Field Studies of Concrete Containing Salts of an Alkenyl-Substituted Succinic Acid

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16. Abstract

The effects of the corrosion inhibitor Hycrete DSS on the physical characteristics of concrete, at full production scale, were evaluated. An extensive literature review, methods for using Hycrete DSS in standard concrete mix designs, results from standardized testing of concrete mixes and implementation projects are presented. Experimental testing included 6 large-scale pours at 3 ready-mixed concrete plants in New England and 1 precast concrete facility. A total of 10 Hycrete DSS mixes and 5 representative control mixes were tested. In these large scale tests it was found Hycrete DSS has no detriment to workability and entrained air at desired levels could be obtained consistently. The absorption of hardened concrete containing Hycrete DSS was less than half of values obtained in the control mixes. If no alterations were made to a mix design, Hycrete DSS was found to reduce the compressive strength of a concrete mix in comparison to the control, with related impact on freeze-thaw durability and bond strength. However the required design parameters for each mix were met or exceeded. Four applications, including methods for long term corrosion monitoring, were chosen as potential implementation projects. Two projects were completed; major structural components of a ferry terminal (Maine) and a bridge curb (Vermont). Initial ferry terminal concrete batching procedures required modifications to meet specified air content. Other considered implementations included patching of deteriorated overpass bridge bent columns (Massachusetts) and large precast culverts (New York). Highway barriers previously implemented by the Connecticut Department of Transportation (Connecticut) are also described.

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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	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		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 temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres 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	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F
-40 0 40 80 120 180 200
-40 -20 0 20 40 60 80 100
°C 37 °C

ABSTRACT

The effects of the corrosion inhibitor Hycrete DSS on the physical characteristics of concrete, at full production scale, were evaluated. An extensive literature review, methods for using Hycrete DSS in standard concrete mix designs, results from standardized testing of concrete mixes and implementation projects are presented. Experimental testing included 6 large-scale pours at 3 ready-mixed concrete plants in New England and 1 precast concrete facility. A total of 10 Hycrete DSS mixes and 5 representative control mixes were tested. In these large scale tests it was found Hycrete DSS has no detriment to workability and entrained air at desired levels could be obtained consistently. The absorption of hardened concrete containing Hycrete DSS was less than half of values obtained in the control mixes. If no alterations were made to a mix design, Hycrete DSS was found to reduce the compressive strength of a concrete mix in comparison to the control, with related impact on freeze-thaw durability and bond strength. However the required design parameters for each mix were met or exceeded. Four applications, including methods for long term corrosion monitoring, were chosen as potential implementation projects. Two projects were completed; major structural components of a ferry terminal (Maine) and a bridge curb (Vermont). Initial ferry terminal concrete batching procedures required modifications to meet specified air content. Other considered implementations included patching of deteriorated overpass bridge bent columns (Massachusetts) and large precast culverts (New York). Highway barriers previously implemented by the Connecticut Department of Transportation (Connecticut) are also described.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Snow and ice have a major impact on the safety and operation of New England roads. The use of solid chemicals and chemical solutions as deicers and anti-icing treatments is at the core of winter maintenance programs practiced by state transportation agencies. Chloride salt is traditionally used as the principal deicer. Problematically, corrosion of bridge decks and other reinforced concrete transportation infrastructure is accelerated due to the use of these deicing salts. Alternatives to deicing salts have been investigated but in general have not been found to be cost competitive, readily available, safe, and/or effective. Therefore the use of chloride salts is not expected to decrease and it is important for transportation agencies to explore state of the art methods to mitigate the adverse effects of deicing salts.

For this reason, transportation agencies in New England and in other parts of the country have recently become interested in a new proprietary chemical admixture for concrete, Hycrete DSS. This chemical was investigated in two laboratory studies conducted by regional transportation research organizations in New England. When compared to other common defensive strategies against chloride attack, Hycrete DSS was found to provide excellent damp proofing and corrosion resisting characteristics in reinforced concrete specimens. Based upon the apparent potential benefits of the admixture the New England Transportation Consortium (NETC) has invested in the reported study to verify full-scale mixture poperties and aid implementation of the new admixture.

By developing design and control procedures for standard Hycrete DSS concrete mixes, New England transportation organizations will be able to implement Hycrete DSS in full-scale transportation infrastructure applications. Expected results will include increased service lives, longer intervals between repairs and remediation, and increased structural integrity of transportation infrastructure elements.

1.2 Organization of Document

Chapter 2 summarizes background information relevant to the study: corrosion mechanisms, corrosion costs, corrosion mitigation solutions, life cycle analyses, supplemental information on the chemical Hycrete DSS, and corrosion field evaluation techniques. Chapter 3 contains a literature review specific to the topic of Hycrete DSS concrete. Chapter 4 outlines the approach and methods for conducting a field study for an experimental concrete mix with applicable test specifications and evaluation techniques. The results and appropriate discussions are presented in Chapter 5. Chapter 6 addresses field implementation projects. In the final section of the document, Chapter 7, overall conclusions are developed for the field study along with recommendations for future research. Previously unreported data from the University of Massachusetts (UMass) relating to the project, but not part of this research project, is reported in Section 5.2.3.2.

CHAPTER 2

CORROSION OF REINFORCED CONCRETE AND TEST METHODS

2.1 Corrosion Effects

One of the clearest measures of the impact of corrosion is cost. A recent study of corrosion costs was published in 2001, and was carried out in fulfillment of an amendment for the cost of corrosion that was included in the Transportation Equity Act for the 21st Century (TEA-21). This report, Corrosion Cost and Preventive Strategies in the United States (Koch 2001), estimated the total cost of metallic corrosion in the United States to be $276 billion per year, which was 3.1 percent of the U.S. gross domestic product in 1998. Regarding transportation infrastructure, corrosion of highway bridges accounted for $8.3 billion, which includes $3.8 billion to replace structurally deficient bridges over the next 10 years, $2.0 billion for maintenance and cost of capital for concrete bridge decks, and $2.0 billion for maintenance and cost of capital for concrete substructures (minus decks).

Another reference, National Cost of Damage to Infrastructure from Highway Deicing (Menzies 1992), reported in 1992 the findings from a National Research Council committee about the specific costs associated to highway deicing. The annual cost to infrastructure from deicing was estimated to be between 400 and 900 million dollars per year. Menzies states, “Bridge decks are the principal recipient of salt’s adverse effects” (p. 31).

Based upon 2005 data from the National Bridge Inventory (NBI) there are 11,608 concrete bridges in New England and New York State alone, comprising 33% of the bridges, by material type, in this region (http://www.fhwa.dot.gov/bridge/nbi.htm).

2.2 Corrosion Process of Reinforced Concrete

Iron (Fe), the main ingredient of structural steel is commonly found naturally in the form, iron oxide (Fe_2O_3). When pure metallic iron (Fe) in steel is exposed to the air (O_2) and water (H_2O), it will return to the more common form, iron oxide. This is the principal mechanism for the aqueous corrosion of steel (see Figure 2.1). This simple explanation is the starting point for understanding the more specific process of corrosion in reinforced concrete.

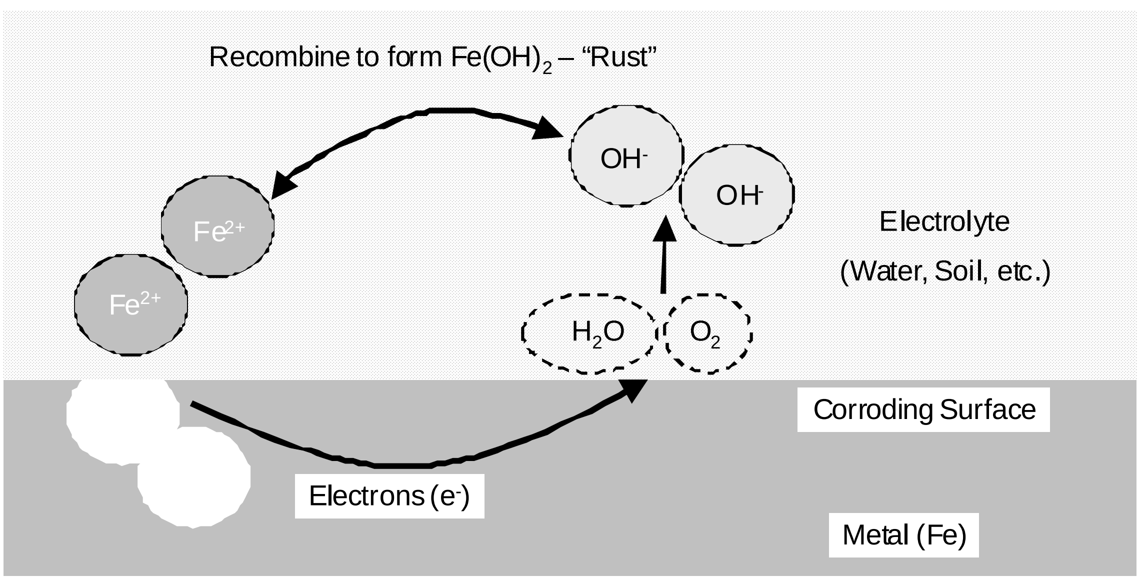


Figure 2.1: Corrosion of Solid Iron (www.corrosion-club.com)

In reinforced concrete structural steel bars are the most common material used for reinforcement. Standard reinforcing bars (rebar) are referred to as black steel bars. This black rebar will corrode, as illustrated in Figure 2.1, in the presence of oxygen and water. These elements can migrate through concrete through a pore structure of entrained air and micro-cracks. Corrosion of reinforcement in concrete is an electrochemical process with an anodic dissolution of iron reaction and a balancing cathodic oxygen reduction reaction. These electrochemical cells can be localized over one piece of reinforcement or between layers of reinforcement connected by ties or stirrups. The severity of corrosion is often measured by the corrosion rate. When rebar is embedded in concrete and is in the absence of chlorides, it will exhibit strongly passive behavior. The corrosion rate of the rebar is retarded due to the highly alkaline environment of the concrete and the formation of iron-oxide compounds (byproducts of the initial corrosion process), which create an insoluble passivating layer on the surface of the rebar.

Of specific importance to reinforced transportation structures in the Northeast United States is the affect of deicing salts on the corrosion process. The presence of chlorides (e.g. calcium chloride ($CaCl_2$) and sodium chloride (NaCl)) from deicing salts in sufficient concentration at the rebar level dramatically increases the corrosion rate. Chlorides can migrate though the concrete pore structure in the form of brine (a combination of road salts and melted snow or ice). The increase in corrosion rate is due to the weakening of the passivating layer (described previously) by the following means. When chlorides are present, the chloride ions (Cl^-) will compete with the hydroxide ions (OH^-) from the water and oxygen molecules to combine with the ferrous

(Fe^{2+}) cations from the pure iron in the steel. The passivating layer created from this reaction is thought to be unstable and soluble. When chloride content reaches a critical chloride threshold limit the passivating layer can break down. The anodic reaction is no longer inhibited and the corrosion process can continue. The uninhibited dissolution of iron cations is the loss of structural steel.

Another effect of corrosion of reinforced concrete is delamination and spalling of concrete. Delamination and spalling of concrete results from significant internal stresses caused by the byproducts of the corrosion, which occupy two to eight times the amount of space as the reinforcing steel. Spalling and cracking allow the direct access of chlorides, water, and air to the reinforcement, greatly accelerating the reactions previously described. Iron loss and concrete damage can lead to high repair costs and decreased service lives of transportation structures (Berke et. al.1992).

2.3 Service Life Model and Corrosion Mitigation Solutions

The corrosion process of reinforced concrete can be separated into two phases: the initiation phase and the propagation phase. In the initiation phase the chlorides on the surface of the concrete diffuse through the concrete and accumulate on the reinforcing bar. When the concentration of chlorides reaches a critical threshold level the passivity layer on the reinforcing bar becomes ineffective and the corrosion process initiates. The initiation phase ends and the propagation phase begins with the onset of corrosion. In the propagation phase the reinforcing bars will corrode at a certain rate until the corrosion reaches an unacceptable level. At this point the reinforced concrete structure has reached its service life and repair is necessary (Bentz and Thomas 2001).

Mishra (2000) argues that, “the primary aim of design must be to prevent permeation of corrodents onto the rebar.” In other words the initiation phase is the most critical in corrosion mitigation. One method of preventing corrodents from reaching the concrete reinforcement is to set the reinforcing steel apart from the corrosive environment. Some specific methods include: increase concrete cover, minimize cracking, create dense and homogenous concrete, and provide barrier to the intrusion of salt, water and oxygen. The latter is often in the form of a coating, penetrating sealer or membrane. Alternative methods can be used when the rebar cannot be set apart from the corrosive environment. These alternative methods include the use of epoxy coated rebar, corrosion resistant reinforcement, corrosion inhibiting chemicals, and cathodic protection.

Normally transportation agencies take a multi-method approach in protecting transportation infrastructure. For example in a bridge deck, concrete cover may be increased, epoxy coated rebar could be used, and a concrete mixture design with low permeability could be used at the same time. This project focuses on one specific corrosion inhibiting chemical admixture, Hycrete DSS.

2.4 Hycrete DSS Concrete Admixture

Hycrete DSS is technically referred to as disodium tetrapropenyl succinate (DSS), which is a salt of an alkenyl-substituted succinic acid. Hycrete DSS was developed by Broadview Technologies and now produced and distributed by Hycrete Technologies LLC. According to representatives from Hycrete Technologies LLC and the company website, the chemical was developed from an oil soluble rust inhibitor that was used in the motor oil and lube industries (hycrete.com 2005). The chemical was evaluated as a concrete additive by University of Connecticut Department of Civil Engineering Professors Greg Franz and Jack Stephens.

Hycrete DSS in appearance is a clear to slightly hazy light yellow liquid. According to manufacturer specifications, Hycrete DSS is a water-soluble chemical that is volatile organic compound (VOC) free and environmental friendly. Hycrete DSS was recognized by McDonough Braungart Design Chemistry (MBDC) with a "Cradle to Cradle™ Environmental Certification". This recognition certifies that Hycrete DSS has met stringent environmental and human health standards in product design.

Hycrete DSS is delivered as a solution containing 80% water and 20% Hycrete DSS solids, with a density of approximately 66 lb/ft^3 (1055 kg/m^3), slightly higher than that of water. The manufacturer's recommended dosage for Hycrete DSS in a concrete mix is 1-2 gal/yd^3 (5-10 L/m^3) of concrete, depending on the amount of corrosion resisting performance required. This recommendation is roughly equivalent to 0.25 lb to 0.50 lb (0.11 kg to 0.23 kg) Hycrete DSS solids per 100 lb (45 kg) of cementitious materials, for a standard concrete mix with a cementitious materials content of 700 lb/yd^3(413 kg/m^3).

Hycrete DSS is a multi-purpose additive serving primarily as a corrosion inhibitor but also as an air entrainer. This report uses the same working definition of a corrosion inhibitor as stated by Pierre Roberge in the *Handbook of Corrosion Engineering*, "a chemical substance that, when added in small concentration to an environment, effectively decreases the corrosion rate" (Roberge 1997). As a corrosion inhibitor for the reinforcement, Hycrete DSS is reported to act as an anodic inhibitor, a precipitation inhibitor, and as a concrete waterproofer. According to a slide presentation given by the President of Broadview Technologies (Rhodes 2004) the effectiveness of Hycrete DSS is based upon the following mechanisms:

1. *Anodic Inhibitor* - During the half-cell reaction the anode becomes positively charged and attracts the electronegative end of the Hycrete DSS, creating a hydrophobic layer of protection around the anode.
2. *Precipitation Inhibitor* - Hycrete DSS will remain in solution in fresh concrete. However when the freewater is used up in the hydration process of fresh concrete Hycrete DSS precipitates as a solid protective waxy coating on the rebar.
3. *Waterproofer* - Hycrete DSS reacts with metals in concrete to form insoluble or slightly soluble waxy precipitates that fill voids in the concrete microstructure.

While these specific modes have not been independently verified, laboratory testing by three independent agencies (University of Connecticut, University of Massachusetts, University of Kansas) have indicated excellent performance as an overall corrosion inhibitor. Details of these tests are provided in the literature review section (Chapter 3) of this report.

As an air entrainer Hycrete DSS has been found to reliably introduce uniform and stable micro-air voids in two studies conducted by independent state transportation agencies (additional information and references are provided in Chapter 3).

2.5 Nondestructive Evaluation Techniques for Determining Corrosion in the Field

An important aspect of this study is to monitor Hycrete DSS concrete field placements. This is integral to the project as a means of evaluating the performance of Hycrete DSS as a corrosion inhibitor and also as a tool to estimate the service life of reinforced concrete structures. In this section a selection of reusable nondestructive corrosion monitoring devices that were considered for use on this project are summarized.

Nondestructive evaluation techniques that can quantify corrosion of reinforced concrete typically use electrochemical techniques. Half-cell potentials, as described in ASTM C 876 (ASTM 1999), is the most common electrochemical corrosion monitoring technique cited in engineering literature for transportation infrastructure. Half-cell devices, as depicted in Figure 2.2, measure half-cell potentials and these measurements indicate the presence or absence of corrosion of steel embedded in concrete. This method can be used to measure the potential of a single piece of embedded rebar or to create Equipotential Contour Maps in applications where rebar is laid out in a grid (creating a continuous electrical circuit).

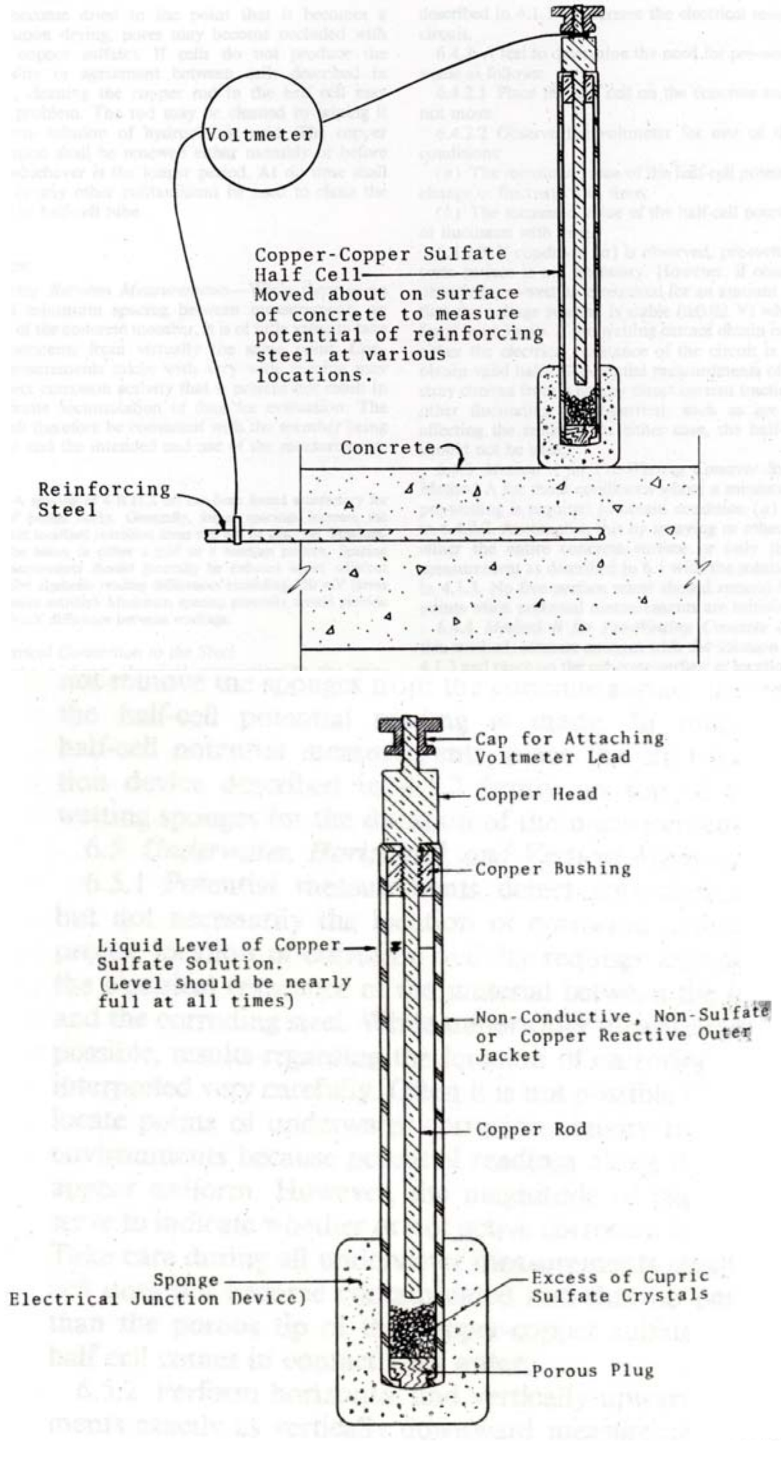


Figure 2.2: Copper-Copper Sulfate Half Cell Circuitry (ASTM 1999)

In terms of service life modeling, half-cell measurements can only indicate the extent of the initiation phase. To quantify the propagation phase and determine the extent of damage to the reinforcement from corrosion, corrosion rate measurements are necessary. Corrosion rate has been traditionally measured through the linear polarization technique, as described in the standard test method ASTM G 59 (ASTM 2003). In the linear polarization technique a potential is applied to a corroding surface and the current response is measured. The ratio of the applied potential and the current response is the polarization resistance. The polarization resistance is inversely proportional to the corrosion rate. When this technique is used for reinforced concrete a guard ring is used to confine the application of current at the concrete surface, thus, yielding a well defined rebar area (Tullmin et. al. 1996). Using data collected over discrete time intervals the corrosion rate readings can be used to estimate the amount of iron loss at a specific location.

Another corrosion rate measuring technique is the galvanostatic pulse technique. Devices using this technique impose an anodic current pulse onto the rebar for a short period of time, using a counter electrode positioned on the surface of the concrete. The resultant rebar potential change is recorded with reference to time. When the slope of the potential versus time curve is relatively high the reinforcement is in a passive state and when the slope is very small there is localized corrosion of the reinforcement. Figure 2.3 shows the GalvaPulse, an instrument which utilizes the galvanostatic pulse technique. The GalvaPulse is manufactured by Germann Instruments.

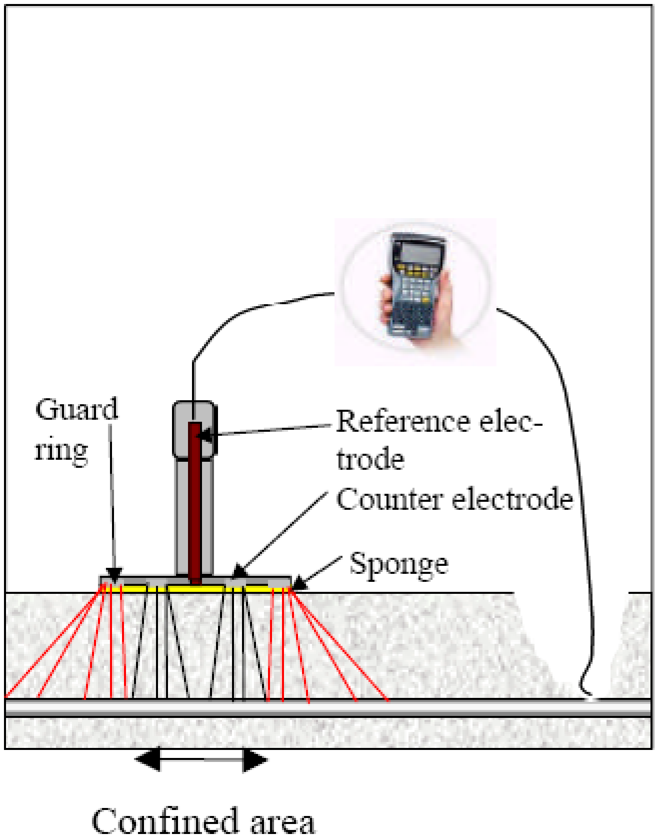


Figure 2.3: Galvapulse (www.germann.org)

A selection of commercially available hand held nondestructive equipment that are capable of measuring corrosion rate of reinforcement in concrete are shown in Table 2.1.

Table 2.1: Corrosion Monitoring Equipment

Equipment	Manufacturer
GalvaPulse	Germann Instruments
Gecor 6 (Gecor 8)	James Instruments Inc.
PR 45000	CC Technologies

CHAPTER 3

LITERATURE REVIEW

3.1 Summary of Available Studies

This chapter evaluates all available data regarding Hycrete DSS concrete testing except for data obtained as part of the current project. Results of this data are presented in Chapter 5. There are three major academic studies in which Hycrete DSS was investigated. At least two transportation organizations have studied Hycrete DSS as a complement to these full academic studies. Product specifications, data from independent laboratory tests, and summaries of completed projects are available from the manufacturer of Hycrete DSS. Several laboratory investigations and field studies have been performed by both private and public entities, although the information from these studies is either confidential or has not been published in a complete form. Brief summaries of the studies considered in the literature review are presented in Section 3.1. A summary and discussion of the overall results from all of the literature review citations is presented in Section 3.2.

Previously unpublished chloride ingress data from the University of Massachusetts (UMass) is presented in Section 5.2.3.2. Unpublished field data of Hycrete DSS concrete and control concrete barriers from the Connecticut Department of Transportation (CTDOT) is presented in Section 6.6.

3.1.1 University Publications and Research

Three major academic studies were published on Hycrete DSS. The first project was performed by the University of Connecticut (UConn), the second by the University of Massachusetts Amherst (UMass), and the most recent study by the University of Kansas (KU).

3.1.1.1 University of Connecticut

The earliest reference including Hycrete DSS reported research conducted at the Concrete Materials Laboratory of the University of Connecticut. This study, Protection of Reinforcement with Corrosion Inhibitors, was led by Professor Frantz and was funded by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation. Two reports and two papers were published based upon the findings from this study (Allyn et al 1998, Allyn and Frantz 2001a, Allyn and Frantz 2001b, Goodwyn et al 2000). The goal of the project was to investigate two prototype concrete corrosion inhibiting chemical admixtures and compare their performance to standard air entrained concrete and two existing commercial concrete corrosion inhibitors. The prototype inhibitors were D.A.S. and D.S.S. (Hycrete DSS); both products were developed by Broadview Technologies. The commercial admixtures were a calcium nitrate based chemical and an organic chemical consisting of amines and esters.

The corrosion study included investigations of lollipop specimens and slab style specimens (ASTM G-109-92). The lollipop specimens were lengths of No. 4 plain Grade 60 rebar encased cylindrically in 2 inches or 3 inches of concrete. Some 3 inch diameter lollipop specimens were saw cut to simulate cracked concrete. All corrosion specimens were subjected to cyclic chloride loading cycle, as described in Table 3.1

and corrosion activity was assessed using the linear polarization method and visual examination techniques.

Table 3.1: UConn Corrosion Study Test Specimens

Specimen	Type	Chloride Loading		Cycle	Total Duration
		Wet	dry	(wk)	(wk)
Lollipop	2", 3", cracked, saw cut	4 days 5" immersed 15% NaCl	3 days air[1]	1	100[2]
Slab	ASTM G-109	4 days 2" pond 15% NaCl	3 days air	1	100

*Notes:
1 - Some specimens were oven dried at 100°F
2 - Cracked lollipop specimens were cycled for 35 cycles

Chloride penetration, absorption, freeze-thaw, strength, and plastic concrete tests were also conducted using standard methods.

3.1.1.2 University of Massachusetts Amherst

The second study was conducted at the Structural Engineering Laboratory at the University of Massachusetts Amherst. An initial study, Performance Evaluation and Economic Analysis of Combinations of Durability Enhancing Admixtures (Mineral and Chemical) in Structural Concrete in the Northeast U.S.A. (funded by the New England Transportation Consortium (NETC 97-2)), and follow up investigations have been completed. One report, two papers, and a conference proceeding were published based upon the findings from this study (Civjan et al 2002, Civjan et al 2005a, Civjan et al 2005b, Civjan et al 2005c). The goal of this study was to gauge the performance of concrete admixtures and pozzolonic cement replacements in single, double, and triple combinations under accelerated corrosion conditions in reinforced concrete. The admixtures and cement replacement materials studied were calcium nitrite, silica fume, fly ash, ground granulated blast furnace slag, and Hycrete DSS. These admixtures were added to standard mix designs and the specimens were designed to model accelerated corrosion in bridge decks in both pre-cracked and non-cracked conditions. All tests used black, uncoated reinforcement.

The test specimens were similar to ASTM G-109 specimens but were modified based upon the Federal Highway Administration report, "Work Plan for In-Concrete Testing" (WJE 1995). Cracked concrete, in selected specimens, was simulated by casting metal shims into the specimens, longitudinally over the top rebar, and removing them after initial set. All specimens were subjected to a cyclic chloride loading cycle (Table 3.2). Corrosion performance of the individual specimens was monitored using half-cell, macro cell, and visual inspection techniques.

Table 3.2: UMass Corrosion Study Test Specimens

Specimen	Type	Chloride Loading		Cycles		Total Cycle	Total Duration
		wet	dry	wet/dry	constant dry	(wk)	(wk)
Slab	WJE 95	4 days 1" pond 15% NaCl	3 days $100^{o}F$	12 wks	12 wks 1" pond 15% NaCl	24	108[1]

Note 1 - Follow up to 204 weeks for many specimens completed and reported (Civjan et al 2005a)

In addition to the main research described, there have also been follow-up experiments conducted at the University of Massachusetts Amherst Structural Engineering Laboratory. The corrosion study was extended past what was originally reported (Civjan et al 2002, Civjan et al 2005b) through 204 weeks for many of the specimens (Civjan et al 2005a) along with data from compression testing of Hycrete DSS specimens with varying dosages of Hycrete DSS.

Previously unpublished chloride ingress data from these corrosion specimens has been compiled and is included in Section 5.2.3.2 of this report. Data from other trial investigations, including investigations of bond development of concrete with Hycrete DSS (Bonczar unpublished laboratory experiments 2003), are unpublished.

3.1.1.3 University of Kansas

The third and most recent study was conducted at the Structural Engineering and Materials Laboratory of the Infrastructure Research Group at the University of Kansas. This study, Evaluation of Multiple Corrosion Protection Systems and Stainless Steel Clad Reinforcement for Reinforced Concrete, was funded by the United States Department of Transportation Federal Highway Administration (FHWA), Kansas Department of Transportation (KDOT), South Dakota Department of Transportation (SDDOT), and National Science Foundation (NSF) (Gong 2006). The goal of the project was to evaluate and compare the corrosion performance of multiple corrosion protection systems and stainless steel clad reinforcement. Conventional steel and conventional epoxy-coated steel served as the control systems. The experimental corrosion inhibiting systems consisted of stainless steel clad reinforcement, conventional epoxy-coated reinforcement cast in concrete containing corrosion inhibitors, epoxy-coated steel with the epoxy applied over a primer coat that contains microencapsulated calcium nitrite, epoxy-coated steel with the epoxy applied after pretreatment of the steel with zinc chromate to improve adhesion between the epoxy and the steel, epoxy-coated steel using improved adhesion epoxies, and multiple coated steel with a zinc layer underlying the epoxy layer. The corrosion inhibitors were Hycrete DSS, a calcium nitrate based chemical admixture, and an organic chemical consisting of amines and esters.

The performance of the systems was evaluated based upon results from a corrosion study consisting of rapid and bench scale (slab) corrosion tests. The rapid tests were rapid macrocell tests. The bench scale (slab) tests included Southern Exposure (SE) specimens (similar to the UMass study), cracked beam specimens (half the size of SE specimens), and ASTM G 109 (similar to the UConn study). Cracked specimens had cracks above and parallel to the reinforcement. The specimens from the rapid test were immersed in a static chloride solution, per Table 3.3, while the bench scale specimens were subject to a cyclic chloride cycle as described in Table 3.4. For all epoxy-coated, some multiple coated, and some stainless steel clad bars, the coating or cladding was drilled with four or ten holes of 1/8 in (3.2 mm) diameter to simulate coating defects. The rapid corrosion tests were evaluated with macrocell corrosion rate and corrosion potential techniques. Bench scale tests were evaluated using macrocell corrosion rate, corrosion potential, mat-to-mat resistance, and polarization resistance techniques. Microstructure analyses of corrosion products along with mechanical testing of reinforcement systems were also completed.

Table 3.3: KU Rapid Corrosion Study Test Specimens

Specimen	Type	Chloride Loading wet
Rapid	bare, wrapped, w/holes	15 wks 3" immersed 4.47%/15%

Table 3.4: KU Corrosion Study Test Specimens

Specimen	Type	Chloride Loading		Cycles		Total Cycle (wk)	Total Duration (wk)
		Wet	Dry	Wet/Dry	Constant		
Slab	SE, CB	4 days 3/4" pond 15% NaCl	3 days 100^oF	12 wks	12 wks 1" pond 15% NaCl	24	96
	ASTM G-109	2 wks 1.5" pond 3% NaCl	2wks air	All	-	4	96

3.1.2 Research from Transportation Organizations

The Connecticut DOT, Kansas DOT, and New Jersey Turnpike Authority have performed some field and/or laboratory studies. The New York/New Jersey Port Authority has performed some field testing. According to Broadview Technologies correspondence, studies are also pending in Florida, Kansas and Texas. Preliminary data from a CT DOT field study and a preliminary report from the Kansas DOT were made available and reported in this Literature Review.

3.1.2.1 Connecticut DOT

Based on the findings from the University of Connecticut study, Paul D'Attilio, An engineer from the Connecticut DOT carried out a study of Hycrete DSS concrete. The plastic and hardened concrete properties of 21 trial Hycrete DSS concrete mix designs were evaluated. The mix designs with optimal characteristics were used to create a set of one sided F-shape highway barriers that were deployed on I-84 in Southington, CT. Monitoring of the corrosion activity of the barriers is to be evaluated utilizing embedded ERE Probes from Germann Instruments to monitor reinforcement potentials and Germann Instruments' "handheld" operated GalvaPulse connected to the barriers by a ground clamp to measure corrosion rate, half-cell potentials, and electrical resistance.

3.1.2.2 Kansas State DOT

In a draft report, "The Effects of DSS Corrosion Inhibitor on the Physical Characteristics of Concrete" (Distlehorst et al 2003), by the Kansas Department of Transportation the effect of Hycrete DSS on the physical characteristics of concrete was investigated. Both concrete with pure Hycrete DSS and Hycrete DSS with a defoaming admixture were compared to a control mix and a control mix with an air entraining chemical. Tests were conducted to determine the freshly mixed concrete properties along with hardened concrete properties of strength and permeability.

3.1.2.3 Others

Other Transportation agencies have implemented Hycrete DSS into a construction project, and likely performed some limited testing of Hycrete DSS concretes, but data has not been published. Specific projects are noted in Section 3.2.6.

3.1.3 Private Research

Significant laboratory and field work has been performed by the developer/manufacturer of Hycrete DSS along with other admixture companies that have considered marketing the admixture, including W.R. Grace and Master Builders. The majority of these results are not published (Civjan 2003). Independent laboratory reports from Construction Technology Laboratories (CTL) and Nelson Testing laboratories (NTL) have been funded by Hycrete Technologies and Broadview

Technologies. These reports include results on testing of physical properties of Hycrete DSS mixes. Descriptions and data from completed and pending construction projects utilizing Hycrete DSS were made available by Hycrete Technologies and were included in this Literature Review. Hycrete DSS has compiled some of this information on their web page (www.Hycrete.com).

3.1.3.1 Broadview/Hycrete Technologies

Mix design development and physical testing of Hycrete DSS concrete has been completed by independent laboratories solicited by the manufacturers of Hycrete DSS . Characteristics investigated include: workability and cohesion, slump retention, air content, setting time, compressive strength, drying shrinkage, hydrostatic pressure resistance, and absorption testing.

3.2 Summary of Findings

Based upon studies by the organizations referenced there have been over 80 unique Hycrete DSS concrete mixes evaluated. Details from these mixes and results from testing are organized in the following sections according to the topics of mixture design, batching, mixing, curing, freshly mixed concrete properties, hardened concrete properties, durability, corrosion, and field applications. A summary of the Hycrete DSS studies with associated references is presented in Table 3.5. In the subsequent sections of Chapter 3 references will be made to the research organization and not the multiple citations based upon the original research project from each organization.

Table 3.5: Summary of Hycrete DSS Studies

Organization	Citations
University of Connecticut (UConn)	Allyn et al 1998, Goodwyn et al 2000, Allyn and Frantz 2001a, Allyn and Frantz 2001b
University of Massachusetts (UMass)	Civjan et al 2002, Civjan et al 2005a, Civjan et al 2005b, Civjan et al 2005c, Data in this report
University of Kansas (KU)	Gong 2006
Connecticut DOT (Conn DOT)	D'Attilio unpublished field study Data in this report
Kansas State DOT (KSDOT)	Distlehorst et al 2003
Hycrete Technologies LLC (Hycrete)	www.Hycrete .com

3.2.1 Mixture Design

In the majority of the studies presented, Hycrete DSS concrete was tested and compared to a control mix. References may be made to these control mixes for comparative observations, but the overall focus is on the Hycrete DSS concrete.

3.2.1.1 Hycrete DSS Dosage

In the studies reported, one evaluated dosage ranges of Hycrete DSS (UConn). All other studies used a concentration of Hycrete DSS of approximately 1/2% Hycrete DSS solids per weight of cementitious materials. This concentration is roughly equivalent to 2 gallons of Hycrete DSS per cubic yard of concrete, for a mixture with a cementitious materials content of 700 lbs/yd^3 (413 kg/m^3). It was found that an increase in the concentration of Hycrete DSS improved corrosion inhibiting performance, but at the same time reduced the strength of the concrete.

Hycrete DSS in concrete has been recommended at dosages of 1/4% to 1/2% weight of Hycrete DSS solids per weight of cementitious materials as a balance between corrosion resistance, strength reduction, and economy (UConn). This concentration corresponds to the current recommended dosage of Hycrete DSS of 1-2 gallons (3.8-7.6 liters) of Hycrete DSS solution (specific gravity (SG) = 1.04 - 1.07) per one cubic yard of concrete (0.76 m^3). Hycrete DSS solids are approximately 1.7 lbs/gal (0.2 kg/l). A 1/2% concentration of Hycrete DSS corresponds to a 2 gal/yd^3 (10 l/m^3) dosage with a total cementitious materials content of 700 lbs/ yd^3 (413 kg/m^3).

3.2.1.2 W/CM and Cementitious Materials Content

The water to cementitious material ratios (w/cm) of the Hycrete DSS concretes used in reported studies were in the range of 0.35 to 0.48 with the exception of one mix with a w/cm of 0.25. Lower water to cementitious materials ratios, for comparable mixes, generally resulted in improved concrete compressive strengths, as would be expected.

The maximum and minimum cementitious materials per cubic yard of concrete were 752 lbs/yd^3 (444 kg/m^3) and 564 lbs/yd^3 (333 kg/m^3), respectively (UConn, UMass, KU, ConnDOT, KSDOT, Hycrete). Higher cementitious materials content generally resulted in stronger Hycrete DSS concretes.

3.2.1.3 Chemical Admixtures and Pozzolonic Materials

A variety of common chemical and mineral admixtures were utilized in Hycrete DSS studies. Hycrete DSS was used in combinations with fly ash (Hycrete), slag (UConn, UMass, Hycrete), silica fume (Hycrete), air entrainer (UMass, KU, Hycrete), water reducers (UMass, KU, ConnDOT, Hycrete), and a calcium-nitrate based corrosion inhibitor (UMass). Also utilized was a defoaming admixture (UConn, KU, ConnDOT, KSDOT, Hycrete). The defoaming admixture was found to reduce the total air content of Hycrete DSS mixes and greatly increase strength performance of Hycrete DSS concrete and subsequently is now premixed in the delivered Hycrete DSS solution. No other detrimental interactions between Hycrete DSS and the chemical and mineral admixtures used in the studies have been reported. Air entrainment emerged in at least two publications as an important parameter when considering the use of Hycrete DSS.

3.2.2 Batching and Mixing

Of the literature available which reported batching and mixing procedures none were batched at full-scale. ConnDOT and Hycrete DSS test mixes were batched at full-scale but batching and mixing procedures were not reported. Although several field installations have been completed, full reports on these large-scale applications have not been made available. All fully reported mixes were batched and mixed in small drum style mixers in batch sizes between 1.0 ft^3 (0.028 m^3) and 2.8 ft^3 (0.079 m^3). All mixes were batched in accordance with normal concrete practices. The exception was the addition of Hycrete DSS. It was found that it is optimal to add Hycrete DSS at the end of the batch process. Hycrete DSS concretes exhibited reduced strength from a comparable normal concrete mix. Although the exact mechanism is not known, it is thought that Hycrete DSS may interact with the hydration process. The working hypothesis includes the position that delaying the addition of Hycrete DSS lessens this interaction. A preliminary laboratory test performed by the manufacturer of Hycrete DSS showed that a delay of 5 min to 30 min to the addition of Hycrete DSS, after the other ingredients have been mixed, increases the early age strength 4% to 14% compared to a Hycrete DSS mix in which the chemical was added immediately following the addition of other batch materials (Hycrete Tech. unpublished laboratory report 2005).

3.2.3 Freshly Mixed Concrete Properties

In all of the studies, freshly mixed concrete properties of slump and air content were reported. Two studies reported temperatures of the Hycrete DSS mixes (ConnDOT, Hycrete). Two studies recorded set times for a Hycrete DSS mix (UConn, Hycrete).

Overall slumps of 1.0 to 8.0 in (2.5 to 20.2 cm) were reported. Water reducing admixtures were used in 4 projects to improve workability; however these were dosed identically to the control mixes (UMass, KU, ConnDOT, Hycrete). None of the studies noted any significant differences in workability between Hycrete DSS and the control mixes.

Air contents of 1.25% to 15.0% were reported with variations corresponding to the research program methods of controlling air content and whether air content was a controlled parameter of the study. Hycrete DSS has been found to entrain air in concrete mixes and this characteristic was utilized in 4 out of 6 studies (UConn, ConnDOT, KSDOT, Hycrete). In these studies an additional air-entraining admixture was not used in the mixes and Hycrete DSS, along with a defoaming admixture were utilized to entrain air to the desired percentage. Target air content was achieved in these studies. Independent laboratory results released by Hycrete Technologies noted that an overdose of defoaming admixture was difficult to correct. In this case, the laboratory added a large dose of air entrainer to correct the defoaming admixture overdose. The mixes prepared for the UMass and the KU corrosion studies used a conventional air entrainer in the Hycrete DSS mixes to maintain consistent admixture additions with control concretes.

As a supplement to the field study presented in this report a small set of trial mixes were tested at the UMass Structural Engineering Laboratory in order to determine the effect of Hycrete DSS, with varying dosages of defoaming admixture, on the air content of concrete over time while continuously mixing. The testing was conducted using a bagged, pre-proportioned dry concrete mix, exceeding ASTM C 387. Water was added to the dry mix according to the manufacturer's specifications. The batch size of the mixes was between 1.2 ft^3 (0.034 m^3) and 2.4 ft^3 (0.068 m^3) depending on the number of air content tests planned to be taken for each mix. A single speed 5.0 ft^3 (0.14 m^3) capacity mixer was used. Total air content versus mixing time data was recorded from the tests. The first time interval was started at 0 minutes when the mix was determined to be homogenously blended, by visual inspection. Air contents were taken at discrete times with the mixer continuously mixing. Air contents were measured following ASTM C 231-97. The dosages of air entrainer, Hycrete DSS, and Hycrete DSS defoaming admixture are shown in Table 3.6, for three test mixes. Figure 3.1 shows air contents versus mix time.

Table 3.6: Trial Air Content Test Mixes

Mix	Air Entrainer		Hycrete DSS		Defoamer		Batch Size	
	oz/yd^3	mL/m^3	gal/yd^3	L/m^3	oz/ yd^3	g/m^3	yd^3	m^3
Control	NA	NA	NA	NA	NA	NA	0.044	0.034
Air Entrained	2.66	103	NA	NA	NA	NA	0.089	0.068
Hycrete DSS (w/defoamer)	NA	NA	2	10	10.1	39.6	0.067	0.051

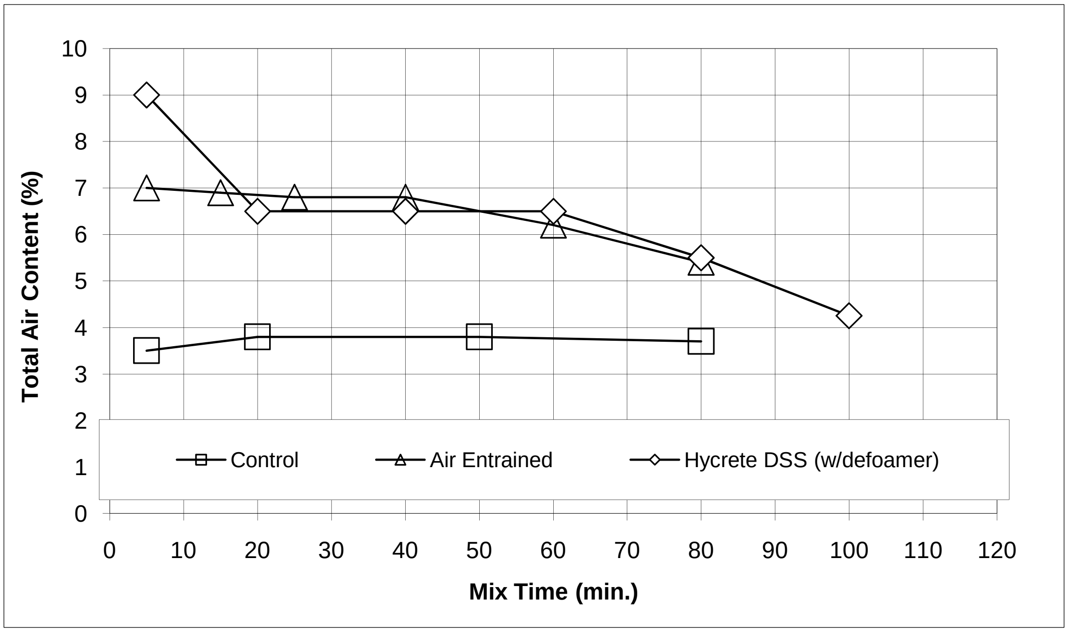


Figure 3.1: Total Air Content vs. Mix Time

A baseline air content of about 3.8% was established for the control mix without additional chemical additives. A total air content range of 5%-8% was established as a performance criterion for the mixes with air entraining admixtures. This was achieved with an addition of an air entrainer at a dosage of 2.66 oz/yd^3 (103 mL/m^3) of concrete for the "Air Entrained" mix. The performance criterion was also met with the Hycrete DSS mix. This mix had a Hycrete DSS dosage of 2 gal/yd^3 (10 L/m^3) of concrete with a defoaming admixture dosage of 10 oz/yd^3 (39.6 mL/m^3) of concrete. As shown in Figure 3.1, the air content of the Hycrete DSS was initially 9% at 5 minutes of mixing. This value dropped nearly 2% after a total of 10 minutes of mixing to remain at a steady measurement of 6.5%-7.0%, comparable to the performance of the conventionally air entrained mix. The data obtained from these trial mixes was used to determine the concentration of defoaming admixture used in the large scale mixes. These results indicate that Hycrete DSS concretes exhibit a stability of air content over time similar to control concretes.

Concrete temperature was not a key subject in any of the reports. One study used refrigerated mix water to retard concrete set in order to make specimens (UConn). Laboratories that recorded set times had conflicting results for Hycrete DSS mixes. An independent laboratory found that the addition of Hycrete DSS delayed the set by 20 minutes when compared to the control, while the UConn study found that Hycrete DSS acted as an accelerator. According to the UConn study at a Hycrete DSS dosage of 1/2%, the set time the concrete mix was 15% faster than when compared to a control. However, the study also noted that decreasing the concentration of Hycrete DSS below the 1/2% concentration also decreased the set time. At a Hycrete DSS concentration of 1/8% the set time was 34% faster than the control. Overall it appears that set time was relatively unchanged and differences are likely due to variability in the concrete mixtures.

When the reports presented criteria for freshly mixed properties, these criteria were acceptable in Hycrete DSS concrete mixes. Based on the available data, the addition of Hycrete DSS was found to have no detrimental effect on the slump or set of concrete. Hycrete DSS adds air to a concrete mix. An additional air entrainer was not needed to achieve typcal required total air content. A defoaming admixture could be added to the Hycrete DSS to reduce the total air content of the mix. However current batches of delivered Hycrete DSS contain a defoaming admixture pre-mixed into the solution.

3.2.4 Curing

In all cases, the curing methods used in each study were the same for Hycrete DSS and control specimens. In all reports the published minimum curing time was 14-days or the date of testing if tested in less than 7 days. Traditional curing methods appear to be adequate for Hycrete DSS specimens.

3.2.5 Hardened Concrete Properties

The hardened concrete properties investigated in the studies were strength, freeze-thaw durability, air void analysis, permeability, and corrosion resistance.

3.2.5.1 Strength

Hycrete DSS concrete strength was evaluated by the percent strength reduction based on a control mix from the same study with similar properties at 28-days. Strengths were not corrected for differences between air contents of the Hycrete DSS and control mixes. An observation made from the UConn study was that an increase in Hycrete DSS dosage led to a decrease in Hycrete DSS compressive strength. This observation has subsequently been verified by laboratory testing conducted by UMass and an independent testing laboratory.

Due to the findings from the original UConn study, a recommended dosage of 1/2% Hycrete DSS solids per weight of cementitious materials was made as a balance between corrosion resistance, strength, and economy. The following observations are therefore for concrete with a Hycrete DSS dosage of 1/2%. When a control specimen was available for comparison, it was found that Hycrete DSS specimens without defoaming admixture experienced strength reductions between 9-31% at 28-days.

Hycrete DSS specimens with defoaming admixture experienced strength reductions between 0-19% at 28–days. In terms of early age testing, of Hycrete DSS mixes have achieved strengths of 3350 psi (23 MPa), 5970 psi (41 MPa), and 6404 psi (44 MPa) for 1, 3, and 7 days respectively, based on a nominal design strength (f'c) of 5000 psi (34.5 MPa) (Hycrete).

3.2.5.2 Permeability

Three different methods were used to evaluate permeability/absorption of Hycrete DSS specimens. These three methods were absorption, evapo-transpiration, and rapid chloride permeability testing.

Absorption testing (ASTM C 642-90) conducted by UConn found that Hycrete DSS concretes with and without a defoaming admixture were at least 50% less permeable than control specimens. Testing by Hycrete Technologies using the British standard, BSI 1881 : Part 122: 1983, found that corrected absorption values ranged from 0.15% to 0.30% for Hycrete DSS concretes.

Two reports tested the permeability of Hycrete DSS using the Rapid Chloride Permeability method (KSDOT, Hycrete). The two studies had conflicting results. One study found that the Hycrete DSS concrete was 15% less permeable than the concrete as compared to the control (Hycrete). The other study reported that the Hycrete DSS specimens were 26% more permeable (as measeured by coloumbs passed), when compared to the control (KSDOT). Further study performed an evapo-transpiration test on the same concretes, which indicated that the Hycrete DSS specimen was 68.4% less permeable than the control. Due to the ionic nature of Hycrete DSS, the standard rapid chloride permeability tests may not adequately measure the performance of Hycrete DSS concrete when compared to a control mix.

It appears that absorption and permeability are reduced by at least 50% due to the addition of Hycrete DSS. Rapid chloride permeability test results are not valid for Hycrete DSS concretes.

3.2.5.3 Durability

Freeze-thaw durability was investigated in the UConn study (see Table 3.7). The Hycrete DSS specimens were generally less durable, but all had a dynamic modulus (Pc) value above 90%, which was considered acceptable performance for high performance concretes.

Table 3.7: Freeze-thaw Durability of Hycrete DSS Specimens (UConn)

Specimen	Pc (%) (300 Cycles)	Wt. Loss (%) (300 Cycles)
Control	99	0.78
Inhibitor A	99	0.21
Inhibitor B	97	0.91
2.0% DSS	91	0.74
0.5% DSS	95	1.11
0.5% DSS-R	93	1.65
2.0% DAS	95	1.21
0.5% DAS-R	94	1.57

3.2.5.4 Air Void Analysis

Results from air void analyses (ASTM C457-90) were presented in two reports (UConn, KSDOT). A total of 3 Hycrete DSS mixes were evaluated. No air entrainer was added to any of the Hycrete DSS mixes and only one out of the three mixes included a defoaming admixture. Both gave values of total air content, entrained air content, and spacing factor. The spacing factor is the generic measurement of the spacing between entrained air voids and gives an indication of the air entrainment quality and expected freeze thaw performance. In both reports the Hycrete DSS mixes had air bubble systems similar to that of the control with air entrainer and superior to that of the control without air entrainer as shown in Table 3.8.

Table 3.8: Results from Hycrete DSS Air Void Analyses (UConn, KSDOT)

Researcher	Mix Name	Total Air Content	Entrained Air Content	Specific Surface Area	Spacing Factor	Spacing Factor
		%	*%*	*in^2/in^2*	*in*	*cm*
UConn	Control w/AEA	7	4.9	799	0.006	0.015
UConn	DSS	7.6	6.3	1065	0.004	0.010
KSDOT	Control	3.75	2.2	NA	0.030	0.076
KSDOT	Control w/AEA	8.75	6.2	NA	0.006	0.015
KSDOT	DSS	13.75	5.8	NA	0.007	0.018
KSDOT	De-foamed DSS	6.4	4.5	NA	0.008	0.020

3.2.5.5 Corrosion Testing

UConn, UMass, and KU have conducted extensive testing on the corrosion resisting performance of Hycrete DSS concrete. ConnDOT is also monitoring field implementations for corrosion, however, only preliminary readings have been taken. Overall observations based on the three completed studies showed that uncracked specimens containing Hycrete DSS showed significant corrosion performance improvements over the control specimens and matched or outperformed the best conventional HPC mixture proportions. Reports concerning cracked concrete were appear conflicting, but are actually consistent. The UConn and UMass studies both reported that Hycrete DSS significantly reduced corrosion even in the presence of cracking. These tests included either very thin “cracks” formed by metal shims, or saw cut “cracks” that stopped short of the reinforcement. The KU study showed similar performance, but in an additional test where a 1/8 inch (3mm) hole was drilled through the reinforcement coating, Hycrete DSS was reported to show no significant ability to inhibit corrosion in the reinforcing steel. This is consistent with general findings which have indicated that Hycrete DSS is not effective in an environment where wetting cycles can wash away the material, due to Hycrete DSS being water soluble. Therefore, the admixture would be effective in cracked concrete of moderate crack sizes, but not effective in the situation of exposed reinforcement.

According to the UConn study, for uncracked lollipop and slab specimens, with a Hycrete DSS concentration of 1/2%, after about 100 weeks of testing, no corrosion activity was detected. The primary mechanism of protection in these specimens was through Hycrete DSS effectively reducing the permeability of the concrete. Based upon analysis of concrete samples taken at depth, no chlorides had reached the rebar level at the conclusion of testing. The saw cut lollipop specimens, had no corrosion except for minor areas at air bubbles after 30 weeks of testing. Where chlorides did penetrate and corrosion began, evidence of corrosion activity was localized to the exposed area.

In the UMass study, through 208 weeks of testing, the Hycrete DSS concrete specimens at a 1/2% concentration exhibited greater corrosion protection than any of the corrosion resisting systems tested, except for one mixture with a triple combination of admixtures that performed comparably. The Hycrete DSS concretes far surpassed all other mix designs in specimens where cracking was simulated through placing metal shims to the level of reinforcement during casting, and removing these shims after first set of the concrete. It was found that traditional corrosion inhibiting admixture (calcium nitrite) was not effective in this situation.

The KU study found that when reinforcing bars were encased in concrete containing Hycrete DSS at a concentration of 1/2%, no significant corrosion was detected at the end of the test protocol and the corrosion rate was essentially 0 μm/year. This observation was made for the four specimen types used in the test protocol, even when the concrete was cracked. However an additional criterion was used to evaluate the corrosion resisting systems based upon localized activity. Holes of 1/8 in diameter were drilled to the reinforcement level (through epoxy), as a method of simulating defects in epoxy coated reinforcement. For specimens with holes the amount of corrosion was based upon the exposed area of steel. Hycrete DSS specimens had measurable corrosion at these exposed areas.

Based upon finding from the three studies, Hycrete DSS at a standard concentration of 1/2% can reduce or effectively inhibit corrosion in reinforcing steel when there is adequate concrete cover, even for a cracked condition. Hycrete DSS provides significant corrosion protection when compared to a concrete mix containing conventional corrosion inhibiting admixtures. Hycrete DSS does not act as a corrosion inhibitor for exposed steel, as it is water soluble and will not adhere to exposed steel.

3.2.6 Field Applications

CT DOT performed trial mixes and chose a CT DOT Class “F” mix to construct highway barriers at a pre-cast concrete plant. These barriers have been placed in the field on a Connecticut state highway where they are subjected to the splash from road salt brine. They are currently in initial phases of being monitored for corrosion. These F-shaped barriers are shown in Figure 3.2. Preliminary results from this study have not been published, and are included in Section 6.6.

Figure 3.2: F-shaped Barriers used in UConn Study (CTDOT)

Several other field applications have been completed. A list of completed and pending projects utilizing Hycrete DSS was provided by Hycrete Technologies and is provided in Table 3.9. The majority of projects are from private industry and residential applications. This is due to these applications, as compared to DOT applications, requiring less product verification prior to use, fewer issues with contracting and/or less risk involved in the project. Of the DOT related projects, there have been three bridge decks. An example is shown in Figure 3.3, a Kansas State DOT bridge construction project utilizing Hycrete DSS.

The research team has contacted representatives from the NJ Turnpike Authority, New Jersey DOT, Ohio DOT, Connecticut DOT, and Kansas DOT to inquire about the performance of these structures to date and any construction issues. Contact was in the form of short phone calls and/or email. Contact was not always with representatives who were involved with the original construction, but they were asked to verify responses with those who were. From this informal survey it was found that Hycrete DSS concrete structures were performing satisfactorily. Comments included the need for trial mix designs, which in some cases were extensive. The only negative comment was in regard to one of the Kansas DOT bridges, where some early cracking was noted in the slab. Further inquiries indicated that cracking was in the negative moment regions and was likely caused by heavy form equipment that was placed on the Hycrete DSS concrete deck, but not on the control structure. However, no official documents were obtained to verify this.

Table 3.9: Hycrete DSS Project List

Completed Projects *Public Projects*	*Commercial Projects*
• Deck for Highway Bridge Overpass – Kansas DOT • Deck for Highway Bridge Overpass – NJ Turnpike Authority • Precast Barriers – Connecticut DOT • Noise Barrier - Ohio DOT • Bridge Overpass - New Jersey DOT	• 18 below grade basement/foundation • 1 footings for structure • 1 shotcrete basement waterproofing • 1 retaining wall • 8 elevator pits • 1 slab on grade • 1 exposed slab on grade • 1 loading dock • 1 elevated slab • 1 elevated walkway • 3 podium decks • 2 parking structures • 1 nuclear waste storage containment • 2 water tanks • 2 sewer tanks • 3 fountains/ornamental water containment •

Figure 3.3: Kansas State DOT Hycrete DSS Project (Courtesy of Hycrete Technologies)

CHAPTER 4

FIELD STUDY APPROACH AND METHODS

4.1 Project Background

The goal of this research is to conduct field studies on Hycrete DSS concrete, and monitor those characteristics that would be important to ready-mixed concrete suppliers and transportation agencies. The following subsections outline the approach and methods used in the Hycrete DSS concrete field study. A total of 15 different mixture designs (10 Hycrete DSS concretes, 5 control) were evaluated at 4 sites on 6 different testing dates.

4.2 Development of Mix Designs

Information on mix designs was collected from each state agency involved in the project to develop a set of mixes to be used in a test matrix that would typically be used in reinforced concrete structures important to transportation agencies. The mix designs reported are generic specifications for classes of concrete based upon minimum 28-day compressive strength, minimum total cementitious materials content, maximum water-cementitious materials ratio, maximum aggregate size, and the expected ranges for slump and total air content. The standard mix designs considered for this project are presented in Table 4.1and Table 4.2. These mixes represent a range of high performance concretes typically used throughout New England that would most likely utilize a corrosion inhibitor. Actual mix designs provided by ready-mixed concrete suppliers to meet these criteria are provided in Section 4.3.2.

Table 4.1: Classes of HPC Mixes Used in New England Region (english units)

D.O.T.	Class	Strength (psi)	Min T.C.M. (lbs/yd^3)	w/cm	Max Agg. Size (in)	Slump (in)	Air Content (%)
CT	C	3000	658	0.53	0.75	2.5+/-0.5	5+/-1
	F	4000	658	0.44	0.75	2.5+/-0.5	5+/-1
MA	HP-3/4in	5000	710	NA	0.75	3+/-1	6+/-1
	HP-3/8in	5000	760	NA	0.375	4+/-1	6+/-1
ME	A	4350	658*	0.4*	0.75	7.5+/-2.5*	7+/-1.5
	LP	5075	658*	0.4*	0.75	7.5+/-2.5*	7+/-1.5
NH	AA	4000	NA	0.44	0.75	3+/-1	7+/-2
	AAA	5000	NA	0.4	0.75	8**	7+/-2
NY	F	4000***	718	0.38	1	3.5+/-0.5	6.5+/-1.5
	HP	NA	685	0.4	1	6+/-1	6.5+/-1.5
RI	XX	4000	658	0.42	0.75	2+/-1	6.5+/-1.5
	HP	5000	705	0.4	0.75	5.5+/-2.5	6.5+/-1.5
VT	HPC B	3500	611	0.49	0.75	7**	5+/-1.5
	HPC A	4000	660	0.44	0.75	7**	6+/-1.5

* precast structural concrete
** maximum when water reducing admixture used
*** pavement applications

Table 4.2: Classes of HPC Mixes Used in New England Region (metric units)

D.O.T.	Class	Strength (MPa)	Min T.C.M. (kg/m^3)	w/cm	Max Agg. Size (mm)	Slump (mm)	Air Content (%)
CT	C	21	390	0.53	19	66+/-12	5+/-1
	F	28	390	0.44	19	66+/-12	5+/-1
MA	HP-20mm	35	420	NA	19	75+/-25	6+/-1
	HP-10mm	35	450	NA	9.5	100+/-25	6+/-1
ME	A	30	400*	0.4*	19	190+/-65*	7+/-1.5
	LP	35	400*	0.4*	19	190+/-65*	7+/-1.5
NH	AA	30	NA	0.44	19	62.5+/-12.5	7+/-2
	AAA	35	NA	0.4	19	150+/-25	7+/-2
NY	F	28***	425	0.38	25	62.5+/-12.5	6.5+/-1.5
	HP	NA	405	0.4	25	100+/-25	6.5+/-1.5
RI	XX	30	390	0.42	19	50+/-25	6.5+/-1.5
	HP	35	417	0.4	19	140+/-60	6.5+/-1.5
VT	HPC B	25	362	0.49	19	180*	5+/-1.5
	HPC A	30	391	0.44	19	180*	6+/-1.5

* precast structural concrete
** maximum when water reducing admixture used
*** pavement applications

4.3 Large Scale Mixing

Information from each state agency was used to organize large scale truck batched mixes at DOT concrete suppliers. It was the intent that the data obtained from these large scale concrete mixes would be used to develop Hycrete DSS concrete specifications for future field applications. All of the ready-mixed concrete plants used in the project were pre-qualified by the states they serviced. Therefore, it was assumed that all applicable ready-mixed concrete specifications, even those not specifically addressed, were acceptable to the state agencies and typical of normal practice.

4.3.1 Test Sites and Material Properties

Concrete is a heterogeneous material made up of aggregate, Portland cement, and water. In addition to these ingredients high performance concrete mixes typically contain supplemental admixtures to improve specific properties of the basic mix. The properties of a concrete mixture depend on the interaction and properties of its components. It is impossible to predict the performance of all concrete mixes based on one test mix because there is such a large range of cement suppliers, aggregate sources, and admixture types and manufacturers in the concrete industry. In an effort to include a representative range of these materials, the transportation agencies and regional ready-mixed concrete companies were contacted to determine aggregate types and sources and cement and concrete admixture types and manufacturers that are typically used in New England. Based upon this information three ready-mixed concrete companies from New England, along with one precast structural building components plant, were chosen as test sites. Each plant had unique cement suppliers, aggregate sources, and concrete mixes containing a variety of admixtures types from different manufacturers. The concrete plants used were Aggregate Industries (Swampscott, Massachusetts), Carroll Concrete (West Lebanon, New Hampshire), Oldcastle Precast Building Systems Division (South Bethlehem, New York), and Tilcon-CT (New Britain, Connecticut). A total of six concrete pours were conducted. The dates of the pours are listed in Table 4.3 and the locations of the ready-mixed concrete companies are shown in Figure 4.1. Manufacturer specifications were obtained and evaluated for the other admixtures and cementitious materials used in the mix designs from the four concrete plants. Table 4.4 contains a full list of the concrete materials used in the project.

Table 4.3: Large Scale Pour Dates

Plant	Pour Date
Aggregate Industries	08/16/05
Carroll Concrete	03/09/05 11/07/05
Oldcastle Precast	06/20/06
Tilcon-CT	08/03/05 02/16/06

Figure 4.1: Locations of Concrete Plants

Table 4.4: Concrete Materials List

Category	Name	Manufacture	AASHTO	ASTM
Portland, Blended and Other Hydraulic Cements				
Blended Hydraulic Cement (Type I (PM))	Tercem 3000	Lafarge Corporation	M 240	C 595, C 1157
Blended Hydraulic Cement (Type I (PM))	SF Cement	Lafarge Corporation	M 240	C 595
Portland Cement (Type I)	St. Lawrence Type I	St. Lawrence Cement	M 85	C 150
Portland Cement (Type I-II)	Lafarge Type I-II	Lafarge Corporation	M 85	C 150
Portland Cement (Type I-II)	St. Lawrence Type I/II	St. Lawrence Cement	M 85	C 150
Fly Ash, Slag, Silica Fume, and Natural Pozzolans				
FlyAsh (Class F)	ProAsh	STI	M 295	C 618
Ground Granulated Furnace Slag (GGBFS) Grade 100	Grancem (Mtrl 377)	St. Lawrence Cement	M 302	C 989
Ground Granulated Furnace Slag (GGBFS) Grade 120	NewCem	Lafarge Corporation	M 302	C 989
Aggregates for Concrete				
Coarse Aggregate	3/8" Stone	Tilcon New Britain	M 80	C 33
Coarse Aggregate	3/8" Stone	Aggregate Industries Swampscott	M 80	C 33
Coarse Aggregate	3/4" Ledge	Lebanon Crushed Stone	M 80	C 33
Coarse Aggregate	3/4" Stone	Tilcon New Britain	M 80	C 33
Coarse Aggregate	3/4" Stone	Aggregate Industries Swampscott	M 80	C 33
Fine Aggregate	Sand	Lebanon Crushed Stone	M 6	C 33
Fine Aggregate	Sand	Oddipee Aggreagates	M 6	C 33
Fine Aggregate	Sand	Tilcon Southington	M 6	C 33
Admixtures for Concrete				
Air Entrainer	Darex II AEA	Grace Construction Products	M 154	C 260
Corrosion Inhibitor	DCI-S	Grace Construction Products	NA	NA
Corrosion Inhibitor	Hycrete DSS	Hycrete Technologies	NA	NA
Defoamer	BYK 25	BYK-Chemie	NA	NA
Defoamer	BYK 94	BYK-Chemie	NA	NA
Defoamer	Tributyl Phosphate Package (TBP)	NA	NA	NA
Defoamer	Geo FM A-7	GEO Specialty Chemicals	NA	NA
Mid Range Water Reducer (M.R.W.R)	Daracem 55	Grace Construction Products	M 194	C 494, Type A,F
Mid Range Water Reducer (M.R.W.R.)	Polyheed 997	Master Builders/Degussa Admixtures	M 194	C 494, Type A
High Range Water Reducer (H.R.W.R.)	ADVA 100 Superplasticizer	Grace Construction Products	M 194	C 494, Type A,F
High Range Water Reducer (H.R.W.R.)	Advaflow	Grace Construction Products	M 194	C 494, Type F
Polycarboxylate Superplasticizer	ADVA Cast 530	Grace Construction Products	M 194	C 494, C 1017
Retarder	Daratard 17	Grace Construction Products	M 194	C 494, Type B,D

4.3.2 Mix Proportion and Design Procedure

Hycrete DSS concrete mix designs were proportioned using standard New England DOT mix designs as the basis. For each pour location, a list of the available DOT mixes was obtained, consisting of mixes given in Table 4.5 and Table 4.6. Note that total water in the mix includes the added water (in Tables) as well as water added in Hycrete DSS solution (13.3 lb/yd^3 (7.9 kg/m^3)) and DCI solution (21 lb/yd^3 (12.5 kg/m^3). From the list, classes of concrete mixes were organized based upon minimum strength requirements, cementitious materials content, water to cementitious materials ratio (w/cm), and typical application usage. Mixes were selected for testing based on priorities determined through discussions with members of the project technical committee. Specific attention was paid to select a range of mixes that would help evaluate the effect of concrete variables such as cement type, water reducers, and superplasticizers on a Hycrete DSS concrete mix. Hycrete DSS was added to each of the mix designs at a standard dosage of 2 gal/yd^3 (10 L/m^3) concrete and an estimate was made to the defoaming admixture dosage based upon cementitious material content, previous experience (as reported in Chapter 3), and discussions with representatives from Hycrete Technologies. The final mix design selection was made with the approval of the technical committee. The final proportions, as-tested, are presented in these tables, including any adjustments made to the mixes in the field. These adjustments are noted in Tables 4.5 and 4.6 and could include adding additional air entraining or defoaming admixtures to adjust measured air content and adding additional water and/or water reducing chemicals to the mixes to improve workability. Additional water and/or chemical admixtures were added directly to concrete trucks and mixed for an appropriate amount of time to obtain homogenous distribution. The defoaming admixture is most effective when mechanically mixed with the Hycrete DSS and less effective when added straight to a mix rather than to the Hycrete DSS solution (thus a higher concentration is required). It is noted that adjustments were less likely in subsequent mix designs, and were a result of working with new mixture proportions rather than any variability in response for a given mixture design. Mixes are designated using the following convention:

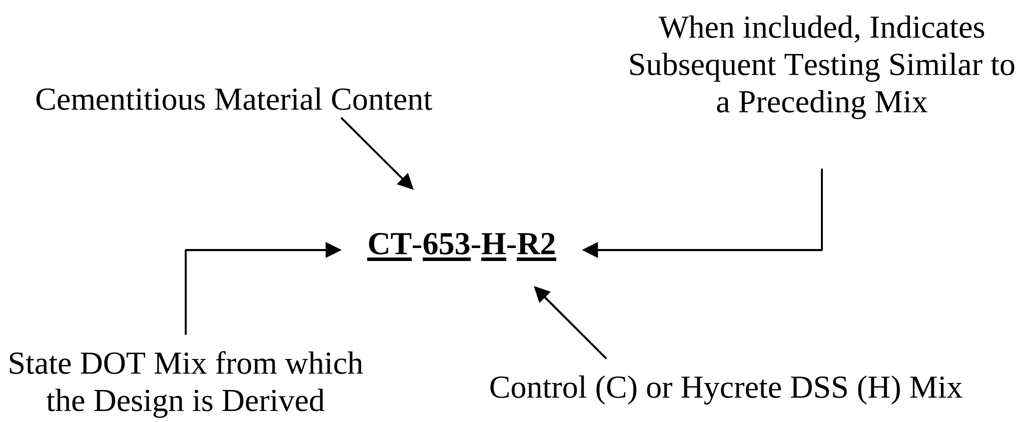


Table 4.5: SSD Mix Designs (1 yd3) (US)

Mix Design Proportions as Tested (1 cuyd SSD)							
	Project ID	CT673C[1]	MA744C	NH657C[2]	NY679C		VT617C[3]
	Date	08/02/05	08/16/05	03/09/05	06/20/06		03/09/05
	DOT ID	*CT State Class F*	*MHD HP*	*NH AA HRWR*	*Oldcastle SCC*		*VT HPCB*
	Location	*Tilcon-CT*	*Aggregate Ind.*	*Carroll Concrete*	*Oldcastle*		*Carroll Concrete*
	Cementitious (lbs)	673	744	657	679		617
	Coarse - 3/4" max (lbs)	1813	1858	1733	1400		1733
	Fines (lbs)	1260	1029	1328	1323		1451
	Water Reducer (oz)	39.3	32.7	33.3	28.0	89.0	31.3
	Type	Pollyheed 997	ADVAFlow	ADVA 100	DARECEM 55	AD 530	ADVA 100
	Air Entrainer (oz)	4.7 (3.4+1.3)	4.0	2.0 (0.9+1.1)	2.0		3.0
	Type	Darex II	Darex II	Darex II	DARAVAIR		Darex II
	Retarder (oz)	0.0	0.0	14.0	0.0		12.7
	Type	NA	NA	Daratard 17	NA		Daretard 17
	Water (lbs)	275	249	225	315		234 (231+3)
	% Cement	100	69	50	68		73
	% Slag	0	25	50	0		22
	% SF	0	6	0	0		5
	% FA	0	0	0	32		0
	Corrosion Inhibitor(gal)	0	3	0	0		0
	Type	NA	DCI	NA	NA		NA
	Defoamer (oz)	0.0	0.0	0.0	0.0		0.0

Notes:

1. 1.3 oz of air entrainer was added to the mix as originally batched
2. 1.1 oz of air entrainer was added to the mix as originally batched
3. 2.8 lb of water was added to the mix as originally batched

Table 4.5: SSD Mix Designs (1 yd3) (US)

Mix Design Proportions as Tested (1 cuyd SSD)	Project ID	CT687H[4]	CT663HR1	CT653HR2	MA746H	NH653H[5]
	Date	08/02/05	02/16/06	02/16/06	08/16/05	03/09/05
	DOT ID	*CT State Class F*	*CT State Class F*	*CT State Class F w/FA*	*MHD HP*	*NH AA HRWR*
	Location	*Tilcon-CT*	*Tilcon-CT*	*Tilcon-CT*	*Aggregate Ind.*	*Carroll Concrete*
	Cementitious (lbs)	687	663	653	746	653
	Coarse - 3/4" max (lbs)	1807	1807	1773	1850	1719
	Fines (lbs)	1286	1272	1285	1029	1344
	Water Reducer (oz)	39.7	39.7	39.7	32.7	33.7
	Type	Pollyheed 998	Pollyheed 998	Pollyheed 998	ADVAFlow	ADVA 100
	Air Entrainer (oz)	0.0	0.0	0.0	0.0	4.0
	Type	NA	NA	NA	NA	Darex II
	Retarder (oz)	0.0	0.0	0.0	0.0	13.7
	Type	NA	NA	NA	NA	Daretard 17
	Water (lbs)	261	255	260	257	217 (209+8)
	% Cement	100	100	85	69	50
	% Slag	0	0	0	25	50
	% SF	0	0	0	6	0
	% FA	0	0	15	0	0
	Corrosion Inhibitor(gal)	2	2	2	2	2
	Type	Hycrete DSS	Hycrete DSS	Hycrete DSS	Hycrete DSS	Hycrete DSS
	Defoamer (oz)	12.1(3.1+8.0)	5.3	4.0	4.4	7.9

Notes:
4. 8 oz of defoamer was added to the mix after originally batched – post addition requires higher dosage
5. 8 lb of water and 4.0 oz of air entrainer was added to the mix as originally batched

Table 4.5: SSD Mix Designs (1 yd3) (US)

Mix Design Proportions as Tested (1 cuyd SSD)

Project ID	NH653HR1[6]	NH607HR2[7,8]	NY679H		VT617H[9]	VT610HR1[10,11,12]
Date	11/07/05	11/07/05	06/20/06		03/09/05	11/07/05
DOT ID	*NH AA HRWR*	*NH AA HRWR*	*Oldcastle SCC*		*VT HPCB*	*VT HPCB 7%*
Location	*Carroll Concrete*	*Carroll Concrete*	*Oldcastle*		*Carroll Concrete*	*Carroll Concrete*
Cementitious (lbs)	653	607	798		617	610
Coarse - 3/4" max (lbs)	1655	1761	1400		1713	1721
Fines (lbs)	1356	1379	1323		1436	1434
Water Reducer (oz)	46.3	43.0	28.0	89.0	31.0	43.0 (31+12)
Type	ADVA 100	ADVA 100	DARECEM 55	AD 530	ADVA 100	ADVA 100
Air Entrainer (oz)	0.0	2.0	0.0		0.0	0.0
Type	NA	Darex II	NA		NA	NA
Retarder (oz)	26.3	26.3	0.0		12.7	12.3
Type	Daratard 17	Daratard 17	NA		Daretard 17	Daretard 17
Water (lbs)	246 (227+19)	231	303		223 (206+17)	248 (235+13)
% Cement	70	70	68		73	73
% Slag	30	30	0		22	22
% SF	0	0	0		5	5
% FA	0	0	32		0	0
Corrosion Inhibitor(gal)	2	2	2		2	2
Type	Hycrete DSS	Hycrete DSS	Hycrete DSS		Hycrete DSS	Hycrete DSS
Defoamer (oz)	5.0	5.0	4.0		7.9	5.0

Notes:

6. 19 lb of water was added to the mix as originally batched
7. Reduced cement content from original mix design
8. 2.0 oz of air entrainer added to the mix as originally batched
9. 17 lb of water was added to the mix as originally batched
10. Increased design air content from original mix design
11. 13 lb of water added to the mix as originally batched
12. 12 oz of water reducer added to the mix as originally batched

Table 4.6: SSD Mix Designs (1 m3) (metric units)

Mix Design Proportions as Tested (1 m^3 SSD)

Project ID	CT673C[1]	MA744C	NH657C[2]	NY679C		VT617C[3]
Date	08/02/05	08/16/05	03/09/05	06/20/06		03/09/05
DOT ID	*CT State Class F*	*MHD HP*	*NH AA HRWR*	*Oldcastle SCC*		*VT HPCB*
Location	*Tilcon-CT*	*Aggregate Ind.*	*Carroll Concrete*	*Oldcastle*		*Carroll Concrete*
Cementitious (kg)	397	439	387	473		364
Coarse - 19 mm max (kg)	1070	1096	1022	826		1022
Fines (kg)	747	607	783	781		856
Water Reducer (mL)	1521.4	1263.5	1289.3	1083.0	3442.5	1212.0
Type	Pollyheed 997	ADVAFlow	ADVA 100	DARECEM 55	AD 530	ADVA 100
Air Entrainer (mL)	183.1 (132.8+50.3)	154.7	77.4 (34.9+42.5)	77.4		116.0
Type	Darex II	Darex II	Darex II	NA		Darex II
Retarder (mL)	0.0	0.0	541.5	0.0		489.9
Type	NA	NA	Daratard 17	NA		Daretard 17
Water (kg)	163	147	133	186		138 (136+2)
% Cement	100	69	50	68		73
% Slag	0	25	50	0		22
% SF	0	6	0	0		5
%FA	0	0	0	32		0
Corrosion Inhibitor(L)	0	15	0	0		0
Type	NA	DCI	NA	NA		NA
Defoamer (ml)	0.0	0.0	0.0	0.0		0.0

Notes:

1. 50.3 ml of air entrainer was added to the mix as originally batched
2. 42.5 ml of air entrainer was added to the mix as originally batched
3. 1.7 kg of water was added to the mix as originally batched

Table 4.6: SSD Mix Designs (1 m3) (metric units)

Mix Design Proportions as Tested (1 m³ SSD)	Project ID	CT687H[4]	CT663HR1	CT653HR2	MA746H	NH653H[5]
	Date	08/02/05	02/16/06	02/16/06	08/16/05	03/09/05
	DOT ID	*CT State Class F*	*CT State Class F*	*CT State Class F w/FA*	*MHD HP*	*NH AA HRWR*
	Location	*Tilcon-CT*	*Tilcon-CT*	*Tilcon-CT*	*Aggregate Ind.*	*Carroll Concrete*
	Cementitious (kg)	405	391	385	440	385
	Coarse - 19 mm max (kg)	1066	1066	1046	1092	1014
	Fines (kg)	759	751	758	607	793
	Water Reducer (mL)	1534.3	1534.3	1534.3	1263.5	1302.2
	Type	Pollyheed 998	Pollyheed 998	Pollyheed 998	ADVAFlow	ADVA 100
	Air Entrainer (mL)	0.0	0.0	0.0	0.0	154.7
	Type	NA	NA	NA	NA	Darex II
	Retarder (mL)	0.0	0.0	0.0	0.0	528.6
	Type	NA	NA	NA	NA	Daretard 17
	Water (kg)	154	151	154	152	129 (124+5)
	% Cement	100	100	85	69	50
	% Slag	0	0	0	25	50
	% SF	0	0	0	6	0
	%FA	0	0	15	0	0
	Corrosion Inhibitor(L)	10	10	10	10	10
	Type	Hycrete DSS	Hycrete DSS	Hycrete DSS	Hycrete DSS	Hycrete DSS
	Defoamer (ml)	468.0 (158.6+309.4)	206.3	154.7	170.2	306.3

Notes:
4. 309.4 ml of defoamer was added to the mix after originally batched – post addition requires higher dosage
5. 4.9 kg water and 154.7 ml of air entrainer was added to the mix as originally batched

Table 4.6: SSD Mix Designs (1 m3) (metric units)

Mix Design Proportions as Tested (1 m^3 SSD)						
Project ID	NH653HR1[6]	NH607HR2[7,8]	NY679H		VT617H[9]	VT610HR1[10,11,12]
Date	11/07/05	11/07/05	06/20/06		03/09/05	11/07/05
DOT ID	*NH AA HRWR*	*NH AA HRWR*	*Oldcastle SCC*		*VT HPCB*	*VT HPCB 7%*
Location	*Carroll Concrete*	*Carroll Concrete*	*Oldcastle*		*Carroll Concrete*	*Carroll Concrete*
Cementitious (kg)	385	358	473		364	360
Course - 19 mm max (kg)	976	1039	826		1011	1016
Fines (kg)	800	813	781		847	846
Water Reducer (mL)	1792.2	1663.2	1083.0	3442.5	1199.1	1663.2 (1199+464)
Type	ADVA 100	ADVA 100	DARECEM 55	AD 530	ADVA 100	ADVA 100
Air Entrainer (mL)	0.0	77.4	0.0		0.0	0.0
Type	NA	Darex II	NA		NA	NA
Retarder (mL)	1018.6	1017.3	0.0		489.9	477.1
Type	Daratard 17	Daratard 17	NA		Daretard 17	Daretard 17
Water (kg)	146 (135+11)	136	179		132 (122+10)	147 (139+8)
% Cement	70	70	68		73	73
% Slag	30	30	0		22	22
% SF	0	0	0		5	5
%FA	0	0	32		0	0
Corrosion Inhibitor(L)	10	10	10		10	10
Type	Hycrete DSS	Hycrete DSS	Hycrete DSS		Hycrete DSS	Hycrete DSS
Defoamer (ml)	191.5	191.5	154.7		306.3	191.5

Notes:

6. 11 kg of water was added to the mix as originally batched
7. Reduced cement content from original mix design
8. 77.4 ml of air entrainer added to the mix as originally batched
9. 10 kg of water was added to the mix as originally batched
10. Increased design air content from original mix design
11. 7.7 kg of water added to the mix as originally batched
12. 464.2 ml of water reducer added to the mix as originally batched

4.3.3 Batching and Mixing

A mix size of three cubic yards was determined to be an appropriate mix scale, qualifying as a “large scale mix”. The batching process was determined in consultation with the ready-mixed concrete plants involved in the large scale mixes. Batching of aggregate, cementitious materials, and water was done by mass and batching of liquid admixtures was measured by volume. Saturated surface dry (SSD) mix designs were adjusted to account for the moisture content of the aggregates and the additional free water added by the Hycrete DSS solution.

All plants used in the project had central batching and mixing plants feeding truck mounted mixers as shown in Figure 4.2. Hycrete DSS was added to the batching process based upon the researchers’ advice. In all cases Hycrete DSS was added as the last ingredient in the batching process. In the case of the of the March 2005 Carroll Concrete pour , the February 2006 Tilcon-CT pour, and the June 2006 Oldcastle pour Hycrete DSS was added from the central mixer directly and in the case of the remaining pours the Hycrete DSS solution was added directly to the truck mixers. In all cases the addition of the Hycrete DSS was made no greater than five minutes after the other ingredients were batched. The batching process was monitored by the researchers and present technical committee members.

Figure 4.2: Central Batching and Mixing Plant Feeding Truck Mounted Concrete Mixers

All batches were central mixed. The mixes in which Hycrete DSS was added directly to the truck were truck mixed in standard 9 to 11 cubic yard capacity front or rear discharge concrete trucks (as shown in Figure 4.3 and Figure 4.4) for an additional 5 to 10 minutes following the addition of Hycrete DSS, followed by approximately 15 minutes at slow rotation of the drum to simulate travel to a site (except for Tilcon-CT mixes of February 2006 which travelled 12 miles to the test site). When an additional defoaming admixture was to be added to the mix it was premixed with the Hycrete DSS using a high speed drill and paint mixer attachment. All mixes were tested on-site at the ready-mixed plant for freshly mixed properties except for the mixes batched at Tilcon-CT on February 2006. These were hauled 12 miles to the CT DOT Materials Research Laboratory, with a transit time for each of theses mixes of less than 15 minutes. The mixing process was monitored by the researchers and present technical committee members.

Figure 4.3: Rear Discharge Concrete Truck

Figure 4.4: Front Discharge Truck

4.3.4 Evaluation of Freshly Mixed and Hardened Concrete Characteristics

The evaluation of each mix was conducted using standard state DOT test sampling and testing procedures conforming to ASTM and AASHTO specifications (Table 4.8). These tests were carried out directly by or under the supervision of researchers and present technical committee members. A list of mixes and the tests performed on them is shown in Table 4.7, with designations of specific tests provided in Table 4.8.

Table 4.7: Test Matrix

Mix ID	Comp[1]							Split[1]	Rapid Perm[1]	Absor[1]	Freeze[1]	Bond[1]
	1	3	5	7	14	28	84					
CT673C	x	x	-	x	x	x	x	x	x	x	x	x
MA744C	x	x	-	x	x	x	x	x	x	x	x	-
NH657C	-	-	x	x	x	x	x	x	x	-	x	-
NY679C	x	x	-	x	x	x	x[2]	x	-	x	-	-
VT617C	-	-	x	x	x	x	x	x	x	-	x	-
CT687H	x	x	-	x	x	x	x	x	x	x	x	-
CT663HR1	x	x	-	x	x	x	x	x	-	x	x	-
CT653HR2	x	x	-	x	x	x	x	x	-	x	x	-
MA746H	x	x	-	x	x	x	x	x	x	x	x	-
NH653H	-	x	x	x	x	x	x	x	x	-	x	-
NH653HR 1	x	x	-	x	x	x	x	x	x	x	x	x
NH607HR 2	x	x	-	x	x	x	x	x	x	x	x	-
NY679H	x	x	-	x	x	x	x[2]	x	-	x	-	-
VT617H	-	x	x	x	x	x	x	x	x	-	x	-
VT610HR1	x	x	-	x	x	x	x	x	x	x	x	x

x: Data Obtained as Part of Report
Note 1: Test Designation in Table 4.8
Note 2: Long term test completed at 215 days

Hardened concrete properties were tested at Gunness Structural Engineering Laboratory at the University of Massachusetts, Amherst (UMass), and/or State DOT testing laboratory facilities. Strength testing occurred at both UMass and at least one State DOT laboratory testing facility for each mix. Typically this was the state corresponding to the mix design. All freeze thaw testing was conducted by VTrans, and all rapid chloride permeability testing by VTrans or NHDOT. The American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) designation for each test specification described for the large scale field mixes are given in Table 4.8.

Some tests were modified slightly from the applicable standards in an effort to tailor the tests to the goals of this specific project. The modifications include using 4x8 cylinders for compressive strength tests and using a 15% saline solution in the freeze-thaw testing protocol. The use of 4x8 cylinders is permitted according to AASHTO T 23-02 when the maximum aggregate size does not exceed 1 in (2.54 cm). A 15% saline solution was used to better simulate the harsh environment that roads are subjected to in the Northeast United States and is typical of testing performed by the Vermont Agency of Transportation.

In addition to the test protocol summarized in Table 4.8, selected mixes were used to study how Hycrete DSS effects the bond strength of concrete. The test protocol was carried out using ASTM C 234-91a, "Standard Test Method for Comparing Concretes on the Basis of the Bond Development with Reinforcing Steel" and associated referenced documents in the standard. While this standard has been withdrawn, (ASTM A 944-05 is currently used for bond strengths) it was felt to be a valid test for comparing relative bond strengths between concrete mix designs with minimum of additional test apparatus. Both types of molds for bond test specimens, as described in the Standard C 234 were used. The mold for vertical bars was formed from a Modulus of Rupture (MOR) beam mold conforming to ASTM C 78 with three dividers inserted to create a triple cube prism Figure 4.5 (right) rather than the single cube test specimen described in the standard as shown in Figure 4.5 (left). The mold for the horizontal bars conformed to the standard as shown in Figure 4.6.

Table 4.8: AASHTO/ASTM Test Designations

Specification Description	Designation AASHTO	Designation ASTM	Project
Ready-mixed Concrete	M 157-97 (2001)	C 94-97	NA
Concrete Made by Volumetric Batching and Continuous Mixing	M 241-97 (2001)	C 685-95a	NA

Test Description	Designation AASHTO	Designation ASTM	
Compressive Strength of Cylindrical Concrete Specimens	T 22-97	C 39-86	COMP
Practice for Making and Curing Test Specimens in the Field	T 23-02	C 31 C 31M-96	NA
Slump of Hydraulic Cement Concrete	T 119-99	C 143 C143M-97	SLUMP
Mass per Cubic Meter (Cubic Foot), Yield, and Air Content (Gravimetric)	T 121-97 (2001)	C 138-92	DENSITY
Sampling Freshly Mixed Concrete	T 141-01	C 172-97	NA
Air Content of Freshly Mixed Concrete by Pressure Method	T 152-01	C 231-97	AIR CONTENT
Comparing Concrete on the Basis of the Bond Developed with Reinforcing Steel-*Discontinued*	T 159-88 (2000)	C 234-87	BOND
Resistance of Concrete to Rapid Freezing and Thawing	T 161-00[1]	C 666-97[1]	FREEZE
Time of Setting of Concrete Mixtures by Penetration Resistance	T 197-00	C 403 C 403M-97	SET
Splitting Tensile Strength of Cylindrical Concrete Specimens	T 198-02	C 496-96	SPLIT
Air Content of Freshly Mixed Concrete by the Chase Indicator	T 199-00	NA	AIR
Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration	T 277-96 (2000)	C 1202-94	RAPID PERM
Temperature of Freshly Mixed Portland Cement Concrete	T 309-1	C 1064-86 (1993)	TEMP
Water Content of Freshly Mixed Concrete Using Microwave Oven Drying	T318-1	NA	MEASURED W/CM
Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete	NA	C 457-90	AIR VOID

Other Tests

Other Tests	Designation	Project
Method for Determination of Water Absorption	BSI 1881 : Part 122: 1983	ABSORP

Note 1: Variation used per VTrans standard test procedure

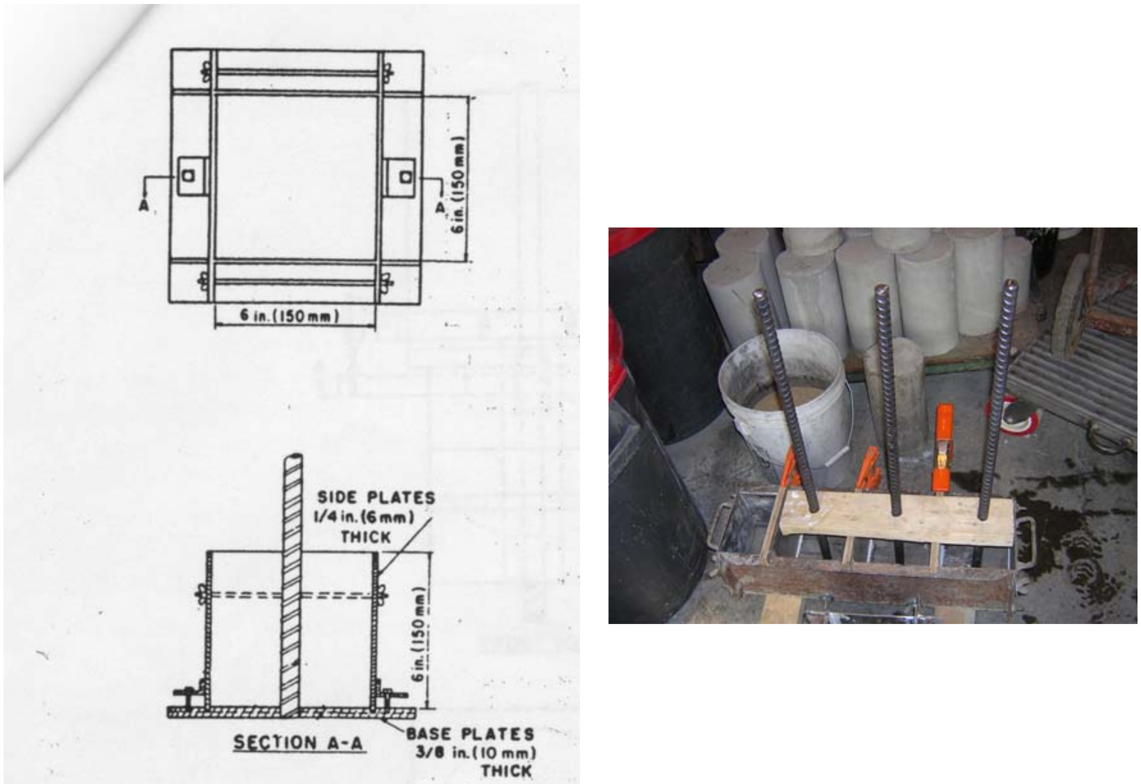


Figure 4.5: Mold for Vertical Bars (Left to Right - ASTM Schematic/As-Used)

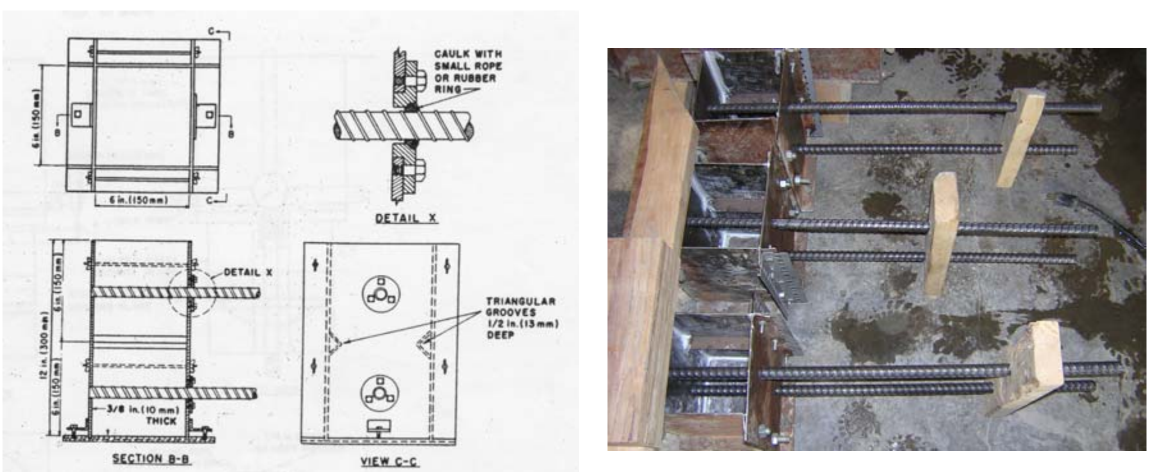


Figure 4.6: Mold for Horizontal Bars (Left to Right - ASTM Schematic/As-Used)

The measuring apparatus was simplified from the measuring apparatus illustrated in Standard C 234. Instead of measuring the displacement of a lower yoke connected to the reinforcing bar in relation to an upper yoke connected to the concrete block, the direct slip of the reinforcing bar was measured at the head of the bar with a string potentiometer linear motion transducer affixed to a bent connected to the top of the concrete block. The apparatus as-used is shown in Figure 4.7.

Figure 4.7: Measuring Apparatus

The testing apparatus followed the Standard C 234. The setup consisted of the bearing surface of the concrete supported by a bearing plate and then followed by a slotted block supported by a spherically seated bearing block. Also shown in Figure 4.8 is a ring style load cell supported on a supplementary bearing plate. The rebar was held in place with the steel grips from the Universal Testing System (UTS) shown in Figure 4.9.

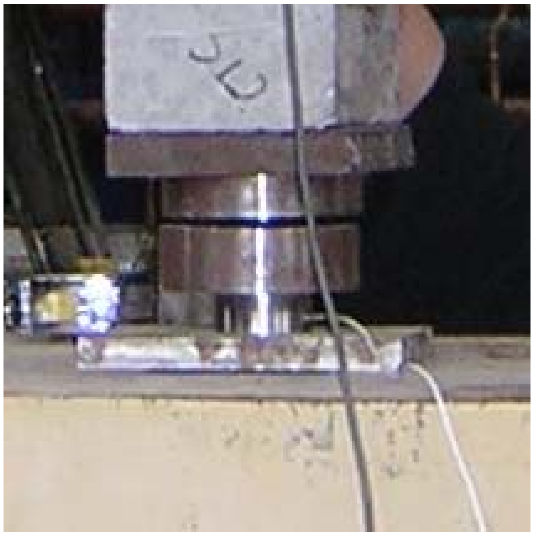


Figure 4.8: Testing Apparatus

Figure 4.9: Rebar Grips

The concrete used in the testing was obtained from the field study. For each mix four bond strength specimens were prepared. Mixes CT673C, CT687H, NH653HR1, and VT610HR1 were tested as proportioned according to Table 4.5 and Table 4.6.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Freshly Mixed Concrete

A total of 15 mixes were batched, mixed, and tested for this project. A total of 5 control mixes were tested and a total of 10 Hycrete DSS mixes were tested. A matrix of all test mixes is presented in Table 5.1.

Table 5.1: Mix Matrix

Mix ID	Location	DOT ID
Control Mixes		
CT673C	Tilcon-CT	CT State Class F
MA744C	Aggregate Industries	MHD HP
NH657C	Carroll Concrete	NH AA HRWR
NY679C	OldCastle	NA
VT617C	Carroll Concrete	VT HPCB
Hycrete DSS Mixes		
CT687H	Tilcon-CT	CT State Class F
CT663HR1	Tilcon-CT	CT State Class F
CT653HR2	Tilcon-CT	CT State Class F w/FA
MA746H	Aggregate Industries	MHD HP
NH653H	Carroll Concrete	NH AA HRWR
NH653HR1	Carroll Concrete	NH AA HRWR
NH607HR2	Carroll Concrete	NH AA HRWR
NY679H	OldCastle	NA
VT617H	Carroll Concrete	VT HPCB
VT610HR1	Carroll Concrete	VT HPCB

As stated in Chapter 4 the evaluation of each mix was conducted using standard state DOT test sampling and testing procedures conforming to ASTM and AASHTO specifications (see Table 4.8). For convenience all mixes are designated by the Project ID. The results of testing completed on freshly mixed concrete are presented in Tables 5.2 and 5.3.

Table 5.2: Freshly Mixed Concrete Properties (US)

Mix I.D.	w/cm	w/cm	Temperature	Unit Weight	Air Content	Slump	Final Set Time
	(calc.)	(measured)	(°F)	(lb/ft^3)	(%)	(in)	(hrs)
Control Mixes							
CT673C	0.41	0.46	87	156.7	4.40	2.00	NA
MA744C	0.37	NA	81	150.0	6.00	7.50[3]	NA
NH657C	0.34	0.38	56.8	149.9	6.40	4.75	13.75
NY679C	0.40	NA	74	148.2	4.50[3]	Note 1	NA
VT617C	0.38	0.42	52.8	148.5	6.90	6.50	9.68
Hycrete Mixes							
CT687H	0.40	0.51	93	148.2	6.00	2.00	NA
CT663HR1	0.40	NA	86	149.0	5.50	2.00	NA
CT653HR2	0.42	NA	84	150.1	5.00	2.00	NA
MA746H	0.36	NA	81	148.4	7.00	2.25[3]	NA
NH653H	0.35	0.42	57	150.5	5.20	5.50	16.73
NH653HR1	0.40	0.42	70	148.5	7.00	3.00	NA
NH607HR2	0.40	0.45	66	150.7	4.90	4.50	NA
NY679H	0.40	NA	80	140.9	7.00	Note 2[3]	NA
VT617H	0.38	0.43	51	149.7	5.20	4.25	10.70
VT610HR1	0.43	0.45	72	146.1	7.90[3]	4.00	NA

Note 1: Spread 24 in, time 3 sec

Note 2: Spread 17 in, time 5 sec

Note 3: Slightly out of spec – deemed OK per those present at site

Table 5.3: Freshly Mixed Concrete Properties (Metric)

Mix I.D.	w/cm (calc.)	w/cm (measured)	Temperature (^oC)	Unit Weight (kg/m^3)	Air Content (%)	Slump (cm)	Final Set Time (hrs)
Control Mixes							
CT673C	0.41	0.46	31	92.7	4.40	5.08	NA
MA744C	0.37	NA	27	88.8	6.00	19.05[3]	NA
NH657C	0.34	0.38	14	88.7	6.40	12.07	13.75
NY679C	0.40	NA	23	87.7	4.50[3]	Note 1	NA
VT617C	0.38	0.42	12	87.9	6.90	16.51	9.68
Hycrete Mixes							
CT687H	0.40	0.51	34	87.7	6.00	5.08	NA
CT663HR1	0.40	NA	30	88.2	5.50	5.08	NA
CT653HR2	0.42	NA	29	88.8	5.00	5.08	NA
MA746H	0.36	NA	27	87.8	7.00	5.72[3]	NA
NH653H	0.35	0.42	14	89.1	5.20	13.97	16.73
NH653HR1	0.40	0.42	21	87.9	7.00	7.62	NA
NH607HR2	0.40	0.45	19	89.2	4.90	11.43	NA
NY679H	0.40	NA	27	83.4	7.00	Note 2[3]	NA
VT617H	0.38	0.43	11	88.6	5.20	10.80	10.70
VT610HR1	0.43	0.45	22	86.4	7.90[3]	10.16	NA

Note 1: Spread 61 cm, time 3 sec

Note 2: Spread 43 cm, time 5 sec

Note 3: Slightly out of spec – deemed OK per those present at site

Tested mixes had calculated w/cm ratios of 0.34 to 0.43. These water content values were checked for 9 out of the 15 mixes presented using the microwave oven drying method (AASHTO T318-1). In all cases the w/cm ratio determined from the microwave oven method provided a value greater than that calculated from the plant batch tickets. Microwave test values from the control mixes were between 10% and 15% greater, while the values from the Hycrete DSS mixes were as high as 27% greater. It has been reported by the Wisconsin Department of Transportation that microwave oven testing in the field tends to lead to moisture recoveries of over 100 percent of the moisture reported in batch sheets (Dowell 2002). The microwave oven method requires that the moisture content obtained from a concrete sample be compared to the amount of concrete material reported on the batch sheet to determine the w/cm ratio. The discrepancy may partly result from the variability of plant-stored aggregate moisture contents and batch mixing and sampling size variation. Based on 2 of 3 readings, it appears that Hycrete DSS concretes may result in higher actual w/cm ratios than control concrete. Perhaps this is due to the admixture repelling surface water from the aggregate materials into the cement paste. However, any reported increase in w/cm ratio is not sufficient to solely account for any observed strength changes.

Ambient temperatures of 15 ^{o}F to 89 ^{o}F (-9.4 ^{o}C to 31 ^{o}C) were recorded during the large scale pours. Fresh concrete temperatures of 51 ^{o}F to 93 ^{o}F (10 ^{o}C to 34 ^{o}C) were measured. The coldest large scale pour occurred at Carroll Concrete in West Lebanon, NH on 3/9/05 with an ambient temperature of about 15 ^{o}F (-9.4 ^{o}C). This pour resulted in the coldest freshly mixed concrete temperature of 50.5 ^{o}F (10 ^{o}C) for the Hycrete DSS mix, VT617H. The corresponding control mixture, VT617C, had a freshly mixed concrete temperature of 52.8 ^{o}F (12 ^{o}C). The specimens from this pour were cast and poured in a heated enclosure with an ambient temperature of 51.6 ^{o}F (11 ^{o}C) and stored overnight before being transported to the testing laboratory. Based upon the workability of the mix and the resulting hardened concrete properties, it is assumed that the cooler ambient temperatures had no detrimental effects on the tested mixes. The hottest large scale pour occurred on 8/3/05 at Tilcon-CT in New Britain, CT with an average ambient temperature of 89 ^{o}F (32 ^{o}C) during testing. This pour resulted in the hottest freshly mixed concrete temperature of 93 ^{o}F (34 ^{o}C) for the Hycrete DSS mix, CT687H. The corresponding control mixture, CT673C, had a freshly mixed concrete temperature of 87 ^{o}F (31 ^{o}C). The specimens from this pour were cast and poured outdoors and then stored overnight under wet burlap and polyethylene sheeting to prevent moisture loss before being transported to the testing laboratory. Based upon the appearance of the resulting hardened concrete specimens it was determined that environmental effects reduced the workability of the mixes (slump was 2 in. (50mm) for all mixes) and led to poor consolidation under standard rodding of cylinders. Figure 5.1 pitting of a concrete cylinder. Results of specimens from mix CT687H are therefore not representative of batched concrete as they would have been rejected. Consequently CT663HR1 should be evaluated as an acceptable CT DOT comparison to CT673C.

Figure 5.1: Hardened Concrete Defect Related to Hot Weather (Specimen CT687H)

The unit weights of the concretes tested were as expected for normal weight concrete. The unit weights of the mixes were between 146 lbs/ft^3 and 157 lb/ft^3 (83 kg/m^3 and 93 kg/m^3) and varied based upon the air content and mix proportions.

Air contents obtained by the pressure method ranged between 4.4% and 7.9%. One control and one Hycrete DSS concrete fell slightly outside of the specifications (See Tables 5.2 and 5.3), but were deemed acceptable by those present at the site as deliverable concrete. Hycrete DSS added air to a concrete mix and therefore additional air entrainer was not needed to achieve the required total air content, though some additional defoaming admixture was required for some batches.

The workability of each mix was evaluated on the basis of the standard slump test. Values of slump ranged between 2.0 in and 7.5 in (51 mm and 190 mm). The only significant variation from control concrete values occurred with the Massachusetts mix design, where the control exceeded the allowable slump and the Hycrete DSS concrete did not reach an acceptable slump. This was the only mix design to use the AdvaFlow high range water reducer. Adva100 from the same company was used in other mixes with no significant variation in slump between control and Hycrete DSS mixes. The addition of Hycrete DSS was found to have no significant effect on the slump of the other 9 Hycrete DSS concrete mixes, though measured slumps tended to be slightly less than the comparable control mixes. The workability of the self consolidating concrete (SCC) mix, NY679H, was tested using the "spread test" by the precast plant's quality control technician, in accordance with applicable SCC test standards. It did not meet the requirement for SCC concrete. However, it is felt that an increase to the high range water reducer and SCC admixture would easily correct this. Plant personnel felt that the mix could still be cast normally, so a second batch was not tested. A similar mix design will be varied slightly for an implementation project.

Set times were recorded only on mixes from the Carroll Concrete large scale pour completed on 11/7/05. These mixes included NH657C, VT617C, and Hycrete DSS mixes NH653H and VT617H. Mixes VT617C and VT617H had the shortest set times with final sets of 9.7 hr and 10.7 hr respectively. The quicker set was most likely due to the fact that these mixes had a smaller percentage of slag, which is known to retard a set, and 5% silica fume replacement which has been found to increase the early age strength of a mix. On average the Hycrete DSS mixes had a 16 % greater final set time than their control mix equivalents. These variations in set time were felt to be minor issues and would not affect a typical concrete placement.

5.2 Hardened Concrete

The evaluation of each mix was conducted using standard state DOT test sampling and testing procedures conforming to ASTM and AASHTO specifications (see Table 4.8).

5.2.1 Compressive Strength

All concrete mixtures tested had average 28-day compressive strengths which exceeded the specified minimum required strength for each mix as reported in Table 5.4 and Table 5.5. With the exception of mix CT687H all mixes, including Hycrete DSS mixes had average 28-day compressive strengths 25% greater than required by nominal requirements. Three Hycrete DSS mixtures had 28-day compressive strengths 50% or higher than the nominal requirement. This is typical of high performance concretes used in DOT projects, where a focus on reducing concrete permeability results in compressive strengths that are often much higher than specified minimum values. Therefore, for typical applications, any strength reduction in Hycrete DSS concrete is of minor consequence, provided that early age strengths are not reduced significantly.

Table 5.4: 28 Day Compressive Strengths of Concrete Mixes (US)

Mix ID	Required f'_{28}	Measured f'_{28}	Difference
	(psi)	(psi)	%
Control			
CT673C	4000	5109	28%
MA744C	5000	8784	76%
NH657C	4000	7665	92%
NY679C	NA	7785	-
VT617C	3500	7535	115%
Hycrete DSS			
CT687H	4000	4123	3%
CT663HR1	4000	5769	44%
CT653HR2	4000	5256	31%
MA746H	5000	6428	29%
NH653H	4000	6542	64%
NH653HR1	4000	5891	47%
NH607HR2	3500	5800	66%
NY679H	NA	5536	-
VT617H	3500	6204	77%
VT610HR1	3500	5042	44%

Table 5.5: 28 Day Compressive Strengths of Concrete Mixes (Metric)

Mix ID	Required f'_{28}	Measured f'_{28}	Difference
	(Mpa)	(Mpa)	%
Control			
CT673C	28	35.2	28%
MA744C	34	60.6	76%
NH657C	28	52.9	92%
NY679C	NA	53.7	-
VT617C	24	52.0	115%
Hycrete DSS			
CT687H	28	28.4	3%
CT663HR1	28	39.8	44%
CT653HR2	28	36.2	31%
MA746H	34	44.3	29%
NH653H	28	45.1	64%
NH653HR1	28	40.6	47%
NH607HR2	24	40.0	66%
NY679H	NA	38.2	-
VT617H	24	42.8	77%
VT610HR1	24	34.8	44%

The mix with the highest 28-day compressive strength was the MA744C mix, while the lowest strength mix was CT687H. The MA744C mix achieved the highest strength because it was the control mix with the highest cement content of all mixes. As noted previously CT687H mix was not acceptable due to the high ambient temperatures during the pour and resulting poor quality concrete. A subsequent report of this mixture, designated CT663HR1 verifies that when ambient temperatures were lower the mix performed much better with 28-day compressive strengths exceeding 5500 psi (38 MPa), higher than the control specimens (which had some hot-weather problems as well). The highest 28 day strength Hycrete DSS mix was NH653H with a 28-day compressive strength of 6542 psi (45MPa).

An evaluation of concrete strengths with age are shown in Table 5.6, which includes average results of test cylinders from all testing laboratories. Only UMass test results are shown in Figure 5.2, which indicate the compressive strength gain over time. Aside from strength reductions, trends in strength gains are similar between Hycrete DSS and control concretes. The Hycrete DSS mixes with highest early age strength were MA746H, NY679H and NH607HR2 with 7-day compressive strengths of 5265 psi (36.3 MPa), 4717 psi (32.5 MPa) and 4613 psi (31.8 MPa) and respectively. Half of these strengths were reached between 1 and 2 days.

When Hycrete DSS mixtures were batched with a directly corresponding control mixture, strengths of the Hycrete DSS specimens were reduced from the control. While the following comparison does not account for variations in air content and w/cm which also impact strength, Hycrete DSS concretes had strength reductions from -12% (strength increase) to 33% from the control. On average, Hycrete DSS concretes had a

28-day compressive strength reduction of approximately 20% from the control. These reductions were typical at all concrete ages as can be seen in Figure 5.2.

Table 5.6: Compressive Strengths of Concrete Mixes (US)

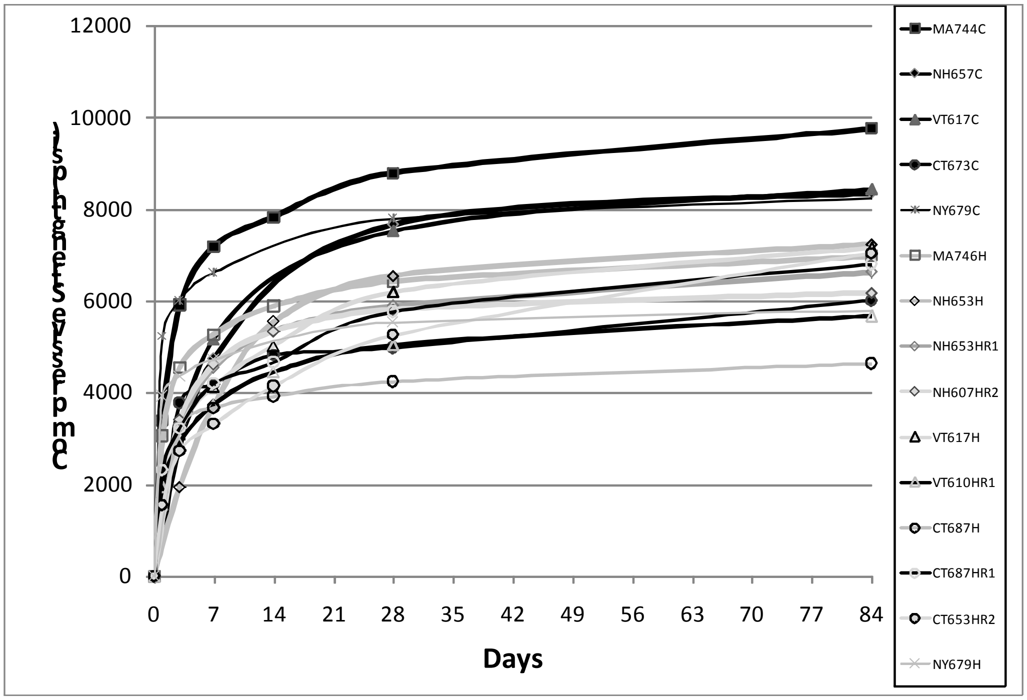
Mix ID	Strength at Age (Days)								Testing Agency
	1 (psi)	3 (psi)	5 (psi)	7 (psi)	14 (psi)	28 (psi)	84 (psi)	215 (psi)	
Control									
CT673C		3773		4172	4818	4978	5999		UMASS
		2393	3313		3943	4850	5240		CTDOT[3]
							5714[1]		NHDOT[1]
MA744C	3389	5916		7181	7830	8784	9763		UMASS
					7000		9070		MassHighway
NH657C				4732		7665	8354		UMASS
			4190		6885	7500			VTrans
						8759			NHDOT
NY679C	5240	5990		6611		7785		9032	UMASS
VT617C				5164		7535	8440		UMASS
				4005	6050	6495			VTrans
						8058			NHDOT
Hycrete DSS									
CT687H		3216		3662	3923	4242	4631		UMASS
		2313	2727		3187	3637	4003		CTDOT[3]
CT687HR1	2310	3216		4198	4658	5769	6805		UMASS
		1634		3670	4147	4653	5333		CTDOT[3]
CT653HR2	1536	2731		3312	4140	5256	7033		UMASS
		1202		3283	3617	4663	5437		CTDOT[3]
							4353[1]		NHDOT[1]
MA746H	3060	4550		5265	5890	6428	6979		UMASS
					4985		6270		MassHighway
NH653H		1941		3722	5548	6542	7235		UMASS
			3590		5825	6955			VTrans
						7570			NHDOT
NH653HR1	1440	3312		4534	5343	5891	6625		UMASS
				5230[2]	5185	6375			VTRANS[2]
						6000			NHDOT
NH607HR2	1702	3419		4613	5341	5800	6180		UMASS
				5015[2]	5365	6410			VTRANS[2]
						6080			NHDOT
NY679H	3923	4355		4717		5536		6224	UMASS
VT617H		3096		4122	5018	6204	7142		UMASS
				3760	5235	5755			VTrans
						6684			NHDOT
VT610HR1	1944	2896		3741	4455	5042	5665		UMASS
				4115[2]	5280	5440			VTRANS[2]
						5372			NHDOT

Note 1: 2 NHDOT records at 56 days rather than 84 days
Note 2: 3 VTrans tested at 8 days rather than 7 days
Note 3: CTDOT tested larger cylinder sizes

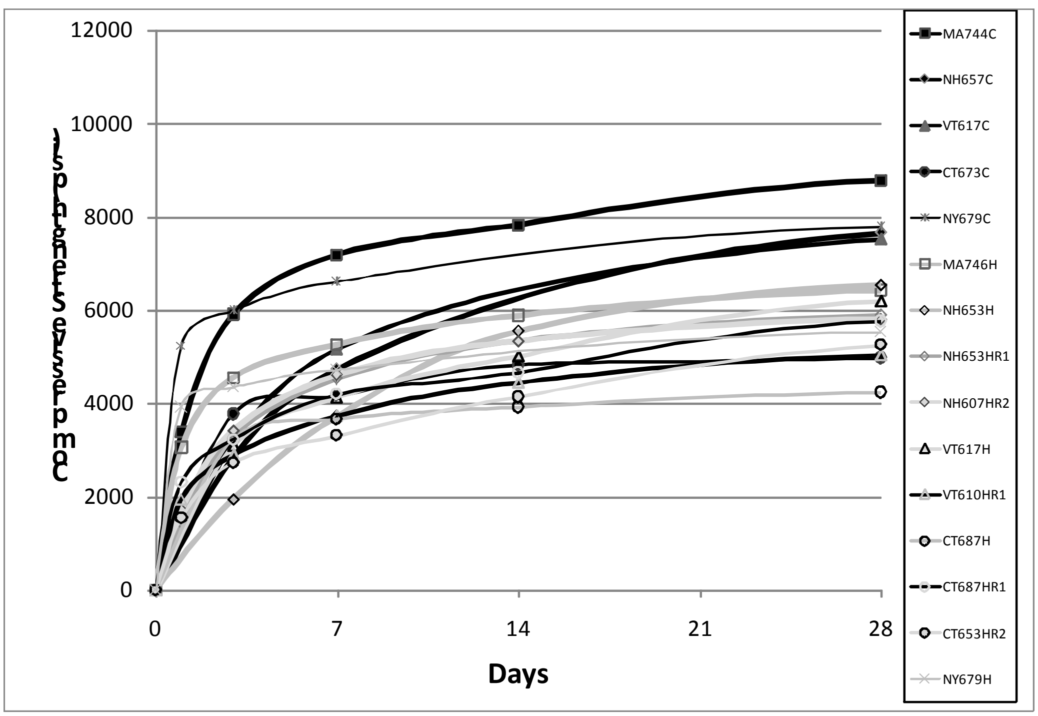
Table 5.7: Compressive Strengths of Concrete Mixes (Metric)

Mix ID	Strength at Age (Days)								Testing Agency
	1 (psi)	3 (psi)	5 (psi)	7 (psi)	14 (psi)	28 (psi)	84 (psi)	215 (psi)	
Control									
CT673C		26.0		28.8	33.2	34.3	41.4		UMASS
		16.5	22.8		27.2	33.4	36.1		CTDOT[3]
							39.4[1]		NHDOT[1]
MA744C	23.4	40.8		49.5	54.0	60.6	67.3		UMASS
					48.3		62.5		MassHighway
NH657C				32.6		52.9	57.6		UMASS
			28.9		47.5	51.7			VTrans
						60.4			NHDOT
NY679C	36.1	41.3		45.6		53.7		62.3	UMASS
VT617C				35.6		52.0	58.2		UMASS
				27.6	41.7	44.8			VTrans
						55.6			NHDOT
Hycrete DSS									
CT687H		22.2		25.2	27.0	29.2	31.9		UMASS
		15.9	18.8		22.0	25.1	27.6		CTDOT[3]
CT687HR1	15.9	22.2		28.9	32.1	39.8	46.9		UMASS
		11.3		25.3	28.6	32.1	36.8		CTDOT[3]
CT653HR2	10.6	18.8		22.8	28.5	36.2	48.5		UMASS
		8.3		22.6	24.9	32.2	37.5		CTDOT[3]
							30.0[1]		NHDOT[1]
MA746H	21.1	31.4		36.3	40.6	44.3	48.1		UMASS
					34.4		43.2		MassHighway
NH653H		13.4		25.7	38.3	45.1	49.9		UMASS
			24.8		40.2	48.0			VTrans
						52.2			NHDOT
NH653HR 1	9.9	22.8		31.3	36.8	40.6	45.7		UMASS
				36.1[2]	35.8	44.0			VTRANS[2]
						41.4			NHDOT
NH607HR 2	11.7	23.6		31.8	36.8	40.0	42.6		UMASS
				34.6[2]	37.0	44.2			VTRANS[2]
						41.9			NHDOT
NY679H	27.0	30.0		32.5		38.2		42.9	UMASS
VT617H		21.3		28.4	34.6	42.8	49.2		UMASS
				25.9	36.1	39.7			VTrans
						46.1			NHDOT
VT610HR1	13.4	20.0		25.8	30.7	34.8	39.1		UMASS
				28.4[2]	36.4	37.5			VTRANS[2]
						37.0			NHDOT

Note 1: 2 NHDOT records at 56 days rather than 84 days
Note 2: 3 VTrans tested at 8 days rather than 7 days
Note 3: CTDOT tested larger cylinder sizes



a) 0 to 84 Day Strengths



b) 0 to 28 Day Strengths

Figure 5.2: Compressive Strengths Over Time

5.2.2 Tensile Strength

Typically splitting tensile strength is about 8% to 14% of the compressive strength or is derived using the relationship:

$$5.0 \text{ to } 7.5\sqrt{f'c}$$

For calculations the lower limit in this equation is used. At higher compressive strengths, this relationship exhibits greater scatter. The mixture with the highest splitting tensile strength was NH657C and the mixture with the lowest splitting tensile strength was CT687H. The splitting tensile strengths for all of the mixes in the test protocol is presented in Table 5.8 and 5.9.

Table 5.8: Splitting Tensile Strength of Concrete Mixes (US)

Mix ID	Calculated* Nominal f_{ct}	Calculated* f_{ct} based on actual f_{28}	Measured f_{ct}	Difference from Calculated (Nominal)	Difference from Calculated (Actual)
	(psi)		(psi)	%	%
Control					
CT673C	316	357	401	27%	12%
MA744C	354	469	654	85%	39%
NH657C	316	438	656	108%	50%
NY679C	-	441	573	-	30%
VT617C	296	434	395	33%	-9%
Hycrete DSS					
CT687H	316	321	321	2%	0%
CT663HR1	316	380	383	21%	0%
CT653HR2	316	362	412	30%	14%
MA746H	354	401	396	12%	-1%
NH653H	316	404	622	97%	54%
NH653HR1	316	384	486	54%	27%
NH607HR2	296	381	478	61%	25%
NY679H	-	372	491	-	32%
VT617H	296	394	377	27%	-4%
VT610HR1	296	355	422	43%	19%

*5(sqrt(f'$_{28}$))

Table 5.9: Splitting Tensile Strength of Concrete Mixes (Metric)

Mix ID	Calculated* Nominal f_{ct}	Calculated* f_{ct} based on actual f_{28}	Measured f_{ct}	Difference from Calculated (Nominal)	Difference from Calculated (Actual)
	(MPa)	(MPa)	(MPa)	%	%
Control					
CT673C	2.18	2.46	2.76	27%	12%
MA744C	2.44	3.23	4.51	85%	39%
NH657C	2.18	3.02	4.52	108%	50%
NY679C	-	3.04	3.95	-	30%
VT617C	2.04	2.99	2.72	33%	-9%
Hycrete DSS					
CT687H	2.18	2.21	2.21	2%	0%
CT663HR1	2.18	2.62	2.64	21%	0%
CT653HR2	2.18	2.50	2.84	30%	14%
MA746H	2.44	2.76	2.73	12%	-1%
NH653H	2.18	2.79	4.29	97%	54%
NH653HR1	2.18	2.65	3.35	54%	27%
NH607HR2	2.04	2.63	3.30	61%	25%
NY679H	-	2.56	3.39	-	32%
VT617H	2.04	2.72	2.60	27%	-4%
VT610HR1	2.04	2.45	2.91	43%	19%

Test data showed considerable scatter from calculated values, as is typical in tensile strength calculations. Similar scatter is seen in both control and Hycrete DSS concrete results. All specimens exceeded tensile capacities based on nominal strengths, and none were below 90% of tensile capacities based on actual strengths.

5.2.3 Chloride Ion Penetration and Absorption

The following section relates to results from Absorption Testing and Rapid Chloride Penetration Test results for specimens obtained in this study. In addition, specimen samples that had been saved from NETC 98-2 (Civjan et al 2002, Civjan et al 2005c) were tested for chloride penetration. These results are presented in section 5.2.3.2.

5.2.3.1 Chloride Ion Penetration and Absorption

Simple absorption tests were conducted at 28 days and 90 days for selected specimens. Rapid chloride permeability tests were conducted by three different agencies, including the New Hampshire Department of Transportation (NHDOT), the Vermont Agency Of Transportation (VTrans), and the Massachusetts Highway Department (MHD), and results are presented in Table 5.10. As noted in Chapter 3, previous literature has noted that rapid chloride permeability data does not correspond to actual absorption properties for Hycrete DSS concretes. Results of this study corroborate previous results. The VTrans test were conducted at 69 days, while the other departments conducted tests at 56 days.

The absorption test measured the capacity of a hardened concrete mix to absorb water while rapid chloride permeability tests give an indication of a hardened concrete mix's ability to repel ion penetration. Both tests are often used as a means of evaluating the relative ability of a hardened concrete mix to protect steel reinforcement from chemical attack. A decision to evaluate absorption was made after the 1st concrete pour, so data comparisons are not available for all control concretes.

Absorption values for control specimens were approximately 2%, while Hycrete DSS specimens were typically below 1%. Absorption tests at 90 days indicated that the average absorption capacity of Hycrete DSS mixes were reduced 70% to 80% from the corresponding control mixes.

Evaluation of results from the rapid chloride permeability test were based on Table 1 from the AASHTO T 277 test standard for Electrical Indication of Concrete's Ability to Resists Chloride Ion Penetration. Both control and Hycrete DSS concretes were found to have “very low” (100 to 1000 coulombs passed), “low” (1000 to 2000 coulombs passed) and “high” (greater than 4000 coulombs passed) chloride ion penetrability results for different mix designs. The performance of the CT673C and CT687H mixes is likely due to poor concrete quality as noted previously. In general it was found that the rapid chloride permeability test indicated minimal differences in permeability between control and Hycrete DSS concretes, which is a very different conclusion than shown by absorption testing. As reported in Section 3.2.5.2 of the Literature Review, due to the ionic nature of Hycrete DSS, the standard chloride permeability test may not adequately measure the performance of Hycrete DSS concrete when compared to a control mixture. Therefore permeability criteria of Hycrete DSS concretes should be based on actual absorption tests. The actual benefit of Hycrete DSS additions with respect to reduced concrete permeability is apparent under these test regimens, which are directly related to actual conditions.

5.2.3.2 Chloride Ion Penetration Data from Previous Specimens

At the conclusion of NETC project 98-02 (Civjan et al 2002), specimens which were not autopsied were tested under the same regimen through a period of 208 weeks. Corrosion results for these specimens were reported in Civjan et. al. 2005c. Samples were obtained at the conclusion of these tests for chloride testing, but these tests were not completed as part of previous projects. Powdered samples were obtained at 0 to ½ in, ½ to 1 in, 1 to 1 ½ in, 1 ½ to 2 in, and 2 to 2 ½ in (0 to 12.5 mm, 12.5 to 25.5 mm, 25.5 to 38.0 mm, 38.0 to 51.0 mm, and 51.0 to 63.5 mm). Testing of these samples was performed by the VTrans in accordance with AASHTO T-260 (Standard Method of

Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials), with results in parts per million of acid soluble chloride per sample. Results of this testing are shown in Figure 5.3.

Table 5.10: Results from Rapid Chloride Permeability and Absorption Testing

Mix I.D.	NHDOT (56days)	VTAOT (69days)	MHD (56days)	28	90
	perm	Perm	perm	abs	abs
	coulombs passed			%	
Control					
CT673C	7022	>6000	NA	NA	2.779
MA744C	NA	NA	652	NA	1.794
NH657C	1305	1177	NA	NA	NA
NY679C	NA	NA	NA	1.89[2]	NA
VT617C	753	652	NA	NA	NA
Hycrete DSS					
CT687H	>9000	>9000	NA	NA	0.882
CT663HR1	NA	NA	NA	0.691	0.577
CT653HR2	NA	NA	NA	1.101	0.639
MA746H	NA	NA	301	NA	0.316
NH653H	1395	1195	NA	NA	NA
NH653HR1	1931	2200	NA	0.346	0.305
NH607HR2	1971	2405	NA	0.405	0.284
NY679H	NA	NA	NA	0.307[2]	NA
VT617H	809	695	NA	NA	NA
VT610HR1	756	646	NA	0.308	0.331

Note 1: Test data not yet available
Note 2: Test at 45 days

In addition, after 136 weeks of testing, 4 samples were sent to Grace Chemical Company for Chloride analysis. These included 2 samples from the control specimen (Mix 1 of that project) and 2 samples from the Hycrete DSS specimen (Mix 6 of that project). Specimen numbers were not provided to Grace until after results were reported. Analysis reported from Grace noted that the diffusion coefficient of the the Hycrete DSS samples were approximately “1/40 to 1/50” of the control. Results of Chloride content at depth is shown in Figure 5.4.

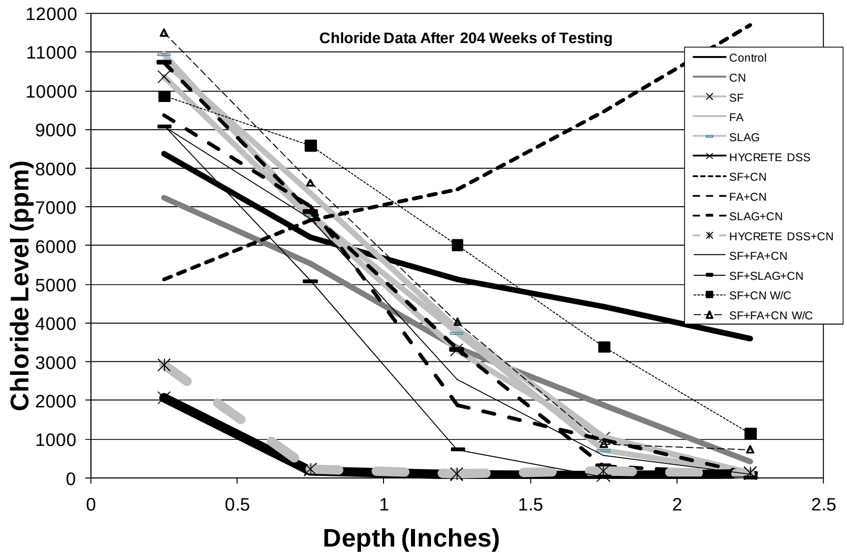


Figure 5.3: Chloride Level Versus Depth (VTrans Results)

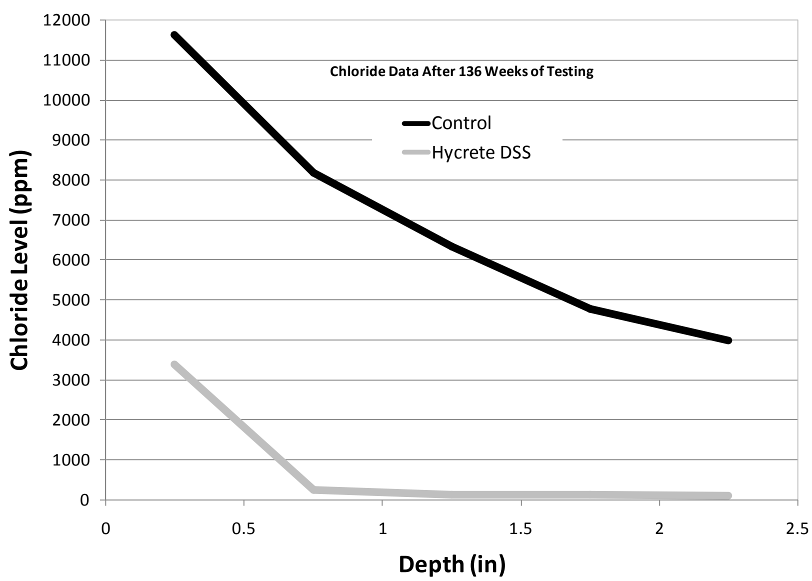


Figure 5.4: Chloride Level Versus Depth (Grace Results)

Results are similar in both cases. Surface chlorides (in the first ½ in (12.5 mm) were greatly reduced and little if any penetration occurred in Hycrete DSS samples. This performance was significantly better than that of any other combination of admixtures and pozzolonic additions, representative of current high performance concretes. The specimen which has an increased concentration with depth was shown in the previous study to have problems with microcracking. Those with a WC designation in the chart have higher w/cm ratios and would be expected to have greater chloride penetration than their counterparts.

5.2.4 Freeze-Thaw Durability

All mixes from the mix matrix were tested for freeze-thaw durability by VTrans, with results shown in Table 5.11. In almost all cases the control specimens performed better than the corresponding Hycrete DSS specimens, as would be expected due to higher concrete strengths in control concretes. Differences in mass loss for all tested samples is shown in Figure 5.5. VTrans has no specific acceptance criteria for freeze-thaw durability testing, but uses the test data for comparative purposes between mixes.

Freeze-thaw performance is generally affected by a variety of factors including strength, air entrainment, w/cm, and curing. The pair of mixes from the Aggregate Industries Pour on 8/16/06 had the best performance of all of the mixes resulting in the lowest mass losses, highest durability factors, and visual ratings. These mixes also exhibited highest strengths, had entrained air contents around 7%, and relatively low w/cm's. With the exception of the CT687H and CT683HR1 mixes, which had poor concrete quality, and evidence of honeycombing, all mixes had adequate freeze-thaw protection based upon FHWA guidelines for high performance concrete (HPC) with durability factors in excess of 80% (VT617H is a borderline not acceptable case) (Goodspeed 2003).

Table 5.11: Results from Freeze Thaw Testing

Mix ID	Cycles	% Mass Loss	Durability Factor %	Visual
Control				
CT673C	328	7.2	104.9 (100)[1]	Some mortar loss on side and bottom. Small loss of #4 and 3/4' aggregate
MA744C	328	0.4	102.9 (100)[1]	Excellent performance
NH657C	318	2.6	92.2	Hardly any mortar
NY679C	-	-	-	-
VT617C	318	8.8	94.2	Some mortar loss and small aggregate
Hycrete DSS				
CT687H	328	25.3	97.5 (80.3)[1]	Heavy mortar and coarse aggregate loss
CT663HR1	313	34.7	Not Readable	Heavy loss of aggregate and mortar
CT653HR2	313	13.2	103.2 (98.3)[1]	Mortar loss and up to 3/4 " aggregate loss
MA746H	328	2.0	98.5	Light mortar loss and light scaling
NH653H	318	8.1	90.6	Mortar loss and some small aggregate
NH653HR1	321	6.8	90.4	Some scaling and mortar loss. Loss of some 3/8" aggregate.
NH607HR2	321	9.5	90.4	Some 3/8" aggregate loss
NY679H	-	-	-	-
VT617H	318	15.6	78.1	Heavy mortar loss on all sides and loose coarse aggregate
VT610HR1	321	5.0	89.2	Mortar loss and up to 3/4" aggregate loss

Note 1: At least one durability factor result > 100%. Number in parenthesis is result if value is assumed to have a maximum of 100%.

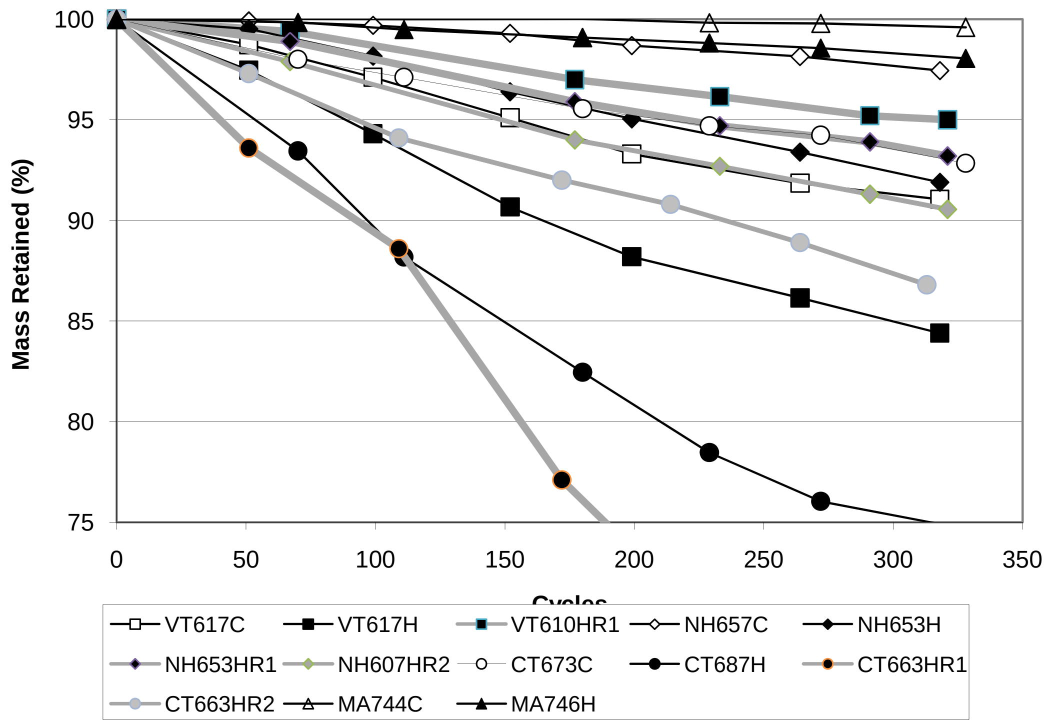


Figure 5.5: Percent Mass Loss of Specimens in Freeze Thaw Test Protocol

It is clearly shown that for any design criteria, such as 90% mass retained and durability factor greater than 90%, there were acceptable mixes both in control and Hycrete DSS concretes. In addition, several Hycrete DSS concretes performed as well as control concretes typically used in DOT projects.

5.2.5 Bond Development

Though not required by the project, a small sampling of bond development tests were conducted. Mixes CT673C, CT687H, NH653HR1, and VT610HR1 were selectively tested for bond strength. The results of the mix CT687H are not presented because the mix was not found to be acceptable, as noted previously. The nominal average bond stress is equal to the measured load on the rebar at any stage of the test divided by the embedded surface area of the rebar. For No.6 deformed bars having an embedment length of 6 in (15 cm) the surface area is calculated to be 14.14 in^2 (230 cm^2). The slip of the bars during the tests was taken as the direct measurement of the linear potentiometer. The concrete mix, the type of specimen (horizontal (H) or vertical (V)), the ultimate bond strength, controlling limit state, and concrete compressive strength at date of testing are given for each specimen in Table 5.12 and Table 5.13. The ultimate strength was based on the last recorded value of load before the occurrence of the controlling limit state (enclosing concrete splitting controlled all specimens, though reinforcing bar yielding or excessive slip of reinforcing bar could also control). The concrete strength for each set of specimens was obtained from an average of three companion 4x8 concrete cylinders tested in compression on the same date of the bond test.

Table 5.12: Ultimate Bond Strength

Mix	Bond Strength (psi)	Mold Type	Limit State	f'c (psi)
CT673C	1599	H	split	6555
	1622	H	split	6555
	2009	H	split	6555
	1569	H	split	6555
NH653HR1	1077	H	split	5891
	1756	H	split	5891
	1214	V	split	5891
	1200	V	split	5891
VT610HR1	1312	H	split	5042
	1198	H	split	5042
	1766	H	split	5042
	1941	H	split	5042

H - horizontal bar mold specimen
V - vertical bar mold specimen

Table 5.13: Ultimate Bond Strength (Metric)

Mix	Bond Strength (MPa)	Mold Type	Limit State	f'c (MPa)
CT673C	11.03	H	split	45
	11.18	H	split	45
	13.85	H	split	45
	10.82	H	split	45
NH653HR1	7.42	H	split	41
	12.11	H	split	41
	8.37	V	split	41
	8.27	V	split	41
VT610HR1	9.05	H	split	35
	8.26	H	split	35
	12.18	H	split	35
	13.38	H	split	35

H - horizontal bar mold specimen
V - vertical bar mold specimen

As noted in Table 5.12 and Table 5.13 the limit state (LS) for all specimens was concrete splitting. The test results were evaluated by comparing the test data from Hycrete mixes to the control mix and to two empirical models. The first model is Equation 12-1 from ACI 318-02:

$$l_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f'_c}} \frac{\alpha\beta\gamma\lambda}{\left(\frac{c + K_{tr}}{d_b} \right)} \right) d_b$$

Equation 1

This expression estimates the embedded length (l_d) of reinforcement in concrete needed to develop the full stress of the reinforcement. In Equation 1 c is a factor that represents the smallest side of cover over the bar (measured to center of bar). K_{tr} is a factor that represents the contribution of confining reinforcement (for this case K_{tr}=0). α is the reinforcement location factor (in this case α =1). β is the reinforcement coating factor β is taken as 1.0. for uncoated bars. γ is the reinforcement size factor, taken as 0.8 for No. 6 bars and smaller. λ is the lightweight aggregate concrete factor and is taken as 1.0 for normal weight concrete. The compressive strength of concrete (f'_c) and specified yield strength of reinforcement (f_y) are determined by Standard C 39 and Standard A 615. Figure 5.6 shows the comparison of the bond strengths of the tested specimens to the expected bond strengths from Equation 1 versus the square root of the compressive strength of the concrete.

The second model was presented by Esfani and Rangan (1998) for estimating the local splitting bond resistance for normal strength concrete (f'_c less than 50MPa):

$$u_{\max} = 4.9 \frac{c/d_b + 0.5}{c/d_b + 3.6} f_{ct}$$ **Equation 2**

where the tensile strength (f_{ct}) of concrete (MPa) is taken as equal to $0.55\sqrt{f'_c}$. The expected ultimate bond strength from a splitting type failure from the empirical equation developed by Esfani and Rangan to the actual ultimate bond strength measured for each test specimen is shown in Figure 5.6 versus the square root of the compressive strength of the concrete.

Bond capacities exceed the ACI design values and appear to be reasonably approximated by Esfani and Rangan (1998). While results appear to be acceptable, only a small sample was evaluated. It is also noted that more scatter in bond strength was exhibited by Hycrete DSS concretes. Therefore additional testing would be required to provide a conclusive statement on the acceptability of Hycrete DSS concrete's bond performance, though these very preliminary results do not indicate any problems.

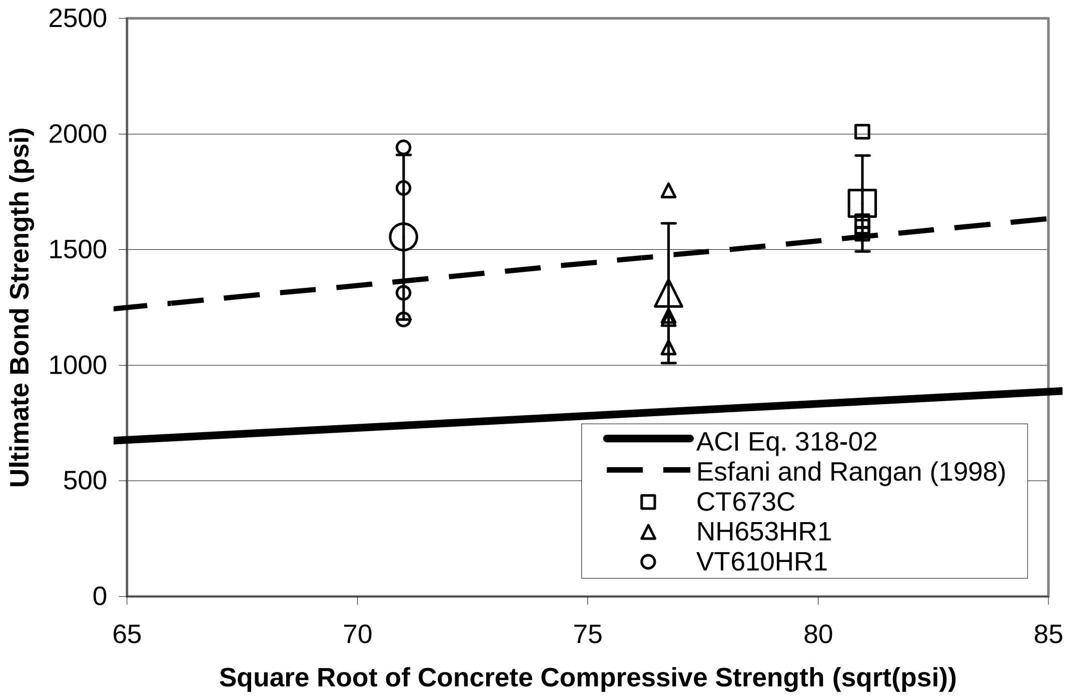


Figure 5.6: Bond Strengths of Hycrete DSS Specimens

CHAPTER 6

IMPLEMENTATION PROJECTS

6.1 Considered Projects

Discussions with each of the New England States and New York were initiated through the advisory group affiliated with this project (one representative from each state). A specific goal was to define potential projects for Hycrete DSS concretes in "severe" environments (freeze-thaw, deicing salt, marine environment) with a range of distinct applications. Implementation projects were considered in Maine, Massachusetts, New York and Vermont and are shown in Table 6.1. To date the Maine project is under construction, with a significant amount of Hycrete DSS concrete placed and the Vermont project is complete. The Massachusetts and New York projects had not been contracted at the completion of this project.

Table 6.1: Planned Implementation Projects

State	Project	Scope	Status
ME	Large Scale Ferry Terminal	Dolphins and Columns alternating Hycrete DSS and Control Concretes. Sacrificial Black Steel Reinforcement	Under Construction. Partial Initial Readings Complete
MA	Patching Repairs of Columns and Bents in Deteriorating Structures	Patches of Hycrete DSS and Control Concretes. Standard MA half-cell wiring details.	Not Contracted
NY	Large scale Precast Concrete Culvert	Alternating sections of Hycrete DSS and Control Concrete. Pre-Wired at Precast Facility	Test Project Being Sought by DOT and Precaster.
VT	Bridge Curb	90 Foot Bridge Curb at Approach Span With Alternating Hycrete DSS and Control Concrete. Plus Test Slabs of Varying Concrete Cover. All Include Wiring to Reinforcement.	Construction Complete. Initial Readings Complete.

The Vermont application is a curb on a rural bridge. This application is a non-critical placement from a structural perspective, but provided the opportunity for extensive monitoring, including test slabs which were placed adjacent to the structure. The Maine application is a large scale ferry terminal. This project presents a unique case of severe corrosion in a marine environment, large scale concrete placement, long transport time from the ready-mix plant to the site and pumped placement application. Both of these construction projects were implemented during the course of this research project. The remaining two projects provide unique applications, but have not yet been initiated. The New York application would address precast elements, namely large scale culvert sections. The Massachusetts application would address the use of Hycrete DSS in patching and repair of highway substructure elements. This application would draw heavily on the laboratory response of Hycrete DSS to not only deter the initiation of corrosion, but mitigate chloride ingress at cracking which is likely to occur at the interface of the existing concrete and patch materials. Finally, though not directly part of this research project, an implementation of barriers used in work zones in Connecticut is reported.

For each placement control elements were planned along with Hycrete DSS elements for comparative evaluation. Each project included simple instrumentation for long term corrosion monitoring for comparison data between Hycrete DSS and control concretes. A single connection to the embedded reinforcement, required for most corrosion monitoring instruments, was accomplished through the use of a lead wire connected to the reinforcement and terminating the wire outside of the concrete, or a sacrificial piece of black reinforcement bar. Monitoring plans included measurement of half cell potentials to determine the initiation of corrosion and/or measurements using the Galvapulse instrument. Gage clip from either instrument would be attached to the appropriate wire and readings taken at the surface of the concrete located at the black reinforcement bar locations. For sections using only epoxy coated reinforcement, the same method could be used, although the readings would not be directly indicative of the amount of corrosion, but could presumably locate corrosion at holiday locations.

In each completed implementation project (Maine and Vermont), specification modifications were made by the DOT to waive contractor incentives/penalties for high early strength and delete rapid chloride permeability test result requirements.

6.2 Maine Ferry Terminal

6.2.1 Description of Project

The ferry terminal implementation project is located in Rockland, Maine. This application is significant in many regards. First, it is a large scale application, including approximately 300 yd^3 (230 m^3) of Hycrete DSS concrete placement, in addition to approximately 460 yd^3 (350 m^3) of control concretes. Second it is in a highly corrosive marine environment. Third, the dispatch time is over one hour from the batch plant to the site. Fourth, the concrete placement was a pumped application. Finally, the ready-mix company and DOT had not had any previous experience with Hycrete DSS, so this is seen as an independent implementation scenario. An overview of the ferry terminal layout is shown in Figure 6.1. Major components consist of 7 dolphins, hoist tower foundations, piers, and miscellaneous structures. Details for dolphins 1 to 4 can be seen in Figure 6.2, while dolphins 5 to 7 are similar but do not have battered piles. Details of the hoist tower foundation can be seen in Figure 6.3. Four of the dolphins (numbers 1,2,5 and 7) were placed using Hycrete DSS concrete and three of the dolphins (numbers 3,4 and 6) placed using control HPC concrete which includes DCI. In addition, foundations for hoist tower 1 were placed with Hycrete DSS concrete, while the foundations for hoist tower 2 were placed with control HPC.

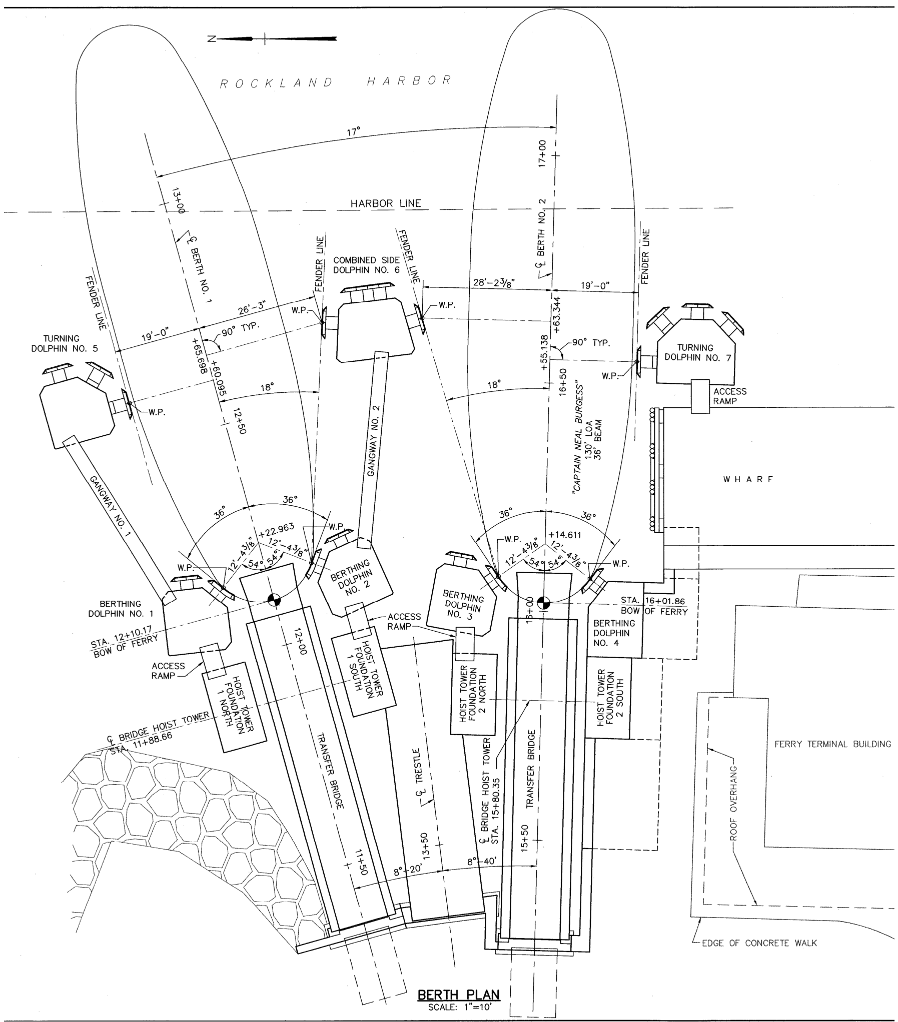


Figure 6.1: Ferry Terminal Plan View (Courtesy of Maine DOT)

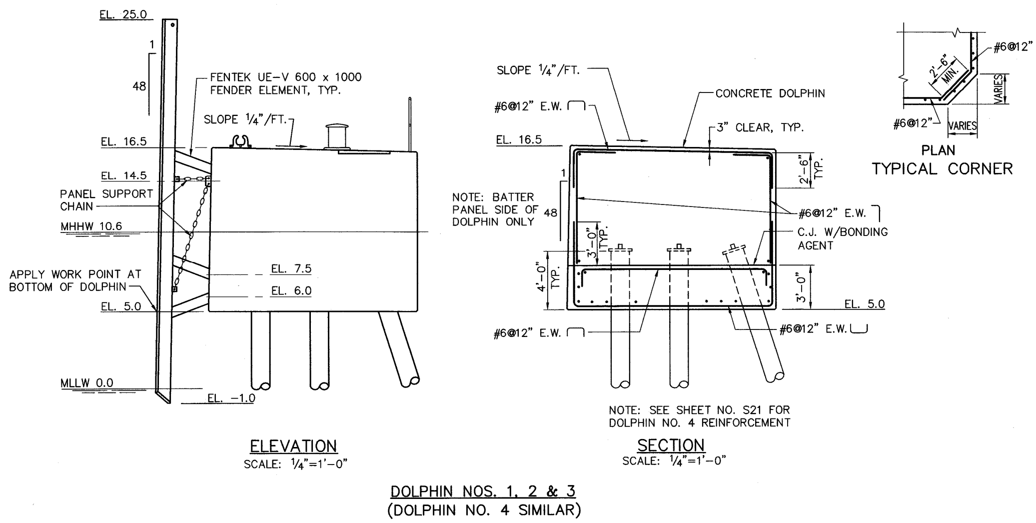


Figure 6.2: Dolphin Details (Courtesy of Maine DOT)

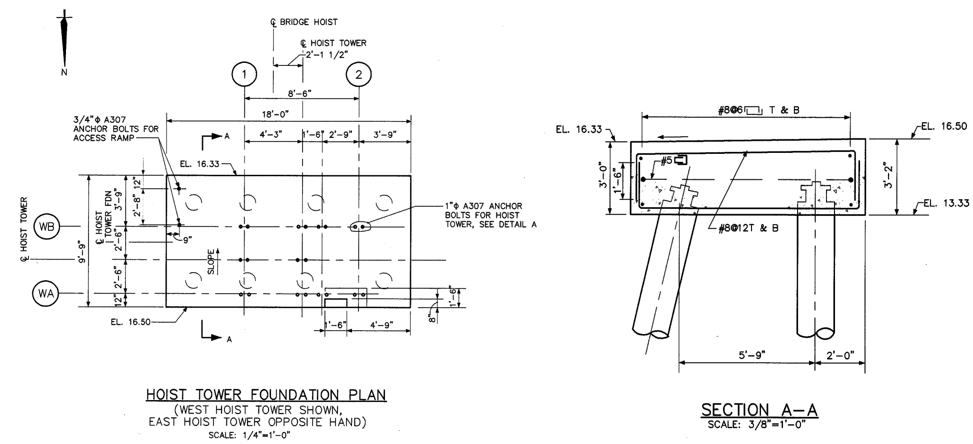


Figure 6.3: Hoist Tower Foundation Details (Courtesy of Maine DOT)

6.2.2 Monitoring Methods

Discussions with the Maine DOT determined that monitoring would be accomplished by providing two sacrificial black steel bars in each dolphin which extend approximately 7 feet (2.1 m) from the top of the dolphin which extends into an area which is wetted and dried during high and low tide. One bar is placed at the north, and one at the south face of the dolphin (geometry required the south bar in dolphin 4 to be placed in the south-east corner). These reinforcing bars will extend above the top of the dolphin by approximately 2 inches (50mm) in their finished condition and be coated with epoxy in the exposed area. Placement varied from 4 to 10 inches (10 to 25 cm) from the face of the dolphin at the concrete top surface. When taking readings, a portion of the epoxy will be ground off of the bar and contact made to the exposed steel. The Galvapulse or half cell instrument will then take readings at the surface of the concrete along the length of the reinforcing bar. It is expected that readings will be taken at every one to two feet (0.3 to 0.6 m) along the bar length. During initial readings it was found that monitoring methods indicated corrosion had occurred along the bars. It was verified that the contractor had not cleaned the bars prior to placement. All bars had been stored exposed to the marine environment for approximately three months for dolphins 3 and 4 (control) and over a year for dolphins 1 and 2 (Hycrete DSS). This resulted in "significant" corrosion in the latter bars which was left in place when the reference bars were placed. As would be expected, this has led to a loss of direct comparison between the mixture designs, with relative behavior better measured by long term visual performance of the overall structures (not at the reference black bar locations).

6.2.3 Implementation and Construction

To date all HPC components have been placed, and Hycrete DSS hoist tower foundations and dolphins 1, 2 and 7 have been placed, with 5 to be completed in the near future (Figure 6.4). Control HPC were placed first, though rates of DCI in the concretes were not consistent. Dosage was specified at 3 gallons/yd^3 (15 L/m^3) but was applied at 2 gallons/yd^3 (10 L/m^3) in dolphins 3, 4 and the lower section of hoist tower foundation 2. Dolphin 6 and the upper portions of hoist tower foundation 2 included the correct dosage. Hycrete DSS concretes were then placed. Mixture designs and batch tickets were not available to the research team.

Figure 6.4: Construction of Ferry Terminal (Courtesy of Maine DOT)

Placement of Hycrete DSS concretes highlighted the needs for attention to detail on trial batching and critical dosage of defoamer for a mixture design when strict specifications are required on air content. Hycrete DSS concretes placed on and subsequent to 5/28/08 were acceptable and within specifications. Three previous placements had varying results. The fine tuning required for the mix designs is now explained, though it is important to note that subsequent placements were acceptable. Trial batches had taken place in March 2007 and resulted in acceptable concretes, with Hycrete DSS being delivered with defoaming admixture pre mixed into the solution at a 1% dosage by weight of Hycrete DSS and the solution batched at the end of the plant batch process. However, it was noted that the concrete prior to Hycrete DSS addition had an air content of 7% which was noticeably high for entrapped air. Hycrete DSS was shipped to the site based on these trial batches and had a defoaming admixture pre-mixed into the solution. Batched Hycrete DSS concrete on 12/21/07 (Dolphin 7) had acceptable air contents in 2 of 3 trucks, but low values in the first truck (no information was provided on the quality of remaining concrete for this dolphin, estimated at 6 trucks). In March 2008 the PI received email including concerns of air content in Hycrete DSS concretes. This was confirmed in trucks delivered 4/30/08 in which concrete was rejected due to low air content even when dosed with very high levels of air entraining admixture. The deliveries exhibited behavior typical of Hycrete DSS concretes which have been overdosed with defoaming admixture. In general, air content was below the specified range, and addition of air entraining admixture, even at very high dosages generally had no effect, in some cases the air content decreased further with continued mixing. In essence, the defoaming admixture was still available in the mixture, counter-acting any air entrainer and continued mixing resulted in only entrapped air contents. Hycrete Technologies quickly obtained samples of the stored material and verified that the defoaming admixture was dosed as shipped and still suspended in solution. Hycrete DSS was replaced with pure Hycrete DSS solution (no defoaming admixture) and separate defoaming admixture, as was done in the large scale mixing procedures of Chapter 4 of this report. For the next two placements (5/13/08 and 5/15/08) both Hycrete DSS and defoaming admixture were batched at the site. Results were much better, with 1 of 6 trucks having low air when batched with higher amount of defoaming admixture, though multiple air content testing and mixing resulted in a very long placement operation. Starting on 5/30/08 the dosages and placement were consistent. The method consisted of adding a total of 2.5 to 3.5 oz (74 to 104 ml) of defoamer to each 10 cubic yard (7.6 m^3) truck. For each truck 1 oz (30 ml) of defoamer was batched at the plant and the remainder batched along with high range water reducer at the site. On 5/30/08 109 yd^3 (83 m^3) of concrete was placed in 4 hours, all within specification. A final placement (dolphin 5) will verify whether results are consistent.

Initial readings were taken at all dolphins except number 5 on 6/9/08. Results can be seen in Table 6.2. All results are an average of two readings at each location, with the exception of areas which could not be read, either due to tidal fluctuations (depths 3 and 4, as depths 3 to 7 were accessed from a boat) or no valid reading being obtained by the instrument after multiple attempts (depths 0 to 2). As noted previously, the reference black bars were not cleaned by the contractor prior to placement, resulting in significant corrosion of the reinforcing bars prior to placement. Exposure of the bars in dolphins 1 and 2 (Hycrete) was approximately one year longer than that in dolphins 3 and 4 (control). It is noted that half-cell potentials are very high negative values for the Hycrete DSS bars, indicating that corrosion has initiated. While half-cell values are not as high on the Control bars, it is apparent from the corrosion rate readings that corrosion is occurring, and many of the half-cell readings are at the borderline of indication of corrosion. It is interesting to note that resistance is consistent at all depths for Hycrete concretes, while it tends to decrease with depth on the Control concretes. This likely indicates the variation in moisture penetration in the control concretes (larger depths have longer exposure under the water while approximately depths 0 to 2 are above the high tide level), though it could also be an indication that the bars are not vertical which was not measured during placement. Readings from half-cell mode are not presented, but were similar in value to those shown. In general, all bars indicate a level of active corrosion, (5 to 20 μA/cm2 per the Galvapulse reference manual, see also Andrade and Alonso (2001) and Clear (1989) for additional criteria). In the case of the placed

Table 6.2: Ferry Terminal Initial Readings

Dolphin	Distance from Top (ft)	PULSE MODE – North Bar Potential mV	PULSE MODE – North Bar Corrosion $\mu A/cm^2$	PULSE MODE – North Bar Resistance kOhm	PULSE MODE – South Bar Potential mV	PULSE MODE – South Bar Corrosion $\mu A/cm^2$	PULSE MODE – South Bar Resistance kOhm
1 Hycrete	0	-479	15.42	1.8	-457	7.79	1.8
	1	-452	6.63	1.3	-524	N/A	2.0
Bar Side	2	-483	6.40	1.6	-500	N/A	2.0
Cover	3	-480	6.57	1.3	N/A	N/A	N/A
North	4	-494	2.57	1.9	-518	0.99	1.6
6.0 in	5	-487	1.35	2.1	-520	1.40	1.9
South	6	-488	4.80	1.1	-486	1.12	1.4
7.5 in	7	-520	4.22	1.0	-542	2.87	1.6
2 Hycrete	0	-545	6.13	2.6	-339	6.76	1.3
	1	-558	6.01	3.8	-359	6.69	1.8
Bar Side	2	-559	1.60	4.3	-369	7.57	2.0
Cover	3	N/A	N/A	N/A	N/A	N/A	N/A
North	4	N/A	N/A	N/A	N/A	N/A	N/A
7.0 in	5	-558	1.04	1.3	-486	2.77	1.4
South	6	-560	2.37	1.0	-487	7.94	1.1
8.5 in	7	-604	4.69	1.0	-527	5.28	0.8
3 Control	0	-231	8.06	4.2	-168	2.63	5.3
	1	-236	5.73	3.8	-154	4.10	5.0
Bar Side	2	-233	7.30	4.0	-156	4.56	5.8
Cover	3	N/A	N/A	N/A	-113	0.68	2.1
North	4	N/A	N/A	N/A	-176	1.70	2.0
8.5 in	5	-258	1.85	1.4	-226	2.14	2.2
South	6	-246	2.50	1.7	-197	2.10	1.9
10.0 in	7	-265	2.47	0.7	-207	3.79	1.1
4 Control	0	-82	3.13	4.0	-125	2.75	4.0
	1	-75	3.72	3.8	-85	4.48	3.9
Bar Side	2	-87	2.18	4.3	-124	4.65	4.3
Cover	3	-175	8.53	3.9	-121	3.36	2.8
North	4	-265	11.88	3.9	-165	3.35	2.5
4.0 in	5	-227	7.91	3.5	-159	2.51	2.4
South	6	-259	13.43	2.7	-170	2.35	1.5
6.5 in	7	-252	34.27	2.3	-165	8.12	1.4

reinforcement which was actively corroding and is now placed in concrete with corrosion inhibiting admixtures and potentially reduced access to water and salts, it is not clear what short term corrosion rates should be. It is recommended that these be monitored yearly to evaluate whether corrosion rates stabilize or increase as a comparison between materials. The most direct comparison will be visual observations of long term performance of concretes in areas away from the black bars.

6.3 Massachusetts Bridge Pier Column Repair

6.3.1 Description of Project

The use of Hycrete DSS in repair methods for deteriorating structures may prove to be a very valuable contribution. The combined effects of minimizing continued corrosion of reinforcement in repaired sections, significant reduction in permeability and effectiveness in concretes with small width cracking is expected to extend the life of repair patches. It is expected that the performance of Hycrete DSS concretes at crack locations will especially help prevent ingress of corrosion components (water and chlorides) at the interface between the base concrete and patch materials.

Figure 6.5 Shows typical deterioration of repair patches on a bridge pier. These patches have been in service for 3 years (longer for that showing corrosion residue) and show cracking, likely due to continued corrosion of the reinforcement. It is expected that the use of Hycrete DSS in these applications would significantly extend the repair life and thereby reduce maintenance costs. The project selection was specifically intended to be a small scale patching operation for two reasons. First, this would be a fairly simple implementation which could be included in patching work on a single overpass. Second, this would be the only small scale mix included in the implementation projects as the contractor typically batches the concrete in a small drum mixer at the site.

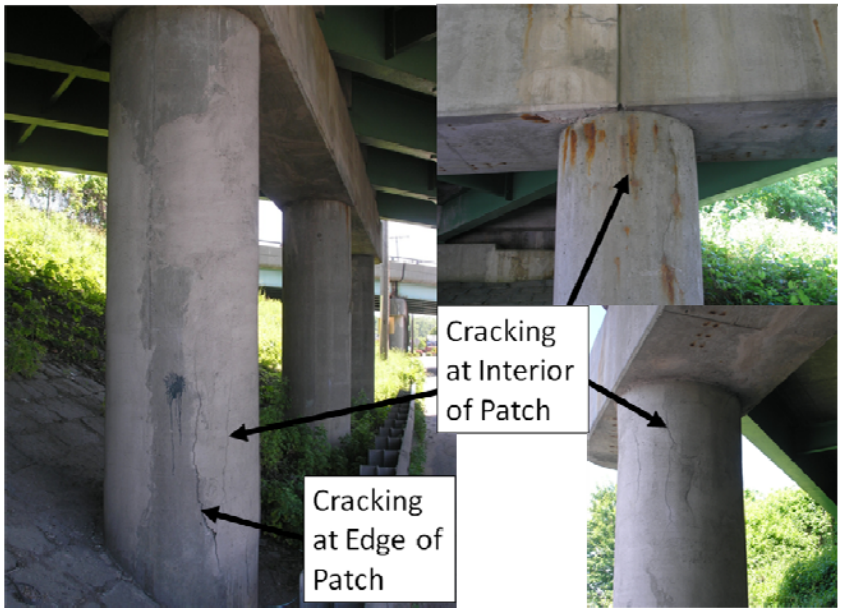


Figure 6.5: I-91 Patch Deterioration

6.3.2 Monitoring Methods

For this implementation it was proposed to use an existing Massachusetts Highway Department detail for half-cell measurements. This detail has been phased out with the prevalence of epoxy coated reinforcement in new construction, but would be applicable to the proposed project where existing concrete includes black reinforcing bars. A sample detail which could be modified for this application is shown in Figure 6.6. This detail could be used with either half cell potentials to determine the initiation of corrosion and/or measurements using the Galvapulse instrument.

6.3.3 Implementation and Construction

This project has not been implemented though upcoming maintenance contracts for repair to I-91 overpasses was discussed. Although a contractor bidding on the work contacted the PI regarding Hycrete DSS and monitoring needs this contract is initiating without the implementation of Hycrete DSS due to issues regarding approval of a non-standard mixture design.

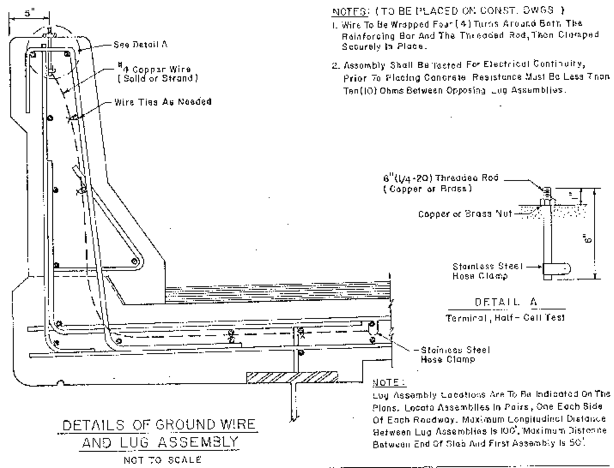


Figure 6.6 MassHighway 1970's Half Cell Wiring Detail (Courtesy of MassHighway)

6.4 New York Precast Culvert

6.4.1 Description of Project

This implementation project was chosen for the evaluation of a precast product application, specifically a large precast culvert section. Kistner Concrete Products, Inc. of East Pembroke, NY was selected as a likely supplier of culvert sections for NYDOT projects over the following year. Michael Kistner of the Lockport, NY plant was supportive of the project, and was asked to select a specific contract for approval by NYDOT. Due to scheduling issues, final selection of a project has not yet occurred, so the implementation of this project is still pending. A section of typical culvert products are shown in Figure 6.7

Figure 6.7: Precast Culvert Photos (Courtesy of Kistner Concrete Products, Inc.)

6.4.2 Monitoring Methods

Monitoring discussed with Michael Kistner included the provision of two black bar pieces of reinforcing steel embedded in the culvert sections. Sections were expected to be approximately 12 in. (0.3 m) in length, and there was still discussion ongoing regarding whether these would be placed in the current forms, or as an additional concrete section which would be isolated from the main culvert cross section to minimize any effects of long term corrosion in this piece of reinforcement. A pair of wires from each bar would extend through the forms to the inside wall of the culvert, at an accessible height. These would be enclosed in a water-tight enclosure once placed in the field. This detail could be used with either half cell potentials to determine the initiation of corrosion and/or measurements using the Galvapulse instrument. Alternatively wiring could be attached to the reinforcement cage (Figure 6.8) directly and run through the forms to the inside of the formwork.

6.4.3 Implementation and Construction

This implementation project is still in the planning phase, with no final project chosen. Delays in selecting a project were partially due to scheduling issues, but also related to uncertainty regarding whether the DOT or Precast Supplier should initiate a request for a variation in mixture design and implementation (which could have implications on liability for any delays or additional costs). It is expected that a project with multiple culverts will be chosen. At least 2 sections of one culvert will be placed with Hycrete DSS concrete, with corresponding sections in the adjacent culvert of typical mixture design. The monitoring plan will be straight forward once the location of black reinforcement bar is chosen.

Figure 6.8: Partial Reinforcement (Courtesy of Kistner Concrete Products, Inc.)

6.5 Vermont Bridge Curb

6.5.1 Description of Project

The implementation project for the State of Vermont was a curb on the approach slab for a new bridge construction in the town of Hartland, VT. The overall bridge structure was 230 feet (70 m) in length and carries traffic along U.S Route 5. The curb used for implementation of Hycrete DSS is at the North-East curb (Westbound) of the structure over the extended wingwall/retaining wall at the approach span of the structure. The curb is approximately 58 feet (17.7 m) in length with details as shown in Figures 6.9 and 6.10. Note that some reinforcing steel (1 top bar and two bottom bars) were added in the field and are not represented on original detail drawings. The curb has an overall length of 58.5 feet (17.8 m), and was installed in 4 alternating placements with the first and third (starting from the east) being control HPC concrete. The second and fourth (ending at the abutment) were Hycrete DSS concrete. A splice in reinforcement was indicated at 25.0 feet (7.6 m) from the east end of the curb, though the added reinforcement was spliced at other locations. In addition, 8 test slabs, as noted in the next section, were cast in formwork, cured and then placed to the outside of the curb. The ready-mix supplier was Carroll Concrete of West Lebanon, NH, which was the same supplier used in mixture evaluations reported in Chapters 4 and 5 of this report.

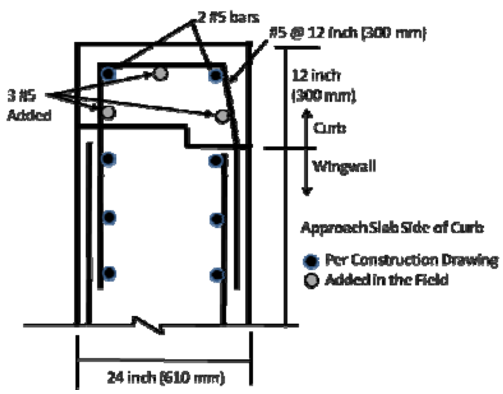


Figure 6.9: Curb Details

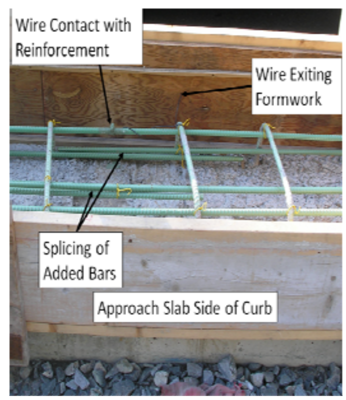


Figure 6.10: Curb Detail Photo

6.5.2 Monitoring Methods

The curb was placed in 4 sections. The top reinforcement bars on the wingwall side of the curb were instrumented to be monitored. All reinforcement is epoxy coated, which will not give accurate results using the Galvapulse monitoring equipment, nor traditional half-cell monitoring. However, it is expected that elevated readings will still be noted at any areas of corrosion, so long as the measurements are made at relatively close spacing. Therefore, wiring was applied at approximately every 4 feet (1.2 m) to ensure that even should some be damaged during construction there would be several points of contact on each section of reinforcement. For monitoring, one should attach the Galvapulse gage clip to one of the wires extending out to the side of the curb (and enclosed in an electrical conduit box), and take measurements at the outside curb face (wing wall side) near the top of the curb. Multiple attachments are available for each bar (spliced as noted previously), though any one is acceptable. It is recommended that a reading not be taken more than 20 feet (6 m) from the conduit attachment, and cross verification of results by attachment to another wire is advisable.

Figure 6.11: Test Slab Construction (One Set for Each Placement)

To ensure that readings are also taken which can be directly applied to measured performance of black reinforcing bars as calibrated with the Galvapulse instrument, eight test slabs were also constructed and placed to the side of the curb. Slabs were 12x10x6 inches (305x255x150 mm), with black reinforcing bars as shown in Figure 6.11. Top cover was ½ in. (13 mm), ¾ in. (19 mm), or 1 in. (25 mm), with two samples of each and one slab of unreinforced plain concrete only. The sides of each slab were coated with an epoxy paint, while the top and bottom surface were left as is to allow water and air access. Wiring from each slab is buried at the site and routed to a central conduit box. For readings, one should attach the Galvapulse gage clip to the appropriate wire in the conduit box (labeled), and take readings at the surface of the corresponding slab. Readings could also be taken with a half cell instrument.

6.5.3 Implementation and Construction

Prior to concrete placements of the curb, a member of the research team ground off approximately 1 square inch (600 mm^2) of the epoxy coating at each location where a monitoring wire was to be attached. Wire was attached by wrapping bare wire around the reinforcement, tying in place with either a stainless steel strap or plastic ties, and then coating the entire area with approved epoxy touch up paint (3M ScotchKote 413/215 two part epoxy patching material). Two types of wire were used, 14 gage solid copper (stiff) on the outer reinforcing bar, and 12 gage zinc coated stranded copper wire (flexible) on the inner reinforcing bar. It was found that the latter were damaged at a much higher rate when the contractor stripped the formwork, though both gave comparable readings. A final attachment of each type can be seen in Figure 6.12. Wires were routed through the formwork and terminate in an electrical box on the final structure as shown in Figure 6.13.

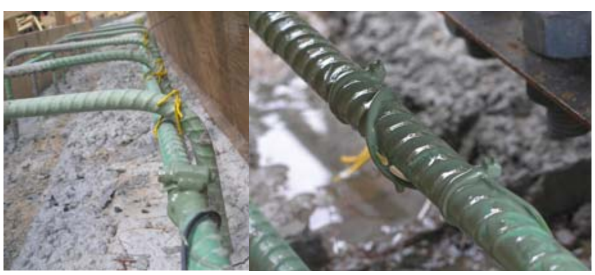


Figure 6.12: Wire Installation

Figure 6.13: Electrical Box

A representative of the research team and a representative from Hycrete Technologies were present for the truck mixing and delivery of Hycrete DSS concretes, while the research team was also present for the HPC curb placements. Concrete mixtures were based on a 4000 psi (28 MPa) Class A mix design with or without Hycrete DSS. This differed from the Vermont Class B mix design reported in Chapters

4 and 5. During placement of curbs, test cylinders were taken for strength evaluation (results shown in Table 6.3), and test slabs were constructed. Placement of the four curb sections took place on 7/25/06 and 7/27/06 for the control HPC and Hycrete DSS placements, respectively. Construction can be seen in Figure 6.14. Control concrete had a slump of 6.5 in. (165 mm) and air content of 5.6%, while the Hycrete DSS concrete had a slump of 7 in. (180 mm) and air content of 8.4%.

Table 6.3: Compressive Strength Curb Mixes

Mixture Design	Age		
	7 day psi (MPa)	14 day psi (MPa)	28 day psi (MPa)
Control HPC	6290 (43.4)	7404 (51.0)	8043 (55.5)
Hycrete DSS	4464 (30.8)	5166 (35.6)	5625 (38.8)

Figure 6.14: Curb Concrete Placement and Cold Joint

Test slabs were placed next to the bridge on 4/14/07. Wires are collected in an electrical box located within the web of the nearest guardrail support. Test slab placements and callouts can be seen in Figure 6.15.

Initial Galvapulse readings were taken on 7/26/07 and are provided in Tables 6.4 for the curb and Table 6.5 for the test slabs. Readings were taken at 5 equally spaced points along each curb. While results appear to be highly variable this is due to the low readings. In general current of less than 0.5 μA/cm^2 and potentials more positive than -350 mV indicate little to no corrosion activity. One notable result of the initial readings is the significantly higher resistance of the Hycrete DSS concretes.

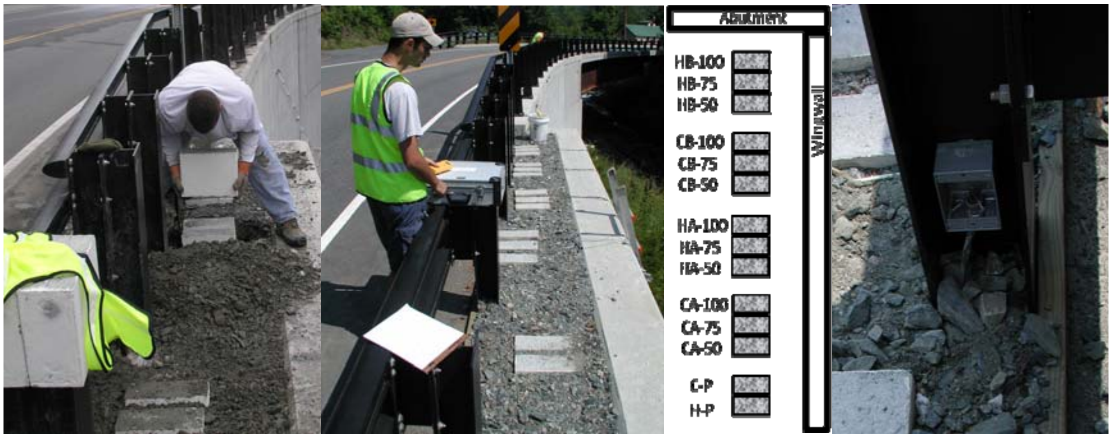


Figure 6.15: Placement of Test Slabs

Table 6.4: Initial Readings of Top of Bridge Curb

Location		PULSE MODE			HALF CELL MODE	
		Potential	Corrosion	Resistance	Potential	Resistance
		mV	μA/cm^2	kOhm	mV	kOhm
HPC	1	17	0.22	9.4	143	4
	2	257	0.44	15.1	141	5
	3	77	0.28	9.4	69	3
	4	173	0.53	10.9	107	4
	5	133	0.29	10.2	87	4
Hycrete DSS	6	-8	0.09	32.2	-38	17
	7	163	0.13	47.8	59	10
	8	155	0.15	51.2	59	18
	9	229	0.21	18.0	54	13
	10	44	0.04	45.4	78	21
HPC	11	168	0.24	8.2	140	4
	12	298	0.31	8.8	149	8
	13	230	0.27	6.9	81	4
	14	298	0.24	7.6	143	4
	15	301	0.38	8.7	64	3
Hycrete DSS	16	-38	0.19	54.6	-51	31
	17	2	0.39	26.3	-48	18
	18	129	0.42	60.3	-38	25
	19	110	0.27	18.8	-76	23
	20	122	0.19	32.2	-10	15

The curb implementation went smoothly and will provide two comparisons of Hycrete DSS to HPC performance. Curb readings will determine long term performance of epoxy coated reinforcement in concrete. Long term performance will predominantly be visual, though wiring is provided to obtain Galvapulse or traditional Half-cell readings. These readings should be evaluated as comparative values only, as traditional results are based on black bar readings. In order to obtain black bar results, 8 test slab sections have been placed to the outside of the curb. These have varying cover depths over black bar reinforcement and are expected to provide accelerated results for comparison of the two mixture designs.

Table 6.5: Initial Readings of Test Slabs

Specimen		End	PULSE MODE			HALF CELL MODE	
			Potential	Corrosion	Resistance	Potential	Resistance
			mV	$\mu A/cm^2$	kOhm	mV	kOhm
HPC	CA50	1	4	0.51	2.9	4	1
	CA50	2	26	0.43	4.2	13	1
	CA75	1	-1	0.67	3.5	-19	1
	CA75	2	-4	0.63	3.4	-17	1
	CA100	1	-3	0.47	3.6	-8	1
	CA100	2	10	0.49	4.5	-17	2
Hycrete DSS	HA50	1	72	0.39	27.9	66	9
	HA50	2	53	0.29	21.1	21	10
	HA75	1	93	0.31	18.2	57	7
	HA75	2	57	0.37	20.3	47	8
	HA100	1	124	0.24	23.6	52	8
	HA100	2	107	0.17	26.4	54	9
Control	CB50	1	-17	0.59	2.5	-1	1
	CB50	2	12	0.43	2.5	12	1
	CB75	1	36	0.54	3.4	6	1
	CB75	2	83	0.59	3.4	20	2
	CB100	1	10	0.47	4.2	8	2
	CB100	2	52	0.68	4.3	1	2
Hycrete DSS	HB50	1	39	0.35	25.2	52	11
	HB50	2	22	0.11	29.3	68	10
	HB75	1	40	0.41	27.5	63	9
	HB75	2	65	0.33	37.9	63	12
	HB100	1	97	0.23	28.2	43	13
	HB100	2	68	0.22	22.7	47	8

6.6 Connecticut Highway Construction Barriers

6.6.1 Description of Project

The Connecticut DOT independently implemented Hycrete DSS in precast Jersey Barriers for use in highway work zones, independent of this project. This effort is reported as an example of a New England implementation project with related goals to this project. The project consists of 10 Jersey Barriers which have been positioned along the I-84 corridor.

6.6.2 Monitoring Methods

For each barrier, an embedded reference electrode (ERE20) was provided at the reinforcement in the middle of the front face of the barriers. Readings were taken with a multimeter by attaching directly to the ERE20 wiring.

6.6.3 Implementation and Construction

A series of mixture design trial batches were performed by the CT DOT in February through September of 2003. A total of 25 Hycrete DSS concrete and 25 control concrete barriers were fabricated at Atlantic Pipe Corporation, Plainville, CT. Ten barriers (five containing Hycrete DSS), with fabrication dates in May (8 barriers) and September (2 barriers) of 2003, were placed along I-84. Hycrete DSS concrete mixture proportions were from batches “F” and “G” and are shown in Tables 6.6 and 6.7. Control concretes were CT Class F 4000 psi (27.6MPa) concrete. The barriers were positioned along I-84. Barriers 1-6 are positioned in order going uphill on the

Westbound lanes, while Barriers 7 and 8 are further up the hill. Barriers 9 and 10 were removed from the site prior to the first year of readings.

Table 6.6: Barrier SSD Mix Designs (1 yd3) (US)

Mix Design Proportions as Batched (1 cuyd SSD)	Project ID: CT Barriers	Barrier Mix Hycrete DSS F/G 05/27/03 (F) 05/28/03 (F) 09/10/03 (G)
	Cement (lbs)	588
	Coarse - 3/4" max (lbs)	2223
	Fines (lbs)	1003
	Water Reducer (oz)	50.0
	Type	Rheobuild 1000
	Air Entrainer (oz)	0.0
	Type	NA
	Hycrete DSS (20% sol) (lbs)	14.7
	Water (lbs)	258
	Corrosion Inhibitor(gal)	0
	Type	NA
	Defoamer (oz)	1.6 Type A (F) 2.25 Type B (G)

Table 6.7: Barrier SSD Mix Designs (1 m3) (Metric)

Mix Design Proportions as Batched (1 cuyd SSD)	Project ID: CT Barriers	Barrier Mix Hycrete DSS F/G 05/27/03 (F) 05/28/03 (F) 09/10/03 (G)
	Cement (kg)	347
	Coarse - 3/4" max (kg)	1312
	Fines (kg)	592
	Water Reducer (mL)	1935
	Type	Rheobuild 1000
	Air Entrainer (mL)	0.0
	Type	NA
	Hycrete DSS (20% sol) (kg)	8.7
	Water (kg)	152
	Corrosion Inhibitor(gal)	0
	Type	NA
	Defoamer (oz)	1.6 Type A (F) 2.25 Type B (G)

To date, readings have been collected on July 18 (initial reading) and seven dates over the following 5 years . Readings to date can be seen in Table 6.8. In general, the Hycrete DSS concrete barriers have lower half-cell readings, though not at all locations. Barriers 5 and 6 are away from the traffic due to construction staging and have very comparable half cell readings to each other, though are lower than the other placements. Readings in barriers 1 and 2 have been relatively constant (Hycrete DSS) while readings in 3 and 4 have increased slightly (control). Half cell readings for both Hycrete DSS and control barriers 7-10 have decreased slightly. None of the readings indicate any initiation of corrosion at this time.

Table 6.8 CT PreCast Barrier Half Cell Readings (mV)

Reading Date	Barrier Number Mixture Design Fabrication Date									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	DSS A 5/28/03	DSS B 5/2803	Control A 5/28/03	Control B 5/28/03	DSS A 5/27/03	Control B 5/27/03	Control A 9/10/03	DSS A 9/10/03	Control A 5/27/03	DSS B 5/27/03
7/18/03	237.41	233.56	240.38	240.59	236.33	238.56			227.63	235.24
7/30/03	231.50	227.90	234.39	234.76	231.74	233.85			223.51	229.95
9/10/03	204.55	214.13	213.08	211.72	214.74	209.00			213.38	214.42
7/19/05	239.40	241.70	261.90	260.10	199.80	204.60	216.80	191.30		
6/13/06	239.10	241.12	256.01	256.36	200.47	206.31	203.00	179.42		
8/23/06	238.67	243.67	254.69	251.53	195.30	204.16	202.32	177.58		
1/3/07	247.38	241.63	258.30	255.03	204.94	197.58	191.32	177.78		
6/7/07	235.89	241.44	253.40	253.37	201.84	203.50	193.75	177.71		

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The use of road salts in New England leads to corrosion of reinforced concrete structures, most notably bridge decks. Corrosion reduces the effective service lives of reinforced concrete structures. The cost associated with deterioration due to corrosion has been the impetus to research and develop high performance concrete mixtures, corrosion resistant reinforcement, and other corrosion mitigating technologies. Hycrete DSS, a concrete admixture, has shown promise as a corrosion inhibitor for high performance concrete. Previous laboratory testing indicates that Hycrete DSS provides excellent protection of reinforcement embedded in non-cracked or pre-cracked concrete, when compared to normal concrete and concrete with other commercially available admixtures. Laboratory results also showed that Hycrete DSS may reduce concrete strengths and increase air contents of concrete mixtures compared to control mixtures. The testing protocol outlined in this report was undertaken to determine the field applicability of Hycrete DSS, and provide implementation projects using the admixture in New England. This report presents evidence that specifications for high performance concrete mixtures typically used by DOT's throughout New England can be achieved in Hycrete DSS concretes and has set up long term monitoring to evaluate corrosion resistance of these concretes.

A series of large scale mix tests were conducted as part of the field studies. In these tests, freshly mixed properties of concretes were not significantly affected by the addition of Hycrete DSS. Also there were no noticeable interactions between Hycrete DSS and the other concrete admixtures used in this project, with the possible exception of the AdvaFlow high range water reducer which did not appear to be effective in a Hycrete DSS concrete. Use of this particular admixture combination should be evaluated in trial mixtures or replaced with an alternate product. All Hycrete DSS concretes used in this project exceeded nominal 28-day design strength requirements , though they had average strength reductions of 16% when compared to control mixtures at 28 days. The freeze-thaw durability performance of Hycrete DSS concrete mixtures was somewhat reduced from control mixes, likely attributable to reduced strength, but most mix designs were found to be adequate for high performance concretes. Concrete absorption was greatly reduced, up to 80%, when Hycrete DSS was included, though the rapid chloride permeability test method did not give accurate indications of this benefit for Hycrete DSS concretes. Therefore, standard absorption or permeability tests should be used rather than the rapid test method.

Subsequently, four implementation projects were pursued, a ferry terminal in Maine, patching of highway column bents in Massachusetts, pre-cast large scale culverts in New York, and a bridge curb in Vermont. Each implementation was chosen to be distinct and provide information on different performance criteria for Hycrete DSS and control concretes. For each application a long term corrosion monitoring plan was developed. Two of these projects (Maine and Vermont) have been successfully completed. The Vermont project utilized a concrete supplier who had participated in the large scale mix tests and the construction went smoothly. The Maine project involved a team who had no previous experience using Hycrete DSS. This site required several iterations in the mixture design before consistently obtaining specified air contents. Previous comparison of concrete barriers in work zones in Connecticut was also reported.

7.2 Recommendations

Concrete mixtures proportions including Hycrete DSS were acceptable for the typical range of DOT concrete mixtures investigated in this report. There was no measurable difference between adding Hycrete DSS to a central mixer or truck mounted mixer. Changes to standard mixture proportioning include addition of Hycrete DSS with defoaming admixture (typically delivered pre-mixed in adequate quantity with Hycrete DSS), correction for water included in the Hycrete DSS admixture solution, and exclusion of any air entraining admixture. Standard ready-mixed concrete practices should be followed along with specific methods for batching Hycrete DSS solution and defoaming admixture. Some additional defoaming admixture may be required based upon manufacturer recommendations and/or trial batching. All defoaming admixtures should be premixed with the Hycrete DSS solution prior to batching. The addition of Hycrete DSS should be made at the end of the ready-mixed concrete batch process. Self consolidating concrete which includes Hycrete DSS is also possible.

If required, any resulting strength reductions can be compensated for by increasing the cementitious materials content of a mixture or by reducing the water to cementitious materials ratio. Rapid chloride permeability tests should not be used with Hycrete DSS concretes as the test is not accurate.

Hycrete DSS is a very promising corrosion inhibiting admixture. The results of this study show that full scale batched Hycrete DSS concretes can have similar properties to typical high performance concretes currently used by New England DOT’s. Advantages include reduced permeability and excellent corrosion prevention in laboratory testing.

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