220	60	0.2145	0.2145	60	0.204	0.202
7.50 pm	80.8	60	0.2523	0.250	60	0.2210	0.223	60	0.2111	0.2111	60	0.1846	0.183
8.20 pm	80.8	60	0.2289	0.227	60	0.2102	0.212	60	0.2079	0.2079	60	0.1808	0.179
8.50 pm	80.6	60	0.2389	0.237	60	0.2005	0.203	60	0.2009	0.2009	60	0.17	0.168
9.20 pm		60	0.2221	0.220	60	0.2024	0.204	60	0.1947	0.1947	60	0.164	0.162
Total Charge Passed		Q1=	4671.267	Coulombs	Q2 =	4391.636	Coulombs	Q2 =	4151.34	Coulombs	Q2 =	3770.733	Coulombs
Average Charge Passed, Coulombs									**4246.24**				

Table C.29: Abrasion Test, Mixture CW

Date of Casting	29-Mar-08		Date of Testing		29-Jun-08	Time of Testing		
Mix ID	Control Mix		Mix Type		None	Curing Peroid		93 days
	Mix Id No.	CW-1	Mix Id No.		CW-2	Mix Id No.		CW-3
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.104	0.152	0.048	0.093	0.128	0.04	0.107	0.153	0.05
2	0.104	0.152	0.048	0.094	0.128	0.03	0.115	0.153	0.04
3	0.106	0.152	0.046	0.088	0.128	0.04	0.108	0.153	0.05
4	0.105	0.152	0.047	0.086	0.128	0.04	0.108	0.153	0.05
5	0.106	0.152	0.046	0.087	0.128	0.04	0.114	0.153	0.04
6	0.106	0.152	0.046	0.080	0.128	0.05	0.112	0.153	0.04
7	0.105	0.152	0.047	0.081	0.128	0.05	0.110	0.153	0.04
8	0.109	0.152	0.043	0.089	0.128	0.04	0.107	0.153	0.05
9	0.108	0.152	0.044	0.093	0.138	0.05	0.108	0.153	0.05
10	0.110	0.152	0.042	0.085	0.138	0.05	0.104	0.153	0.05
11	0.102	0.152	0.050	0.077	0.138	0.06	0.095	0.153	0.06
12	0.095	0.152	0.057	0.088	0.138	0.05	0.098	0.153	0.06
13	0.093	0.152	0.059	0.079	0.138	0.06	0.090	0.153	0.06
14	0.095	0.152	0.057	0.083	0.138	0.06	0.087	0.153	0.07
15	0.089	0.152	0.063	0.082	0.138	0.06	0.088	0.153	0.07
16	0.087	0.152	0.065	0.086	0.138	0.05	0.088	0.153	0.07
17	0.084	0.152	0.068	0.093	0.138	0.05	0.091	0.153	0.06
18	0.084	0.152	0.068	0.098	0.138	0.04	0.093	0.153	0.06
19	0.087	0.152	0.065	0.095	0.138	0.04	0.088	0.153	0.07
20	0.087	0.152	0.065	0.092	0.138	0.05	0.083	0.153	0.07
21	0.091	0.152	0.061	0.088	0.138	0.05	0.082	0.153	0.07
22	0.100	0.152	0.052	0.094	0.138	0.04	0.083	0.153	0.07
23	0.108	0.152	0.044	0.096	0.138	0.04	0.094	0.153	0.06
24	0.106	0.152	0.046	0.089	0.138	0.05	0.103	0.153	0.05
Average	0.099	0.152	0.053	0.088	0.135	0.046	0.098	0.153	0.055

Table C.30: Abrasion Test, Mixture CSA

Date of Casting	29-Mar-08		Date of Testing		29-Jun-08	Time of Testing		
Mix ID	Control Mix, Steam Curing A		Mix Type		None	Curing Peroid		93 days
	Mix Id No.	CSA-1	Mix Id No.		CSA-2	Mix Id No.		CSA-3
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.126	0.200	0.074	0.135	0.202	0.07	0.107	0.186	0.08
2	0.129	0.199	0.070	0.128	0.199	0.07	0.103	0.191	0.09
3	0.129	0.189	0.060	0.111	0.187	0.08	0.104	0.183	0.08
4	0.122	0.194	0.072	0.104	0.195	0.09	0.107	0.185	0.08
5	0.125	0.094	-0.031	0.104	0.186	0.08	0.108	0.181	0.07
6	0.117	0.185	0.068	0.108	0.183	0.08	0.108	0.174	0.07
7	0.109	0.198	0.089	0.107	0.187	0.08	0.105	0.176	0.07
8	0.109	0.178	0.069	0.110	0.188	0.08	0.109	0.174	0.07
9	0.106	0.198	0.092	0.111	0.194	0.08	0.113	0.170	0.06
10	0.113	0.179	0.066	0.121	0.199	0.08	0.113	0.159	0.05
11	0.109	0.177	0.068	0.115	0.207	0.09	0.119	0.169	0.05
12	0.110	0.186	0.076	0.119	0.212	0.09	0.102	0.164	0.06
13	0.107	0.181	0.074	0.134	0.216	0.08	0.105	0.163	0.06
14	0.106	0.188	0.082	0.141	0.222	0.08	0.107	0.160	0.05
15	0.104	0.180	0.076	0.144	0.220	0.08	0.111	0.174	0.06
16	0.107	0.172	0.065	0.138	0.231	0.09	0.112	0.178	0.07
17	0.111	0.182	0.071	0.130	0.226	0.10	0.107	0.177	0.07
18	0.113	0.180	0.067	0.128	0.223	0.10	0.102	0.166	0.06
19	0.115	0.182	0.067	0.133	0.220	0.09	0.101	0.177	0.08
20	0.110	0.190	0.080	0.127	0.219	0.09	0.114	0.186	0.07
21	0.123	0.179	0.056	0.131	0.219	0.09	0.115	0.194	0.08
22	0.118	0.184	0.066	0.133	0.213	0.08	0.109	0.187	0.08
23	0.118	0.190	0.072	0.134	0.216	0.08	0.106	0.177	0.07
24	0.137	0.181	0.044	0.141	0.209	0.07	0.111	0.181	0.07
Average	0.116	0.182	0.066	0.124	0.207	0.083	0.108	0.176	0.068

Table C.31: Abrasion Test, Mixture CSB

Date of Casting		3/29/2008		Date of Testing		6/29/2008	Time of Testing		
Mix ID		Control Mix, Steam Curing B		Mix Type		None	Curing Peroid		93 days
	Mix Id No.		CSB-1	Mix Id No.		CSB-2	Mix Id No.		CSB-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.141	0.238	0.097	0.133	0.262	0.13	0.142	0.246	0.10
2	0.140	0.242	0.102	0.140	0.262	0.12	0.148	0.240	0.09
3	0.137	0.233	0.096	0.152	0.263	0.11	0.157	0.241	0.08
4	0.131	0.244	0.113	0.162	0.271	0.11	0.152	0.234	0.08
5	0.123	0.231	0.108	0.164	0.258	0.09	0.150	0.224	0.07
6	0.113	0.217	0.104	0.155	0.244	0.09	0.150	0.240	0.09
7	0.107	0.222	0.115	0.142	0.241	0.10	0.142	0.244	0.10
8	0.110	0.214	0.104	0.143	0.235	0.09	0.129	0.222	0.09
9	0.120	0.212	0.092	0.138	0.222	0.08	0.127	0.223	0.10
10	0.131	0.208	0.077	0.125	0.229	0.10	0.128	0.223	0.10
11	0.120	0.220	0.100	0.120	0.237	0.12	0.125	0.230	0.11
12	0.119	0.220	0.101	0.116	0.225	0.11	0.117	0.224	0.11
13	0.109	0.226	0.117	0.119	0.223	0.10	0.118	0.193	0.08
14	0.111	0.227	0.116	0.120	0.226	0.11	0.120	0.222	0.10
15	0.131	0.236	0.105	0.118	0.233	0.12	0.114	0.210	0.10
16	0.133	0.235	0.102	0.121	0.230	0.11	0.110	0.194	0.08
17	0.132	0.249	0.117	0.126	0.231	0.11	0.120	0.181	0.06
18	0.136	0.251	0.115	0.145	0.239	0.09	0.123	0.192	0.07
19	0.140	0.246	0.106	0.119	0.237	0.12	0.114	0.207	0.09
20	0.136	0.237	0.101	0.126	0.229	0.10	0.129	0.224	0.10
21	0.143	0.236	0.093	0.122	0.242	0.12	0.140	0.225	0.09
22	0.152	0.236	0.084	0.129	0.233	0.10	0.135	0.225	0.09
23	0.148	0.231	0.083	0.131	0.255	0.12	0.139	0.224	0.09
24	0.143	0.238	0.095	0.130	0.265	0.14	0.139	0.233	0.09
Average	0.129	0.231	0.102	0.133	0.241	0.108	0.132	0.222	0.090

Table C.32: Abrasion Test, Mixture EAW

Date of Casting	24-Mar-08		Date of Testing		22-Jun-08	Time of Testing		
Mix ID	Exp A, Water Curing		Mix Type		Slag + Gravel	Curing Peroid		91 days
	Mix Id No.	EAW-3	Mix Id No.		EAW-1	Mix Id No.		EAW-2
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.149	0.288	0.139	0.144	0.210	0.066	0.167	0.231	0.064
2	0.164	0.277	0.113	0.154	0.221	0.067	0.153	0.230	0.077
3	0.153	0.253	0.100	0.163	0.228	0.065	0.152	0.224	0.072
4	0.156	0.264	0.108	0.168	0.230	0.062	0.133	0.207	0.074
5	0.156	0.262	0.106	0.176	0.238	0.062	0.126	0.192	0.066
6	0.153	0.260	0.107	0.177	0.239	0.062	0.107	0.176	0.069
7	0.154	0.252	0.098	0.183	0.252	0.069	0.122	0.177	0.055
8	0.153	0.260	0.107	0.176	0.240	0.064	0.115	0.167	0.052
9	0.156	0.261	0.105	0.171	0.243	0.072	0.109	0.158	0.049
10	0.152	0.255	0.103	0.170	0.232	0.062	0.118	0.166	0.048
11	0.143	0.253	0.110	0.159	0.230	0.071	0.117	0.146	0.029
12	0.152	0.230	0.078	0.152	0.224	0.072	0.110	0.167	0.057
13	0.145	0.244	0.099	0.141	0.207	0.066	0.109	0.170	0.061
14	0.146	0.241	0.095	0.131	0.195	0.064	0.112	0.164	0.052
15	0.147	0.233	0.086	0.128	0.184	0.056	0.117	0.191	0.074
16	0.154	0.255	0.101	0.132	0.196	0.064	0.131	0.206	0.075
17	0.158	0.245	0.087	0.126	0.189	0.063	0.139	0.210	0.071
18	0.164	0.248	0.084	0.132	0.185	0.053	0.147	0.208	0.061
19	0.159	0.257	0.098	0.136	0.194	0.058	0.156	0.217	0.061
20	0.158	0.262	0.104	0.137	0.189	0.052	0.168	0.222	0.054
21	0.155	0.257	0.102	0.137	0.190	0.053	0.168	0.223	0.055
22	0.164	0.261	0.097	0.134	0.196	0.062	0.168	0.227	0.059
23	0.171	0.283	0.112	0.131	0.197	0.066	0.169	0.228	0.059
24	0.164	0.280	0.116	0.136	0.200	0.064	0.171	0.229	0.058
Average	0.155	0.258	0.102	0.150	0.213	0.063	0.137	0.197	0.061

Table C.33: Abrasion Test, Mixture EASA

Date of Casting	25-Mar-08		Date of Testing		23-Jun-08	Time of Testing		
Mix ID	Exp A, Steam Curing A		Mix Type		Slag + Gravel	Curing Peroid		91 days
	Mix Id No.	EASA-2	Mix Id No.		EASA-3	Mix Id No.		EASA-1
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.102	0.162	0.060	0.096	0.138	0.042	0.102	0.140	0.038
2	0.103	0.157	0.054	0.098	0.136	0.038	0.088	0.134	0.046
3	0.105	0.162	0.057	0.089	0.130	0.041	0.089	0.117	0.028
4	0.101	0.148	0.047	0.089	0.137	0.048	0.088	0.122	0.034
5	0.104	0.153	0.049	0.093	0.142	0.049	0.082	0.135	0.053
6	0.106	0.148	0.042	0.091	0.144	0.053	0.085	0.133	0.048
7	0.106	0.146	0.040	0.103	0.148	0.045	0.086	0.141	0.055
8	0.109	0.154	0.045	0.093	0.144	0.051	0.085	0.139	0.054
9	0.109	0.145	0.036	0.096	0.144	0.048	0.082	0.136	0.054
10	0.109	0.156	0.047	0.104	0.164	0.060	0.081	0.132	0.051
11	0.106	0.149	0.043	0.099	0.153	0.054	0.081	0.141	0.060
12	0.104	0.164	0.060	0.100	0.163	0.063	0.078	0.136	0.058
13	0.103	0.162	0.059	0.106	0.157	0.051	0.078	0.146	0.068
14	0.103	0.158	0.055	0.104	0.153	0.049	0.086	0.122	0.036
15	0.107	0.165	0.058	0.103	0.144	0.041	0.093	0.121	0.028
16	0.104	0.163	0.059	0.108	0.162	0.054	0.083	0.133	0.050
17	0.097	0.155	0.058	0.108	0.176	0.068	0.078	0.133	0.055
18	0.099	0.164	0.065	0.110	0.162	0.052	0.085	0.144	0.059
19	0.106	0.167	0.061	0.117	0.166	0.049	0.083	0.134	0.051
20	0.108	0.163	0.055	0.110	0.158	0.048	0.081	0.139	0.058
21	0.102	0.153	0.051	0.104	0.155	0.051	0.078	0.136	0.058
22	0.103	0.163	0.060	0.100	0.144	0.044	0.080	0.124	0.044
23	0.098	0.164	0.066	0.102	0.140	0.038	0.084	0.132	0.048
24	0.100	0.160	0.060	0.102	0.131	0.029	0.087	0.113	0.026
Average	0.104	0.158	0.054	0.101	0.150	0.049	0.084	0.133	0.048

Table C.34: Abrasion Test, Mixture EASB

Date of Casting	25-Mar-08		Date of Testing	23-Jun-08		Time of Testing		
Mix ID	Exp A, Steam Curing B		Mix Type	Slag + Gravel		Curing Peroid		91 days
	Mix Id No.	EASB-1	Mix Id No.		EASB-3	Mix Id No.		EASB-2
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.112	0.179	0.067	0.098	0.174	0.076	0.114	0.179	0.065
2	0.121	0.194	0.073	0.099	0.166	0.067	0.105	0.181	0.076
3	0.132	0.198	0.066	0.104	0.174	0.070	0.100	0.170	0.070
4	0.134	0.197	0.063	0.114	0.192	0.078	0.101	0.176	0.075
5	0.127	0.194	0.067	0.124	0.187	0.063	0.087	0.162	0.075
6	0.126	0.212	0.086	0.118	0.189	0.071	0.095	0.152	0.057
7	0.124	0.198	0.074	0.119	0.212	0.093	0.105	0.150	0.045
8	0.127	0.190	0.063	0.124	0.206	0.082	0.097	0.163	0.066
9	0.120	0.183	0.063	0.126	0.214	0.088	0.097	0.155	0.058
10	0.110	0.179	0.069	0.120	0.217	0.097	0.098	0.156	0.058
11	0.110	0.175	0.065	0.122	0.232	0.110	0.105	0.172	0.067
12	0.104	0.167	0.063	0.124	0.208	0.084	0.101	0.186	0.085
13	0.109	0.158	0.049	0.124	0.211	0.087	0.109	0.180	0.071
14	0.107	0.157	0.050	0.122	0.206	0.084	0.109	0.190	0.081
15	0.110	0.170	0.060	0.122	0.195	0.073	0.113	0.184	0.071
16	0.113	0.173	0.060	0.116	0.203	0.087	0.110	0.195	0.085
17	0.115	0.174	0.059	0.103	0.193	0.090	0.107	0.202	0.095
18	0.110	0.177	0.067	0.101	0.196	0.095	0.107	0.190	0.083
19	0.111	0.165	0.054	0.097	0.194	0.097	0.113	0.190	0.077
20	0.115	0.171	0.056	0.098	0.181	0.083	0.113	0.182	0.069
21	0.104	0.170	0.066	0.103	0.169	0.066	0.113	0.189	0.076
22	0.100	0.171	0.071	0.107	0.173	0.066	0.114	0.184	0.070
23	0.101	0.164	0.063	0.104	0.173	0.069	0.118	0.185	0.067
24	0.107	0.163	0.056	0.097	0.175	0.078	0.111	0.175	0.064
Average	0.115	0.178	0.064	0.112	0.193	0.081	0.106	0.177	0.071

Table C.35: Abrasion Test, Mixture EBW

Date of Casting		02-Apr-08		Date of Testing		3-Jul-08	Time of Testing		
Mix ID		Exp-B, Water Curing		Mix Type		Slag + Crushed rock	Curing Peroid		93 days
	Mix Id No.		EBW-1	Mix Id No.		EBW-2	Mix Id No.		EBW-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.096	0.125	0.029	0.125	0.149	0.02	0.103	0.113	0.01
2	0.092	0.121	0.029	0.123	0.147	0.02	0.108	0.131	0.02
3	0.091	0.120	0.029	0.112	0.144	0.03	0.112	0.142	0.03
4	0.093	0.126	0.033	0.108	0.131	0.02	0.125	0.147	0.02
5	0.098	0.129	0.031	0.105	0.135	0.03	0.117	0.149	0.03
6	0.098	0.130	0.032	0.100	0.129	0.03	0.131	0.152	0.02
7	0.093	0.135	0.042	0.101	0.124	0.02	0.129	0.148	0.02
8	0.100	0.124	0.024	0.094	0.119	0.03	0.118	0.142	0.02
9	0.096	0.124	0.028	0.084	0.111	0.03	0.122	0.137	0.02
10	0.097	0.122	0.025	0.084	0.107	0.02	0.109	0.125	0.02
11	0.100	0.132	0.032	0.082	0.106	0.02	0.099	0.123	0.02
12	0.100	0.128	0.028	0.088	0.106	0.02	0.094	0.123	0.03
13	0.104	0.134	0.030	0.094	0.114	0.02	0.096	0.116	0.02
14	0.100	0.132	0.032	0.096	0.121	0.03	0.094	0.123	0.03
15	0.103	0.138	0.035	0.101	0.120	0.02	0.103	0.127	0.02
16	0.104	0.135	0.031	0.096	0.125	0.03	0.099	0.124	0.03
17	0.107	0.133	0.026	0.096	0.125	0.03	0.111	0.133	0.02
18	0.112	0.134	0.022	0.103	0.130	0.03	0.103	0.130	0.03
19	0.111	0.137	0.026	0.112	0.133	0.02	0.103	0.127	0.02
20	0.107	0.132	0.025	0.118	0.142	0.02	0.104	0.128	0.02
21	0.105	0.125	0.020	0.113	0.146	0.03	0.102	0.116	0.01
22	0.096	0.121	0.025	0.111	0.134	0.02	0.099	0.130	0.03
23	0.094	0.117	0.023	0.116	0.140	0.02	0.094	0.123	0.03
24	0.099	0.123	0.024	0.124	0.145	0.02	0.099	0.122	0.02
Average	0.100	0.128	0.028	0.104	0.128	0.025	0.107	0.130	0.023

Table C.36: Abrasion Test, Mixture EBSA

Date of Casting		31-Mar-08		Date of Testing		1-Jul-08	Time of Testing		
Mix ID		Exp-B, Steam Curing A		Mix Type		Slag + Crushed rock	Curing Peroid		93 days
	Mix Id No.		EBSA-1	Mix Id No.		EBSA-2	Mix Id No.		EBSA-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.082	0.146	0.064	0.111	0.160	0.05	0.112	0.154	0.04
2	0.093	0.158	0.065	0.115	0.150	0.04	0.112	0.170	0.06
3	0.096	0.159	0.063	0.101	0.149	0.05	0.120	0.171	0.05
4	0.100	0.161	0.061	0.103	0.138	0.04	0.119	0.177	0.06
5	0.104	0.171	0.067	0.095	0.136	0.04	0.124	0.157	0.03
6	0.104	0.168	0.064	0.095	0.141	0.05	0.125	0.166	0.04
7	0.106	0.152	0.046	0.087	0.139	0.05	0.121	0.163	0.04
8	0.103	0.164	0.061	0.103	0.138	0.04	0.117	0.155	0.04
9	0.104	0.162	0.058	0.093	0.144	0.05	0.113	0.151	0.04
10	0.105	0.158	0.053	0.094	0.136	0.04	0.116	0.152	0.04
11	0.117	0.161	0.044	0.095	0.132	0.04	0.116	0.149	0.03
12	0.115	0.173	0.058	0.098	0.132	0.03	0.111	0.148	0.04
13	0.123	0.183	0.060	0.093	0.134	0.04	0.110	0.148	0.04
14	0.130	0.174	0.044	0.098	0.140	0.04	0.111	0.155	0.04
15	0.143	0.183	0.040	0.106	0.144	0.04	0.118	0.158	0.04
16	0.132	0.182	0.050	0.113	0.156	0.04	0.121	0.162	0.04
17	0.127	0.176	0.049	0.122	0.161	0.04	0.124	0.164	0.04
18	0.115	0.162	0.047	0.124	0.164	0.04	0.127	0.165	0.04
19	0.107	0.158	0.051	0.125	0.156	0.03	0.126	0.160	0.03
20	0.108	0.157	0.049	0.125	0.172	0.05	0.123	0.169	0.05
21	0.108	0.156	0.048	0.122	0.180	0.06	0.125	0.170	0.05
22	0.098	0.155	0.057	0.119	0.165	0.05	0.109	0.169	0.06
23	0.091	0.158	0.067	0.123	0.168	0.05	0.107	0.153	0.05
24	0.090	0.160	0.070	0.120	0.167	0.05	0.105	0.165	0.06
Average	0.108	0.164	0.056	0.108	0.150	0.043	0.117	0.160	0.043

Table C.37: Abrasion Test, Mixture EBSB

Date of Casting		31-Mar-08		Date of Testing		1-Jul-08	Time of Testing		
Mix ID		Exp-B, Steam Curing B		Mix Type		Slag + Crushed rock	Curing Peroid		93 days
	Mix Id No.		EBSB-1	Mix Id No.		EBSB-2	Mix Id No.		EBSB-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.100	0.136	0.036	0.094	0.149	0.06	0.099	0.151	0.05
2	0.094	0.133	0.039	0.105	0.143	0.04	0.104	0.133	0.03
3	0.088	0.132	0.044	0.094	0.138	0.04	0.108	0.158	0.05
4	0.093	0.143	0.050	0.101	0.138	0.04	0.124	0.165	0.04
5	0.090	0.139	0.049	0.108	0.141	0.03	0.109	0.164	0.06
6	0.102	0.143	0.041	0.104	0.141	0.04	0.112	0.148	0.04
7	0.113	0.155	0.042	0.108	0.135	0.03	0.110	0.150	0.04
8	0.118	0.152	0.034	0.102	0.128	0.03	0.102	0.135	0.03
9	0.122	0.162	0.040	0.111	0.130	0.02	0.093	0.135	0.04
10	0.133	0.166	0.033	0.108	0.137	0.03	0.098	0.135	0.04
11	0.137	0.160	0.023	0.116	0.137	0.02	0.101	0.123	0.02
12	0.142	0.158	0.016	0.115	0.138	0.02	0.095	0.140	0.05
13	0.140	0.160	0.020	0.119	0.138	0.02	0.101	0.132	0.03
14	0.122	0.160	0.038	0.112	0.141	0.03	0.100	0.138	0.04
15	0.124	0.164	0.040	0.107	0.142	0.04	0.105	0.134	0.03
16	0.112	0.168	0.056	0.103	0.135	0.03	0.102	0.130	0.03
17	0.113	0.148	0.035	0.095	0.143	0.05	0.096	0.130	0.03
18	0.110	0.159	0.049	0.092	0.133	0.04	0.102	0.135	0.03
19	0.110	0.143	0.033	0.094	0.131	0.04	0.103	0.139	0.04
20	0.113	0.165	0.052	0.103	0.144	0.04	0.098	0.138	0.04
21	0.116	0.158	0.042	0.102	0.154	0.05	0.101	0.141	0.04
22	0.103	0.154	0.051	0.108	0.154	0.05	0.098	0.144	0.05
23	0.093	0.145	0.052	0.100	0.143	0.04	0.102	0.138	0.04
24	0.098	0.140	0.042	0.090	0.133	0.04	0.088	0.154	0.07
Average	0.112	0.152	0.040	0.104	0.139	0.036	0.102	0.141	0.039

Table C.38: Abrasion Test, Mixture ECW

Date of Casting	26-Mar-08		Date of Testing		24-Jun-08	Time of Testing		
Mix ID	Exp C, Water Curing		Mix Type		Fly ash + Gravel	Curing Peroid		91 days
	Mix Id No.	ECW-3	Mix Id No.		ECW-2	Mix Id No.		ECW-1
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.135	0.213	0.078	0.141	0.222	0.081	0.130	0.201	0.071
2	0.137	0.215	0.078	0.140	0.222	0.082	0.129	0.207	0.078
3	0.136	0.222	0.086	0.131	0.217	0.086	0.121	0.198	0.077
4	0.128	0.226	0.098	0.139	0.213	0.074	0.114	0.204	0.090
5	0.125	0.202	0.077	0.123	0.207	0.084	0.114	0.193	0.079
6	0.124	0.205	0.081	0.116	0.206	0.090	0.119	0.194	0.075
7	0.119	0.213	0.094	0.115	0.207	0.092	0.108	0.196	0.088
8	0.101	0.200	0.099	0.117	0.203	0.086	0.111	0.189	0.078
9	0.120	0.205	0.085	0.115	0.194	0.079	0.112	0.191	0.079
10	0.128	0.200	0.072	0.116	0.184	0.068	0.120	0.195	0.075
11	0.132	0.203	0.071	0.119	0.182	0.063	0.126	0.197	0.071
12	0.118	0.188	0.070	0.119	0.195	0.076	0.119	0.206	0.087
13	0.126	0.207	0.081	0.128	0.193	0.065	0.121	0.203	0.082
14	0.121	0.208	0.087	0.128	0.210	0.082	0.122	0.204	0.082
15	0.126	0.202	0.076	0.143	0.218	0.075	0.123	0.216	0.093
16	0.133	0.206	0.073	0.145	0.218	0.073	0.122	0.226	0.104
17	0.126	0.199	0.073	0.140	0.211	0.071	0.136	0.205	0.069
18	0.133	0.199	0.066	0.143	0.221	0.078	0.128	0.207	0.079
19	0.126	0.183	0.057	0.151	0.221	0.070	0.140	0.204	0.064
20	0.131	0.196	0.065	0.137	0.201	0.064	0.142	0.211	0.069
21	0.125	0.201	0.076	0.149	0.220	0.071	0.140	0.202	0.062
22	0.110	0.201	0.091	0.154	0.214	0.060	0.133	0.193	0.060
23	0.128	0.209	0.081	0.155	0.219	0.064	0.124	0.241	0.117
24	0.130	0.186	0.056	0.149	0.206	0.057	0.130	0.203	0.073
Average	0.126	0.204	0.078	0.134	0.209	0.075	0.124	0.204	0.079

Table C.39: Abrasion Test, Mixture ECSA

Date of Casting	3/28/2008		Date of Testing		6/26/2008	Time of Testing		
Mix ID	Exp C, Steam Curing A		Mix Type		Fly ash + Gravel	Curing Peroid		91 days
	Mix Id No.	ECSA-1	Mix Id No.		ECSA-2	Mix Id No.		ECSA-3
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.107	0.200	0.093	0.120	0.188	0.068	0.128	0.199	0.071
2	0.103	0.201	0.098	0.111	0.191	0.080	0.125	0.203	0.078
3	0.105	0.203	0.098	0.102	0.173	0.071	0.129	0.213	0.084
4	0.101	0.182	0.081	0.097	0.179	0.082	0.130	0.204	0.074
5	0.093	0.195	0.102	0.097	0.187	0.090	0.128	0.195	0.067
6	0.096	0.193	0.097	0.096	0.186	0.090	0.125	0.205	0.080
7	0.094	0.196	0.102	0.098	0.164	0.066	0.114	0.204	0.090
8	0.092	0.195	0.103	0.102	0.170	0.068	0.108	0.167	0.059
9	0.096	0.176	0.080	0.098	0.145	0.047	0.103	0.169	0.066
10	0.093	0.161	0.068	0.091	0.154	0.063	0.101	0.168	0.067
11	0.093	0.155	0.062	0.097	0.152	0.055	0.100	0.190	0.090
12	0.093	0.162	0.069	0.092	0.156	0.064	0.106	0.169	0.063
13	0.094	0.150	0.056	0.092	0.165	0.073	0.107	0.194	0.087
14	0.094	0.165	0.071	0.101	0.151	0.050	0.107	0.180	0.073
15	0.092	0.155	0.063	0.095	0.177	0.082	0.109	0.181	0.072
16	0.101	0.161	0.060	0.100	0.158	0.058	0.116	0.194	0.078
17	0.101	0.167	0.066	0.107	0.179	0.072	0.116	0.188	0.072
18	0.104	0.177	0.073	0.111	0.181	0.070	0.119	0.188	0.069
19	0.119	0.168	0.049	0.114	0.193	0.079	0.128	0.199	0.071
20	0.127	0.198	0.071	0.114	0.182	0.068	0.128	0.184	0.056
21	0.130	0.197	0.067	0.116	0.196	0.080	0.134	0.190	0.056
22	0.127	0.206	0.079	0.118	0.178	0.060	0.128	0.189	0.061
23	0.126	0.206	0.080	0.121	0.191	0.070	0.130	0.195	0.065
24	0.113	0.196	0.083	0.118	0.189	0.071	0.139	0.192	0.053
Average	0.104	0.182	0.078	0.105	0.174	0.070	0.119	0.190	0.071

Table C.40: Abrasion Test, Mixture ECSB

Date of Casting		3/28/2008		Date of Testing		6/26/2008	Time of Testing		
Mix ID		Exp C, Steam Curing B		Mix Type		Fly ash + Gravel	Curing Peroid		91 days
	Mix Id No.		ECSB-1	Mix Id No.		ECSB-2	Mix Id No.		ECSB-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0.000	30	Difference	0.000	30.000	Difference
1	0.122	0.360	0.238	0.113	0.30	0.19	0.121	0.219	0.10
2	0.111	0.351	0.240	0.119	0.30	0.19	0.124	0.323	0.20
3	0.112	0.345	0.233	0.122	0.29	0.16	0.126	0.339	0.21
4	0.105	0.351	0.246	0.125	0.27	0.14	0.120	0.333	0.21
5	0.102	0.340	0.238	0.139	0.28	0.14	0.130	0.340	0.21
6	0.103	0.340	0.237	0.151	0.28	0.13	0.119	0.316	0.20
7	0.098	0.339	0.241	0.157	0.27	0.11	0.117	0.298	0.18
8	0.101	0.343	0.242	0.146	0.30	0.16	0.112	0.306	0.19
9	0.101	0.365	0.264	0.150	0.31	0.16	0.118	0.314	0.20
10	0.097	0.313	0.216	0.143	0.32	0.18	0.117	0.306	0.19
11	0.106	0.317	0.211	0.139	0.34	0.20	0.111	0.306	0.20
12	0.107	0.329	0.222	0.144	0.35	0.20	0.119	0.291	0.17
13	0.112	0.337	0.225	0.151	0.36	0.21	0.124	0.301	0.18
14	0.104	0.340	0.236	0.147	0.38	0.23	0.125	0.276	0.15
15	0.104	0.331	0.227	0.154	0.40	0.24	0.130	0.326	0.20
16	0.108	0.321	0.213	0.155	0.39	0.23	0.144	0.320	0.18
17	0.104	0.314	0.210	0.148	0.37	0.22	0.143	0.297	0.15
18	0.109	0.305	0.196	0.149	0.39	0.24	0.142	0.325	0.18
19	0.114	0.293	0.179	0.141	0.37	0.23	0.146	0.326	0.18
20	0.116	0.308	0.192	0.128	0.33	0.20	0.139	0.324	0.19
21	0.115	0.316	0.201	0.117	0.32	0.21	0.134	0.321	0.19
22	0.114	0.330	0.216	0.115	0.31	0.20	0.123	0.292	0.17
23	0.124	0.336	0.212	0.117	0.31	0.20	0.123	0.306	0.18
24	0.118	0.354	0.236	0.121	0.31	0.19	0.122	0.300	0.18
Average	0.109	0.332	0.224	0.137	0.326	0.189	0.126	0.309	0.182

Table C.41: Abrasion Test, Mixture EDW

Date of Casting		02-Apr-08		Date of Testing		3-Jul-08	Time of Testing		
Mix ID		Exp-D, Water Curing		Mix Type		FA+ Crushed Rock	Curing Peroid		93 days
	Mix Id No.		EDW-1	Mix Id No.		EDW-2	Mix Id No.		EDW-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.108	0.144	0.036	0.113	0.142	0.03	0.103	0.146	0.04
2	0.105	0.146	0.041	0.113	0.141	0.03	0.104	0.146	0.04
3	0.100	0.139	0.039	0.112	0.139	0.03	0.107	0.142	0.04
4	0.087	0.132	0.045	0.105	0.141	0.04	0.105	0.132	0.03
5	0.091	0.132	0.041	0.110	0.144	0.03	0.115	0.132	0.02
6	0.083	0.126	0.043	0.111	0.149	0.04	0.131	0.126	(0.01)
7	0.092	0.140	0.048	0.111	0.146	0.04	0.111	0.140	0.03
8	0.099	0.131	0.032	0.107	0.140	0.03	0.108	0.131	0.02
9	0.107	0.147	0.040	0.107	0.133	0.03	0.107	0.147	0.04
10	0.109	0.147	0.038	0.105	0.132	0.03	0.109	0.147	0.04
11	0.110	0.142	0.032	0.102	0.129	0.03	0.100	0.142	0.04
12	0.108	0.146	0.038	0.103	0.135	0.03	0.094	0.146	0.05
13	0.108	0.151	0.043	0.106	0.133	0.03	0.095	0.151	0.06
14	0.107	0.148	0.041	0.103	0.131	0.03	0.094	0.148	0.05
15	0.110	0.154	0.044	0.106	0.134	0.03	0.103	0.154	0.05
16	0.108	0.161	0.053	0.102	0.136	0.03	0.100	0.161	0.06
17	0.112	0.162	0.050	0.106	0.137	0.03	0.111	0.162	0.05
18	0.111	0.158	0.047	0.105	0.151	0.05	0.103	0.158	0.06
19	0.114	0.162	0.048	0.106	0.156	0.05	0.103	0.162	0.06
20	0.103	0.160	0.057	0.109	0.161	0.05	0.104	0.160	0.06
21	0.098	0.148	0.050	0.118	0.165	0.05	0.103	0.148	0.05
22	0.110	0.156	0.046	0.112	0.164	0.05	0.099	0.156	0.06
23	0.112	0.152	0.040	0.101	0.145	0.04	0.094	0.152	0.06
24	0.096	0.144	0.048	0.102	0.141	0.04	0.099	0.144	0.05
Average	0.104	0.147	0.043	0.107	0.143	0.035	0.104	0.147	0.043

Table C.42: Abrasion Test, Mixture EDSA

Date of Casting	30-Mar-08		Date of Testing	30-Jun-08		Time of Testing		
Mix ID	Exp-D, Steam Curing A		Mix Type	FA+ Crushed Rock		Curing Peroid		93 days
	Mix Id No.		EDSA-1	Mix Id No.	EDSA-2	Mix Id No.		EDSA-3
Wear depth (in.) at time (min.)								
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.107	0.179	0.072	0.115	0.205	0.09	0.111	0.185	0.07
2	0.105	0.175	0.070	0.112	0.211	0.10	0.114	0.207	0.09
3	0.107	0.182	0.075	0.107	0.197	0.09	0.114	0.211	0.10
4	0.099	0.178	0.079	0.109	0.215	0.11	0.109	0.199	0.09
5	0.106	0.186	0.080	0.113	0.174	0.06	0.119	0.203	0.08
6	0.097	0.182	0.085	0.122	0.192	0.07	0.131	0.225	0.09
7	0.099	0.203	0.104	0.116	0.207	0.09	0.118	0.233	0.12
8	0.122	0.202	0.080	0.117	0.178	0.06	0.137	0.245	0.11
9	0.099	0.186	0.087	0.116	0.178	0.06	0.116	0.215	0.10
10	0.104	0.160	0.056	0.118	0.172	0.05	0.109	0.200	0.09
11	0.111	0.179	0.068	0.114	0.178	0.06	0.107	0.217	0.11
12	0.111	0.180	0.069	0.113	0.168	0.06	0.112	0.179	0.07
13	0.111	0.158	0.047	0.113	0.157	0.04	0.115	0.201	0.09
14	0.110	0.167	0.057	0.104	0.164	0.06	0.125	0.201	0.08
15	0.111	0.174	0.063	0.097	0.162	0.07	0.130	0.184	0.05
16	0.118	0.167	0.049	0.096	0.162	0.07	0.136	0.204	0.07
17	0.116	0.174	0.058	0.096	0.157	0.06	0.129	0.203	0.07
18	0.117	0.178	0.061	0.099	0.172	0.07	0.119	0.198	0.08
19	0.118	0.163	0.045	0.100	0.178	0.08	0.122	0.173	0.05
20	0.110	0.174	0.064	0.099	0.184	0.09	0.113	0.176	0.06
21	0.114	0.161	0.047	0.106	0.182	0.08	0.114	0.171	0.06
22	0.114	0.174	0.060	0.110	0.199	0.09	0.109	0.155	0.05
23	0.109	0.172	0.063	0.108	0.195	0.09	0.109	0.166	0.06
24	0.106	0.165	0.059	0.108	0.197	0.09	0.108	0.185	0.08
Average	0.109	0.176	0.067	0.109	0.183	0.074	0.118	0.197	0.080

Table C.43: Abrasion Test, Mixture EDSB

Date of Casting		30-Mar-08		Date of Testing		30-Jun-08	Time of Testing		
Mix ID		Exp-D, Steam Curing B		Mix Type		FA+ Crushed Rock	Curing Peroid		93 days
	Mix Id No.		EDSB-2	Mix Id No.		EDSB-1	Mix Id No.		EDSB-3
Wear depth (in.) at time (min.)									
Pos.	0	30	Difference	0	30	Difference	0	30	Difference
1	0.108	0.169	0.061	0.109	0.188	0.08	0.147	0.197	0.05
2	0.109	0.187	0.078	0.110	0.188	0.08	0.141	0.218	0.08
3	0.100	0.175	0.075	0.110	0.195	0.09	0.141	0.195	0.05
4	0.109	0.187	0.078	0.108	0.187	0.08	0.142	0.207	0.07
5	0.110	0.196	0.086	0.105	0.189	0.08	0.135	0.204	0.07
6	0.105	0.185	0.080	0.105	0.203	0.10	0.130	0.189	0.06
7	0.098	0.183	0.085	0.097	0.172	0.08	0.111	0.211	0.10
8	0.105	0.182	0.077	0.090	0.189	0.10	0.107	0.156	0.05
9	0.100	0.172	0.072	0.087	0.173	0.09	0.102	0.172	0.07
10	0.095	0.182	0.087	0.097	0.179	0.08	0.108	0.181	0.07
11	0.099	0.155	0.056	0.097	0.164	0.07	0.107	0.193	0.09
12	0.095	0.175	0.080	0.108	0.181	0.07	0.100	0.206	0.11
13	0.094	0.181	0.087	0.107	0.175	0.07	0.108	0.215	0.11
14	0.098	0.177	0.079	0.105	0.180	0.08	0.105	0.205	0.10
15	0.096	0.191	0.095	0.111	0.170	0.06	0.107	0.197	0.09
16	0.091	0.189	0.098	0.123	0.185	0.06	0.118	0.201	0.08
17	0.094	0.177	0.083	0.119	0.188	0.07	0.120	0.203	0.08
18	0.097	0.180	0.083	0.126	0.197	0.07	0.120	0.215	0.10
19	0.100	0.171	0.071	0.125	0.208	0.08	0.127	0.204	0.08
20	0.100	0.178	0.078	0.123	0.205	0.08	0.133	0.213	0.08
21	0.106	0.181	0.075	0.123	0.186	0.06	0.147	0.209	0.06
22	0.108	0.203	0.095	0.121	0.188	0.07	0.148	0.201	0.05
23	0.112	0.183	0.071	0.115	0.183	0.07	0.142	0.199	0.06
24	0.114	0.183	0.069	0.114	0.178	0.06	0.153	0.210	0.06
Average	0.102	0.181	0.079	0.110	0.185	0.076	0.125	0.200	0.075

Table C.44: Freeze-Thaw Test, Mixture CW

Oregon State University

Resistance of Concrete to Rapid Freezing and Thawing.

ASTM C 666 - Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.

ASTM C 215- Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant

Lab Identification No: CW ……………………………………………
Concrete Mix Type:
Length of Specimen, 0.280
Breadth of Specimen, 0.0774 0.078976

Date of Casting: 9-Apr-08
Curing Period: 34 days
Radius of Gyration, K: 0.0789
Correction Factor, T: 1.470
C=0.9464 L^3T/bt^3: 877.741748

Serial	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus	
1	13-May-08	3.566	0	0	2788	E_0	24.33	100	
2	14-May-08	3.566	6	6	2748	E_6	23.64	97.15	
3	15-May-08	3.566	5	11	2728	E_{11}	23.29	95.74	
4	16-May-08	3.566	5	16	2725	E_{16}	23.24	95.53	
5	17-May-08	3.566	5	21	2722	E_{21}	23.19	95.32	
6	19-May-08	3.566	11	32	2721	E_{32}	23.17	95.25	
7	22-May-08	3.566	18	50	2712	E_{50}	23.02	94.62	
8	26-May-08	3.566	23	73	2720	E_{73}	23.16	95.18	
9	1-Jun-08	3.566	33	106	2720	E_{106}	23.16	95.18	
10	7-Jun-08	3.566	30	136	2716	E_{136}	23.09	94.90	
11	12-Jun-08	3.566	32	168	2704	E_{168}	22.89	94.06	
12	18-Jun-08	3.566	34	202	2699	E_{202}	22.80	93.72	
13	24-Jun-08	3.566	35	237	2686	E_{237}	22.58	92.82	
14	29-Jun-08	3.566	31	268	2675	E_{268}	22.40	92.06	
15	5-Jul-08	3.566	33	301	2665	E_{301}	22.23	91.37	

Table C.45: Freeze-Thaw Test, Mixture CSA

Lab Identification No: CSA 2……………………………………………
Concrete Mix Type: Control Mix, Steam Curing A
Length of Specimen, in., 11.064 0.280
Breadth of Specimen, in.: 3.062 0.0780 0.079388
Width of specimen, in. : 3.02 0.0770 1.47388

Date of Casting: / 29-Mar-08
Curing Period: days
Radius of Gyration, K: 0.0794
Correction Factor, T: 1.474
C=0.9464 L^3T/bt^3: 859.89

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus	
1	13-May-08	3.7224	0	0	2968	E_0	28.20	100	
2	14-May-08	3.7224	6	6	2937	E_6	27.61	97.92196	
3	15-May-08	3.7224	5	11	2924	E_{11}	27.37	97.05702	
4	16-May-08	3.7224	5	16	2915	E_{16}	27.20	96.46046	
5	17-May-08	3.7224	5	21	2900	E_{21}	26.92	95.47028	
6	19-May-08	3.7224	11	32	2897	E_{32}	26.86	95.27286	
7	22-May-08	3.7224	18	50	2896	E_{50}	26.85	95.2071	
8	26-May-08	3.7224	23	73	2909	E_{73}	27.09	96.06378	
9	1-Jun-08	3.7224	33	106	2905	E_{106}	27.01	95.79977	
10	7-Jun-08	3.7224	30	136	2895	E_{136}	26.83	95.14136	
11	12-Jun-08	3.7224	32	168	2876	E_{168}	26.48	93.89662	
12	18-Jun-08	3.7224	34	202	2875	E_{202}	26.46	93.83134	
13	24-Jun-08	3.7224	35	237	2870	E_{237}	26.37	93.50525	
14	29-Jun-08	3.7224	31	268	2870	E_{268}	26.37	93.50525	
15	5-Jul-08	3.7224	33	301	2870	E_{301}	26.37	93.51	

Table C.46: Freeze-Thaw Test, Mixture CSB

Lab Identification No:	CSB 2…………………………………………			**Date of Casting:** /	29-Mar-08
Concrete Mix Type:	Control Mix, Steam Curing B			**Curing Period:**days	
Length of Specimen, in.,	11.052	0.281		**Radius of Gyration, K:**	0.0781
Breadth of Specimen, in.:	3.075	0.0780	0.078078	**Correction Factor, T:**	1.461
Width of specimen, in. :	3	0.0760	1.460781	**C=0.9464 L^3T/bt^3:**	895.87

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.77	0	0	3003	E_{0}	30.46	100
2	14-May-08	3.77	6	6	2955	E_{6}	29.49	96.82875
3	15-May-08	3.77	5	11	2953	E_{11}	29.45	96.69772
4	16-May-08	3.77	5	16	2946	E_{16}	29.31	96.23982
5	17-May-08	3.77	5	21	2935	E_{21}	29.09	95.52247
6	19-May-08	3.77	11	32	2935	E_{32}	29.09	95.52247
7	22-May-08	3.77	18	50	2932	E_{50}	29.03	95.32729
8	26-May-08	3.77	23	73	2968	E_{73}	29.75	97.68258
9	1-Jun-08	3.77	33	106	2963	E_{106}	29.65	97.35374
10	7-Jun-08	3.77	30	136	2950	E_{136}	29.39	96.50135
11	12-Jun-08	3.77	32	168	2950	E_{168}	29.39	96.50135
12	18-Jun-08	3.77	34	202	2949	E_{202}	29.37	96.43593
13	24-Jun-08	3.77	35	237	2947	E_{237}	29.33	96.30517
14	29-Jun-08	3.77	31	268	2941	E_{268}	29.21	95.91342
15	5-Jul-08	3.77	33	301	2938	E_{301}	29.15	95.72

Table C.47: Freeze-Thaw Test, Mixture EAW

Lab Identification No:	EAW 1…………………………………………			**Date of Casting:** /	24-Mar-08
Concrete Mix Type:	Exp A- Water Curing			**Curing Period:**days	
Length of Specimen, in.,	11.034	0.280		**Radius of Gyration, K:**	0.0789
Breadth of Specimen, in.:	3.034	0.0771	0.07887	**Correction Factor, T:**	1.469
Width of specimen, in. :	3.011	0.0765	1.468725	**C=0.9464 L^3T/bt^3:**	884.00

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.78	0	0	3148	E_{0}	33.11	100
2	14-May-08	3.78	6	6	3114	E_{6}	32.40	97.85156
3	15-May-08	3.78	5	11	3109	E_{11}	32.30	97.53758
4	16-May-08	3.78	5	16	3078	E_{16}	31.66	95.60218
5	17-May-08	3.78	5	21	3074	E_{21}	31.58	95.35386
6	19-May-08	3.78	11	32	3073	E_{32}	31.55	95.29183
7	22-May-08	3.78	18	50	3073	E_{50}	31.55	95.29183
8	26-May-08	3.78	23	73	3103	E_{73}	32.17	97.16148
9	1-Jun-08	3.78	33	106	3094	E_{106}	31.99	96.59868
10	7-Jun-08	3.78	30	136	3090	E_{136}	31.91	96.34907
11	12-Jun-08	3.78	32	168	3084	E_{168}	31.78	95.97526
12	18-Jun-08	3.78	34	202	3082	E_{202}	31.74	95.85082
13	24-Jun-08	3.78	35	237	3078	E_{237}	31.66	95.60218
14	29-Jun-08	3.78	31	268	3063	E_{268}	31.35	94.67265
15	5-Jul-08	3.78	33	301	3061	E_{301}	31.31	94.55

Table C.48: Freeze-Thaw Test, Mixture EASA

Lab Identification No: EASA 1…………………………………………
Concrete Mix Type: Exp A- Steam Curing A
Length of Specimen, in., 11.008 0.2800
Breadth of Specimen, in.: 3.092 0.0785 0.07939
Width of specimen, in. : 3.042 0.0770 1.47388

Date of Casting: / 25-Mar-08
Curing Period:days
Radius of Gyration, K: 0.0794
Correction Factor, T: 1.474
C=0.9464 L^3T/bt^3: 854.42

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.72	0	0	3168	E_0	31.90	100
2	14-May-08	3.72	6	6	3138	E_6	31.30	98.11503
3	15-May-08	3.72	5	11	3120	E_{11}	30.94	96.99265
4	16-May-08	3.72	5	16	3096	E_{16}	30.47	95.5062
5	17-May-08	3.72	5	21	3085	E_{21}	30.25	94.82874
6	19-May-08	3.72	11	32	3084	E_{32}	30.23	94.76728
7	22-May-08	3.72	18	50	3082	E_{50}	30.19	94.6444
8	26-May-08	3.72	23	73	3099	E_{73}	30.52	95.69138
9	1-Jun-08	3.72	33	106	3097	E_{106}	30.49	95.5679
10	7-Jun-08	3.72	30	136	3095	E_{136}	30.45	95.44451
11	12-Jun-08	3.72	32	168	3092	E_{168}	30.39	95.25957
12	18-Jun-08	3.72	34	202	3092	E_{202}	30.39	95.25957
13	24-Jun-08	3.72	35	237	3088	E_{237}	30.31	95.01326
14	29-Jun-08	3.72	31	268	3085	E_{268}	30.25	94.82874
15	5-Jul-08	3.72	33	301	3082	E_{301}	30.19	94.64

Table C.49: Freeze-Thaw Test, Mixture EASB

Lab Identification No: EASB 3…………………………………………
Concrete Mix Type: Exp A- Steam Curing B
Length of Specimen, in., 11.047 0.2810
Breadth of Specimen, in.: 3.068 0.0779 0.07808
Width of specimen, in. : 3.005 0.0760 1.460781

Date of Casting: / 25-Mar-08
Curing Period:days
Radius of Gyration, K: 0.0781
Correction Factor, T: 1.461
C=0.9464 L^3T/bt^3: 897.02

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.65	0	0	3027	E_0	30.00	100
2	14-May-08	3.65	6	6	3003	E_6	29.53	98.42056
3	15-May-08	3.65	5	11	2994	E_{11}	29.35	97.83151
4	16-May-08	3.65	5	16	2987	E_{16}	29.21	97.37458
5	17-May-08	3.65	5	21	2984	E_{21}	29.15	97.17908
6	19-May-08	3.65	11	32	2984	E_{32}	29.15	97.17908
7	22-May-08	3.65	18	50	2982	E_{50}	29.11	97.04886
8	26-May-08	3.65	23	73	3008	E_{73}	29.62	98.74857
9	1-Jun-08	3.65	33	106	2997	E_{106}	29.41	98.02766
10	7-Jun-08	3.65	30	136	2990	E_{136}	29.27	97.57028
11	12-Jun-08	3.65	32	168	2989	E_{168}	29.25	97.50502
12	18-Jun-08	3.65	34	202	2988	E_{202}	29.23	97.43979
13	24-Jun-08	3.65	35	237	2985	E_{237}	29.17	97.24423
14	29-Jun-08	3.65	31	268	2983	E_{268}	29.13	97.11396
15	5-Jul-08	3.65	33	301	2983	E_{301}	29.13	97.11

Table C.50: Freeze-Thaw Test, Mixture EBW

Lab Identification No: EBW 1………………………………………			**Date of Casting:**	/ 2-Apr-08
Concrete Mix Type:	Exp B- Water Curing		**Curing Period:**days	
Length of Specimen, in.,	11.1	0.2820	**Radius of Gyration, K:**	0.0788
Breadth of Specimen, in.:	3.092	0.0785 0.07882	**Correction Factor, T:**	1.468
Width of specimen, in. :	3.022	0.0770 1.46825	**C=0.9464 L^3T/bt^3:**	869.52

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.92	0	0	3273	E_0	36.51	100
2	14-May-08	3.92	6	6	3236	E_6	35.69	97.75186
3	15-May-08	3.92	5	11	3219	E_{11}	35.32	96.7275
4	16-May-08	3.92	5	16	3195	E_{16}	34.79	95.29052
5	17-May-08	3.92	5	21	3190	E_{21}	34.69	94.99251
6	19-May-08	3.92	11	32	3188	E_{32}	34.64	94.87343
7	22-May-08	3.92	18	50	3187	E_{50}	34.62	94.81392
8	26-May-08	3.92	23	73	3205	E_{73}	35.01	95.88796
9	1-Jun-08	3.92	33	106	3200	E_{106}	34.90	95.58901
10	7-Jun-08	3.92	30	136	3195	E_{136}	34.79	95.29052
11	12-Jun-08	3.92	32	168	3193	E_{168}	34.75	95.17126
12	18-Jun-08	3.92	34	202	3186	E_{202}	34.60	94.75443
13	24-Jun-08	3.92	35	237	3178	E_{237}	34.43	94.27918
14	29-Jun-08	3.92	31	268	3163	E_{268}	34.10	93.39129
15	5-Jul-08	3.92	33	301	3161	E_{301}	34.06	93.27

Table C.51: Freeze-Thaw Test, Mixture EBSA

Lab Identification No: EBSA 1…………………………………………			**Date of Casting:**	/ 31-Mar-08
Concrete Mix Type:	Exp B- Steam Curing A		**Curing Period:**days	
Length of Specimen, in.,	11.0275	0.2800	**Radius of Gyration, K:**	0.0794
Breadth of Specimen, in.:	3.083	0.0780 0.07939	**Correction Factor, T:**	1.474
Width of specimen, in. :	3.023	0.0770 1.47388	**C=0.9464 L^3T/bt^3:**	859.89

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.79	0	0	3133	E_0	31.99	100
2	14-May-08	3.79	6	6	3085	E_6	31.02	96.95932
3	15-May-08	3.79	5	11	3075	E_{11}	30.82	96.33175
4	16-May-08	3.79	5	16	3056	E_{16}	30.44	95.14499
5	17-May-08	3.79	5	21	3054	E_{21}	30.40	95.02049
6	19-May-08	3.79	11	32	3052	E_{32}	30.36	94.89608
7	22-May-08	3.79	18	50	3051	E_{50}	30.34	94.8339
8	26-May-08	3.79	23	73	3075	E_{73}	30.82	96.33175
9	1-Jun-08	3.79	33	106	3067	E_{106}	30.66	95.83116
10	7-Jun-08	3.79	30	136	3056	E_{136}	30.44	95.14499
11	12-Jun-08	3.79	32	168	3055	E_{168}	30.42	95.08273
12	18-Jun-08	3.79	34	202	3055	E_{202}	30.42	95.08273
13	24-Jun-08	3.79	35	237	3054	E_{237}	30.40	95.02049
14	29-Jun-08	3.79	31	268	3052	E_{268}	30.36	94.89608
15	5-Jul-08	3.79	33	301	3052	E_{301}	30.36	94.90

Table C.52: Freeze-Thaw Test, Mixture EBSB

Lab Identification No: EBSB 3……………………………………….				**Date of Casting:**	/ 31-Mar-08
Concrete Mix Type:	Exp B- Steam Curing B			**Curing Period:**days	
Length of Specimen, in.,	11.029	0.2800		**Radius of Gyration, K:**	0.0794
Breadth of Specimen, in.:	3.085	0.0784	0.07939	**Correction Factor, T:**	1.474
Width of specimen, in. :	3.014	0.0770	1.47388	**C=0.9464 L^3T/bt^3:**	855.51

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.82	0	0	3126	E_0	31.93	100
2	14-May-08	3.82	6	6	3095	E_6	31.30	98.02647
3	15-May-08	3.82	5	11	3092	E_{11}	31.24	97.83653
4	16-May-08	3.82	5	16	3073	E_{16}	30.86	96.63783
5	17-May-08	3.82	5	21	3065	E_{21}	30.70	96.13533
6	19-May-08	3.82	11	32	3064	E_{32}	30.68	96.07261
7	22-May-08	3.82	18	50	3062	E_{50}	30.64	95.94723
8	26-May-08	3.82	23	73	3095	E_{73}	31.30	98.02647
9	1-Jun-08	3.82	33	106	3094	E_{106}	31.28	97.96313
10	7-Jun-08	3.82	30	136	3094	E_{136}	31.28	97.96313
11	12-Jun-08	3.82	32	168	3095	E_{168}	31.30	98.02647
12	18-Jun-08	3.82	34	202	3090	E_{202}	31.20	97.71
13	24-Jun-08	3.82	35	237	3088	E_{237}	31.16	97.58356
14	29-Jun-08	3.82	31	268	3084	E_{268}	31.08	97.33091

Table C.53: Freeze-Thaw Test, Mixture ECW

Lab Identification No: ECW 3……………………………………….				**Date of Casting:**	/ 26-Mar-08
Concrete Mix Type:	Exp C- Water Curing			**Curing Period:**days	
Length of Specimen, in.,	11.035	0.2800		**Radius of Gyration, K:**	0.0789
Breadth of Specimen, in.:	3.041	0.0770	0.07887	**Correction Factor, T:**	1.469
Width of specimen, in. :	3.013	0.0765	1.468725	**C=0.9464 L^3T/bt^3:**	885.14

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.62	0	0	2978	E_0	28.42	100
2	14-May-08	3.62	6	6	2926	E_6	27.43	97
3	15-May-08	3.62	5	11	2913	E_{11}	27.19	96
4	16-May-08	3.62	5	16	2903	E_{16}	27.00	95
5	17-May-08	3.62	5	21	2900	E_{21}	26.95	95
6	19-May-08	3.62	11	32	2900	E_{32}	26.95	95
7	22-May-08	3.62	18	50	2897	E_{50}	26.89	95
8	26-May-08	3.62	23	73	2915	E_{73}	27.23	96
9	1-Jun-08	3.62	33	106	2890	E_{106}	26.76	94
10	7-Jun-08	3.62	30	136	2867	E_{136}	26.34	93
11	12-Jun-08	3.62	32	168	2862	E_{168}	26.25	92
12	18-Jun-08	3.62	34	202	2854	E_{202}	26.10	92
13	24-Jun-08	3.62	35	237	2850	E_{237}	26.03	92
14	29-Jun-08	3.62	31	268	2835	E_{268}	25.75	91
15	5-Jul-08	3.62	33	301	2828	E_{301}	25.63	90

Table C.54: Freeze-Thaw Test, Mixture ECSA

Lab Identification No: ECSA 1…………………………………………
Concrete Mix Type: Exp C- Steam Curing A
Length of Specimen, in., 11.061 0.2810
Breadth of Specimen, in.: 3.068 0.0780 0.07839
Width of specimen, in. : 3.003 0.0763 1.463863

Date of Casting: / 28-Mar-08
Curing Period:days
Radius of Gyration, K: 0.0784
Correction Factor, T: 1.464
C=0.9464 L^3T/bt^3: 887.21

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.65	0	0	2984	E_0	28.83	100
2	14-May-08	3.65	6	6	2930	E_6	27.80	96
3	15-May-08	3.65	5	11	2923	E_{11}	27.67	96
4	16-May-08	3.65	5	16	2906	E_{16}	27.35	95
5	17-May-08	3.65	5	21	2882	E_{21}	26.90	93
6	19-May-08	3.65	11	32	2881	E_{32}	26.88	93
7	22-May-08	3.65	18	50	2881	E_{50}	26.88	93
8	26-May-08	3.65	23	73	2906	E_{73}	27.35	95
9	1-Jun-08	3.65	33	106	2900	E_{106}	27.23	94
10	7-Jun-08	3.65	30	136	2897	E_{136}	27.18	94
11	12-Jun-08	3.65	32	168	2886	E_{168}	26.97	94
12	18-Jun-08	3.65	34	202	2877	E_{202}	26.80	93
13	24-Jun-08	3.65	35	237	2853	E_{237}	26.36	91
14	29-Jun-08	3.65	31	268	2848	E_{268}	26.27	91
15	5-Jul-08	3.65	33	301	2842	E_{301}	26.16	91

Table C.55: Freeze-Thaw Test, Mixture ECSB

Lab Identification No: ECSB 2………………………………………
Concrete Mix Type: Exp C- Steam Curing B
Length of Specimen, in., 11.045 0.2810
Breadth of Specimen, in.: 3.083 0.0780 0.07859
Width of specimen, in. : 3.013 0.0765 1.465918

Date of Casting: / 28-Mar-08
Curing Period:days
Radius of Gyration, K: 0.0786
Correction Factor, T: 1.466
C=0.9464 L^3T/bt^3: 881.50

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus
1	13-May-08	3.65	0	0	2930	E_0	27.62	100
2	14-May-08	3.65	6	6	2886	E_6	26.80	97.01914
3	15-May-08	3.65	5	11	2862	E_{11}	26.35	95.41222
4	16-May-08	3.65	5	16	2850	E_{16}	26.13	94.6138
5	17-May-08	3.65	5	21	2848	E_{21}	26.10	94.48105
6	19-May-08	3.65	11	32	2848	E_{32}	26.10	94.48105
7	22-May-08	3.65	18	50	2846	E_{50}	26.06	94.3484
8	26-May-08	3.65	23	73	2868	E_{73}	26.47	95.81269
9	1-Jun-08	3.65	33	106	2862	E_{106}	26.35	95.41222
10	7-Jun-08	3.65	30	136	2856	E_{136}	26.24	95.01259
11	12-Jun-08	3.65	32	168	2850	E_{168}	26.13	94.6138
12	18-Jun-08	3.65	34	202	2849	E_{202}	26.12	94.54741
13	24-Jun-08	3.65	35	237	2842	E_{237}	25.99	94.08338
14	29-Jun-08	3.65	31	268	2839	E_{268}	25.93	93.88486
15	5-Jul-08	3.65	33	301	2836	E_{301}	25.88	93.69

Table C.56: Freeze-Thaw Test, Mixture EDW

Lab Identification No: EDW 1..					**Date of Casting:**	/ 2-Apr-08	
Concrete Mix Type:	Exp D- Water Curing				**Curing Period:**days		
Length of Specimen, in.,	11.074	0.2810			**Radius of Gyration, K:**	0.0786	
Breadth of Specimen, in.:	3.11	0.0791	0.07859		**Correction Factor, T:**	1.466	
Width of specimen, in. :	3.01	0.0765	1.465918		**C=0.9464 L^3T/bt^3:**	869.25	

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus	
1	13-May-08	3.88	0	0	3157	E_0	33.61	100	
2	14-May-08	3.88	6	6	3100	E_6	32.41	96.42158	
3	15-May-08	3.88	5	11	3080	E_{11}	31.99	95.18144	
4	16-May-08	3.88	5	16	3074	E_{16}	31.87	94.81096	
5	17-May-08	3.88	5	21	3062	E_{21}	31.62	94.07218	
6	19-May-08	3.88	11	32	3052	E_{32}	31.42	93.45873	
7	22-May-08	3.88	18	50	3050	E_{50}	31.37	93.33629	
8	26-May-08	3.88	23	73	3059	E_{73}	31.56	93.88794	
9	1-Jun-08	3.88	33	106	3053	E_{106}	31.44	93.51999	
10	7-Jun-08	3.88	30	136	3042	E_{136}	31.21	92.8473	
11	12-Jun-08	3.88	32	168	3042	E_{168}	31.21	92.8473	
12	18-Jun-08	3.88	34	202	3041	E_{202}	31.19	92.78626	
13	24-Jun-08	3.88	35	237	3039	E_{237}	31.15	92.66425	
14	29-Jun-08	3.88	31	268	3038	E_{268}	31.13	92.60328	
15	5-Jul-08	3.88	33	301	3037	E_{301}	31.11	92.54	

Table C.57: Freeze-Thaw Test, Mixture EDSA

Lab Identification No: EDSA 2..					**Date of Casting:**	/ 30-Mar-08	
Concrete Mix Type:	Exp D- Steam Curing A				**Curing Period:**days		
Length of Specimen, in.,	11.024	0.2800			**Radius of Gyration, K:**	0.0788	
Breadth of Specimen, in.:	3.06	0.0776	0.07877		**Correction Factor, T:**	1.468	
Width of specimen, in. :	3.009	0.0764	1.467694		**C=0.9464 L^3T/bt^3:**	881.14	

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus	
1	13-May-08	3.73	0	0	2970	E_0	28.99	100	
2	14-May-08	3.73	6	6	2926	E_6	28.14	97	
3	15-May-08	3.73	5	11	2915	E_{11}	27.93	96	
4	16-May-08	3.73	5	16	2897	E_{16}	27.58	95	
5	17-May-08	3.73	5	21	2892	E_{21}	27.49	95	
6	19-May-08	3.73	11	32	2882	E_{32}	27.30	94	
7	22-May-08	3.73	18	50	2882	E_{50}	27.30	94	
8	26-May-08	3.73	23	73	2902	E_{73}	27.68	95	
9	1-Jun-08	3.73	33	106	2896	E_{106}	27.56	95	
10	7-Jun-08	3.73	30	136	2889	E_{136}	27.43	95	
11	12-Jun-08	3.73	32	168	2884	E_{168}	27.34	94	
12	18-Jun-08	3.73	34	202	2876	E_{202}	27.18	94	
13	24-Jun-08	3.73	35	237	2876	E_{237}	27.18	94	
14	29-Jun-08	3.73	31	268	2872	E_{268}	27.11	94	
15	5-Jul-08	3.73	33	301	2872	E_{301}	27.11	94	

Table C.58: Freeze-Thaw Test, Mixture EDSB

Lab Identification No: EDSB 3……………………………………….					**Date of Casting:**	/ 30-Mar-08	
Concrete Mix Type:	Exp D- Steam Curing B				**Curing Period:**days		
Length of Specimen, in.,	11.043	0.2800			**Radius of Gyration, K:**	0.0792	
Breadth of Specimen, in.:	3.087	0.0784	0.07918		**Correction Factor, T:**	1.472	
Width of specimen, in. :	3.025	0.0768	1.471818		**C=0.9464 L^3T/bt^3:**	861.00	

Serial No.	Date	Weight of specimen, Kg	Number of Freeze & Thaw cycle, C	Cumulative number of freeze and thaw cycle	Fundamental Frequency, Hz	Dynamic Modulus, Gpa		Relative Dynamic Modulus	
1	13-May-08	3.72	0	0	2975	E_0	28.35	100	
2	14-May-08	3.72	6	6	2935	E_6	27.59	97.329	
3	15-May-08	3.72	5	11	2924	E_{11}	27.38	96.60082	
4	16-May-08	3.72	5	16	2905	E_{16}	27.03	95.34948	
5	17-May-08	3.72	5	21	2904	E_{21}	27.01	95.28385	
6	19-May-08	3.72	11	32	2901	E_{32}	26.96	95.08708	
7	22-May-08	3.72	18	50	2900	E_{50}	26.94	95.02154	
8	26-May-08	3.72	23	73	2924	E_{73}	27.38	96.60082	
9	1-Jun-08	3.72	33	106	2919	E_{106}	27.29	96.27073	
10	7-Jun-08	3.72	30	136	2918	E_{136}	27.27	96.20478	
11	12-Jun-08	3.72	32	168	2917	E_{168}	27.25	96.13885	
12	18-Jun-08	3.72	34	202	2915	E_{202}	27.22	96.00706	
13	24-Jun-08	3.72	35	237	2913	E_{237}	27.18	95.87536	
14	29-Jun-08	3.72	31	268	2898	E_{268}	26.90	94.89052	
15	5-Jul-08	3.72	33	301	2895	E_{301}	26.84	94.69	

APPENDIX D
TEST RESULTS FOR PILOT STUDY

Table D.1: Compressive Strength, Run 1

Lab Identification No: ...... Mix 1_ Water Curing for 28 Day

Date of Casting:............23 Nov 2008...........................

Concrete Grade: ......Pilot Study_Mix 1

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
A			4.014	12.648	60800	4807.0561					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
B	1	24-Nov-08	4.018	12.673	60000	4734.3649	4871.694	178.645	3.666999	206.2814	Shear	
C			4.018	12.673	64300	5073.6611					Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
D			4.005	12.591	97500	7743.3683					Shear	Aggregate Failure
E	3	26-Nov-08	4.015	12.654	105500	8337.0365	8065.788	300.124	3.72095	346.5533	Shear	
F			4.001	12.566	102000	8116.9601						Columnar Failure
O			4.017	12.667	123000	9710.2809						Columnar Failure
G	7	30-Nov-08	4.023	12.705	123000	9681.3382	9801.039	182.8358	1.865474	211.1206	Shear	
N			4.012	12.635	126500	10011.497					Shear	
M			4.021	12.692	126500	9966.7307					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
J	14	7-Dec-08	4.028	12.736	138500	10874.297	10450.52	456.7502	4.370597	527.4098	Shear	
I			4.03	12.749	134000	10510.54					Crushed	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
K			4.0138	12.647	143320	11332.499					Shear	
L	28	21-Dec-08	4.0143	12.650	144610	11431.653	11258.84	219.1401	1.946384	253.0412	Crushed	Sample was cured for 27 effective days and 1 day cured outside water
Extra			4.0263	12.726	140140	11012.355					Shear	

Table D.2: Compressive Strength, Run 2

Lab Identification No: ...... Mix 2_ 14 days water curing + a

Date of Casting:............23 Nov 2008...........................

Concrete Grade: ......Pilot Study_Mix 2

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
A			4.0158	12.659	148630	11740.664					Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
B	28	21-Dec-08	4.0176	12.671	157150	12402.684	11689.54	740.0264	6.33067	854.5089	crushed failure	Crushing of aggregate and brusting of sample
C			4.0138	12.647	138170	10925.282					Shear	

Table D.3: Compressive Strength, Run 3

Lab Identification No: …… Mix 3_ 7 day water curing + Am

Date of Casting:…………23 Nov 2008……………………….

Concrete Grade: ……Pilot Study_Mix 3

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
F	14	7-Dec-08	4.01	12.623	121500	9625.3798	10456.86	858.4497	8.209443	991.2524	Crushed	
E			4.015	12.654	143500	11339.95					Shear	
D			4.02	12.686	132000	10405.242					Shear	
A	28	21-Dec-08	4	12.560	132610	10558.121	11187.5	580.6708	5.190353	670.5008	Crushed	
B			4.005	12.591	147350	11702.414					Crushed	Breaking of aggregate
C			4.007	12.604	142450	11301.969					Crushed	

Table D.4: Compressive Strength, Run 4

Lab Identification No: …… Mix 4_ 14 days Water Curing + curing compound + ambient curing upto 28 Days

Date of Casting:…………23 Nov 2008……………………….

Concrete Grade: ……Pilot Study_Mix 4

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
C	28	21-Dec-08	4.0113	12.631	145790	11542.179	11521.43	47.90087	0.415755	55.31116	Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
A			4.009	12.617	144670	11466.654					Crushed	Brusting of aggregate
B			4.016	12.661	146300	11555.461					Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock

Table D.5: Compressive Strength, Run 5

Concrete Grade: ……Pilot Study_Mix 5

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ ft.^{3})	Density in water , (lb/ ft.^{3})	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture
C			4.016	8.034	12.661	3.791	2.132	141.9852	79.8503	117250	9260.9553					Crushed
F	14	25-Dec-08	4.01	8.01	12.623	3.765	2.114	141.8574	79.6512	111370	8822.8687	9165.986	306.86	3.347813	354.3314	Shear
B			4.015	8.0135	12.654	3.767	2.114	141.5177	79.4182	119130	9414.1342					Shear
A			4.014	8.025	12.648	3.792	2.131	142.3236	79.9820	130180	10292.476					Shear
D	28	8-Jan-09	4.015	8.066	12.654	3.818	2.155	142.5001	80.4315	122400	9672.5428	10125.6	396.8629	3.919403	458.2578	Crushed
E			4.023	8.015	12.705	3.752	2.099	140.3679	78.5267	132280	10411.768					Shear

Table D.6: Compressive Strength, Run 6

Lab Identification No: …… Mix 6_ 1Day water curing + Curing Compound + ambient Curing **Date of Casting:…………11 Dec 2008………………………**

Concrete Grade: ……Pilot Study_Mix 6

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
I			4.01	12.623	89500	7090					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
K	3	14-Dec-08	4.01	12.623	81000	6417	6754	476.1519	7.050332	673.3805	Shear	
L			4.015	12.654	2000	158					Shear	Breaking of Machine, wrong results
A			4.01	12.623	90750	7189					Shear	Aggregate Failure
C	7	18-Dec-08	4.16	13.585	104730	7709	7663	451.7875	5.895982	521.6793	Shear	
B			4.01	12.623	102110	8089						Columnar Failure
E			4.01	12.623	119870	9496.2492						Columnar Failure
F	14	25-Dec-08	4.014	12.648	118720	9386.4094	9343.231	178.5674	1.911195	206.1919	Shear	
D			4.015	12.654	115750	9147.033					Shear	
J			4.014	12.648	109790	8680					Crushed	
G	28	8-Jan-09	4.006	12.598	114850	9117	9109	425.0142	4.665801	601.0609	Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
H			4.015	12.654	120600	9530					Columnar	

Table D.7: Compressive Strength, Run 7

Lab Identification No: ...... Mix 7_ 3 Day water curing + Curing Compound + ambient Curing

Date of Casting:............11 Dec 2008...........................

Concrete Grade: ......Pilot Study_Mix 7

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ ft.^{3})	Density in water , (lb/ ft.^{3})	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
A			4.007	8.023	12.604	3.798	2.144	143.0830	80.7714	112540	8929					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
B	7	18-Dec-08	4.008	8.06	12.610	3.803	2.138	142.5425	80.1356	112390	8913	**8921**	**11.56122**	**0.129599**	**16.35004**	Shear	
C			4.011	8.05	12.629	3.796	2.136	142.2438	80.0403	108120	8561					Shear	Breaking of Machine, wrong results
F			4.01	8.02	12.623	3.773	2.12	141.9816	79.7776	120920	9579					Shear	Aggregate Failure
E	14	25-Dec-08	4.0165	8.0375	12.664	3.768	2.102	141.0272	78.6728	114750	9061	**9346**	**262.866**	**2.812622**	**303.5315**	Shear	
D			4.009	8.065	12.617	3.717	2.056	139.1632	76.9759	118560	9397						Columnar Failure
I			4.011	8.0425	12.629	3.809	2.142	142.8641	80.3399	126190	9992					Crushed	Breaking of aggregate
J	28	8-Jan-09	4.017	8.0375	12.667	3.776	2.114	141.2914	79.1022	129390	10215	**9943**	**299.0797**	**3.007914**	**345.3475**	Crushed	Breaking of aggregate
H			4.018	8.026	12.673	3.745	2.088	140.2624	78.2024	121950	9623					Crushed	Breaking of aggregate

Table D.8: Compressive Strength, Run 8

Lab Identification No: ...... Mix 8_ 3 Day water curing + am

Date of Casting:............17 Dec 2008...........................

Concrete Grade: ......Pilot Study_Mix8

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
A			4.0123	12.637	130160	10300					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
D	7	24-Dec-08	4.0135	12.645	122380	9678	**9989**	**439.4137**	**4.399017**	**621.4248**	Shear	
F			4.01	12.623	127850	10128					Shear	
H			4.009	12.617	126870	10056					Shear	Aggregate Failure
B	14	31-Dec-08	4.025	12.717	129930	10217	**10221**	**167.0644**	**1.634558**	**192.9094**	Shear	
C			4.01	12.623	131150	10390					Crushed	
G			4.0063	12.600	139990	11111					Shear	Breaking of aggregate
I	28	14-Jan-09	4.01	12.623	146670	11619	**11004**	**674.2905**	**6.127416**	**778.6036**	Crushed	Breaking of aggregate
E			4.015	12.654	130130	10283					Shear	Breaking of aggregate

Table D.9: Compressive Strength, Run 9

Lab Identification No: ......Mix9_ 1 Day Water Curing + ambient Curing

Date of Casting:...........12 Dec 2008..........................

Concrete Grade: ......Pilot Study_Mix 9

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , ($lb/ft.^3$)	Density in water , ($lb/ft.^3$)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
K			4.01	8.025	12.623	3.542	1.885	133.2058	70.8902	1000	79.221233					Crushed	Problem in Machine, Wrong Results, Pointer not moving up
J	3	15-Dec-08	4.015	8.03	12.654	3.563	1.915	133.5788	71.7944	47290	3737.047	4423.196	970.3609	21.938	1372.298	Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
L			4.017	8.027	12.667	3.582	1.924	134.2076	72.0869	64720	5109.3445					Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
D			4.005	8.035	12.591	3.522	1.9	132.6193	71.5437	69250	5499.777					Shear	Aggregate Failure
E	7	19-Dec-08	4.009	8.024	12.617	3.544	1.886	133.3641	70.9720	71760	5687.7521	5590.846	94.12344	1.683528	108.6844	Shear	
A			4.016	8.03	12.661	3.57	1.914	133.7746	71.7212	70710	5585.0076					Shear	
G			4.015	8.03	12.654	3.498	1.844	131.1419	69.1326	81090	6408.0596					Shear	Pulling out of aggregate, Mortar Failure, breaking of weathered rock
H	14	26-Dec-08	4.014	8.054	12.648	3.578	1.922	133.8081	71.8779	77470	6125.0433	6411.388	288.0235	4.492373	332.5808	Shear	
F			4.016	8.0275	12.661	3.572	1.915	133.8912	71.7810	84840	6701.0614					Crushed	
B			4.012	8.021	12.635	3.351	1.883	125.9599	70.7796	80150	6343					Shear	Presence of unhydrated cement in form of white patch
C	28	9-Jan-09	4.016	8.04	12.661	3.563	1.908	133.3462	71.4074	76530	6045	6172	153.9657	2.4945	217.7404	Shear	Presence of unhydrated cement in form of white patch
I			4.011	8.035	12.629	3.546	1.895	133.1239	71.1421	77400	6129					Shear	Presence of unhydrated cement in form of white patch

Table D.10: Compressive Strength, Run 10

Lab Identification No: ......

Mix 10_ Steam Curing + ambient Curing

Date of Casting:...........12 Dec 2008..........................

Concrete Grade: ......Pilot Study_Mix 10

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
N			4.16	13.585	70000	5153					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
M	1	13-Dec-08	4.02	12.686	68500	5400	5387.726	229.1971	4.25406	264.654	Shear	
O			4.015	12.654	71000	5611					Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
J			4.017	12.667	83460	6589					Shear	Aggregate Failure
K	3	15-Dec-08	4.018	12.673	84920	6701	6574	134.6822	2.048706	155.5176	Shear	
L			4.015	12.654	81400	6433						Columnar Failure
O			4.015	12.654	88600	7001.5302					Columnar Failure	Crushing of aggregate
G	7	30-Nov-08	4.02	12.686	92300	7275.7864	7210.643	185.3368	2.570323	214.0085	Shear	
N			4.02	12.686	93300	7354.6139					Shear	
D			4.0125	12.639	94260	7458					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
H	14	26-Dec-08	4.015	12.654	90690	7167	7159.691	301.9606	4.217509	348.6741	Shear	
I			4.016	12.661	86780	6854					Shear	Presence of unhydrated cement in form of white patch
G			4.007	12.604	88140	6993					Shear	Aggregate Failure
F	28	9-Jan-09	4.017	12.667	87870	6937	6858	187.8803	2.739691	216.9454	Shear	
E			4.012	12.635	83940	6643						Columnar Failure

Table D.11: Compressive Strength, Run 11

Lab Identification No: …… Mix 11_ Steam Curing + Curing compound + ambient Curing **Date of Casting:…………17 Dec 2008………………………**

Concrete Grade: ……Pilot Study_Mix 11

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
M			4.019	12.680	118250	9326					Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
N	1	18-Dec-08	4.015	12.654	113710	8986	8867.442	527.8024	5.952138	609.4537	Shear	
O			4.01	12.623	104650	8291					Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
I			4.0113	12.631	127660	10107					Shear	Aggregate Failure
H	3	20-Dec-08	4.007	12.604	117030	9285	9808	454.611	4.634934	524.9396	Shear	
G			4.0148	12.653	126950	10033						Columnar Failure
K			4.01	12.623	133220	10553.853					Columnar Failure	Crushing of aggregate
C	7	24-Nov-08	4.001	12.566	131060	10429.498	10479.27	65.78475	0.627761	75.96169	Shear	Broken edge
D			4.0125	12.639	132130	10454.462					Shear	
A			4.01	12.623	129900	10291					Columnar	Pulling out of aggregate, Mortar
B	14	31-Dec-08	4.009	12.617	136360	10808	10549.07	258.5802	2.451214	298.5827	Shear	
J			4.013	12.642	133350	10548					Shear	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
L			4.0112	12.630	136870	10837					Shear	Aggregate Failure
E	28	14-Jan-09	4.0095	12.620	133170	10553	10934	439.153	4.016234	507.0902	Shear	
F			4.0026	12.576	143550	11414						Columnar Failure

APPENDIX E
TEST RESULTS FOR PHASE II

Table E.1: Chloride Ion Penetration Test, Control Mix

Mix Id	Control		Mix Type				Curing Period			56 days		
Resistance	Cell 1	0.98	ohm	Cell 2	0.98	ohm	Cell 3	1	ohm	Cell 4	0.99	ohm
Time	Cell 1			Cell 2			Cell 3			Cell 4		
	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
12.34 pm	60	0.0300	0.031	60	0.0372	0.038	60	0.0188	0.01877	60	0.01892	0.019
1.04 pm	60	0.0310	0.032	60	0.0391	0.040	60	0.01906	0.01906	60	0.01866	0.019
1.34 pm	60	0.0321	0.033	60	0.0395	0.040	60	0.0193	0.0193	60	0.01903	0.019
2.04 pm	60	0.0331	0.034	60	0.0404	0.041	60	0.01956	0.01956	60	0.0187	0.019
2.34 pm	60	0.0341	0.035	60	0.0422	0.043	60	0.01992	0.01992	60	0.01905	0.019
3.04 pm	60	0.0352	0.036	60	0.0435	0.044	60	0.0202	0.02024	60	0.01958	0.020
3.34 pm	60	0.0361	0.037	60	0.0437	0.045	60	0.02029	0.02029	60	0.02005	0.020
4.04 pm	60	0.0368	0.038	60	0.0444	0.045	60	0.0212	0.02116	60	0.02046	0.021
4.34 pm	60	0.0362	0.037	60	0.0463	0.047	60	0.02133	0.02133	60	0.02192	0.022
5.04 pm	60	0.0377	0.038	60	0.0473	0.048	60	0.0220	0.0220	60	0.02242	0.023
5.34 pm	60	0.0386	0.039	60	0.0461	0.047	60	0.02204	0.02204	60	0.02288	0.023
6.04 pm	60	0.0392	0.040	60	0.0470	0.048	60	0.02215	0.02215	60	0.02325	0.023
6.34 pm	60	0.0393	0.040	60	0.0475	0.048	60	0.0224	0.0224	60	0.02354	0.024
otal Charge Passe	Q1=	780.1531	Coulombs	Q2 =	958.3806	Coulombs	Q2 =	445.725	Coulombs	Q2 =	449.4727	Coulombs
Average Charge Passed, Coulombs								658.43				

Table E.2: Chloride Ion Penetration Test, Mix A

Mix Id	A			Mix Type				Curing Period			56 days		
Resistance		Cell 1	0.98	ohm	Cell 2	0.97	ohm	Cell 3	0.98	ohm	Cell 4	0.97	ohm
Time	Temperature	Cell 1			Cell 2			Cell 3			Cell 4		
		Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
3.20 pm		60	0.0141	0.014	60	0.0131	0.014	60	0.0125	0.0128	60	0.0128	0.013
3.50 pm		60	0.0144	0.015	60	0.0138	0.014	60	0.0129	0.0132	60	0.0131	0.014
4.20 pm		60	0.0147	0.015	60	0.0142	0.015	60	0.0131	0.0134	60	0.0135	0.014
4.50 pm		60	0.0145	0.015	60	0.0143	0.015	60	0.013	0.0133	60	0.0137	0.014
5.20 pm		60	0.0144	0.015	60	0.0142	0.015	60	0.0128	0.0131	60	0.0138	0.014
5.50 pm		60	0.0145	0.015	60	0.0144	0.015	60	0.0134	0.0137	60	0.014	0.014
6.20 pm		60	0.0149	0.015	60	0.0146	0.015	60	0.0136	0.0139	60	0.0141	0.015
6.50 pm		60	0.0155	0.016	60	0.0151	0.016	60	0.0138	0.0141	60	0.0145	0.015
7.20 pm		60	0.0155	0.016	60	0.0150	0.015	60	0.0144	0.0147	60	0.0145	0.015
7.50 pm		60	0.0159	0.016	60	0.0155	0.016	60	0.0141	0.0144	60	0.0147	0.015
8.20 pm		60	0.0162	0.017	60	0.0153	0.016	60	0.0144	0.0147	60	0.0151	0.016
8.50 pm		60	0.0161	0.016	60	0.0153	0.016	60	0.0146	0.0149	60	0.015	0.015
9.20 pm		60	0.0164	0.017	60	0.0159	0.016	60	0.0144	0.0147	60	0.0152	0.016
Total Charge Passed		Q1=	334.0837	Coulombs	Q2 =	326.9691	Coulombs	Q2 =	300.398	Coulombs	Q2 =	315.4639	Coulombs
Average Charge Passed, Coulombs									319.23				

Table E.3: Chloride Ion Penetration Test, Mix B

Mix Id- B	Curing Period		56 days			
Resistance	Cell 3	0.97	ohm	Cell 4	0.99	ohm
	Cell 3			Cell 4		
Time	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
2.37 pm	60	0.0107	0.011031	60	0.0105	0.01061
3.07 pm	60	0.0112	0.011546	60	0.0111	0.01121
3.37 pm	60	0.0111	0.011443	60	0.0112	0.01131
4.07 pm	60	0.0112	0.011546	60	0.0112	0.01131
4.37 pm	60	0.0111	0.011443	60	0.0111	0.01121
5.07 pm	60	0.0113	0.011649	60	0.0114	0.01152
5.37 pm	60	0.0116	0.011959	60	0.0116	0.01172
6.07 pm	60	0.0116	0.011959	60	0.0117	0.01182
6.37 pm	60	0.0121	0.012474	60	0.012	0.01212
7.07 pm	60	0.0121	0.012474	60	0.0121	0.01222
7.37 pm	60	0.0125	0.012887	60	0.0123	0.01242
8.07 pm	60	0.0125	0.012887	60	0.0126	0.01273
8.37 pm	60	0.0129	0.013299	60	0.0126	0.01273
Charge Pa	Q2 =	259.9794	Coulombs	Q2 =	254.2727	Coulombs

Table E.4: Chloride Ion Penetration Test, Mix C

Mix Id			Mix Type			Curing Period		56 days				
Resistance	Cell 1	0.96	ohm	Cell 2	0.96	ohm	Cell 3	0.96	ohm	Cell 4	0.97	ohm
	Cell 1			Cell 2			Cell 3			Cell 4		
Time	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
12.40 pm	60	0.0212	0.022	60	0.0268	0.028	60	0.0185	0.019271	60	0.02121	0.022
1.10 pm	60	0.0215	0.022	60	0.0290	0.030	60	0.0193	0.020104	60	0.02148	0.022
1.40 pm	60	0.0216	0.022	60	0.0305	0.032	60	0.01942	0.020229	60	0.02121	0.022
2.10 pm	60	0.0220	0.023	60	0.0320	0.033	60	0.01955	0.020365	60	0.0215	0.022
2.40 pm	60	0.0218	0.023	60	0.0319	0.033	60	0.01984	0.020667	60	0.02203	0.023
3.10 pm	60	0.0224	0.023	60	0.0311	0.032	60	0.0200	0.020823	60	0.02287	0.024
3.40 pm	60	0.0233	0.024	60	0.0323	0.034	60	0.02054	0.021396	60	0.02279	0.023
4.10 pm	60	0.0231	0.024	60	0.0323	0.034	60	0.0208	0.021635	60	0.02266	0.023
4.40 pm	60	0.0240	0.025	60	0.0330	0.034	60	0.02133	0.022219	60	0.02304	0.024
5.10 pm	60	0.0241	0.025	60	0.0340	0.035	60	0.0212	0.022073	60	0.0232	0.024
5.40 pm	60	0.0248	0.026	60	0.0344	0.036	60	0.02154	0.022438	60	0.02364	0.024
6.10 pm	60	0.0257	0.027	60	0.0343	0.036	60	0.02182	0.022729	60	0.02375	0.024
6.40 pm	60	0.0256	0.027	60	0.0360	0.038	60	0.02182	0.022729	60	0.02393	0.025
tal Charge Pass	Q1=	520.6125	Coulombs	Q2 =	723.9188	Coulombs	Q2 =	460.2188	Coulombs	Q2 =	502.3299	Coulombs
Average Charge Passed, Coulombs								551.77				

Table E.5: Chloride Ion Penetration Test, Mix D

Mix Id	D		Mix Type			Curing Period		56 days				
Resistance	Cell 1	0.96	ohm	Cell 2	0.94	ohm	Cell 3	0.95	ohm	Cell 4	1.01	ohm
	Cell 1			Cell 2			Cell 3			Cell 4		
Time	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
1.40 pm	60	0.0118	0.012	60	0.0103	0.011	60	0.0119	0.012547	60	0.01107	0.011
2.10 pm	60	0.0119	0.012	60	0.0105	0.011	60	0.01227	0.012916	60	0.0113	0.011
2.40 pm	60	0.0121	0.013	60	0.0106	0.011	60	0.01231	0.012958	60	0.01143	0.011
3.10 pm	60	0.0120	0.012	60	0.0107	0.011	60	0.0123	0.012947	60	0.0115	0.011
3.40 pm	60	0.0119	0.012	60	0.0106	0.011	60	0.01224	0.012884	60	0.01173	0.012
4.10 pm	60	0.0119	0.012	60	0.0105	0.011	60	0.0126	0.013232	60	0.01185	0.012
4.40 pm	60	0.0124	0.013	60	0.0104	0.011	60	0.01272	0.013389	60	0.012	0.012
5.10 pm	60	0.0124	0.013	60	0.0105	0.011	60	0.0129	0.013568	60	0.01234	0.012
5.40 pm	60	0.0129	0.013	60	0.0105	0.011	60	0.01308	0.013768	60	0.01248	0.012
6.10 pm	60	0.0127	0.013	60	0.0106	0.011	60	0.0133	0.013968	60	0.0126	0.012
6.40 pm	60	0.0127	0.013	60	0.0107	0.011	60	0.01347	0.014179	60	0.01304	0.013
7.10 pm	60	0.0131	0.014	60	0.0109	0.012	60	0.01376	0.014484	60	0.013	0.013
7.40 pm	60	0.0132	0.014	60	0.0109	0.012	60	0.0139	0.014632	60	0.01282	0.013
Total Charge Passed	Q1=	278.0719	Coulombs	Q2 =	243.45	Coulombs	Q2 =	291.3916	Coulombs	Q2 =	258.7099	Coulombs
Average Charge Passed, Coulombs								267.9				

Table E.6: Chloride Ion Penetration Test, Mix E

Mix Id	E		Mix Type			Curing Period		56 days				
Resistance	Cell 1	0.98	ohm	Cell 2	0.97	ohm	Cell 3	0.98	ohm	Cell 4	0.97	ohm
	Cell 1			Cell 2			Cell 3			Cell 4		
Time	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
1.05 pm	60	0.0144	0.015	60	0.0119	0.012	60	0.0137	0.013959	60	0.01068	0.011
1.35 pm	60	0.0151	0.015	60	0.0124	0.013	60	0.01428	0.014571	60	0.011096	0.011
2.05 pm	60	0.0154	0.016	60	0.0128	0.013	60	0.01457	0.014867	60	0.01122	0.012
2.35 pm	60	0.0152	0.016	60	0.0130	0.013	60	0.01459	0.014888	60	0.0113	0.012
3.05 pm	60	0.0155	0.016	60	0.0133	0.014	60	0.01458	0.014878	60	0.0114	0.012
3.35 pm	60	0.0157	0.016	60	0.0134	0.014	60	0.0148	0.015061	60	0.01137	0.012
4.05 pm	60	0.0162	0.017	60	0.0136	0.014	60	0.01505	0.015357	60	0.01169	0.012
4.35 pm	60	0.0160	0.016	60	0.0138	0.014	60	0.0154	0.015673	60	0.01178	0.012
5.05 pm	60	0.0164	0.017	60	0.0139	0.014	60	0.01567	0.01599	60	0.01168	0.012
5.35 pm	60	0.0168	0.017	60	0.0142	0.015	60	0.0158	0.016071	60	0.01156	0.012
6.05 pm	60	0.0173	0.018	60	0.0142	0.015	60	0.01595	0.016276	60	0.01166	0.012
6.35 pm	60	0.0170	0.017	60	0.0143	0.015	60	0.01623	0.016561	60	0.01161	0.012
7.05 pm	60	0.0171	0.017	60	0.0143	0.015	60	0.01623	0.016561	60	0.01175	0.012
Charge Pa	Q1=	353.5255	Coulombs	Q2 =	300.5072	Coulombs	Q2 =	333.8173	Coulombs	Q2 =	255.3421	Coulombs
Average Charge Passed, Coulombs								310.80				

Table E.7: Chloride Ion Penetration Test, Mix S

Mix Id	S		Mix Type			Curing Period	56					
Resistance	Cell 1	0.99	ohm	Cell 2	1.1	ohm	Cell 3	0.98	ohm	Cell 4	0.98	ohm
Time	Cell 1			Cell 2			Cell 3			Cell 4		
	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
12.51 pm	60	0.0120	0.012	60	0.0127	0.012	60	0.0095	0.0097	60	0.01028	0.010
1.21 pm	60	0.0121	0.012	60	0.0128	0.012	60	0.00936	0.0096	60	0.0101	0.010
1.51 pm	60	0.0120	0.012	60	0.0128	0.012	60	0.00929	0.0095	60	0.00994	0.010
2.21 pm	60	0.0122	0.012	60	0.0126	0.011	60	0.00915	0.0093	60	0.0097	0.010
2.51 pm	60	0.0122	0.012	60	0.0125	0.011	60	0.00907	0.0093	60	0.00937	0.010
3.21 pm	60	0.0119	0.012	60	0.0123	0.011	60	0.0090	0.0092	60	0.00953	0.010
3.51 pm	60	0.0120	0.012	60	0.0122	0.011	60	0.00895	0.0091	60	0.00942	0.010
4.21 pm	60	0.0119	0.012	60	0.0119	0.011	60	0.0088	0.0090	60	0.00932	0.010
4.51 pm	60	0.0119	0.012	60	0.0116	0.011	60	0.00882	0.0090	60	0.00941	0.010
5.21 pm	60	0.0118	0.012	60	0.0118	0.011	60	0.0088	0.0090	60	0.0094	0.010
5.51 pm	60	0.0116	0.012	60	0.0116	0.011	60	0.00866	0.0088	60	0.00914	0.009
6.21 pm	60	0.0116	0.012	60	0.0116	0.011	60	0.00875	0.0089	60	0.00914	0.009
6.51 pm	60	0.0117	0.012	60	0.0113	0.010	60	0.00867	0.0088	60	0.00934	0.010
Total Charge Passed	Q1=	260.0364	Coulombs	Q2 =	238.23	Coulombs	Q2 =	197.9816	Coulombs	Q2 =	209.8837	Coulombs
Average Charge Passed, Coulombs								226.53				

Table E.8: Chloride Ion Penetration Test, Mix T

Mix Id	T		Mix Type			Curing Period	56					
Resistance	Cell 1	0.99	ohm	Cell 2	1.1	ohm	Cell 3	1	ohm	Cell 4	1	ohm
Time	Cell 1			Cell 2			Cell 3			Cell 4		
	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp	Voltage across binding, V	Voltage across shunt, V	Current through Shunt, amp
12.51 pm	60	0.0124	0.012	60	0.0151	0.014	60	0.0135	0.0135	60	0.01294	0.013
1.21 pm	60	0.0125	0.013	60	0.0157	0.014	60	0.01387	0.0139	60	0.01322	0.013
1.51 pm	60	0.0122	0.012	60	0.0160	0.015	60	0.01394	0.0139	60	0.01291	0.013
2.21 pm	60	0.0121	0.012	60	0.0159	0.014	60	0.01382	0.0138	60	0.0130	0.013
2.51 pm	60	0.0120	0.012	60	0.0158	0.014	60	0.01377	0.0138	60	0.01324	0.013
3.21 pm	60	0.0119	0.012	60	0.0155	0.014	60	0.0135	0.0135	60	0.01378	0.014
3.51 pm	60	0.0118	0.012	60	0.0156	0.014	60	0.01337	0.0134	60	0.01355	0.014
4.21 pm	60	0.0117	0.012	60	0.0156	0.014	60	0.0136	0.0136	60	0.01361	0.014
4.51 pm	60	0.0116	0.012	60	0.0155	0.014	60	0.01377	0.0138	60	0.01403	0.014
5.21 pm	60	0.0115	0.012	60	0.0155	0.014	60	0.0136	0.0136	60	0.01417	0.014
5.51 pm	60	0.0116	0.012	60	0.0157	0.014	60	0.01336	0.0134	60	0.0143	0.014
6.21 pm	60	0.0115	0.012	60	0.0158	0.014	60	0.01368	0.0137	60	0.01431	0.014
6.51 pm	60	0.0116	0.012	60	0.0156	0.014	60	0.01343	0.0134	60	0.01439	0.014
tal Charge Pass	Q1=	258.5091	Coulombs	Q2 =	307.3745	Coulombs	Q2 =	294.714	Coulombs	Q2 =	294.885	Coulombs
Average Charge Passed, Coulombs								288.87				

Table E.9: Compressive Strength, Control Mixture

Lab Identification No: ……………

Mix Con Control (Fly ash 30% + MC 4%)

Date of Casting:…………05/7/09………………………

Concrete Grade: ……Phase II_Mix Con

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
3	2	9-May-09	4.01	12.623	82950	6571	**6609**	**44.94152**	**0.679994**	**51.894**	Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
8			4	12.560	83635	6659					Shear	
11			4.02	12.686	83690	6597						
1	28	5-Jun-09	4.01	12.623	100080	7928.461	**7859.57**	**438.8704**	**5.583898**	**506.7639**	Shear	Aggregate Failure
2			4.015	12.654	93520	7390.3285					Shear	
4			4.008	12.610	104160	8259.9209						Columnar Failure
5	56	3-Jul-09	4.012	12.635	96790	7660.1802	**7515.92**	**175.8777**	**2.340069**	**203.0861**	columnar	Columnar Failure
9			4.015	12.654	92630	7319.9971					Shear	
10			4.012	12.635	95620	7567.5837					Shear	

Table E.10: Compressive Strength, Mix A

Lab Identification No: ……Mix A (Slag 27% Silica Fume 7'

Date of Casting:…………04/18/09………………………

Concrete Grade: ……Phase II_Mix A

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
1	1	19-Apr-09	4.01	12.623	91110	7218	**7684**	**419.719**	**5.462351**	**484.6498**	Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
2			4.008	12.610	98380	7802					Shear	
3			4.012	12.635	101490	8032						
4	28	16-May-09	4.01	12.623	123500	9784	**9540.226**	**320.7989**	**3.362592**	**370.4266**	Shear	Aggregate Failure
5			4.012	12.635	122060	9660						Columnar Failure
6			4	12.560	115260	9177					Shear	
7	56	13-Jun-09	4.015	12.654	118430	9358.8174	**9259.108**	**426.1786**	**4.602804**	**492.1086**		Columnar Failure
8			4	12.560	120910	9626.5924					Shear	
9			4.012	12.635	111090	8791.9146					Shear	

Table E.11: Compressive Strength, Mix B

Lab Identification No: …………… Mix B (Slag 24% Silica Fume 10%)

Date of Casting:………..04/17/09………………………

Concrete Grade: ……Phase II_Mix B

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Weight in air, (kg)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture	Remarks
1	1	18-Apr-09	4.015	12.654	3663	94640	7479	7695	200.2913	2.603007	231.2764	Columnar	Pulling out of aggregate, Mortar Faliure, breaking of weathered rock
4			4.01	12.623	3747	99400	7875					Shear	
6			4.01	12.623	3708	97580	7730						
7	28	15-May-09	4.075	13.035	3.652	119609	9176	9702.889	514.9274	5.30695	594.587	Shear	
8			4.012	12.635	3.64	128940	10205					Shear	Aggregate Failure
9			4.01	12.623	3.645	122800	9728						Aggregate Failure
O	56	12-Jun-09	4.005	12.591	3.68	122550	9732.8184	9895.43	279.1065	2.820559	322.2844		
G			4.015	12.654	3.697	123200	9735.7621					Shear	
N			4.022	12.699	3.72	129750	10217.71					Shear	

Table E.12: Compressive Strength, Mix C

Lab Identification No: …………… Mix C (Fly ash 27% + MC 7%)

Date of Casting:………..04/25/09………………………

Concrete Grade: ……Phase II_Mix C

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture
1	2	26-Apr-09	4.02	12.686	66830	5268	5226	66.23087	1.267406	76.47682	Columnar
8			4.01	12.623	65000	5149					Shear
5			4.025	12.717	66890	5260					
D	28	23-May-09	4.02	12.686	69670	5492	5755.302	265.6762	4.616198	306.7764	Shear
7			4.013	12.642	72700	5751					Shear
2			4.015	12.654	76220	6023					
12	56	20-Jun-09	4.013	12.642	70350	5565	5753.718	179.9485	3.127516	207.7866	
10			4.019	12.680	73200	5773					Shear
3			4.013	12.642	74880	5923					Shear

Table E.13: Compressive Strength, Mix D

Lab Identification No: …………… Mix D

Date of Casting:…………04/24/09………………………

Concrete Grade: ……Phase II_Mix D

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture
3	1	25-Apr-09	4	12.560	91870	7314	7265	169.519	2.333217	195.7437	Columnar
4			4.01	12.623	89330	7077					Shear
11			4.02	12.686	93940	7405					Columnar
2	28	22-May-09	4	12.560	116160	9248	8823.164	381.7642	4.32684	440.8233	Shear
6			4.01	12.623	107420	8510					Columnar
9			4.008	12.610	109850	8711					Columnar
O	56	19-Jun-09	4	12.560	113720	9054.1401	9065.481	133.7731	1.475631	154.4678	Shear
G			4.014	12.648	116420	9204.5636					Shear
N			4.01	12.623	112820	8937.7395					Columnar

Table E.14: Compressive Strength, Mix E

Lab Identification No: …………… Mix E

Date of Casting:…………04/21/09………………………

Concrete Grade: ……Phase II_Mix E

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)			STDEV	Co.of Variation	Standard Error	Type of Fracture
11	1	22-Apr-09	4.02	12.686	103200	8135	8204	67.55545	0.823456	78.00632	Columnar
5			4.015	12.654	103850	8207					Shear
9			4.014	12.648	104600	8270					
2	28	19-May-09	4.018	12.673	134340	10600.243	10683.16	369.4957	3.458674	426.6569	Shear
7			4.008	12.610	130670	10362.172					Shear
10			4.015	12.654	140300	11087.073					
8	56	16-Jun-09	4	12.560	127700	10167.197	10165.61	301.9165	2.969978	348.6231	
6			4.015	12.654	132450	10466.734					Shear
1			4.02	12.686	125120	9862.9078					Shear

Table E.15: Compressive Strength, Mix S

Lab Identification No: …………… Mix T

Date of Casting:…………05/21/09………………………

Concrete Grade: ……Phase II_Mix T

Specim. No.	Age	Testing date	Dia ,(in.)	Length (in.)	Area , (in.2)	Weight in air, (kg)	Weight in water, (kg)	Density in air , (lb/ ft.^{3})	Density in water , (lb/ ft.^{3})	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture
2			4.01	8.05	12.623	3.9		146.2138	0.0000	169500	13427.999					Shear
3	28	17-Jun-09	4.009	8.061	12.617	3.892		145.7875	0.0000	172150	13644.74	13595.79	149.4508	1.099244	172.5709	Shear
4			4.015	8.025	12.654	3.912		146.7544	0.0000	173550	13714.623					
1			4.01	7.95	12.623	4.06		154.1269	0.0000	174730	13842.326					
5	56	15-Jul-09	4.009	8.025	12.617	4.09		153.8915	0.0000	176610	13998.243	13898.67	86.48258	0.622236	99.86148	Shear
6			4.012	8.02	12.635	4.056		152.4790	0.0000	175070	13855.437					Shear

Table E.16: Compressive Strength, Mix T

Lab Identification No: …………… Mix T

Date of Casting:…………05/21/09………………………

Concrete Grade: ……Phase II_Mix T

Specim. No.	Age	Testing date	Dia ,(in.)	Area , (in.2)	Max. Load , (lbf)	Compressive Strength , (psi)	Avg. Strength , (psi)	STDEV	Co.of Variation	Standard Error	Type of Fracture
10			4.015	12.654	118660	9377					Columnar
8	1	22-May-09	4.01	12.623	108790	8618	8868	440.9927	4.972959	509.2146	Shear
			4.02	12.686	109200	8608					
D			4.001	12.566	134100	10671.415					Shear
E	28	18-Jun-09	4.012	12.635	129950	10284.538	10436.56	206.3111	1.976811	238.2275	Shear
F			4.015	12.654	131020	10353.73					
1			4.015	12.654	145380	11488.515					
4	56	16-Jul-09	4.008	12.610	139180	11037.018	11055.22	424.4868	3.839695	490.1551	Shear
9			4	12.560	133640	10640.127					Shear

Table E.17: Abrasion Test, Control Mixture, Run 1

Mix ID		Mix P, Control 1			Mix Type : MC- 4 %						Curing Peroid
Mix Id No.	Weight	34.9 lb		Weight	34.45 lb		0.450	Weight	34.3 lb		0.15
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.126	0.128	0.127	0.216	0.214	0.215	0.088	0.269	0.269	0.269	0.054
2	0.123	0.123	0.123	0.211	0.207	0.209	0.086	0.268	0.268	0.268	0.059
3	0.115	0.115	0.115	0.207	0.207	0.207	0.092	0.256	0.256	0.256	0.049
4	0.111	0.110	0.111	0.190	0.190	0.190	0.080	0.241	0.243	0.242	0.052
5	0.116	0.117	0.117	0.188	0.186	0.187	0.071	0.233	0.234	0.234	0.047
6	0.114	0.114	0.114	0.181	0.180	0.181	0.067	0.219	0.219	0.219	0.039
7	0.106	0.107	0.107	0.180	0.179	0.180	0.073	0.221	0.222	0.222	0.042
8	0.102	0.102	0.102	0.177	0.177	0.177	0.075	0.223	0.228	0.226	0.049
9	0.096	0.096	0.096	0.169	0.170	0.170	0.074	0.210	0.213	0.212	0.042
10	0.092	0.093	0.093	0.168	0.167	0.168	0.075	0.210	0.211	0.211	0.043
11	0.095	0.102	0.099	0.165	0.166	0.166	0.067	0.212	0.213	0.213	0.047
12	0.095	0.098	0.097	0.175	0.176	0.176	0.079	0.225	0.227	0.226	0.051
13	0.095	0.096	0.096	0.175	0.176	0.176	0.080	0.221	0.222	0.222	0.046
14	0.100	0.100	0.100	0.179	0.179	0.179	0.079	0.219	0.221	0.220	0.041
15	0.103	0.102	0.103	0.178	0.177	0.178	0.075	0.223	0.224	0.224	0.046
16	0.102	0.103	0.103	0.180	0.181	0.181	0.078	0.216	0.217	0.217	0.036
17	0.103	0.105	0.104	0.171	0.174	0.173	0.069	0.214	0.214	0.214	0.042
18	0.107	0.106	0.107	0.182	0.183	0.183	0.076	0.220	0.221	0.221	0.038
19	0.113	0.113	0.113	0.198	0.199	0.199	0.086	0.242	0.242	0.242	0.044
20	0.140	0.140	0.140	0.217	0.216	0.217	0.077	0.259	0.258	0.259	0.042
21	0.163	0.164	0.164	0.222	0.223	0.223	0.059	0.264	0.264	0.264	0.042
22	0.162	0.159	0.161	0.223	0.224	0.224	0.063	0.266	0.265	0.266	0.042
23	0.157	0.158	0.158	0.229	0.229	0.229	0.072	0.275	0.274	0.275	0.046
24	0.134	0.153	0.144	0.225	0.225	0.225	0.082	0.276	0.276	0.276	0.051
Average	0.115	0.117	0.116	0.192	0.192	0.192	**0.076**	0.237	0.238	0.237	**0.045**

Table E.18: Abrasion Test, Control Mixture, Run 2

Mix ID		Mix P, Control 2			Mix Type : MC- 4 %						Curing Peroid
Mix Id No.	Weight	35.95 lb		Weight	35.7 lb		0.250	Weight	35.6 lb		0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.115	0.115	0.115	0.179	0.178	0.179	0.064	0.219	0.221	0.220	0.042
2	0.116	0.117	0.117	0.164	0.164	0.164	0.048	0.202	0.203	0.203	0.039
3	0.113	0.115	0.114	0.168	0.168	0.168	0.054	0.206	0.206	0.206	0.038
4	0.117	0.119	0.118	0.175	0.175	0.175	0.057	0.207	0.206	0.207	0.032
5	0.121	0.122	0.122	0.171	0.177	0.174	0.053	0.198	0.198	0.198	0.024
6	0.117	0.117	0.117	0.168	0.168	0.168	0.051	0.196	0.196	0.196	0.028
7	0.111	0.105	0.108	0.163	0.163	0.163	0.055	0.186	0.186	0.186	0.023
8	0.106	0.105	0.106	0.152	0.156	0.154	0.049	0.184	0.184	0.184	0.030
9	0.112	0.107	0.110	0.152	0.152	0.152	0.043	0.182	0.180	0.181	0.029
10	0.113	0.119	0.116	0.151	0.154	0.153	0.037	0.178	0.179	0.179	0.026
11	0.104	0.107	0.106	0.156	0.159	0.158	0.052	0.182	0.185	0.184	0.026
12	0.113	0.116	0.115	0.155	0.153	0.154	0.040	0.184	0.184	0.184	0.030
13	0.103	0.108	0.106	0.153	0.153	0.153	0.048	0.192	0.191	0.192	0.039
14	0.102	0.103	0.103	0.165	0.165	0.165	0.063	0.197	0.198	0.198	0.033
15	0.103	0.098	0.101	0.167	0.168	0.168	0.067	0.206	0.206	0.206	0.039
16	0.119	0.119	0.119	0.179	0.179	0.179	0.060	0.214	0.216	0.215	0.036
17	0.133	0.135	0.134	0.188	0.188	0.188	0.054	0.226	0.227	0.227	0.039
18	0.152	0.152	0.152	0.202	0.204	0.203	0.051	0.240	0.242	0.241	0.038
19	0.185	0.185	0.185	0.214	0.214	0.214	0.029	0.244	0.247	0.246	0.032
20	0.153	0.154	0.154	0.208	0.209	0.209	0.055	0.241	0.243	0.242	0.034
21	0.136	0.136	0.136	0.194	0.196	0.195	0.059	0.235	0.236	0.236	0.041
22	0.129	0.133	0.131	0.188	0.190	0.189	0.058	0.230	0.231	0.231	0.042
23	0.115	0.115	0.115	0.178	0.178	0.178	0.063	0.223	0.225	0.224	0.046
24	0.111	0.112	0.112	0.183	0.184	0.184	0.072	0.227	0.229	0.228	0.045
Average	0.121	0.121	0.121	0.174	0.175	0.174	**0.053**	0.208	0.209	0.209	**0.034**

Table E.19: Abrasion Test, Control Mixture, Run 3

Mix ID		Mix P, Control 3			Mix Type : MC- 4 %						Curing Peroid
Mix Id No.	Weight	35.7	lb	Weight	35.5	lb	0.200	Weight	35.4	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.134	0.137	0.136	0.173	0.176	0.175	0.039	0.196	0.200	0.198	0.024
2	0.135	0.139	0.137	0.167	0.169	0.168	0.031	0.192	0.203	0.198	0.030
3	0.136	0.140	0.138	0.169	0.171	0.170	0.032	0.199	0.214	0.207	0.037
4	0.142	0.146	0.144	0.171	0.174	0.173	0.029	0.198	0.200	0.199	0.027
5	0.117	0.121	0.119	0.164	0.166	0.165	0.046	0.185	0.194	0.190	0.025
6	0.098	0.105	0.102	0.152	0.157	0.155	0.053	0.175	0.176	0.176	0.021
7	0.091	0.093	0.092	0.145	0.151	0.148	0.056	0.171	0.171	0.171	0.023
8	0.087	0.089	0.088	0.137	0.140	0.139	0.051	0.168	0.164	0.166	0.028
9	0.095	0.102	0.099	0.137	0.140	0.139	0.040	0.164	0.160	0.162	0.024
10	0.091	0.097	0.094	0.144	0.144	0.144	0.050	0.176	0.174	0.175	0.031
11	0.100	0.097	0.099	0.135	0.136	0.136	0.037	0.162	0.161	0.162	0.026
12	0.103	0.101	0.102	0.137	0.142	0.140	0.038	0.162	0.160	0.161	0.022
13	0.112	0.112	0.112	0.131	0.140	0.136	0.024	0.157	0.154	0.156	0.020
14	0.114	0.113	0.114	0.131	0.144	0.138	0.024	0.161	0.159	0.160	0.023
15	0.100	0.102	0.101	0.136	0.150	0.143	0.042	0.165	0.161	0.163	0.020
16	0.096	0.118	0.107	0.136	0.151	0.144	0.037	0.165	0.164	0.165	0.021
17	0.098	0.124	0.111	0.140	0.152	0.146	0.035	0.178	0.175	0.177	0.031
18	0.100	0.117	0.109	0.140	0.145	0.143	0.034	0.171	0.169	0.170	0.028
19	0.097	0.112	0.105	0.145	0.149	0.147	0.043	0.172	0.171	0.172	0.025
20	0.111	0.121	0.116	0.151	0.154	0.153	0.037	0.180	0.182	0.181	0.029
21	0.118	0.124	0.121	0.154	0.158	0.156	0.035	0.181	0.181	0.181	0.025
22	0.125	0.126	0.126	0.163	0.163	0.163	0.038	0.189	0.189	0.189	0.026
23	0.126	0.123	0.125	0.164	0.165	0.165	0.040	0.200	0.195	0.198	0.033
24	0.124	0.127	0.126	0.166	0.165	0.166	0.040	0.194	0.196	0.195	0.030
Average	0.110	0.116	0.113	0.150	0.154	0.152	**0.039**	0.178	0.178	0.178	**0.026**

Table E.20: Abrasion Test, Mixture A, Run 1

Mix ID		Mix A 1			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	36.75	lb	Weight	36.3	lb	0.450	Weight	35.6	lb	0.7
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.125	0.123	0.124	0.259	0.260	0.260	0.136	0.324	0.324	0.324	0.065
2	0.136	0.136	0.136	0.235	0.235	0.235	0.099	0.309	0.309	0.309	0.074
3	0.121	0.121	0.121	0.243	0.245	0.244	0.123	0.307	0.306	0.307	0.063
4	0.108	0.108	0.108	0.238	0.240	0.239	0.131	0.304	0.302	0.303	0.064
5	0.106	0.107	0.107	0.228	0.231	0.230	0.123	0.304	0.304	0.304	0.075
6	0.105	0.105	0.105	0.220	0.222	0.221	0.116	0.288	0.288	0.288	0.067
7	0.097	0.107	0.102	0.213	0.215	0.214	0.112	0.272	0.271	0.272	0.058
8	0.099	0.100	0.100	0.212	0.215	0.214	0.114	0.278	0.279	0.279	0.065
9	0.104	0.103	0.104	0.205	0.208	0.207	0.103	0.281	0.269	0.275	0.069
10	0.106	0.105	0.106	0.210	0.213	0.212	0.106	0.277	0.270	0.274	0.062
11	0.113	0.124	0.119	0.220	0.223	0.222	0.103	0.281	0.287	0.284	0.063
12	0.117	0.119	0.118	0.203	0.212	0.208	0.090	0.293	0.279	0.286	0.079
13	0.127	0.130	0.129	0.232	0.235	0.234	0.105	0.281	0.300	0.291	0.057
14	0.120	0.121	0.121	0.233	0.229	0.231	0.111	0.297	0.306	0.302	0.071
15	0.118	0.118	0.118	0.245	0.239	0.242	0.124	0.314	0.310	0.312	0.070
16	0.121	0.122	0.122	0.243	0.241	0.242	0.121	0.303	0.297	0.300	0.058
17	0.127	0.128	0.128	0.250	0.249	0.250	0.122	0.305	0.305	0.305	0.056
18	0.134	0.133	0.134	0.254	0.243	0.249	0.115	0.317	0.316	0.317	0.068
19	0.135	0.135	0.135	0.260	0.261	0.261	0.126	0.334	0.328	0.331	0.071
20	0.140	0.141	0.141	0.271	0.267	0.269	0.129	0.330	0.330	0.330	0.061
21	0.138	0.138	0.138	0.270	0.268	0.269	0.131	0.339	0.305	0.322	0.053
22	0.135	0.136	0.136	0.274	0.274	0.274	0.139	0.336	0.336	0.336	0.062
23	0.139	0.140	0.140	0.246	0.246	0.246	0.107	0.318	0.318	0.318	0.072
24	0.136	0.138	0.137	0.262	0.263	0.263	0.126	0.332	0.332	0.332	0.070
Average	0.121	0.122	0.122	0.195	0.239	0.239	**0.117**	0.305	0.303	0.304	**0.065**

Table E.21: Abrasion Test, Mixture A, Run 2

Mix ID		Mix A 2			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	37.6	lb	Weight	37.3	lb	0.300	Weight	37.2	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.082	0.083	0.083	0.152	0.151	0.152	0.069	0.185	0.187	0.186	0.035
2	0.080	0.081	0.081	0.148	0.147	0.148	0.067	0.192	0.191	0.192	0.044
3	0.086	0.087	0.087	0.155	0.152	0.154	0.067	0.196	0.193	0.195	0.041
4	0.089	0.089	0.089	0.164	0.162	0.163	0.074	0.208	0.208	0.208	0.045
5	0.090	0.099	0.095	0.169	0.169	0.169	0.075	0.209	0.209	0.209	0.040
6	0.098	0.097	0.098	0.165	0.167	0.166	0.069	0.214	0.213	0.214	0.048
7	0.110	0.111	0.111	0.175	0.178	0.177	0.066	0.228	0.227	0.228	0.051
8	0.111	0.111	0.111	0.173	0.177	0.175	0.064	0.232	0.264	0.248	0.073
9	0.109	0.108	0.109	0.182	0.185	0.184	0.075	0.234	0.236	0.235	0.052
10	0.115	0.115	0.115	0.184	0.187	0.186	0.071	0.234	0.234	0.234	0.049
11	0.127	0.124	0.126	0.185	0.187	0.186	0.061	0.238	0.242	0.240	0.054
12	0.123	0.122	0.123	0.185	0.185	0.185	0.063	0.235	0.235	0.235	0.050
13	0.119	0.120	0.120	0.184	0.180	0.182	0.063	0.232	0.232	0.232	0.050
14	0.121	0.126	0.124	0.178	0.181	0.180	0.056	0.218	0.218	0.218	0.039
15	0.138	0.138	0.138	0.182	0.184	0.183	0.045	0.219	0.215	0.217	0.034
16	0.136	0.133	0.135	0.178	0.178	0.178	0.044	0.225	0.221	0.223	0.045
17	0.127	0.127	0.127	0.187	0.186	0.187	0.060	0.232	0.226	0.229	0.043
18	0.120	0.124	0.122	0.176	0.176	0.176	0.054	0.220	0.217	0.219	0.043
19	0.113	0.114	0.114	0.173	0.172	0.173	0.059	0.224	0.221	0.223	0.050
20	0.107	0.111	0.109	0.167	0.166	0.167	0.058	0.215	0.213	0.214	0.048
21	0.103	0.104	0.104	0.161	0.161	0.161	0.058	0.206	0.206	0.206	0.045
22	0.100	0.101	0.101	0.161	0.161	0.161	0.061	0.198	0.199	0.199	0.038
23	0.097	0.100	0.099	0.154	0.151	0.153	0.054	0.199	0.197	0.198	0.046
24	0.089	0.088	0.089	0.142	0.142	0.142	0.054	0.192	0.191	0.192	0.050
Average	0.108	0.109	0.108	0.195	0.170	0.170	**0.062**	0.216	0.216	0.216	**0.046**

Table E.22: Abrasion Test, Mixture A, Run 3

Mix ID		Mix A 3			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	36.85	lb	Weight	36.7	lb	0.150	Weight	36.55	lb	0.15
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.091	0.091	0.091	0.136	0.137	0.137	0.046	0.175	0.176	0.176	0.039
2	0.081	0.082	0.082	0.136	0.136	0.136	0.055	0.179	0.180	0.180	0.044
3	0.089	0.087	0.088	0.132	0.133	0.133	0.045	0.171	0.172	0.172	0.039
4	0.091	0.091	0.091	0.146	0.147	0.147	0.056	0.187	0.187	0.187	0.041
5	0.109	0.112	0.111	0.151	0.153	0.152	0.042	0.196	0.197	0.197	0.045
6	0.120	0.120	0.120	0.164	0.160	0.162	0.042	0.202	0.203	0.203	0.041
7	0.113	0.116	0.115	0.160	0.162	0.161	0.047	0.199	0.199	0.199	0.038
8	0.110	0.111	0.111	0.155	0.159	0.157	0.047	0.197	0.199	0.198	0.041
9	0.109	0.111	0.110	0.155	0.154	0.155	0.045	0.198	0.196	0.197	0.043
10	0.106	0.110	0.108	0.156	0.157	0.157	0.049	0.197	0.197	0.197	0.041
11	0.114	0.112	0.113	0.156	0.153	0.155	0.042	0.192	0.192	0.192	0.038
12	0.117	0.120	0.119	0.155	0.154	0.155	0.036	0.194	0.198	0.196	0.042
13	0.121	0.119	0.120	0.150	0.152	0.151	0.031	0.179	0.185	0.182	0.031
14	0.115	0.117	0.116	0.150	0.152	0.151	0.035	0.180	0.181	0.181	0.030
15	0.105	0.106	0.106	0.145	0.147	0.146	0.041	0.177	0.177	0.177	0.031
16	0.103	0.102	0.103	0.140	0.142	0.141	0.039	0.177	0.176	0.177	0.036
17	0.097	0.099	0.098	0.140	0.137	0.139	0.041	0.168	0.163	0.166	0.027
18	0.109	0.107	0.108	0.143	0.147	0.145	0.037	0.182	0.173	0.178	0.033
19	0.101	0.105	0.103	0.143	0.142	0.143	0.040	0.175	0.172	0.174	0.031
20	0.090	0.098	0.094	0.135	0.135	0.135	0.041	0.176	0.175	0.176	0.041
21	0.093	0.097	0.095	0.135	0.136	0.136	0.041	0.179	0.177	0.178	0.043
22	0.094	0.095	0.095	0.140	0.140	0.140	0.046	0.181	0.182	0.182	0.042
23	0.093	0.099	0.096	0.141	0.142	0.142	0.046	0.186	0.187	0.187	0.045
24	0.094	0.098	0.096	0.138	0.138	0.138	0.042	0.182	0.184	0.183	0.045
Average	0.103	0.104	0.104	0.195	0.146	0.146	**0.043**	0.185	0.185	0.185	**0.038**

Table E.23: Abrasion Test, Mixture B, Run 1

Mix ID		Mix B 1			Mix Type :						Curing Peroid - 57 day
Mix Id No.	Weight	35.45	lb	Weight	35.25	lb	0.200	Weight	35.15	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.113	0.116	0.115	0.157	0.158	0.158	0.043	0.186	0.186	0.186	0.029
2	0.120	0.121	0.121	0.166	0.166	0.166	0.046	0.187	0.189	0.188	0.022
3	0.126	0.125	0.126	0.170	0.170	0.170	0.045	0.209	0.207	0.208	0.038
4	0.133	0.126	0.130	0.180	0.181	0.181	0.051	0.199	0.198	0.199	0.018
5	0.117	0.115	0.116	0.182	0.182	0.182	0.066	0.211	0.210	0.211	0.029
6	0.116	0.116	0.116	0.163	0.166	0.165	0.049	0.205	0.204	0.205	0.040
7	0.124	0.125	0.125	0.166	0.168	0.167	0.043	0.195	0.195	0.195	0.028
8	0.111	0.110	0.111	0.170	0.171	0.171	0.060	0.206	0.202	0.204	0.034
9	0.105	0.110	0.108	0.165	0.164	0.165	0.057	0.208	0.208	0.208	0.044
10	0.127	0.124	0.126	0.167	0.168	0.168	0.042	0.221	0.219	0.220	0.053
11	0.108	0.108	0.108	0.160	0.159	0.160	0.052	0.195	0.197	0.196	0.037
12	0.101	0.104	0.103	0.152	0.152	0.152	0.050	0.178	0.179	0.179	0.027
13	0.107	0.109	0.108	0.153	0.152	0.153	0.045	0.181	0.185	0.183	0.031
14	0.099	0.100	0.100	0.150	0.151	0.151	0.051	0.178	0.174	0.176	0.026
15	0.097	0.097	0.097	0.158	0.158	0.158	0.061	0.187	0.186	0.187	0.029
16	0.110	0.110	0.110	0.161	0.162	0.162	0.052	0.191	0.188	0.190	0.028
17	0.110	0.114	0.112	0.153	0.156	0.155	0.043	0.182	0.180	0.181	0.027
18	0.107	0.108	0.108	0.152	0.151	0.152	0.044	0.188	0.191	0.190	0.038
19	0.107	0.107	0.107	0.158	0.157	0.158	0.051	0.189	0.185	0.187	0.030
20	0.112	0.113	0.113	0.159	0.160	0.160	0.047	0.185	0.185	0.185	0.026
21	0.125	0.126	0.126	0.153	0.153	0.153	0.028	0.177	0.176	0.177	0.024
22	0.122	0.127	0.125	0.154	0.155	0.155	0.030	0.180	0.177	0.179	0.024
23	0.132	0.128	0.130	0.166	0.168	0.167	0.037	0.180	0.180	0.180	0.013
24	0.116	0.116	0.116	0.154	0.154	0.154	0.038	0.178	0.176	0.177	0.023
Average	0.114	0.115	0.115	0.195	0.162	0.161	**0.047**	0.192	0.191	0.191	**0.030**

Table E.24: Abrasion Test, Mixture B, Run 2

Mix ID		Mix B 2			Mix Type :						Curing Peroid - 57 day
Mix Id No.	Weight	35.4	lb	Weight	35.15	lb	0.250	Weight	35	lb	0.15
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.133	0.132	0.133	0.171	0.172	0.172	0.039	0.203	0.204	0.204	0.032
2	0.126	0.125	0.126	0.178	0.179	0.179	0.053	0.218	0.218	0.218	0.040
3	0.132	0.132	0.132	0.173	0.173	0.173	0.041	0.210	0.209	0.210	0.037
4	0.123	0.124	0.124	0.177	0.179	0.178	0.055	0.219	0.217	0.218	0.040
5	0.123	0.125	0.124	0.184	0.184	0.184	0.060	0.236	0.234	0.235	0.051
6	0.123	0.121	0.122	0.181	0.179	0.180	0.058	0.228	0.228	0.228	0.048
7	0.138	0.137	0.138	0.186	0.189	0.188	0.050	0.221	0.222	0.222	0.034
8	0.131	0.131	0.131	0.183	0.186	0.185	0.054	0.228	0.227	0.228	0.043
9	0.143	0.139	0.141	0.191	0.192	0.192	0.051	0.234	0.230	0.232	0.041
10	0.143	0.141	0.142	0.185	0.188	0.187	0.045	0.223	0.219	0.221	0.035
11	0.144	0.142	0.143	0.185	0.186	0.186	0.043	0.220	0.221	0.221	0.035
12	0.159	0.155	0.157	0.170	0.171	0.171	0.014	0.205	0.203	0.204	0.034
13	0.145	0.141	0.143	0.171	0.172	0.172	0.029	0.211	0.210	0.211	0.039
14	0.156	0.153	0.155	0.176	0.176	0.176	0.022	0.205	0.206	0.206	0.030
15	0.157	0.149	0.153	0.170	0.159	0.165	0.012	0.215	0.214	0.215	0.050
16	0.158	0.159	0.159	0.169	0.161	0.165	0.007	0.211	0.212	0.212	0.047
17	0.162	0.165	0.164	0.180	0.176	0.178	0.015	0.212	0.215	0.214	0.036
18	0.160	0.160	0.160	0.175	0.174	0.175	0.015	0.207	0.207	0.207	0.033
19	0.148	0.147	0.148	0.163	0.163	0.163	0.016	0.201	0.200	0.201	0.038
20	0.160	0.160	0.160	0.174	0.174	0.174	0.014	0.207	0.206	0.207	0.033
21	0.152	0.156	0.154	0.169	0.171	0.170	0.016	0.214	0.212	0.213	0.043
22	0.159	0.158	0.159	0.169	0.168	0.169	0.010	0.220	0.223	0.222	0.053
23	0.164	0.165	0.165	0.174	0.168	0.171	0.006	0.208	0.210	0.209	0.038
24	0.138	0.139	0.139	0.167	0.171	0.169	0.031	0.201	0.203	0.202	0.033
Average	0.145	0.144	0.144	0.195	0.175	0.176	**0.031**	0.215	0.215	0.215	**0.039**

Table E.25: Abrasion Test, Mixture B, Run 3

Mix ID		Mix B 3							Curing Peroid - 57 day
Mix Id No.	Weight	36.4	lb	Weight	lb	0.400	Weight	lb	0.25
Wear depth (in.) at time (min.)									
Pos.	0 min			30 min			60 Min		
	R1	R2	Average	R1	Average	Difference	R1	Average	Difference
1	0.147	0.147	0.147	0.232	0.232	0.085	0.295	0.295	0.063
2	0.143	0.143	0.143	0.242	0.242	0.099	0.288	0.288	0.046
3	0.137	0.137	0.137	0.250	0.250	0.113	0.290	0.290	0.040
4	0.138	0.138	0.138	0.218	0.218	0.080	0.273	0.273	0.055
5	0.138	0.138	0.138	0.234	0.234	0.096	0.291	0.291	0.057
6	0.120	0.120	0.120	0.232	0.232	0.112	0.293	0.293	0.061
7	0.130	0.130	0.130	0.240	0.240	0.110	0.291	0.291	0.051
8	0.122	0.122	0.122	0.233	0.233	0.111	0.288	0.288	0.055
9	0.123	0.123	0.123	0.244	0.244	0.121	0.298	0.298	0.054
10	0.129	0.129	0.129	0.217	0.217	0.088	0.290	0.290	0.073
11	0.134	0.134	0.134	0.237	0.237	0.103	0.285	0.285	0.048
12	0.127	0.127	0.127	0.237	0.237	0.110	0.294	0.294	0.057
13	0.145	0.145	0.145	0.235	0.235	0.090	0.294	0.294	0.059
14	0.132	0.132	0.132	0.242	0.242	0.110	0.308	0.308	0.066
15	0.134	0.134	0.134	0.243	0.243	0.109	0.301	0.301	0.058
16	0.156	0.156	0.156	0.249	0.249	0.093	0.302	0.302	0.053
17	0.153	0.153	0.153	0.247	0.247	0.094	0.299	0.299	0.052
18	0.160	0.160	0.160	0.264	0.264	0.104	0.308	0.308	0.044
19	0.157	0.157	0.157	0.261	0.261	0.104	0.323	0.323	0.062
20	0.162	0.162	0.162	0.255	0.255	0.093	0.309	0.309	0.054
21	0.152	0.152	0.152	0.260	0.260	0.108	0.320	0.320	0.060
22	0.153	0.153	0.153	0.264	0.264	0.111	0.317	0.317	0.053
23	0.141	0.141	0.141	0.261	0.261	0.120	0.313	0.313	0.052
24	0.141	0.141	0.141	0.254	0.254	0.113	0.321	0.321	0.067
Average	0.141	0.141	0.141	0.195	0.244	**0.103**	0.300	0.300	**0.056**

Table E.26: Abrasion Test, Mixture C, Run 1

Mix ID		Mix C -1			Mix Type : MC-7 %						Curing Peroid - 56 day
Mix Id No.	Weight	33.15	lb	Weight	32.6	lb	0.550	Weight	32.45	lb	0.15
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.150	0.152	0.151	0.292	0.287	0.290	0.139	0.319	0.319	0.319	0.030
2	0.143	0.141	0.142	0.271	0.271	0.271	0.129	0.299	0.300	0.300	0.029
3	0.135	0.136	0.136	0.260	0.260	0.260	0.125	0.300	0.305	0.303	0.043
4	0.131	0.132	0.132	0.264	0.264	0.264	0.133	0.297	0.298	0.298	0.034
5	0.120	0.120	0.120	0.256	0.253	0.255	0.135	0.300	0.300	0.300	0.046
6	0.121	0.121	0.121	0.246	0.247	0.247	0.126	0.295	0.295	0.295	0.049
7	0.119	0.120	0.120	0.249	0.249	0.249	0.130	0.304	0.304	0.304	0.055
8	0.121	0.122	0.122	0.255	0.256	0.256	0.134	0.310	0.313	0.312	0.056
9	0.132	0.131	0.132	0.266	0.268	0.267	0.136	0.308	0.308	0.308	0.041
10	0.130	0.132	0.131	0.268	0.264	0.266	0.135	0.310	0.310	0.310	0.044
11	0.138	0.135	0.137	0.291	0.287	0.289	0.153	0.326	0.325	0.326	0.037
12	0.150	0.150	0.150	0.288	0.282	0.285	0.135	0.338	0.332	0.335	0.050
13	0.150	0.150	0.150	0.294	0.295	0.295	0.145	0.332	0.341	0.337	0.042
14	0.173	0.174	0.174	0.301	0.304	0.303	0.129	0.349	0.350	0.350	0.047
15	0.165	0.165	0.165	0.309	0.309	0.309	0.144	0.347	0.353	0.350	0.041
16	0.156	0.159	0.158	0.275	0.274	0.275	0.117	0.309	0.309	0.309	0.035
17	0.157	0.155	0.156	0.283	0.285	0.284	0.128	0.311	0.315	0.313	0.029
18	0.191	0.191	0.191	0.307	0.310	0.309	0.118	0.333	0.339	0.336	0.028
19	0.197	0.199	0.198	0.325	0.325	0.325	0.127	0.366	0.366	0.366	0.041
20	0.208	0.208	0.208	0.315	0.321	0.318	0.110	0.360	0.360	0.360	0.042
21	0.200	0.198	0.199	0.323	0.323	0.323	0.124	0.364	0.365	0.365	0.042
22	0.193	0.190	0.192	0.313	0.312	0.313	0.121	0.352	0.358	0.355	0.043
23	0.177	0.176	0.177	0.309	0.312	0.311	0.134	0.355	0.360	0.358	0.047
24	0.170	0.169	0.170	0.301	0.303	0.302	0.133	0.334	0.336	0.335	0.033
Average	0.155	0.155	0.155	0.195	0.286	0.286	**0.131**	0.326	0.328	0.327	**0.041**

Table E.27: Abrasion Test, Mixture C, Run 2

Mix ID		Mix C -2			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	33.5	lb	Weight	33.1	lb	0.400	Weight	32.9	lb	0.2
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.106	0.108	0.107	0.204	0.204	0.204	0.097	0.262	0.262	0.262	0.058
2	0.112	0.110	0.111	0.216	0.216	0.216	0.105	0.273	0.273	0.273	0.057
3	0.112	0.113	0.113	0.216	0.216	0.216	0.104	0.282	0.281	0.282	0.066
4	0.116	0.119	0.118	0.213	0.214	0.214	0.096	0.277	0.268	0.273	0.059
5	0.128	0.131	0.130	0.199	0.202	0.201	0.071	0.259	0.260	0.260	0.059
6	0.115	0.116	0.116	0.208	0.209	0.209	0.093	0.273	0.272	0.273	0.064
7	0.108	0.107	0.108	0.211	0.212	0.212	0.104	0.267	0.266	0.267	0.055
8	0.113	0.114	0.114	0.210	0.211	0.211	0.097	0.258	0.267	0.263	0.052
9	0.102	0.099	0.101	0.202	0.203	0.203	0.102	0.262	0.266	0.264	0.062
10	0.106	0.109	0.108	0.199	0.197	0.198	0.091	0.254	0.265	0.260	0.062
11	0.106	0.105	0.106	0.216	0.214	0.215	0.110	0.265	0.268	0.267	0.052
12	0.104	0.102	0.103	0.210	0.207	0.209	0.106	0.262	0.266	0.264	0.056
13	0.105	0.101	0.103	0.202	0.199	0.201	0.098	0.256	0.257	0.257	0.056
14	0.100	0.103	0.102	0.207	0.205	0.206	0.105	0.266	0.266	0.266	0.060
15	0.108	0.107	0.108	0.199	0.196	0.198	0.090	0.251	0.251	0.251	0.054
16	0.109	0.106	0.108	0.214	0.209	0.212	0.104	0.256	0.258	0.257	0.046
17	0.114	0.116	0.115	0.221	0.215	0.218	0.103	0.274	0.279	0.277	0.059
18	0.134	0.133	0.134	0.227	0.229	0.228	0.095	0.274	0.275	0.275	0.047
19	0.133	0.135	0.134	0.232	0.230	0.231	0.097	0.298	0.300	0.299	0.068
20	0.136	0.139	0.138	0.228	0.226	0.227	0.090	0.289	0.290	0.290	0.063
21	0.131	0.128	0.130	0.220	0.220	0.220	0.091	0.273	0.273	0.273	0.053
22	0.127	0.128	0.128	0.210	0.210	0.210	0.083	0.260	0.260	0.260	0.050
23	0.120	0.125	0.123	0.205	0.205	0.205	0.083	0.269	0.268	0.269	0.064
24	0.110	0.108	0.109	0.195	0.194	0.195	0.086	0.249	0.247	0.248	0.054
Average	0.115	0.115	0.115	0.195	0.210	0.211	**0.096**	0.267	0.268	0.268	**0.057**

Table E.28: Abrasion Test, Mixture C, Run 3

Mix ID		Mix C -3			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	33.6	lb	Weight	33.15	lb	0.450	Weight	32.85	lb	0.3
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.118	0.121	0.120	0.212	0.213	0.213	0.093	0.275	0.277	0.276	0.064
2	0.110	0.112	0.111	0.218	0.221	0.220	0.109	0.277	0.274	0.276	0.056
3	0.107	0.107	0.107	0.205	0.207	0.206	0.099	0.267	0.268	0.268	0.062
4	0.102	0.103	0.103	0.209	0.209	0.209	0.107	0.271	0.271	0.271	0.062
5	0.105	0.108	0.107	0.217	0.218	0.218	0.111	0.271	0.271	0.271	0.054
6	0.102	0.100	0.101	0.194	0.195	0.195	0.094	0.263	0.262	0.263	0.068
7	0.108	0.112	0.110	0.220	0.222	0.221	0.111	0.282	0.287	0.285	0.064
8	0.111	0.114	0.113	0.222	0.223	0.223	0.110	0.280	0.281	0.281	0.058
9	0.108	0.115	0.112	0.225	0.225	0.225	0.114	0.288	0.292	0.290	0.065
10	0.117	0.118	0.118	0.230	0.228	0.229	0.112	0.296	0.298	0.297	0.068
11	0.121	0.122	0.122	0.250	0.255	0.253	0.131	0.300	0.308	0.304	0.052
12	0.120	0.121	0.121	0.231	0.227	0.229	0.109	0.292	0.291	0.292	0.063
13	0.123	0.121	0.122	0.236	0.236	0.236	0.114	0.286	0.288	0.287	0.051
14	0.119	0.120	0.120	0.252	0.252	0.252	0.133	0.313	0.309	0.311	0.059
15	0.121	0.119	0.120	0.253	0.254	0.254	0.134	0.300	0.304	0.302	0.049
16	0.117	0.115	0.116	0.252	0.258	0.255	0.139	0.292	0.297	0.295	0.040
17	0.123	0.125	0.124	0.258	0.260	0.259	0.135	0.295	0.296	0.296	0.037
18	0.125	0.123	0.124	0.258	0.258	0.258	0.134	0.312	0.312	0.312	0.054
19	0.126	0.125	0.126	0.244	0.241	0.243	0.117	0.301	0.299	0.300	0.058
20	0.132	0.129	0.131	0.247	0.249	0.248	0.118	0.307	0.304	0.306	0.058
21	0.133	0.137	0.135	0.233	0.233	0.233	0.098	0.294	0.294	0.294	0.061
22	0.136	0.135	0.136	0.245	0.248	0.247	0.111	0.311	0.310	0.311	0.064
23	0.124	0.120	0.122	0.239	0.241	0.240	0.118	0.298	0.297	0.298	0.058
24	0.120	0.118	0.119	0.232	0.232	0.232	0.113	0.285	0.286	0.286	0.054
Average	0.118	0.118	0.118	0.195	0.234	0.233	**0.115**	0.290	0.291	0.290	**0.057**

Table E.29: Abrasion Test, Mixture D, Run 1

Mix ID		Mix D -1			Mix Type :					Curing Peroid - 56 day
Mix Id No.	Weight	36.55	lb	Weight	36.4	lb	0.150	Weight	36.3	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.103	0.107	0.105	0.141	0.141	0.141	0.036	0.173	0.173	0.173	0.032
2	0.096	0.097	0.097	0.133	0.133	0.133	0.037	0.157	0.157	0.157	0.024
3	0.091	0.093	0.092	0.132	0.129	0.131	0.039	0.151	0.155	0.153	0.023
4	0.085	0.087	0.086	0.126	0.121	0.124	0.038	0.148	0.150	0.149	0.026
5	0.086	0.085	0.086	0.121	0.119	0.120	0.035	0.140	0.140	0.140	0.020
6	0.083	0.084	0.084	0.115	0.116	0.116	0.032	0.135	0.137	0.136	0.021
7	0.082	0.088	0.085	0.118	0.122	0.120	0.035	0.144	0.145	0.145	0.025
8	0.087	0.088	0.088	0.123	0.125	0.124	0.037	0.147	0.148	0.148	0.024
9	0.099	0.100	0.100	0.127	0.125	0.126	0.027	0.148	0.147	0.148	0.022
10	0.102	0.103	0.103	0.131	0.129	0.130	0.028	0.149	0.150	0.150	0.020
11	0.109	0.110	0.110	0.141	0.145	0.143	0.034	0.159	0.160	0.160	0.017
12	0.117	0.119	0.118	0.151	0.151	0.151	0.033	0.179	0.181	0.180	0.029
13	0.123	0.124	0.124	0.158	0.158	0.158	0.035	0.180	0.182	0.181	0.023
14	0.120	0.120	0.120	0.161	0.157	0.159	0.039	0.175	0.175	0.175	0.016
15	0.118	0.117	0.118	0.154	0.154	0.154	0.037	0.186	0.189	0.188	0.034
16	0.098	0.099	0.099	0.160	0.158	0.159	0.061	0.195	0.196	0.196	0.037
17	0.120	0.115	0.118	0.158	0.156	0.157	0.040	0.203	0.205	0.204	0.047
18	0.118	0.118	0.118	0.160	0.160	0.160	0.042	0.201	0.211	0.206	0.046
19	0.113	0.113	0.113	0.170	0.172	0.171	0.058	0.193	0.194	0.194	0.023
20	0.124	0.129	0.127	0.160	0.163	0.162	0.035	0.187	0.187	0.187	0.026
21	0.123	0.119	0.121	0.164	0.160	0.162	0.041	0.186	0.186	0.186	0.024
22	0.112	0.113	0.113	0.155	0.153	0.154	0.042	0.176	0.177	0.177	0.023
23	0.112	0.116	0.114	0.147	0.150	0.149	0.035	0.170	0.170	0.170	0.022
24	0.109	0.110	0.110	0.158	0.157	0.158	0.048	0.176	0.176	0.176	0.019
Average	0.105	0.106	0.106	0.195	0.144	0.144	**0.038**	0.169	0.000	0.170	**0.026**

Table E.30: Abrasion Test, Mixture D, Run 2

Mix ID		Mix D 2			Mix Type : MC- 4 %					Curing Peroid-56
Mix Id No.	Weight	36.45	lb	Weight	36.3	lb	0.150	Weight	36.1	lb	0.200
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.104	0.104	0.104	0.150	0.150	0.150	0.046	0.169	0.170	0.170	0.020
2	0.096	0.096	0.096	0.147	0.147	0.147	0.051	0.174	0.175	0.175	0.028
3	0.090	0.090	0.090	0.147	0.147	0.147	0.057	0.176	0.177	0.177	0.030
4	0.094	0.094	0.094	0.145	0.139	0.142	0.048	0.186	0.187	0.187	0.045
5	0.095	0.095	0.095	0.143	0.142	0.143	0.048	0.190	0.189	0.190	0.047
6	0.090	0.090	0.090	0.140	0.137	0.139	0.049	0.183	0.188	0.186	0.047
7	0.096	0.096	0.096	0.137	0.136	0.137	0.041	0.162	0.162	0.162	0.026
8	0.090	0.091	0.091	0.133	0.133	0.133	0.043	0.193	0.181	0.187	0.054
9	0.085	0.084	0.085	0.137	0.138	0.138	0.053	0.207	0.199	0.203	0.066
10	0.087	0.087	0.087	0.146	0.143	0.145	0.058	0.188	0.189	0.189	0.044
11	0.098	0.099	0.099	0.149	0.147	0.148	0.050	0.187	0.194	0.191	0.043
12	0.104	0.105	0.105	0.154	0.153	0.154	0.049	0.222	0.226	0.224	0.071
13	0.107	0.106	0.107	0.160	0.159	0.160	0.053	0.218	0.219	0.219	0.059
14	0.111	0.113	0.112	0.173	0.174	0.174	0.062	0.222	0.224	0.223	0.050
15	0.109	0.109	0.109	0.168	0.169	0.169	0.060	0.223	0.223	0.223	0.055
16	0.109	0.111	0.110	0.160	0.163	0.162	0.052	0.202	0.207	0.205	0.043
17	0.111	0.111	0.111	0.171	0.168	0.170	0.059	0.214	0.206	0.210	0.041
18	0.107	0.107	0.107	0.174	0.175	0.175	0.068	0.201	0.198	0.200	0.025
19	0.114	0.115	0.115	0.168	0.170	0.169	0.055	0.195	0.193	0.194	0.025
20	0.115	0.114	0.115	0.167	0.165	0.166	0.052	0.190	0.191	0.191	0.025
21	0.114	0.114	0.114	0.164	0.164	0.164	0.050	0.177	0.177	0.177	0.013
22	0.116	0.113	0.115	0.165	0.164	0.165	0.050	0.176	0.175	0.176	0.011
23	0.108	0.109	0.109	0.155	0.155	0.155	0.047	0.166	0.165	0.166	0.011
24	0.110	0.109	0.110	0.154	0.150	0.152	0.043	0.163	0.164	0.164	0.012
Average	0.103	0.103	0.103	0.154	0.154	0.154	**0.052**	0.191	0.191	0.191	**0.037**

Table E.31: Abrasion Test, Mixture D, Run 3

Mix ID		Mix D 3			Mix Type : MC- 4 %						Curing Peroid-56
Mix Id No.	Weight	35.9	lb	Weight	35.6	lb	0.300	Weight	35.4	lb	0.200
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.097	0.097	0.097	0.174	0.174	0.174	0.077	0.222	0.219	0.221	0.047
2	0.094	0.095	0.095	0.172	0.173	0.173	0.078	0.222	0.220	0.221	0.049
3	0.095	0.097	0.096	0.174	0.175	0.175	0.079	0.221	0.224	0.223	0.048
4	0.101	0.100	0.101	0.172	0.173	0.173	0.072	0.215	0.218	0.217	0.044
5	0.086	0.088	0.087	0.178	0.176	0.177	0.090	0.218	0.219	0.219	0.042
6	0.103	0.104	0.104	0.187	0.185	0.186	0.083	0.225	0.217	0.221	0.035
7	0.102	0.107	0.105	0.186	0.187	0.187	0.082	0.225	0.217	0.221	0.035
8	0.101	0.103	0.102	0.194	0.194	0.194	0.092	0.231	0.224	0.228	0.034
9	0.102	0.103	0.103	0.197	0.201	0.199	0.097	0.236	0.228	0.232	0.033
10	0.112	0.109	0.111	0.199	0.200	0.200	0.089	0.235	0.230	0.233	0.033
11	0.111	0.113	0.112	0.199	0.199	0.199	0.087	0.238	0.238	0.238	0.039
12	0.122	0.022	0.072	0.199	0.198	0.199	0.127	0.237	0.230	0.234	0.035
13	0.132	0.133	0.133	0.188	0.189	0.189	0.056	0.226	0.228	0.227	0.039
14	0.126	0.127	0.127	0.195	0.195	0.195	0.069	0.238	0.244	0.241	0.046
15	0.121	0.124	0.123	0.194	0.195	0.195	0.072	0.271	0.238	0.255	0.060
16	0.120	0.120	0.120	0.199	0.200	0.200	0.080	0.279	0.247	0.263	0.064
17	0.125	0.124	0.125	0.196	0.197	0.197	0.072	0.224	0.250	0.237	0.041
18	0.118	0.119	0.119	0.193	0.194	0.194	0.075	0.244	0.246	0.245	0.052
19	0.116	0.117	0.117	0.193	0.191	0.192	0.076	0.237	0.238	0.238	0.046
20	0.112	0.112	0.112	0.178	0.177	0.178	0.066	0.231	0.232	0.232	0.054
21	0.110	0.111	0.111	0.184	0.184	0.184	0.074	0.233	0.234	0.234	0.050
22	0.107	0.108	0.108	0.175	0.176	0.176	0.068	0.222	0.223	0.223	0.047
23	0.107	0.106	0.107	0.166	0.166	0.166	0.060	0.205	0.206	0.206	0.040
24	0.096	0.096	0.096	0.186	0.186	0.186	0.090	0.219	0.218	0.219	0.033
Average	0.109	0.106	0.107	0.186	0.187	0.187	**0.079**	0.231	0.229	0.230	**0.043**

Table E.32: Abrasion Test, Mixture E, Run 1

Mix ID		Mix E 1			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	36.95	lb	Weight	36.9	lb	0.050	Weight	36.8	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.140	0.141	0.141	0.162	0.162	0.162	0.022	0.176	0.175	0.176	0.014
2	0.130	0.131	0.131	0.161	0.162	0.162	0.031	0.179	0.179	0.179	0.018
3	0.119	0.119	0.119	0.150	0.149	0.150	0.031	0.166	0.166	0.166	0.017
4	0.096	0.094	0.095	0.125	0.126	0.126	0.031	0.147	0.149	0.148	0.023
5	0.105	0.104	0.105	0.135	0.134	0.135	0.030	0.151	0.153	0.152	0.018
6	0.085	0.087	0.086	0.114	0.113	0.114	0.028	0.132	0.132	0.132	0.019
7	0.087	0.084	0.086	0.128	0.122	0.125	0.040	0.137	0.138	0.138	0.013
8	0.107	0.107	0.107	0.121	0.119	0.120	0.013	0.134	0.134	0.134	0.014
9	0.091	0.091	0.091	0.114	0.114	0.114	0.023	0.130	0.129	0.130	0.016
10	0.098	0.098	0.098	0.125	0.122	0.124	0.026	0.136	0.135	0.136	0.012
11	0.118	0.119	0.119	0.132	0.130	0.131	0.013	0.138	0.139	0.139	0.008
12	0.118	0.120	0.119	0.142	0.140	0.141	0.022	0.152	0.154	0.153	0.012
13	0.122	0.123	0.123	0.143	0.141	0.142	0.020	0.152	0.151	0.152	0.010
14	0.116	0.111	0.114	0.145	0.142	0.144	0.030	0.159	0.162	0.161	0.017
15	0.101	0.105	0.103	0.137	0.135	0.136	0.033	0.152	0.154	0.153	0.017
16	0.093	0.094	0.094	0.130	0.130	0.130	0.037	0.150	0.151	0.151	0.021
17	0.099	0.099	0.099	0.132	0.133	0.133	0.034	0.152	0.151	0.152	0.019
18	0.096	0.096	0.096	0.128	0.129	0.129	0.033	0.151	0.150	0.151	0.022
19	0.104	0.104	0.104	0.137	0.138	0.138	0.034	0.159	0.159	0.159	0.022
20	0.103	0.106	0.105	0.139	0.138	0.139	0.034	0.165	0.165	0.165	0.027
21	0.117	0.117	0.117	0.157	0.157	0.157	0.040	0.173	0.174	0.174	0.017
22	0.124	0.124	0.124	0.155	0.155	0.155	0.031	0.172	0.173	0.173	0.018
23	0.134	0.134	0.134	0.156	0.156	0.156	0.022	0.174	0.175	0.175	0.019
24	0.135	0.136	0.136	0.161	0.161	0.161	0.026	0.177	0.178	0.178	0.017
Average	0.110	0.110	0.110	0.195	0.138	0.138	**0.028**	0.155	0.155	0.155	**0.017**

Table E.33: Abrasion Test, Mixture E, Run 2

Mix ID		Mix E 2			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	37.5	lb	Weight	37.25	lb	0.250	Weight	37.1	lb	0.15
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.097	0.096	0.097	0.161	0.161	0.161	0.065	0.201	0.197	0.199	0.038
2	0.113	0.114	0.114	0.176	0.176	0.176	0.063	0.217	0.213	0.215	0.039
3	0.131	0.133	0.132	0.193	0.193	0.193	0.061	0.233	0.229	0.231	0.038
4	0.149	0.149	0.149	0.203	0.203	0.203	0.054	0.240	0.236	0.238	0.035
5	0.157	0.160	0.159	0.219	0.215	0.217	0.059	0.248	0.245	0.247	0.030
6	0.163	0.163	0.163	0.228	0.228	0.228	0.065	0.260	0.260	0.260	0.032
7	0.162	0.165	0.164	0.227	0.228	0.228	0.064	0.259	0.260	0.260	0.032
8	0.163	0.163	0.163	0.220	0.222	0.221	0.058	0.253	0.253	0.253	0.032
9	0.139	0.140	0.140	0.211	0.213	0.212	0.073	0.244	0.245	0.245	0.033
10	0.120	0.121	0.121	0.192	0.191	0.192	0.071	0.224	0.223	0.224	0.032
11	0.107	0.106	0.107	0.180	0.179	0.180	0.073	0.218	0.215	0.217	0.037
12	0.106	0.106	0.106	0.181	0.182	0.182	0.076	0.214	0.210	0.212	0.031
13	0.118	0.116	0.117	0.187	0.187	0.187	0.070	0.209	0.211	0.210	0.023
14	0.129	0.128	0.129	0.193	0.194	0.194	0.065	0.207	0.209	0.208	0.015
15	0.137	0.136	0.137	0.192	0.188	0.190	0.054	0.203	0.206	0.205	0.015
16	0.133	0.137	0.135	0.184	0.184	0.184	0.049	0.198	0.200	0.199	0.015
17	0.129	0.129	0.129	0.182	0.183	0.183	0.054	0.199	0.199	0.199	0.017
18	0.112	0.113	0.113	0.175	0.172	0.174	0.061	0.195	0.196	0.196	0.022
19	0.101	0.102	0.102	0.163	0.163	0.163	0.062	0.186	0.187	0.187	0.024
20	0.104	0.104	0.104	0.168	0.168	0.168	0.064	0.198	0.199	0.199	0.031
21	0.108	0.108	0.108	0.167	0.166	0.167	0.059	0.198	0.199	0.199	0.032
22	0.109	0.105	0.107	0.175	0.175	0.175	0.068	0.204	0.207	0.206	0.031
23	0.108	0.108	0.108	0.166	0.166	0.166	0.058	0.189	0.191	0.190	0.024
24	0.097	0.099	0.098	0.160	0.160	0.160	0.062	0.197	0.197	0.197	0.037
Average	0.125	0.125	0.125	0.195	0.187	0.188	**0.063**	0.216	0.216	0.216	**0.029**

Table E.34: Abrasion Test, Mixture E, Run 3

Mix ID		Mix E 3			Mix Type :						Curing Peroid - 56 day
Mix Id No.	Weight	37.55	lb	Weight	37.45	lb	0.100	Weight	37.35	lb	0.1
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.146	0.151	0.149	0.172	0.171	0.172	0.023	0.224	0.223	0.224	0.052
2	0.151	0.163	0.157	0.198	0.187	0.193	0.036	0.231	0.231	0.231	0.039
3	0.152	0.154	0.153	0.200	0.202	0.201	0.048	0.231	0.233	0.232	0.031
4	0.145	0.154	0.150	0.196	0.194	0.195	0.046	0.225	0.224	0.225	0.030
5	0.135	0.136	0.136	0.191	0.191	0.191	0.056	0.213	0.210	0.212	0.021
6	0.138	0.136	0.137	0.191	0.190	0.191	0.054	0.216	0.212	0.214	0.024
7	0.142	0.147	0.145	0.179	0.181	0.180	0.036	0.200	0.197	0.199	0.019
8	0.143	0.139	0.141	0.175	0.176	0.176	0.035	0.190	0.190	0.190	0.015
9	0.120	0.119	0.120	0.163	0.159	0.161	0.042	0.176	0.174	0.175	0.014
10	0.111	0.109	0.110	0.146	0.144	0.145	0.035	0.165	0.165	0.165	0.020
11	0.107	0.100	0.104	0.131	0.130	0.131	0.027	0.151	0.152	0.152	0.021
12	0.104	0.093	0.099	0.126	0.122	0.124	0.026	0.143	0.143	0.143	0.019
13	0.090	0.083	0.087	0.116	0.116	0.116	0.030	0.136	0.134	0.135	0.019
14	0.089	0.084	0.087	0.113	0.113	0.113	0.027	0.136	0.133	0.135	0.022
15	0.092	0.086	0.089	0.116	0.119	0.118	0.029	0.133	0.133	0.133	0.016
16	0.098	0.094	0.096	0.121	0.123	0.122	0.026	0.145	0.141	0.143	0.021
17	0.098	0.096	0.097	0.123	0.125	0.124	0.027	0.147	0.143	0.145	0.021
18	0.090	0.087	0.089	0.120	0.121	0.121	0.032	0.140	0.142	0.141	0.021
19	0.109	0.112	0.111	0.127	0.127	0.127	0.017	0.146	0.146	0.146	0.019
20	0.093	0.098	0.096	0.132	0.137	0.135	0.039	0.152	0.155	0.154	0.019
21	0.113	0.110	0.112	0.143	0.138	0.141	0.029	0.173	0.173	0.173	0.033
22	0.140	0.123	0.132	0.152	0.145	0.149	0.017	0.187	0.184	0.186	0.037
23	0.136	0.130	0.133	0.156	0.160	0.158	0.025	0.199	0.198	0.199	0.041
24	0.136	0.142	0.139	0.164	0.163	0.164	0.025	0.212	0.214	0.213	0.050
Average	0.120	0.119	0.119	0.195	0.151	0.152	**0.033**	0.178	0.177	0.178	**0.026**

Table E.35: Abrasion Test, Mixture S, Run 1

Mix ID		Mix S 1			Mix Type :						Curing Peroid- 56 day
Mix Id No.	Weight	39.05	lb	Weight	39	lb	0.050	Weight	38.9	lb	0.100
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.064	0.064	0.064	0.067	0.068	0.068	0.004	0.075	0.074	0.075	0.007
2	0.065	0.065	0.065	0.069	0.070	0.070	0.005	0.077	0.078	0.078	0.008
3	0.061	0.063	0.062	0.064	0.065	0.065	0.003	0.076	0.076	0.076	0.012
4	0.062	0.063	0.063	0.069	0.071	0.070	0.008	0.076	0.076	0.076	0.006
5	0.064	0.063	0.064	0.068	0.067	0.068	0.004	0.077	0.077	0.077	0.009
6	0.067	0.065	0.066	0.069	0.069	0.069	0.003	0.079	0.081	0.080	0.011
7	0.064	0.064	0.064	0.077	0.077	0.077	0.013	0.079	0.078	0.079	0.002
8	0.071	0.074	0.073	0.078	0.077	0.078	0.005	0.078	0.081	0.080	0.002
9	0.070	0.070	0.070	0.077	0.075	0.076	0.006	0.080	0.080	0.080	0.004
10	0.068	0.067	0.068	0.074	0.072	0.073	0.005	0.076	0.077	0.077	0.004
11	0.064	0.063	0.064	0.071	0.070	0.071	0.007	0.076	0.075	0.076	0.005
12	0.062	0.062	0.062	0.068	0.069	0.069	0.007	0.071	0.072	0.072	0.003
13	0.063	0.063	0.063	0.069	0.068	0.069	0.006	0.071	0.073	0.072	0.003
14	0.062	0.062	0.062	0.067	0.066	0.067	0.005	0.072	0.073	0.073	0.006
15	0.062	0.062	0.062	0.066	0.065	0.066	0.004	0.070	0.072	0.071	0.006
16	0.061	0.061	0.061	0.066	0.065	0.066	0.005	0.071	0.073	0.072	0.006
17	0.061	0.061	0.061	0.065	0.066	0.066	0.005	0.072	0.072	0.072	0.006
18	0.062	0.062	0.062	0.066	0.068	0.067	0.005	0.074	0.073	0.074	0.006
19	0.066	0.066	0.066	0.070	0.066	0.068	0.002	0.077	0.077	0.077	0.009
20	0.063	0.063	0.063	0.066	0.069	0.068	0.005	0.074	0.074	0.074	0.007
21	0.064	0.064	0.064	0.068	0.069	0.069	0.005	0.078	0.078	0.078	0.009
22	0.066	0.066	0.066	0.070	0.068	0.069	0.003	0.075	0.075	0.075	0.006
23	0.063	0.062	0.063	0.066	0.066	0.066	0.004	0.074	0.075	0.075	0.008
24	0.062	0.062	0.062	0.066	0.067	0.067	0.005	0.074	0.075	0.075	0.008
Average	0.064	0.064	0.064	0.069	0.069	0.069	**0.005**	0.075	0.076	0.075	**0.006**

Table E.36: Abrasion Test, Mixtures S, Run 2

Mix ID		Mix S2			Mix Type :						Curing Peroid- 56 day
Mix Id No.	Weight	38.9	lb	Weight	38.8	lb	0.100	Weight	38.75	lb	0.050
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.066	0.061	0.064	0.072	0.073	0.073	0.009	0.079	0.079	0.079	0.007
2	0.066	0.064	0.065	0.077	0.079	0.078	0.013	0.085	0.084	0.085	0.007
3	0.069	0.067	0.068	0.082	0.084	0.083	0.015	0.094	0.089	0.092	0.008
4	0.075	0.071	0.073	0.088	0.088	0.088	0.015	0.091	0.092	0.092	0.004
5	0.080	0.079	0.080	0.085	0.088	0.087	0.007	0.097	0.096	0.097	0.010
6	0.080	0.080	0.080	0.084	0.089	0.087	0.006	0.100	0.098	0.099	0.013
7	0.082	0.080	0.081	0.092	0.091	0.092	0.011	0.097	0.098	0.098	0.006
8	0.083	0.081	0.082	0.090	0.089	0.090	0.007	0.100	0.098	0.099	0.010
9	0.075	0.071	0.073	0.084	0.081	0.083	0.010	0.088	0.089	0.089	0.006
10	0.069	0.067	0.068	0.080	0.079	0.080	0.012	0.086	0.086	0.086	0.006
11	0.060	0.060	0.060	0.073	0.072	0.073	0.013	0.079	0.080	0.080	0.007
12	0.061	0.060	0.061	0.070	0.072	0.071	0.011	0.076	0.078	0.077	0.006
13	0.062	0.061	0.062	0.071	0.070	0.071	0.009	0.077	0.078	0.078	0.007
14	0.063	0.063	0.063	0.073	0.072	0.073	0.009	0.081	0.079	0.080	0.008
15	0.067	0.066	0.067	0.076	0.075	0.076	0.009	0.082	0.081	0.082	0.006
16	0.071	0.071	0.071	0.080	0.081	0.081	0.010	0.087	0.087	0.087	0.006
17	0.076	0.076	0.076	0.080	0.081	0.081	0.005	0.087	0.087	0.087	0.006
18	0.072	0.073	0.073	0.081	0.080	0.081	0.008	0.085	0.084	0.085	0.004
19	0.075	0.074	0.075	0.079	0.081	0.080	0.006	0.085	0.085	0.085	0.005
20	0.074	0.073	0.074	0.076	0.077	0.077	0.003	0.082	0.080	0.081	0.005
21	0.073	0.072	0.073	0.074	0.076	0.075	0.003	0.081	0.080	0.081	0.006
22	0.068	0.068	0.068	0.069	0.070	0.070	0.002	0.077	0.077	0.077	0.007
23	0.063	0.062	0.063	0.067	0.068	0.068	0.005	0.076	0.076	0.076	0.008
24	0.062	0.062	0.062	0.067	0.067	0.067	0.005	0.075	0.075	0.075	0.008
Average	0.071	0.069	0.070	0.078	0.078	0.078	**0.008**	0.085	0.085	0.085	**0.007**

Table E.37: Abrasion Test, Mixture T, Run 1

Mix ID		Mix T 1			Mix Type :						Curing Peroid- 56 day
Mix Id No.	Weight	36.15	lb	Weight	35.9	lb	0.250	Weight	35.75	lb	0.150
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.092	0.086	0.089	0.128	0.128	0.128	0.039	0.159	0.155	0.157	0.029
2	0.091	0.084	0.088	0.131	0.134	0.133	0.045	0.153	0.150	0.152	0.019
3	0.100	0.094	0.097	0.129	0.130	0.130	0.033	0.154	0.152	0.153	0.024
4	0.082	0.083	0.083	0.136	0.138	0.137	0.055	0.165	0.162	0.164	0.027
5	0.079	0.083	0.081	0.144	0.146	0.145	0.064	0.171	0.169	0.170	0.025
6	0.081	0.085	0.083	0.149	0.148	0.149	0.066	0.169	0.179	0.174	0.026
7	0.088	0.089	0.089	0.148	0.149	0.149	0.060	0.179	0.175	0.177	0.029
8	0.089	0.089	0.089	0.143	0.143	0.143	0.054	0.175	0.172	0.174	0.031
9	0.082	0.083	0.083	0.138	0.137	0.138	0.055	0.171	0.172	0.172	0.034
10	0.083	0.084	0.084	0.136	0.136	0.136	0.053	0.171	0.164	0.168	0.032
11	0.079	0.077	0.078	0.139	0.139	0.139	0.061	0.162	0.162	0.162	0.023
12	0.073	0.073	0.073	0.137	0.138	0.138	0.065	0.164	0.167	0.166	0.028
13	0.077	0.077	0.077	0.133	0.134	0.134	0.057	0.156	0.155	0.156	0.022
14	0.073	0.072	0.073	0.124	0.131	0.128	0.055	0.156	0.156	0.156	0.029
15	0.081	0.081	0.081	0.137	0.136	0.137	0.056	0.163	0.162	0.163	0.026
16	0.086	0.086	0.086	0.145	0.139	0.142	0.056	0.162	0.164	0.163	0.021
17	0.087	0.086	0.087	0.143	0.143	0.143	0.057	0.167	0.169	0.168	0.025
18	0.086	0.088	0.087	0.148	0.145	0.147	0.060	0.168	0.166	0.167	0.021
19	0.084	0.084	0.084	0.140	0.131	0.136	0.052	0.159	0.160	0.160	0.024
20	0.084	0.084	0.084	0.147	0.139	0.143	0.059	0.157	0.158	0.158	0.015
21	0.084	0.081	0.083	0.142	0.133	0.138	0.055	0.155	0.156	0.156	0.018
22	0.086	0.087	0.087	0.137	0.129	0.133	0.047	0.151	0.153	0.152	0.019
23	0.078	0.079	0.079	0.141	0.131	0.136	0.058	0.152	0.154	0.153	0.017
24	0.086	0.086	0.086	0.134	0.127	0.131	0.045	0.148	0.150	0.149	0.019
Average	0.084	0.083	0.084	0.139	0.137	0.138	**0.054**	0.162	0.162	0.162	**0.024**

Table E.38: Abrasion Test, Mixture T, Run 2

Mix ID		Mix T 2			Mix Type :						Curing Peroid- 56 day
Mix Id No.	Weight	36.15	lb	Weight	35.95	lb	0.200	Weight	35.85	lb	0.100
Wear depth (in.) at time (min.)											
Pos.	0 min			30 min				60 Min			
	R1	R2	Average	R1	R2	Average	Difference	R1	R2	Average	Difference
1	0.071	0.069	0.070	0.113	0.110	0.112	0.042	0.123	0.123	0.123	0.012
2	0.068	0.068	0.068	0.113	0.109	0.111	0.043	0.119	0.118	0.119	0.007
3	0.068	0.068	0.068	0.112	0.108	0.110	0.042	0.119	0.119	0.119	0.009
4	0.069	0.065	0.067	0.100	0.096	0.098	0.031	0.113	0.113	0.113	0.015
5	0.062	0.062	0.062	0.107	0.099	0.103	0.041	0.112	0.113	0.113	0.009
6	0.062	0.059	0.061	0.096	0.095	0.096	0.035	0.114	0.116	0.115	0.020
7	0.066	0.065	0.066	0.089	0.091	0.090	0.025	0.114	0.112	0.113	0.023
8	0.064	0.064	0.064	0.094	0.094	0.094	0.030	0.116	0.117	0.117	0.023
9	0.065	0.065	0.065	0.092	0.089	0.091	0.026	0.112	0.112	0.112	0.022
10	0.063	0.063	0.063	0.095	0.093	0.094	0.031	0.111	0.111	0.111	0.017
11	0.064	0.066	0.065	0.099	0.092	0.096	0.031	0.114	0.115	0.115	0.019
12	0.063	0.064	0.064	0.091	0.089	0.090	0.027	0.112	0.112	0.112	0.022
13	0.067	0.067	0.067	0.096	0.096	0.096	0.029	0.113	0.113	0.113	0.017
14	0.066	0.066	0.066	0.099	0.099	0.099	0.033	0.116	0.116	0.116	0.017
15	0.070	0.070	0.070	0.102	0.102	0.102	0.032	0.122	0.122	0.122	0.020
16	0.070	0.069	0.070	0.106	0.105	0.106	0.036	0.120	0.120	0.120	0.015
17	0.070	0.069	0.070	0.112	0.113	0.113	0.043	0.121	0.121	0.121	0.008
18	0.069	0.068	0.069	0.112	0.111	0.112	0.043	0.124	0.123	0.124	0.012
19	0.073	0.072	0.073	0.110	0.110	0.110	0.038	0.123	0.122	0.123	0.013
20	0.074	0.073	0.074	0.114	0.114	0.114	0.041	0.127	0.127	0.127	0.013
21	0.074	0.075	0.075	0.114	0.114	0.114	0.040	0.127	0.127	0.127	0.013
22	0.074	0.074	0.074	0.112	0.112	0.112	0.038	0.131	0.130	0.131	0.019
23	0.069	0.068	0.069	0.112	0.112	0.112	0.044	0.132	0.132	0.132	0.020
24	0.069	0.067	0.068	0.111	0.111	0.111	0.043	0.131	0.130	0.131	0.020
Average	0.068	0.067	0.068	0.104	0.103	0.103	**0.036**	0.119	0.119	0.119	**0.016**

APPENDIX F:
FIELD STUDY RECOMMENDATIONS

Field Study Recommendations

One of the limitations of the laboratory study was that all of the tests for the different response variables were conducted in a way that precluded the confounding effects of, and the interaction between, the different response variables. Although this approach simplified the study, it also merely simulated in-service conditions. Therefore, a field study that includes the combined effects of studded tire wear and the environment is essential to validate laboratory results.

The following briefly outlines a potential plan for a field study with an objective to assess, under in-service conditions, the wear resistance of bridge deck panels fabricated with high performance concrete (HPC) and placed on a bridge exposed to studded tires. It proposes the mixtures to investigate and general guidance with regard to the location of the bridge on which to place the precast panels, the number of panels to construct and layout of the panels on the bridge, performance monitoring techniques and data to collect, and data analyses.

Mixtures

The findings from the laboratory study indicated that Mixtures E, S, and T outperformed the control mixture with regard to resistance to wear and chloride ion penetration. Mixtures S and T contained a greater quantity of cement relative to Mixture E and the control mixture, and Mixture S also contained a higher percentage of silica fume. However, since Mixture T performed only marginally better than Mixture E in terms of both abrasion resistance and chloride ion penetration resistance, it may be advised to exclude it from the field study. As a minimum, it is proposed that the field study include the control mixture and Mixtures E and S. Table F.1 summarizes the mix designs for these four mixtures, and indicates inclusion of Mixture T is optional. All mixtures should contain entrained air as per Section 02001 of the Oregon 2008 Standard Specifications for Construction.

Table F.1 – Proposed Mixture Designs

Constituent	Quantity, lb/ft^3			
	Control Mixture	Mixture E	Mixture S	Mixture T (Optional)
Cement (Type III)	541	541	604	604
Fly Ash	246	0	0	0
Slag	0	246	365	396
Silica Fume	33	33	74	42
Water	245	245	269	279
Coarse Aggregate (3/4 x 1/2 in.)	661	661	620	624
Sand	928	963	1065	1062
w/cm ratio	0.30	0.30	0.26	0.27

Bridge Location

It is essential that the location of the bridge be chosen such that it is exposed to vehicles with studded tires. Highways with high traffic volumes are recommended. Highways leading to ski resorts (e.g., U.S. 26, U.S. 20, OR 22, and OR 58, to name a few) are likely to be good candidates for roadways with vehicles equipped with studded tires.

In addition, the bridge should be located in an area that is likely to experience many freeze-thaw cycles. As such, it is recommended that the bridge be located in the mountains or on the east side of the Cascades at an elevation above 1,000 feet.

Consideration should also be given to exposure to deicing salts. Although selection of a particular bridge should not be based on whether or not it is exposed to deicing salts, use of these materials should be taken into account since performance of the concrete mixtures may be impacted by these materials.

Number of Precast Panels and Layout

In order to conduct an analysis of variance (see below), variance of the response variable (i.e., wear depth) is required for each set of panels. This necessitates constructing more than one panel for each mix design. Ideally, multiple panels per mix design should be constructed. However, keeping in mind costs of construction and performance monitoring will be directly proportional to the number of panels constructed, a reasonable compromise is to recommend three panels per mix design. As a bare minimum, two panels per mix design will be required.

Figure F.1 illustrates a conceptual layout of the precast panels. Note that if Mixture T is included in the field study, three additional panels would be needed. The relative positions of the panels to one another are included for illustrative purposes only; the actual positioning of the panels should be chosen by a random selection process. However, the panels should be positioned near the center of the span so as to minimize the effects due to the dynamics of vehicle suspensions.

Note that Figure F.1 suggests that the panels span the entire width of the bridge (i.e., travel lanes plus shoulders). This has been assumed to be the case for this type of bridge deck design. However, if this is not the case, the panels should at least span the entire width of the travel lanes.

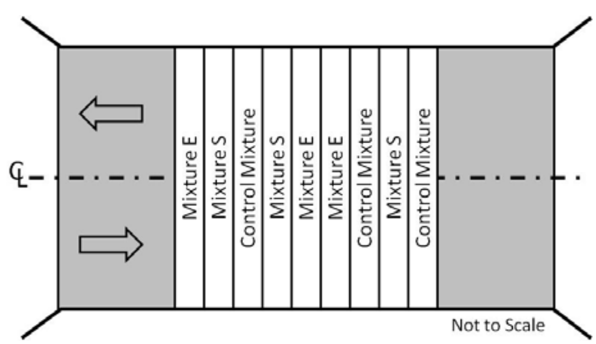

Figure F.1: Conceptual Layout of Panels

Performance Monitoring

The study proposes to investigate the wear resistance of precast bridge deck panels constructed with different HPC mixtures. A key component of the investigation is monitoring the performance characteristics of the various panels in such a way as to accurately determine wear depth. Such information would allow comparisons of the various mixtures with regard to wear resistance.

Inclusion of traffic information would significantly enhance the potential for further analysis. Such information could be used for predicting life expectancy which, in turn, could be used for the purposes of life cycle cost analyses.

The following paragraphs briefly describe potential methods for measuring the surface profile of the deck panels and for determining traffic characteristics. It also discusses the duration over which the performance monitoring should be conducted and the frequency of data collection.

Surface Profile

Wear depth in the wheel paths due to studded tires is the principal surface characteristic of concern. Hence, measurement of transverse profile is recommended. As a minimum, measurements should be made at two locations in the longitudinal direction within each panel. One longitudinal location should be near one of the transverse edges (joints) of the panel and one should be approximately midway (longitudinally) between the edges. If measurements are not made at both longitudinal locations within each panel, then measurements should be made at the central location.

Surface profile measurements in the transverse direction should be made at multiple locations. First-time measurements should be only inches apart so as to establish a well-defined datum that is certain to capture the as-yet undeveloped rut for each longitudinal location as illustrated conceptually in Figure F.2. Subsequent measurements at such fine increments could be confined to only a few transverse locations within the wheel paths once the rut develops. However, three to five transverse locations in each wheel path are recommended so that an average wear depth can be estimated. The three to five locations for each wheel path should be chosen such they approximately centered within the wheel paths.

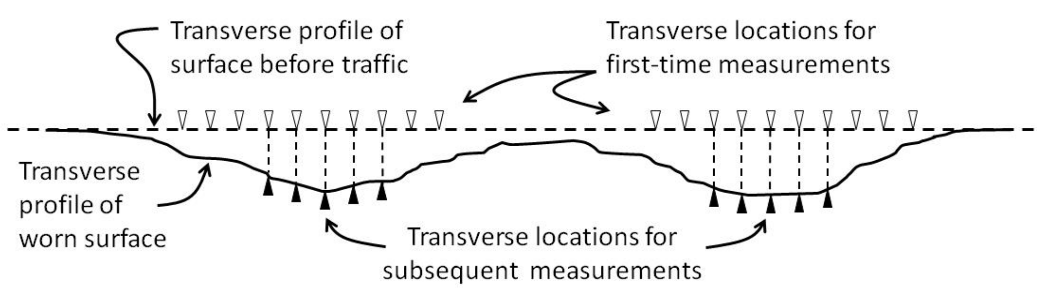

Figure F.2: Conceptual Layout of Surface Profile Measurement Locations

Irrespective of the number of measurement locations, it will be essential to accurately establish the longitudinal and transverse positions of the measurements so that these can be made at the same locations over time. It is also essential that the measurements made in the transverse direction be of sufficient accuracy so as to detect very small changes in depth.

There are many ways to measure the transverse profile of pavements ranging from a simple, low-cost straightedge to rod and level surveys at moderate expense to sophisticated, but usually quite expensive, laser profiling devices. Aside from cost, each has distinct advantages and disadvantages. For the purposes of the field study, and keeping in mind the need for measurement accuracy and the ability to relocate positions in the longitudinal direction where the measurements are made (which would most likely preclude laser profiling devices), it is recommended to either conduct rod and level surveys or use a Dipstick device for the transverse profile measurements. ODOT personnel could be used for rod and level surveys, whereas the manufacturer of the Dipstick device, which essentially performs a differential survey semi-automatically, rents the device on a weekly or monthly basis.

Traffic Characteristics

Collection of traffic data is optional, but it could add significant benefit to the study. The desired information regarding traffic characteristics includes, as a minimum, total vehicles traversing each bridge in both directions during each data collection period (see below). However, it is suggested to also estimate the number of these vehicles equipped with studded tires. Obtaining traffic counts could be accomplished with the assistance of the Transportation Development Division within ODOT. It will be important to conduct the counts in such a way as to obtain reasonably accurate information for the purposes of estimating life expectancy.

Data Collection Periods and Frequency

Permitted use of studded tires in Oregon ordinarily runs from November 1 through April 1 (herein referred to as the studded tire season), unless extended due to particularly inclement weather. Hence, data collection should be constrained to approximately this period, but should occur over at least two studded tire seasons. Note that data collection over additional seasons would strengthen estimates for life expectancy and life cycle costs (discussed below).

Baseline measurements for transverse profile should be performed prior to each studded tire season (say, in late October). As a minimum, these measurements should also be made at the end of each studded tire season (say, in early April). However, it is recommended that at least one set of measurements be made at approximately mid-season during each data collection period.

If traffic counts are to be collected, it is recommended that basic traffic data (i.e., total number of vehicles) be collected continuously, using automated counters, over each studded tire season. If automated counters are not employed, the number of manual counts should be sufficiently large so as to obtain as accurate of information as possible. If counts for the number of vehicles equipped with studded tires are also to be collected, these should be accomplished using manual counts. Again, the number of manual counts should be sufficiently large so as to obtain as accurate of information as possible. Both types of counts could be collected simultaneously.

Analyses

Comparison of wear depths on the panels with the various mixtures is the principal outcome desired from the data analysis. If traffic data is also collected, life expectancy can be estimated for the purposes of conducting life cycle cost analyses. The following paragraphs discuss how the data should be analyzed.

Wear Depth

For the purposes of the field study, wear depth should be defined as the change (decrease) in elevation of the deck panel surface at a specific longitudinal and transverse location. That is, the depth should be measured and evaluated at specific locations so as to eliminate measurement location as a variable. It was recommended above that measurements be made at three to five locations within each wheel path so that the individual depths could be averaged as illustrated in Figure F.3 (using five measurements in the example shown). Using the average wear depth in this manner will, to some degree, reduce the effects of wheel wander. The average wear depths of the two wheel paths could be averaged as well to provide an overall average wear depth for each longitudinal location.

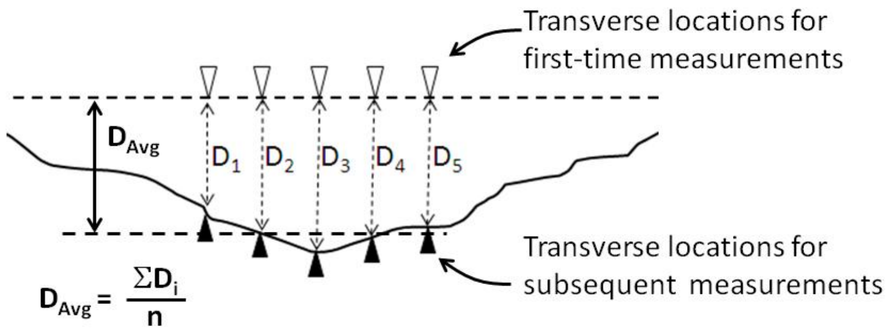

Figure F.3: Determination of the Average Wear Depth within a Single Wheel Path

A statistical method for comparing the response variable (i.e., average wear depth of each longitudinal location on each panel) should be employed to determine if the response variable is significantly different amongst the panels comprised of the various mixtures. Perhaps the most efficient way to accomplish this is to conduct an analysis of variance for each longitudinal location.

Life Expectancy and Life Cycle Costs

Life expectancy of each bridge deck panel is the one of the principal outcomes desired from analysis of the data. Another is life cycle cost of each deck panel. The following paragraphs provide an overview of how the data can be analyzed to achieve these outcomes.

Life expectancy can be obtained through estimates of wear rates and traffic coupled with definition of a wear depth that signifies a terminal condition (e.g., end of useful in terms of functional performance). Note that definition of a terminal condition is typically a policy decision. Also, the accuracy of the estimate for life expectancy depends, to a large extent, on the accuracy of wear depth measurements and traffic counts (including the proportion of vehicles equipped with studded tires). Hence, collection of accurate data cannot be overemphasized.

The wear rate can be estimated by dividing the recorded wear depth by the traffic count, both determined over the same period for a given panel. Wear depth has the units of length (e.g., inches) and traffic count is an integer representing the number of vehicles equipped with studded tires, which could be divided by, say, one thousand for ease of interpreting the wear rate (e.g., 0.002 inches per thousand vehicles with studded tires). The number of vehicles with studded tires could also be expressed as a percentage of average daily traffic, or total number of vehicles (with and without studded tires).

Once the wear rate has been estimated, a chosen wear depth representing a terminal condition (say, 0.25 inches) can be divided by the wear rate to provide an estimate of the total traffic required to cause the chosen wear depth. The total traffic can then be divided by estimates of future traffic to predict the time to the terminal condition (i.e., life expectancy).

For example, a wear rate of 0.002 inches per thousand vehicles with studded tires and a terminal wear depth of 0.25 inches gives 0.25/0.002/1,000 = 125,000 vehicles with studded tires. Now, if only 10% of vehicles in a given area had studded tires, and average daily traffic is estimated to be 5,000 for a given highway segment in the area, then the predicted number of days required to reach a wear depth of 0.25 inches would be 125,000/(0.10)(5,000) = 250 days, or less than two studded tire seasons. Obviously, these are hypothetical results, but they do illustrate how life expectancy can be estimated.

Estimates of life expectancy for each deck panel can be used in life cycle cost analyses to compare the cost effectiveness of the mixtures used to construct the panels. For example, one mixture may cost substantially more than another to construct panels of equal dimensions, but the panel with the higher-cost mixture may outlast (have a greater life expectancy than) the panel with the lower-cost mixture. Life cycle cost analysis is a tool that can be used to determine which alternative has the lower overall cost over a given period.

In conducting a life cycle cost analysis, it will be important to select an analysis period that has duration of at least the greatest life expectancy of the panels being investigated. However, the FHWA recommends that the analysis period be of sufficient duration so as to include at least one rehabilitation activity for each alternative investigated. In addition, it is essential that all panels are evaluated using the same analysis period. Typically, relative cost effectiveness of the alternatives is evaluated based on present worth cost or equivalent annual cost; however, there are other measures such as cost-benefit ratio and minimum attractive rate of return.