DURABILITY PERFORMANCE OF ECO-FRIENDLY DUCTILE CEMENTITIOUS COMPOSITE (EDCC) AS A REPAIR MATERIAL

by

YANG DU

B. Eng. (Civil Engineering), Southeast University, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(CIVIL ENGINEERING)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

August 2016

© Yang Du, 2016

ABSTRACT

The objective of the experimental program in this thesis is to investigate the durability performance of Eco-friendly ductile cementitious composite (EDCC), a newly developed repair material for seismic retrofitting.

Several aspects of the durability performance of EDCC were investigated in this work, in terms of restrained shrinkage resistance, freeze and thaw resistance and bond strength degradation before and after environmental exposure. All the tests focused on repair overlay and substrate composite assembly. Six different EDCC fiber mixes were involved in the testing to discover the best mix in terms of performance and economical aspects. The substrate of the composite assembly includes concrete, masonry blocks and clay blocks. EDCC can be applied on different substrates by hand casting and spraying. EDCC application on concrete substrates employing the hand casting process is used to explore the durability performance of EDCC. Clay and masonry substrates, along with the spray application process, are only used to compare the influence of different application methods on the bond strength based on the bond strength data obtained in Yuan Yan's thesis.

After the whole experimental program, regarding hand applied process, both 2% PVA and 1% PVA and 1% PET hybrid mix yields to the best durability performance. In spray process, clay substrate specimens give better bond strength than the specimens prepared through hand applied process, however, masonry specimens show lower bond strength than hand applied specimens. Overall 1% PVA and 1% PET will be recommended for future seismic retrofitting application due to lower cost compared to 2% PVA EDCC.

It is noted that the performance of EDCC depends greatly on good material mixing for different application processes. In order to obtain a good EDCC mix, a rigorous mixing procedure should be followed. Hence, future in-situ applications should guarantee a proper mixing procedure for good quality control.

The spray process was found to be very successful with very little rebound and nearly no material sloughing off. The results of the experiments done in this study indicated that the spray process increases the material application speed to further reduce potential high labor cost.

PREFACE

This thesis is an original, unpublished, independent work by the author, Yang Du, under the supervision of Professor Nemkumar Banthia. This research program is part of the collaborative project: Development of Sustainable Masonry Rehabilitation Technology (SMART) using EDCC.

TABLE OF CONTENTS

Abstract	. ii
Preface	iii
Table of Contents	iv
List of Tablesv	iii
List of Figures	ix
Acknowledgements	кіі
1. Introduction	. 1
1.1. Study background	. 1
1.2. Thesis outline	. 2
2. Literature review	. 4
2.1. Shrinkage performance of fiber reinforced cementitious composite	. 4
2.1.1. Shrinkage of cementitious materials	. 4
2.1.2. Shrinkage resistance of fiber reinforced cementitious composite	. 5
2.1.3. Restrained shrinkage test methods	. 6
2.2. Freeze and thaw resistance of high strength concrete	. 8
2.2.1. Freeze and thaw resistance of high strength concrete	. 8
2.2.2. Freeze and thaw resistance quantification methods	. 9
2.3. ECC and durability	10
2.3.1. Engineered cementitious composite properties	10
2.3.2. Engineered cementitious composite shrinkage resistance	11
2.3.3. Engineered cementitious composite freeze and thaw resistance	13
2.3.4. Green Engineered cementitious composite	14
2.3.5. From green ECC to EDCC	14
2.3.6. Sprayable ECC for shotcreting	15
2.4. Bond test techniques and bond performance	16
2.4.1. Bond test methods	16
2.4.2. Bond strength affecting parameters	17
2.4.3. Bond durability	18
2.5. Surface roughness	19
2.5.1. Surface roughness quantification techniques	19
2.5.2. Surface roughness impacts on bond strength	20
3. Materials properties	22

	3.1	Sub	strate materials	22
	3.1	1.1.	High strength concrete	22
3.1.2.		1.2.	Clay and concrete masonry blocks	24
	3.2.	Ove	erlay materials	25
	3.2	2.1.	Fibers	25
	3.2	2.2.	Mix proportion	25
	3.2	2.3.	Mixing procedure	26
	3.3.	Oth	er materials	27
	3.3	3.1.	Mold	27
	3.3	3.2.	Spacers	27
	3.3	3.3.	Epoxy	28
	3.3	3.4.	Release agent	28
4.	Re	estrai	ned Plastic Shrinkage Performance of EDCC	29
	4.1	Intr	oduction	29
	4.2	Shr	inkage test base development	30
	4.2	2.1	Compressive strength of concrete bases	30
	4.2	2.2	Base high strength concrete air content trials	30
	4.2	2.3	High strength concrete substrate dimension	32
	4.3	Sur	face sandblasting treatment	33
	4.3	3.1	Preliminary studies	33
	4.3	3.2	Sandblasting system upgrade	34
	4.3	3.3	Sandblasting operation	34
	4.4	Sur	face roughness choice and quantification	35
	4.4	4.1	Preliminary studies	35
	4.4	4.2	Roughness quantification	36
	4.5	Shr	inkage testing execution	41
	4.6	Cra	ck measurements	43
	4.7	Shr	inkage test results and discussion	44
5.	Fr	eeze	and thaw resistance of EDCC	45
	5.1	Intr	oduction	45
	5.2	Tes	t set-up	45
	5.3	ED	CC characterization	46
	5.3	3.1	Air content	46
	5.3	3.2	Workability	46

	5.3.3 Compressive strength		47					
	5.4	EDCC overlay dimension control						
	5.5	Fre	eeze and thaw test execution					
	5.6	Fre	Freeze and thaw test results					
	5.6	5.1	1% PVA freeze and thaw resistance	49				
	5.6	5.2	1% PVA (with shrinkage exposure) freeze and thaw resistance	51				
	5.6	5.3	1% PET freeze and thaw resistance	52				
	5.6	5.4	1% PET (with shrinkage exposure) freeze and thaw resistance	53				
	5.6	5.5	2% PVA freeze and thaw resistance	54				
	5.6	5.6	2% PVA (with shrinkage exposure) freeze and thaw resistance	55				
	5.6	5.7	2% PET freeze and thaw resistance	56				
	5.6	5.8	2% PET (with shrinkage exposure) freeze and thaw resistance	57				
	5.6	5.9	1% PVA&1% PET freeze and thaw resistance	58				
	5.6	5.10	1% PVA&1% PET (with shrinkage exposure) freeze and thaw resistance	59				
	5.6	5.11	Plain mortar freeze and thaw resistance	60				
	5.6	5.12	Plain mortar (with shrinkage exposure) freeze and thaw resistance	60				
	5.7	Fre	eze and thaw test results discussion	61				
6.	. Bo	nd d	urability of EDCC	62				
	6.1	Intr	oduction	62				
	6.2	Bor	nd test design	62				
	6.3	Pul	l-off test preparation and set-up	63				
	6.3	8.1	Bond test preparation	63				
	6.3	8.2	Bond test set-up	64				
	6.4	Pul	l-off test bond strength results	65				
	6.4	.1	1% PVA bond strength	65				
	6.4	.2	1% PET bond strength	66				
	6.4	.3	2% PET bond strength	67				
	6.4	.4	2% PVA bond strength	68				
6.4.5		.5	1% PVA&1% PET bond strength	69				
	6.4	.6	Plain mortar bond strength	70				
	6.5	Pul	l-off test bond strength results discussion	70				
7.	. Bo	nd p	erformance of sprayed EDCC	72				
	7.1	Intr	oduction	72				
	7 7	Spr	av procedures	72				

Referer	nces	80
8. Co	onclusions and recommendations for future work	78
7.7	Bond strength results comparison with hand applied data	76
7.6	Bond strength results	75
7.5	Spray process and quality control	74
7.4	Specimen coring	73
7.3	Testing set-up	72

LIST OF TABLES

Table 1 Testing scheme	2
Table 2 High strength concrete base mix design	23
Table 3 Properties of PVA and PET fibers	25
Table 4 Base concrete and EDCC mix design (Unit:Kg/m3)	26
Table 5 Base concrete compressive strength	30
Table 6 Air entrained and non-air entrained compressive strength comparison	31
Table 7 Target Industrial sand properties (from Target Products Ltd.)	33
Table 8 EDCC air content	46
Table 9 Superplasticizer dosage and slump of EDCC	46
Table 10 EDCC compressive strength	47
Table 11 Tensile strength of EDCC [30]	63
Table 12 1% PVA bond strength value (Unit: MPa)	65
Table 13 1% PET bond strength value (Unit: MPa)	66
Table 14 2% PET bond strength value (Unit: MPa)	67
Table 15 2% PVA bond strength value (Unit: MPa)	68
Table 16 1% PVA&1% PET bond strength value (Unit: MPa)	69
Table 17 Plain mortar bond strength value (Unit: MPa)	70
Table 18 Concrete specimen bond strength	75
Table 19 Brick specimen bond strength	75

LIST OF FIGURES

Figure 1 ACI evaporation nomograph [6]	5
Figure 2 Steel ring mold and concrete ring specimen [11]	6
Figure 3 Steel ring stress versus specimen age [11]	6
Figure 4 Different substrate surface finishes [3]	7
Figure 5 Improved restrained shrinkage test method [13]	7
Figure 6 Freeze and thaw durability of non-entrained concrete without silica fume [16]	8
Figure 7 Freeze-thaw durability of non-air-entrained concrete with varying silica fume conter [17]	nts 9
Figure 8 Pulse velocity and resonant frequency method comparison (left [18]) pulse velocity schematic (right) [44]	test 10
Figure 9 ECC strain-hardening behaviour [19] [20]	10
Figure 10 hysteresis loops of column members under fully reversed cyclic loading [21]	11
Figure 11 Layered repaired system for ECC [22]	12
Figure 12 Shrinkage strain comparison between LSECC and traditional ECC [23]	12
Figure 13 ECC pore distribution [25]	13
Figure 14 Relative pulse velocity and mass loss with number of freeze and thaw cycles [27]	14
Figure 15 Tensile behavior of different EDCC fiber mixtures [30]	15
Figure 16 Different bond test methods [32]	16
Figure 17 Pull-off test method schematic and different failure modes [4]	17
Figure 18 Mohr circle [35]	18
Figure 19 Bond strength change in different repair systems under cyclic freeze and thaw and temperature change [36]	19
Figure 20 2D and 3D laser scanner [38]	20
Figure 21 10mm and 20mm coarse aggregate	22
Figure 22 Sand gradation curve	23
Figure 23 Dimensions of CMU building blocks	24
Figure 24 CMU substrate before and after spray	24
Figure 25 Clay substrates before and after spray	25
Figure 26 Substrate for shrinkage test (Rishi, 2008)	29
Figure 27 Properties of 10mm rebar (Harrris Rebar Inc)	32
Figure 28 High strength concrete substrate with rebars and rebar layout during casting	32
Figure 29 Repair overlay detached from substrate	33
Figure 30 Substrate overlap design	33

Figure 31 Industrial sand gradation curve (data from Target is redrawn here)	33
Figure 32 BE pressure washer, wet sandblasting kit and system set up	34
Figure 33 Sandblasting operation schematic [41]	35
Figure 34 Sandblasted surface and shrinkage preliminary test	36
Figure 35 Replicable cracks in samples with similar roughness	36
Figure 36 Concrete surface profiles and Sand Patch Test	37
Figure 37 Average roughness Ra [33]	38
Figure 38 Laser scan set up	38
Figure 39 Form removed curve	39
Figure 40 Roughness and waviness profile after filtering	39
Figure 41 Roughness and waviness parameter comparison of the two samples	40
Figure 42 Abbot Curve comparison of two samples	40
Figure 43 Single channel environmental chamber schematic [13]	41
Figure 44 Single channel shrinkage chamber set-up	41
Figure 45 Pre-moisturized surface	42
Figure 46 Cracks in plain mix	43
Figure 47 Crack measurements under optical magnifier and under microscope with image analysis software	43
Figure 48 Measurements with image analysis software	44
Figure 49 Plain mortar spacers to fix the substrate	48
Figure 50 Freeze and thaw cabinet	48
Figure 51 Ultrasonic pulse velocity tester	49
Figure 52 1% PVA Mass loss curve (FT only)	50
Figure 53 1% PVA pulse velocity curve (FT only)	50
Figure 54 1% PVA mass loss curve after shrinkage exposure	51
Figure 55 1% PVA pulse velocity curve after shrinkage exposure	51
Figure 56 1% PET Mass loss curve (FT only)	52
Figure 57 1% PET pulse velocity curve (FT only)	52
Figure 58 1% PET Mass loss curve with shrinkage exposure	53
Figure 59 1% PET pulse velocity curve after shrinkage exposure	53
Figure 60 2% PVA Mass loss curve (FT only)	54
Figure 61 2% PVA pulse velocity curve (FT only)	54
Figure 62 2% PVA Mass loss curve with shrinkage exposure	55
Figure 63 2% PVA pulse velocity curve after shrinkage exposure	55

Figure 64 2% PET Mass loss curve (FT only)
Figure 65 2% PET pulse velocity curve (FT only)
Figure 66 2% PET Mass loss curve with shrinkage exposure
Figure 67 2% PET pulse velocity curve after shrinkage exposure
Figure 68 1% PVA&1% PET Mass loss curve (FT only) 58
Figure 69 1% PVA&1% PET pulse velocity curve (FT only)
Figure 70 1% PVA&1% PET Mass loss curve with shrinkage exposure
Figure 71 1% PVA&1%PET pulse velocity curve after shrinkage exposure
Figure 72 Plain mortar after 30 freeze and thaw cycles
Figure 73 Plain mortar with shrinkage exposure after 60 freeze and thaw cycles
Figure 74 Bond test coring preparation
Figure 75 Pull-off bond test set-up
Figure 76 1% PVA bond strength degradation curve
Figure 77 1% PET bond strength degradation curve
Figure 78 2% PET bond strength degradation curve
Figure 79 2% PVA bond strength degradation curve
Figure 80 1% PVA&1% PET bond strength degradation curve70
Figure 81 Residual bond strength71
Figure 82 Spray set-up
Figure 83 Brick substrate coring layout (right figure source from reference [1])74
Figure 84 Concrete substrate specimen coring layout (right figure source from reference [1])74
Figure 85 Spray process
Figure 86 Pulled cores
Figure 87 Bond strength comparison with reference [1]

ACKNOWLEDGEMENTS

I would like to thank all the people who helped and encouraged me during my graduate studies at the Department of Civil Engineering, Faculty of Applied Science of the University of British Columbia.

Personally, I want to express thanks to my supervisor, Nemkumar Banthia for his great support, invaluable advice and great dedication to better research through the whole master study. It is a great honor to work with him.

I also want to express my gratitude to Mr. Harald Schrempp and Bill Leung for helping me with technical challenges that I faced in the lab. Special thanks go to Ms. Wu for helping me overcome many difficulties throughout the course of my research and life in this lab.

My deepest gratitude goes to my parents and my girlfriend (future wife) for their continuous support and selfless love at every stage of my life.

1. Introduction

1.1. Study background

British Columbia, located in one of the world most active seismic Cascadia Subduction zones, undoubtedly, is one of the most earthquake-prone regions across the whole country. A megathrust of 9.2 magnitude earthquake shook the southern coast of British Columbia 316 years ago, in 1700, and it is estimated that there is still a 10 to 15 percent chance of the so-called "Big One" that is yet to come, sometime over the next 50 years, along the fault line from Vancouver Island to Northern California. It is estimated that this big earthquake will reach a magnitude of at least 9.0. Based on that estimate, in 2004, the Ministry of Education (MOE) engaged the APEGBC and UBC to implement the School Seismic Upgrade Program to ensure the safety of British Columbian BC students, safety with the goal of strengthening 342 schools built before 1992. Quite a few of these high-risk schools were built as unreinforced masonry structures, without provision for seismic design making them highly vulnerable to earthquakes and very likely to collapse in the event of an earthquake.

However, complete replacement of these deficient structures is neither financially feasible nor culturally acceptable. Thus, devising better rehabilitation and repair techniques is crucial, to increase the structural integrity and seismic resistance of such vulnerable structures, and have them comply with modern building codes. A new sprayable eco-friendly ductile cementitious composite (EDCC) repair material has been developed at the UBC Civil Engineering Materials Lab to help strengthen the aforementioned vulnerable masonry structures. Unlike normal engineered cementitious composite [19] which contains a large amount of cement for better workability and interfacial bond between fibers and matrix), EDCC, on the other hand consists of 70% industrial by-products from cementitious materials, replacing over 2/3 of the cement with fly ash and silica fume [30]. As we know, global warming is becoming a serious and urgent problem that the entire human race is faced with. One of the major sources of global greenhouse gas emission, CO₂, is from cement production which takes up to 9% of the total amount of the global emission. Instead of phasing out the use of traditional cement production, replacing cement with industrial by-products is one of the most effective and feasible ways to tackle this problem.

Although many high strength repair materials have been developed over the past decade, repair systems usually fail under service conditions due to poor durability. For example, the failure of debonding between repair and substrate systems indicates poor durability rather than strength failure in the repair material itself. EDCC is a strain-hardening fiber-reinforced mortar, with a large amount of fly ash content which can be sprayed to facilitate the repair application. The durability performance of this material, however, is poorly known. This master's thesis will focus on three aspects of durability: shrinkage of EDCC, freeze and thaw resistance of this material, and the examination of how bond performance with concrete is affected by these environmental factors. This study also includes a comparative study with Ms. Yan's thesis [1], perceiving how the spray process influences the bond strength between EDCC and the concrete masonry and clay substrates.

1.2. Thesis outline

The objective of this thesis is to explore the durability performance of different EDCC mixtures in terms of shrinkage resistance, freeze and thaw resistance and the bond strength. By comparing different EDCC fiber combinations, based on performance and economics, an optimal option is sought for future application.

Sixty beam specimens were cast following ASTM C1609 [2] freeze and thaw test, restrained shrinkage test [3], and ASTM C1583 [4] pull-off bond test. A pull-off test on 4 clay beams and 6 masonry beams sprayed with EDCC was also carried out for comparative study and for providing guidance for the large-scale wall test. For clarity, a table capturing different test series performed on two repair application processes is given below.

		Spray						
Series	1%	1%	2%	2%	10/ DV A 8-10/ DET	W/O	10/ DV A 8-10/ DET	
	PVA	PET	PVA	PET	1%PVA&1%PE1	Fiber	1%PVA&1%PE1	
1			Bond test					
2	Freeze and thaw test							
3	Shrinkage and freeze and thaw test							
4	Bond test after test series 1-3							

The thesis comprises eight chapters as presented below.

Chapter 1 Introduction

Chapter 2 Literature review

Chapter 3 Materials properties

Chapter 4 Shrinkage performance

Chapter 5 Freeze and thaw resistance of EDCC

Chapter 6 Bond performance of EDCC

Chapter 7 Comparative study of bond strength between sprayed and hand applied EDCC

Chapter 8 Conclusions and recommendations

Chapter 1 provides the background information and objectives of this project, as well as the outline of the thesis with short discussions.

Chapter 2 includes related, recent literature reviews about different properties of engineered cementitious composite (ECC), shrinkage resistance of fiber-reinforced concrete and shrinkage testing methods, freeze and thaw resistance of high strength concrete and the durability of bond for cementitious repair systems, plus corresponding methods to evaluate bond strength for composite repair assemblies. Surface roughness characterization methodologies are also reviewed.

Chapter 3 presents the basic properties of all the materials, details of the clay and masonry blocks, as well as mix designs for substrate and different EDCC mixtures used in this project.

Chapter 4 covers shrinkage test composite assembly base development, surface sandblasting treatment, interface roughness laser scan characterization, preliminary shrinkage test results and crack measurements after shrinkage exposure.

Chapter 5 presents the freeze and thaw resistance of different EDCC repair mixes according to ASTM C666 and bond performance after shrinkage exposure, freeze and thaw exposure and under both environmental attacks. Related UPV loss and mass loss curves are also presented for freeze and thaw damage quantification.

Chapter 6 discusses the bond performance of different EDCC mixes after different environmental attacks, to further evaluate the durability performance of EDCC. Bond strength degradation curves with the increase of freeze and thaw cycle and bond strength comparison between different mixes and environmental conditions are also discussed in Chapter 6 to characterize the bond performance of EDCC repair.

Chapter 7 shows how the spray process of EDCC works and compares the bond strength of the spray process with the hand-applied process from Ms. Yan's thesis [1].

Chapter 8 summarizes the conclusions of this research project and proposes recommendations for further study of this repair material.

2. Literature review

As cement-based materials become some of the most widely used repair materials, nowadays, their durability challenges also arise, due to poor shrinkage resistance, freeze and thaw resistance and bond performance. A significant amount of research has been carried out to better understand the durability of cementitious composite repair materials. In this chapter, a review of past research findings in this area are presented.

2.1. Shrinkage performance of fiber reinforced cementitious composite

2.1.1. Shrinkage of cementitious materials

Generally, there are three main types of shrinkage: autogenous shrinkage, plastic shrinkage and drying shrinkage.

Autogenous shrinkage is also called chemical shrinkage or self-desiccation, and is caused by cement hydration. This process develops with macroscopic volume change and surface cracks without moisture exchange with the environment. It is of great importance when new concrete is placed over old concrete.

Plastic shrinkage happens when the mix is plastic and flowable, before it has hardened. Cementitious materials will undergo macroscopic volume change and cause cracks on the surface because of loss of water in evaporation and cement hydration. It is found that the volume reduction of cement paste goes up to 1% of the volume of dry cement (Banthia & Nandakumar 2001) [5]. This becomes a very serious issue in repair applications due to strong restraints from the substrate.

Drying shrinkage continues for a long time even after concrete has hardened. This is caused by moisture loss from evaporation. Drying shrinkage can also create cracks and deflection on specimens without external loading.

In terms of external factors, moisture loss due to evaporation is the most critical one. As shown in the ACI evaporation nomograph in the ACI Manual of Concrete Practice, Section 305R, "Hot Weather Concreting," (ACI 305R-96, 1996) in Figure 1 [6], four main key external factors (air temperature, relative humidity, concrete temperature and wind velocity) affect the evaporation rate of moisture.

4



Figure 1 ACI evaporation nomograph [6]

2.1.2. Shrinkage resistance of fiber reinforced cementitious composite

Usually in repair applications, if the cementitious repair is free from any internal or external restraint and is free to expand, contract and deflect, no cracks are expected to develop in the repair materials. However, the repair materials are always restrained by the old concrete specimens being repaired or by internal steel reinforcements. These restraints will create tensile stresses internally and cracks will develop when that tensile stresses exceed the tensile strength of the repair material. Much research has shown that different fiber additions to the cementitious materials can effectively prevent shrinkage cracking.

For example, according to Miroslaw et al. [7], 0.25% polypropylene fibers can reduce drying shrinkage cracks from 1mm (plain mortar) to 0.5mm. Steel fibers are more effective, and can further reduce the crack width to 0.2mm with 0.25% fiber volume addition.

Wang et al. [8] also find that adding fibers will likely introduce groups of large pores which can help reduce the capillary pressure in the paste to relieve shrinkage stresses, and he further proved this by adding 0.1% PVA, cellulose and polypropylene fibrillated fibers, showing that the crack areas could be reduced by 30-40%.

Wu et al. [9] also used a ring test to show that recycled tire fabric can improve the performance of restrained plastic shrinkage performance.

2.1.3. Restrained shrinkage test methods

In this thesis, only restrained plastic shrinkage resistance of EDCC is considered and tested, so only test methods for restrained shrinkage are presented here.

(1) Ring type tests

This test was employed by Grzybowski et al. [10] and is based on the principle that shrinkage is developed in concrete ring specimens in the mold (Figure 2) which is restrained by a steel ring mold at the center. Tensile stresses developed which can be then monitored and recorded over the course of time to help evaluate the performance. Now this method has been introduced to ASTM standard C1581 [11] to determine the age at cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage as shown in Figure 3.





Figure 2 Steel ring mold and concrete ring specimen [11]



Figure 3 Steel ring stress versus specimen age [11]

(2) Bonded overlay technique (developed by Dr. Banthia and Rishi Gupta at UBC)

Although ring tests are widely recognized as a standard method used to test restrained shrinkage, this method itself is not actually simulating the restrained stress condition in reality. A unique technique, first developed by Banthia and co-workers [12,13,14] has the advantage of producing a more realistic restrained shrinkage stress condition especially for repair applications.

A very stiff, hardened base with protrusions was first made and a thin coat of the fresh repair material is placed on the substrate. Then, the entire bonded overlay composite assembly is transferred to a linear environmental chamber at a high temperature and at a very low humidity for some time. Cracks occur on the surface of the overlay repair material with time.

The protrusions on the base are used to provide full restraint of the overlay, originally achieved by different methods, such as aggregate finish and concrete protrusions, as shown in Figure 4.



Figure 4 Different substrate surface finishes [3]

At the beginning, the aggregate finish was used. But due to poor uniformity and difficulty in making these substrates, Gupta [13] improved the method by using protrusion shown in Figure 5.



Figure 5 Improved restrained shrinkage test method [13]

2.2. Freeze and thaw resistance of high strength concrete

The composite assembly with high strength concrete substrate and EDCC repair overlay is further conditioned by exposing it to freeze and thaw cycles. It is very important to make sure that the high strength concrete substrate remains intact, without further damage, after a certain number of freeze and thaw cycles. Related review of research concerning the freeze and thaw resistance of high strength concrete are presented here.

Resistance to freeze and thaw cycles depends on various factors including permeability, degree of saturation of the cement paste, the amount of freezable water and the average maximum distance from any point in the paste to a free surface where ice can form safely. So it is essential to keep a good air void system with a certain level of air content and average spacing factor by incorporating an air-entraining agent. Of course, the concrete itself should maintain a certain strength to withstand freeze and thaw damage. [15]

2.2.1. Freeze and thaw resistance of high strength concrete

Theoretically, when the water cement ratio drops below 0.36, an air-entraining agent will would not be needed because the amount of freezable water is would be insufficient to cause frost damage [15]. Experimentally, it is shown that an air entraining agent is not needed when the water cement ratio drops under 0.24 as given in Figure 6. [16]



Figure 6 Freeze and thaw durability of non-entrained concrete without silica fume [16]

Other research also suggests that it is possible to obtain non-air-entrained, high strength concrete with good freeze and thaw resistance if the w/cm is low enough, for example, 0.24, 0.25 and 0.29. [17]

Usually, a relatively high amount of silica fume is found in high strength concrete giving it its high strength, as shown in Figure 7. It is has also been found by Y. Li et al. [17] that the amount of silica fume also has an impact on the frost resistance of high strength concrete. A mix with 10% silica fume exhibits an over 20% drop in frost resistance after 1000 cycles, compared to mix without any silica fume. Therefore, it is also suggested that it is preferable to keep the silica content under 10%.



Figure 7 Freeze-thaw durability of non-air-entrained concrete with varying silica fume contents [17]

Based on the above, the water cement ratio of base high strength concrete in this experimental program is 0.27, so the author of this study is quite confident that very little damage will be developed in the concrete substrate within 90 cycles.

2.2.2. Freeze and thaw resistance quantification methods

According to ASTM C666 [2], the way to quantify and evaluate the damage caused by freeze and thaw cycles is by testing the resonant frequency of the standard sample.

However, Menashi et al. [18] also propose that pulse velocity could be an alternative way to evaluate the deterioration. Although the pulse velocity calculated modulus might be a bit higher

than the resonant frequency calculated modulus, the overall trend is still reliable, as shown in Figure 8 on the left.

In this experimental program, due to a machine issue, the pulse velocity testing method (Figure 8 right) was used as a way to quantify the freeze and thaw deterioration.



Figure 8 Pulse velocity and resonant frequency method comparison (left [18]) pulse velocity test schematic (right) [44]

2.3. ECC and durability

2.3.1. Engineered cementitious composite properties

Engineered cementitious composite was first developed by Victor Li [19]. He incorporated 2 vol% of PVA-REC oil-coated fiber into cement paste. With the help of the fiber bridging properties of the PVA fibers, ECC can exhibit tension strain-hardening behavior, to have tensile strain capacity in excess of 4%, as shown in Figure 9 [19] [20]. The strain-hardening behavior of ECC has led to tremendous improvement in ductility and toughness, compared to normal concrete a very brittle behavior in tension.



Figure 9 ECC strain-hardening behaviour [19] [20]

ECC shows great potential in structural applications with its unique strain-hardening behaviour and high ductility. Figure 10 [21] shows a comparison of hysteresis loops of column members, under fully reversed cyclic loading for steel reinforced concrete specimens with stirrups and steel-reinforced ECC specimens without stirrups. Note that the reinforced ECC columns exhibit better energy absorption and better resilience under seismic reverse cyclic loading.





2.3.2. Engineered cementitious composite shrinkage resistance

Apart from the excellent mechanical properties, such as its strain-hardening behaviour, the durability performance of ECC is especially important in repair applications. Particularly, when the ECC repair is restrained by concrete structures to be repaired, the tensile stress developed in the repair overlay due to shrinkage will cause cracks and delamination leading to serious durability problems.

In terms of the shrinkage resistance of ECC, Li et al. [22] developed a layered repair system shown in Figure 11 to measure the delamination and crack width of 3 repair overlay materials – concrete, SFRC (steel fiber reinforced concrete) and normal ECC, by exposing the system to a dry environment after a 28-day moisture cure. It was found that the ECC repair exhibited 53 μ m interface delamination at the end of 50 days, as compared to 65 μ m to the concrete repair and 275 μ m as compared with the SFRC repair overlay. As for cracks, 76 micro-cracks were found on the surface with a maximum crack width of around 60 μ m as compared to SFRC with 3 visible 270 μ m wide localized fractures, and 4 visible 140 μ m wide localized fractures on the

concrete specimens. It is also worth mentioning that this testing method is very similar and comparable to the one used in this thesis.



Figure 11 Layered repaired system for ECC [22]

Based on normal ECC, Low Shrinkage ECC (LSECC) and ECC with internal curing have been developed and tested to further improve the shrinkage resistance of normal ECC. Zhang et al. [23] experimentally evaluate the shrinkage induced cracking performance of LSECC, through standard ring tests, by changing ordinary Portland cement with the newly developed low dry shrinkage composite cement. The results in Figure 12 show a significant reduction in shrinkage tensile strain on the steel ring, without compromising the anti-cracking advantage and strain-hardening behaviour.



Figure 12 Shrinkage strain comparison between LSECC and traditional ECC [23]

Mustafa et al. [24] incorporates the concept of internal curing into traditional ECC by replacing 10% and 20% silica sand with light weight aggregate (LWA). Up to 67% reduction in autogenous shrinkage and 37% in drying shrinkage was noted, compared to normal ECC without

internal curing, although the strain capacity also reduced by 20% maintaining around 2% ultimate tensile strain which is acceptable compared to conventional concrete and FRC.

2.3.3. Engineered cementitious composite freeze and thaw resistance

When evaluating the durability of ECC, especially in the harsh environment of the Canadian winter, freeze and thaw resistance is another important property. Li et al. [25] carried out mercury intrusion and porosimetry of the standard ECC mix, and found a large porosity of 21.6% small pores discovered because of fibers. It is expected that ECC should possess a very good freeze and thaw resistance based on current pore distribution (Figure 13) even without the help of an air entraining agent.



Figure 13 ECC pore distribution [25]

This assumption has been further validated by research at Purdue University [26]. Their findings show that ECC specimens survive 300 freeze and thaw cycles, while normal concrete fails after 110 cycles. After freeze and thaw tests, the specimen could still maintain a 2% ultimate strain capacity and a minimum of 31MPa compressive strength.

Mustafa et al. [27] also assessed the frost resistance of ECC containing fly ash and found that fly ash replaced ECC also has great durability in terms of freeze and thaw resistance. ECC in their case survived 300 cycles and maintained good residual flexural strength compared to plain ECC matrix without PVA fibers. This is shown in Figure 14. The addition of PVA fibers should be responsible for this excellent frost resistance improvement.



Figure 14 Relative pulse velocity and mass loss with number of freeze and thaw cycles [27]

2.3.4. Green Engineered cementitious composite

Normal ECC contains a large amount of cement which is typically two to three times greater than normal concrete mix for better fiber dispersion and rheology control. Global yearly cement production is responsible for 9% of the world's annual greenhouse gas emissions. In order to make traditional ECC more sustainable and greener, a myriad of research has been done to find a substitute for cement with industrial by-products, such as fly ash and bottom ash.

Wang et al. [28] find that by replacing 2/3 of the cement with fly ash and bottom ash, an acceptable 3 to 4% tensile strain capacity and over 4.5% tensile strength are still maintained.

Similar findings are reported by Yang [29] et al. High fly ash content also tends to reduce the crack width and free drying shrinkage, which is good for the application of green ECC, although 28-day compressive strength were reduced down to only 35MPa; this was still good for regular concrete applications.

2.3.5. From green ECC to EDCC

Although ECC has excellent mechanical properties as well as durability performance, its application is still very limited. One of the main reasons for this is its high cost compared to normal concrete. In order to further reduce the material cost and sustainability, environmental-friendly ductile cementitious composite (EDCC) has been developed here at UBC. By replacing 2/3 cement with fly ash, silica sand with ordinary sand and the 2% oiled-coated PVA fiber with a hybrid of 1% non-oiled coated PVA fiber and 1% polyethylene terephthalate (PET) fiber, it is aimed to reduce cost while maintaining a desirable, strain-hardening property.

Wang [30] performed uniaxial tensile strength tests on different EDCC fiber mixtures. In Figure 15, 4 different mixtures (M4: 2% PVA, M5: 2% PET, M6: 1% PVA and M7 1% PVA&1% PET)

are shown tested under uniaxial tensile load. M4 and M7 are found to exhibit strain-hardening behaviour with tensile strain capacity of 3.89% and 1.67% respectively, while M6 fails at a very low strain level and M5 shows strain softening behaviour.

The entire experimental program in this thesis is based on these EDCC mixes that have been developed here at UBC to further evaluate the durability performance.



Figure 15 Tensile behavior of different EDCC fiber mixtures [30]

2.3.6. Sprayable ECC for shotcreting

The advent of the shotcrete technique opens a whole new approach of rapid placement of repair materials. Shotcrete is a way of conveying fresh materials through the hose and projecting them pneumatically with high velocity from the nozzle, onto structures, such as bridge decks. Because of the special way of material transportation and pneumatic compaction, the material usually requires a desirable workability for ease of transportation (pumpability) and increased viscosity after the material is sprayed out of the nozzle for better adhesion onto the substrate (sprayability and buildability).

Kim [31] at el. designed an ECC mix, suitable for wet-mixture shotcreting. The pumpbility is evaluated through pump-out tests and the sprayability is assessed by filled-up tests and spray-on tests. Kim's study shows the potential of spraying ECC for repair applications.

The spray process of EDCC has also been successfully developed and applied on beams and wall specimens. Sprayable EDCC will also be discussed in Chapter 7in more detail.

2.4. Bond test techniques and bond performance

In most repair applications, the interfacial bond is always the weakest link between repair and the substrate. The bond strength and bond durability plays an important role in the success of a repair.

2.4.1. Bond test methods

There are three main categories of bond test methods: bond under tensile stress, bond under shear stress and bond under a combination of shear and compression, as shown in Figure 16. The dominant method for bond under tension is the pull-off test (a) which is adopted in this thesis and the splitting test (b). Shear bond test methods mainly include the direct shear test (c). The third category of both shear and compression is the slant shear test. [32]



Figure 16 Different bond test methods [32]

The pull-off test is used in this experimental program according to ASTM C1583. The principle of this test method is fairly simple. By attaching a steel disk to a pre-drilled circular cut, a pulling force is applied to the steel disk until the core is pulled off under a constant loading rate. The force/pressure is recorded as the bond strength between the overlay and substrate. There are generally four failure modes, as shown in Figure 17: failure in the substrate, failure at concrete/overlay interface, failure in the overlay and bond failure at epoxy/overlay interface. One of the disadvantages of this test method is that the bond strength value is always the lower bound of the real interfacial bond strength because it cannot be guaranteed that the failure occurs precisely at the interface every time.



Figure 17 Pull-off test method schematic and different failure modes [4]

2.4.2. Bond strength affecting parameters

The worst scenario designed for the ultimate limit state (ULS) for concrete to concrete bond is subject to both tension perpendicular to the interface and shear parallel to the interface. In *fib* Model Code 2010 [33], a formula is given, as follows interpreting different factors affecting the bond strength.

$$\tau_u = \tau_a + \mu \cdot (\sigma_n + k_1 \cdot \rho \cdot f_y)$$

where:

$$\tau_u$$
: ultimate bond strength

 μ : friction coefficient

 $\tau_a:$ is the shear resistance due to adhesive bond/interlocking

 k_1 : is interaction (effectiveness) factor

 σ_n : is (lowest) compressive stress resulting from a normal force acting on the interface

 ρ : is the ratio of reinforcement crossing the interface ($\rho = A_s/A_c$)

This formula is actually from the Coulomb theory shown in Figure 18 [34] [35]. And τ_a is contributed by adhesion, which is from chemical bonding and mechanical interlocking which requires appropriate surface roughness.

$$\tau_n = c + \mu \sigma_n$$

 τ_n : the shear stress acting on the bond interface

c: adhesion strength

 μ : coefficient of friction

 σ_n : the normal stress acting on the bond interface



Figure 18 Mohr circle [35]

2.4.3. Bond durability

Long-term bond performance is very critical in ascertaining the durability of the repair system, so it will be of significance to evaluate the durability of the interfacial bond between repair and substrate. However, few research studies cover this aspect. Naderi [36] studied the effect of cyclic freeze and thaw cycles and cyclic temperature changes on shear bond strength of concrete repair systems through friction transfer method and the results are given in Figure 19.

	Number	Changes in shear bond		Number	Changes in shear
Repair material	of cycles	strength (%)	Repair material	of cycles	bond strength (%)
Epoxy resin mortar	0	0	Epoxy resin mortar	0	0
	33	-6.58	8	33	+17.23
	100	-11.56	5	100	-0.45
	200	-21.09		200	-0.23
	300	+32.88	3	300	-21.09
Polyester resin mortar	0	0	Polyester resin mortar	0	3.57
	33	-13.73	6	33	-26.05
	100	-26.33	6	100	-27.09
	200	-49.86	5	200	-30.53
	300	-62.73	6	300	-37.25
Styrene butadiene rubber	0	0	Styrene butadiene rubber	0	0
modified cementitious mortar	33	+17.73	modified cementitious mortar	33	+13.15
	100	-32.27	1	100	+34.25
	200	-48.56	5	200	-8.49
	300	-62.73	8	300	-3.29
Fiber reinforced acrylic	0	0	Fiber reinforced acrylic	0	0
modified cementitious mortar	33	+14.62	modified cementitious mortar	33	+28.65
	100	+10.53	8	100	+13.74
	200	-3.80		200	+0.88
	300	-25.15	5	300	-2.54
Sand/cement mortar +	0	0	Sand/cement mortar +	0	0
epoxy bonding agent	33	-4.06	epoxy bonding agent	33	+31.30
	100	-27.25	5	100	+6.67
	200	-21.74	L .	200	+9.56
	300	-32.75		300	+7.54
Sand/cement mortar +	0	0	Sand/cement mortar +	0	0
cement bonding grout	33	+23.67	cement bonding grout	33	+40.28
	100	+33.22	2	100	-4.88
	200	+10.60		200	-60.42
	300	+30.39)	300	-89.05

Figure 19 Bond strength change in different repair systems under cyclic freeze and thaw and temperature change [36]

2.5. Surface roughness

As previously mentioned, the surface roughness plays an important role in determining τ_a in the interfacial bond strength. In practice, a certain level of surface treatment needs to be carried out before applying the repair material to the substrate in order to guarantee adequate bond strength.

2.5.1. Surface roughness quantification techniques

Although surface roughness of the substrate affects the reliability, strength and durability of the bond performance, when assessing the roughness, usually a very qualitative and empirical visual inspection is adopted which is based on personal subjective opinions. In order to overcome this disadvantage, the International Concrete Repair Institute (ICRI) [37] issued a set of concrete surface profile chips with different roughness profiles for visual and touch comparisons.

With the development of modern technologies, such as laser profilometry, more and more quantitative methods have been proposed for better surface roughness quantification. For the first time, the new fib Model Code 2010 also put forward Average Roughness (R_a) as a roughness parameter for surface roughness quantification.

Overall, the roughness quantification methods are classified as contact and non-contact techniques. The contact methods are, for example, the sand patch tests and mechanical contact profilometer and the non-contact methods are, for example, laser triangulation and digital imaging techniques. Due to the complexity of these advanced methods, their use has been mostly limited to laboratory investigations.

Laser profilometry analysis is a relatively mature technique to obtain a very precise surface profile compared to other advanced methods. There are two different laser scanning processes available – 2D and 3D laser scanning in Figure 20 [38].

For 2D laser scanning, firstly, several typical and representative lines on the surface are scanned with a 2D laser scanner. Then the data obtained is processed with a professional commercial software. Finally, related surface roughness parameters and curves are plotted using the software. With the advent of the 3D laser scanner, a full surface profile can be re-established on a computer and more detailed surface parameters derived from the scanned surface profile [38]. Obviously, 2D laser scanning is much more easily implemented than 3D laser scanning and many researchers build portable 2D laser roughness analyzer for in-situ purposes.



Figure 20 2D and 3D laser scanner [38]

2.5.2. Surface roughness impacts on bond strength

There are several different types of surface treatment techniques that condition the surface with a certain degree of roughness such as grinding, wire-brushing, chipping, milling, shot blasting, sandblasting and water jetting. According to many research studies [39, 40, 41], water jetting and sandblasting are the most reliable surface preparation methods.

In Eduardo et al [39], the pull-off and slant shear test were carried out for different surface preparation methods such as brushing, chipping and sandblasting, sandblasting show the best bond strength value in both tension and shear.

Pedro et al. [40] correlated the bond strength gained from the pull-off and slant shear tests with surface roughness, characterized by several roughness parameters and showed that it is possible to establish correlation between some roughness parameters and bond strength in shear and tension.

Garbacz et al. [41] investigated the effect of several different surface treatments including grinding, sandblasting, milling and shot-blasting on adhesion with and without bonding agent and found that the roughness of a surface affects adhesion when no bond coating is used. Sandblasting and shot blasting yield the highest pull-off bond strength compared to other methods without coating.

3. Materials properties

3.1 Substrate materials

Three kinds of substrates were used: high strength concrete, clay and concrete masonry. High strength concrete substrates were adopted for all shrinkage and freeze and thaw testing. Clay and concrete masonry substrates were chosen for both the spray process and the hand-applied process.

3.1.1. High strength concrete

(1) Cement, fly ash and silica fume

Type 10 (CSA GU) cement and Type F fly ash from Lafarge, Canada, as well as densified silica fume from Basalite Concrete Products were used in all mixes.

(2) Coarse aggregate

Two kinds of coarse aggregate were used in the mix, 20mm and 10mm, as shown in Figure 21. 20mm aggregate was initially used in the preliminary shrinkage test, however, in order to further increase the strength, stiffness and freeze and thaw resistance, 10mm aggregate was chosen to be used in all the high strength concrete mixes. Further details will be given in Chapter 3. Water absorption of approximately 0.65% was tested following ASTM C127 [43]; this was also duly considered in the mix design.



Figure 21 10mm and 20mm coarse aggregate

(3) Fine aggregate

Sand with a fineness modulus of 2.55 provided by Lafarge was used. The moisture content of the sand was also strictly monitored and calculated before every mix and the moisture content ranged from 2.1% to 4.9% due to different sand batches. The gradation curve for sand is shown in Figure 22.



Figure 22 Sand gradation curve

(4) Admixtures

AVDA 195 high-range water reducing admixture with a density of 1.1 kg/L and 32% solids content was used in all high strength concrete and EDCC mixes. A stronger AVDA CAST 575 high-range water reducing admixture with the same density but 40% solid content was used in EDCC spray process. Both superplasticizers came from Grace, Inc.

DAREX II AEA air-entraining agent with a density of 1.04 kg/L was also added at the maximum recommended dosage by the manufacturer at 320ml/100kg of cement to acquire the proper air entrainment. More details will be discussed in the following chapters.

(5) Mix proportion

The mix proportion of base concrete is shown in Table 1. The sand and water content needed to be adjusted each time before mixing.

Base Mix	Notes	
Cement (kg)	535.50	
Water (w/c=0.31) (kg)	166.60	Adjusted as per sand moisture
C. Agg (10mm) (kg)	809.20	
F. Agg (kg)	809.20	Test moisture every mix
Silica Fume (kg)	59.50	
Air Entraining Agent	320ml/100kg cement	density=1.04kg/L
Superplasticizer (L)	3.22	density=1.1kg/L (AVDA 195)

Table 2 High strength concrete base mix design

(6) Slump and air content

A slump test was performed according to ASTM C143 [45]. A 45mm slump indicated a good compaction. An air content test was also conducted according to AMST C143 to confirm that

there was no damage in the substrate during freeze and thaw test and a 3.5% entrained air content was guaranteed for all substrates.

3.1.2. Clay and concrete masonry blocks

In the spray process, two substrates were used which were made of regular weight 10cm Concrete Masonry Units (CMU) and normal weight standard clay bricks, both produced by Gracom, Inc.

For the CMU block with nominal dimensions of 400×100×200mm (L×W×H), the exact dimensions are specified below in Figure 23. In order to better understand the bond strength between EDCC and CMU blocks at mortar joint, some substrates consisting of two building blocks joined by 10mm mortar joints were used, as shown in Figure 24. CMU specimens after spraying are also shown in Figure 24.



Figure 23 Dimensions of CMU building blocks



Figure 24 CMU substrate before and after spray

In terms of clay brick specimens, each single building block was $194mm \times 92mm \times 57mm$ (L×W×H). Also to evaluate the bond at specific brick joints, each clay beam specimen had 7 clay
blocks connected by 10mm standard Type S mortar joints with 28-day compressive strength of approximately 12.4 MPa. Clay substrates before and after spraying are presented in Figure 25.



Figure 25 Clay substrates before and after spray

3.2. Overlay materials

Six different EDCC mixes were tested as overlay repair materials for shrinkage and freeze and thaw tests and were applied using hand application; only one EDCC mix was applied using the spray process.

3.2.1. Fibers

Two different fibers were investigated, Recs 15×8 PVA fiber from Kuraray Co., Ltd. Japan and PET fiber from Reliance Industries Ltd. India. The basic properties of these two fibers are shown in Table 2. It is also worthwhile to mention, that unlike normal engineered cementitious composite (ECC), EDCC uses much less expensive, non-oiled PVA fiber instead of oil-coated PVA fiber, to reduce the cost of the material itself.

Type of fiber	Length, mm	Diameter, µm	Tensile strength, MPa	Elastic modulus, GPa
PVA	8	40	1560	40
PET	6	33-36	400-600	9-10

Table 3 Properties of PVA and PET fibers

3.2.2. Mix proportion

Five EDCC and one control plain mix proportions are listed in Table 3. It is noted that the water and sand contents here don't consider the moisture content from the sand. The sand moisture content was determined and the mix water was adjusted accordingly.

		5	fume					1	1	
	385.63	3 771.27	77.13	462.76	333.19	13.00	10.00		2.00	
M	lixture ID	С	FA	SF	S/CM ratio ^a	W/CM ratio ^b	PET (t volu	fiber y ime)	PVA fibe (by volum	er ie)
	M1	1	2	0.2	0.375	0.27	0	%	0%	
	M2	1	2	0.2	0.375	0.27	0	%	1%	
	M3	1	2	0.2	0.375	0.27	0	%	2%	
	M4	1	2	0.2	0.375	0.27	1	%	0%	
	M5	1	2	0.2	0.375	0.27	1	%	1%	
	M6	1	2	0.2	0.375	0.27	2	%	0%	

Table 4 Base concrete and EDCC mix design (Unit:Kg/m3)

Sand

Water PVA PET Superplasticizer

Silica

^aS/CM: sand/cementitious materials

Cement Fly ash

^bW/CM: water/cementitious materials

Because two different types of SP are used, a different dosage was used for each one. For handapplied batches, AVDA 195 (4 kg/m³) was used; for spray batches, AVDA CAST 575 ($2kg/m^3$) was used.

3.2.3. Mixing procedure

EDCC is a very tough and cohesive material which is optimized for spray applications. A Hobart mixer was used for the small hand-applied 5 liter batches and a high shear Omni Mixer was used for large 35 liter batches.

The following procedures were followed for hand-applied EDCC: For the 1% PET and 1% PVA mix, the PVA fibers were added first in step 3. For the 2% PET fiber mix, roughly ¹/₄ of the amount of PET fibers was added in procedure 3, because of the difficulty to disperse.

- (1) All cement, fly ash and silica fume were premixed for 2 minutes at a low speed.
- (2) The AVDA 195 superplasticizer was diluted with 40-60ml of water and 1/3 of the water was added into the dry mix.
- (3) Nearly ½ the amount of fiber was added into the mix and all the sand was added to help break the fibers into a dampened condition.
- (4) A small amount of superplasticizer and another 1/3 of the water were added to the mix to maintain the cohesiveness.

- (5) The rest of the fibers were added to the mix gradually, and at the same time, the rest of the water and superplasticizer were also slowly added until all the fibers were added.
- (6) The combination was mixed for another 3 to 5 minutes, to get a well-dispersed mix with desirable workability.

When it comes to large batches of sprayed EDCC with 1% PET & 1% PVA mix, the mixing procedure needed to be adjusted accordingly. Instead of adding fiber before all the sand was added, fibers were added until a very cohesive and tough mixture was obtained. The following procedure needed to be followed strictly to avoid fiber balls and make sure of best fiber dispersion was obtained for spray, otherwise, it is very likely to get the spray gun clogged.

- (1) The cement, fly ash and sand were premixed for 3 minutes.
- (2) AVDA CAST 575 superplasticizer was diluted with 100ml water and 1/3 of the rest of water was added to the dry mix and mixed for 5 minutes.
- (3) Silica fume and the other 1/3 of water were added at the same time and mixed for 5 minutes to make sure of a very cohesive mixture.
- (4) Slowly add fibers, water and a small amount of superplasticizer to keep the cohesiveness until all the fiber, water and superplasticizer were added.

This whole process might take more than 20 minutes to get good fiber dispersion and desirable workability for the spray.

- 3.3. Other materials
 - 3.3.1. Mold

PVC mold with dimensions of $400 \times 75 \times 100$ (L×W×H) were used for hand-applied samples. Selfmade plywood frames were used in sprayed samples to help control repair material thickness and avoid size effect. More details will be described in Chapter 7.

3.3.2. Spacers

Plywood spacers and mortar spacers were used in this project to help adjust desirable thickness. More detailed information will be presented in the following chapters.

3.3.3. Epoxy

Using a good epoxy is actually very important for execution of the pull-off bond test, and poor quality epoxy will lead to undesirable results, failure at epoxy and trouble with cleaning. As recommended by the manufacturer, Devcon 2 Ton Epoxy was used throughout the testing program.

3.3.4. Release agent

Organic, biodegradable, canola-based, reactive form release agent manipulated by Green Release was used to coat the molds prior to casting the EDCC and the concrete specimens.

4. Restrained Plastic Shrinkage Performance of EDCC

4.1 Introduction

Plastic shrinkage occurs when the mix is still in a fluid state before hardening, which causes volumetric contraction because of the difference between the surface moisture evaporation loss and water bleeding out onto the surface [15]. Sometimes due to weather conditions, surface moisture evaporation speed exceeds the water bleeding rate and this causes surface plastic shrinkage cracking [15]. If this problem is not addressed properly, it will cause serious durability concerns. Shrinkage cracking not only creates easy access routes for deleterious agents to enter the overlay-substrate interface but also allows for an early saturation of the overlay material resulting in freeze-thaw damage, swelling, scaling, discoloration and eventual debonding. Especially in repair applications, when patching the repair material onto the structure being repaired, due to the restraints from the substrate, cracks tend to become more significant compared to free plastic shrinkage in new cast structures. Much research has confirmed the effectiveness of fibers in preventing early plastic shrinkage cracks and many different testing methods are available. This chapter will use the technique developed at UBC [12] to evaluate the restrained shrinkage performance of EDCC.

In order to simulate the real stress conditions in repair and substrate assembly, a novel and effective testing method has been developed to simulate extreme plastic shrinkage conditions. A very stiff base, reinforced with rebars and high strength concrete with compressive strength around 85MPa can provide extreme restraints with protuberances for overlay repair materials during early plastic shrinkage. In Figure 27 the dimension, mold and cast substrate are shown.



Figure 26 Substrate for shrinkage test (Rishi, 2008)

4.2 Shrinkage test base development

One of the main purposes of this project is to evaluate the bond performance after both shrinkage and freeze and thaw environmental damage has occurred. Although the freeze and thaw ASTM C666 standard allows for various dimensions, the freeze and thaw chamber specifies the standard sample size as $405 \times 105 \times 76$ (L×W×H). In order to continue the freeze and thaw test after the shrinkage test, the same dimension as $405 \times 105 \times 76$ (L×W×H) is needed in the shrinkage test. So new bases conforming to new dimension requirements with sandblasting treatment on the surface were used here.

4.2.1 Compressive strength of concrete bases

The mix design was shown in Chapter 3, Table 3 and because high strength is required, a standard compressive test according to ASTM C39 [42] was performed here to obtain the strength development of this mix. Results are given in Table 4. The samples were all 100×200 (D×L) cylinders.

Sample No.	Age/day	Compressive Strength /MPa	Average /MPa	COV	
1	3	80.8			
2	3	81.2	81.23	0.45%	
3	3	81.7			
4	7	100.2			
5	7	101.5	101.47	1.01%	
6	7	102.7			
7	28	114.5			
8	28	114.1	114.73	0.55%	
9	28	115.6			

Table 5 Base concrete compressive strength

4.2.2 Base high strength concrete air content trials

In order to ensure the integrity of the substrate under freeze and thaw cycles, a proper air void system should be established. So, an air-entraining agent is used to incorporate air into the mix. Things become complicated when trying to increase the air content from 1.8% to 5%. Therefore, different trials had to be conducted in order to get 5% air.

Trial 1: Dry materials were added and mixed for 3 minutes (because related research has found that longer mixing time will possibly break the bubbles prematurely), and diluted AVDA 195 superplasticizer was added.

Although we added the recommended maximum amount, only 3.2% percent is got. Doubled or even tripled dosages of air entraining agent was added but the air content still stayed around 3%. A potential conflict between superplasticizer and air entraining agent is doubted, so another AVDA CAST 575 was tried.

Trial 2: Dry materials were added and mixed for 3 minutes; diluted AVDA cast 575 superplasticizer and water were added into the mix gradually. Finally, an air entraining agent was added to the mix, and mixing continued for 2 more minutes.

Unfortunately, the air content did not increase beyond 3.5%. A different mixing sequence was tried, by adding the air entraining agent before the superplasticizer was added but no increase in air content was found.

To more thoroughly arrest whether the air entraining agent was really working in the mix, two groups of cylinder samples, Group 1 single recommended maximum dosage added and group 2 without adding AEA were cast for comparison. The compressive strength is shown in Table 5.

Group No.	Age/day	Compressive Strength /MPa	AEA Content /ml/m ³ (cement)
1	3	78.8	320
2	3	81.2	0
1	7	97.4	320
2	7	100.2	0

Table 6 Air entrained and non-air entrained compressive strength comparison

It was seen that the air entraining agent did have an effect on the mix, which caused a 3 percent strength loss. It is still unknown why further increasing the AEA did not increase the air content and that investigation is beyond the scope of this project. Much of the previous research has shown that for high strength concrete, the freeze and thaw resistance is not usually a problem. This is true also for this project, because only 100 freeze and thaw cycles were imposed.

Rebar is also added approximately halfway through the thickness of the base (see Figure 28) to increase the stiffness and integrity of the substrate and it is expected that the freeze and thaw resistance could be increased, as well, to ensure that the damage that might be found in succeeding tests is not from degradation of the substrate.

The properties of rebar are shown in Figure 27. In each mix, 2×365 mm 10mm rebars are embedded in the substrate, as shown in Figure 28. Before making the substrate, a marked center line is drawn on the wood spacer to help identify the moment to put rebar into the mold after casting half of the base.

Chemical Composition (%)							Mechanical Properties								
						Yield Point	Ultimate Tensile	Elongation	Cold						
С	S	Р	Si	Mn	Cr	Ni	Cu	V	Nb	Mo	Ceq	(Mpa)	Strength(Mpa)	(%)	Bend
0.20	0.029	0.016	0.41	1.06	0.06	0.04	0.14	0.017	0.032	0.005	0.39	490	620	19	ОК

Figure 27 Properties of 10mm rebar (Harrris Rebar Inc)



Figure 28 High strength concrete substrate with rebars and rebar layout during casting

4.2.3 High strength concrete substrate dimension

In the beginning of the experiment, the dimension of the base is designed as $405 \times 75 \times 75$ (L×W×H) without leaving any space around the sample. Trial shrinkage testing was performed and it was found that after 24 hours the repair became detached from the substrate. This is because the mold was removed 2 hours after the fresh mix was cast and the condition of the interface at that time is very delicate so that any external movement will jeopardize the interface, causing it to debond, as shown in Figure 29. So, an overlap design was adopted to make sure the repair material had a full overlap around the base to diminish the edge effect. Finally, the base was confirmed with dimension at $385 \times 65 \times 75$ and the repair was designed with a 25mm thickness, as shown in Figure 30.



Figure 29 Repair overlay detached from substrate

Figure 30 Substrate overlap design

4.3 Surface sandblasting treatment

In repair applications, the substrate-repair interface always needs to have a certain amount of roughness to make sure that a good bond will be developed afterwards. Among all different surface treatment techniques, sandblasting is believed to be one of the most reliable and effective methods [39, 40, 41].

4.3.1 Preliminary studies

A Karcher Honda GC190 Gas-Powered 3000 psi pressure washer with Karcher sandblasting Kit was used. Very dry and fine (see gradation curve in Figure 31) industrial sandblasting sand from Target was used and the properties of which are listed below in Table 6.



Table 7 Target Industrial sand properties (from Target Products Ltd.)

Figure 31 Industrial sand gradation curve (data from Target is redrawn here)

Twenty-eight day sandblasting was planned at the beginning of the study. This was performed on 5 specimens and unfortunately found to be extremely difficult in terms of achieving the desired roughness, because the base is made of very high strength concrete (over 110MPa) and the pressure that the machine provided was not sufficient. Considering that the 3-day strength of base concrete reached over 80MPa, a 3-day sandblasting was performed. Unfortunately, it was still very problematic to get desirable roughness within reasonable time and sand consumption.

4.3.2 Sandblasting system upgrade

Due to very low efficiency and high cost of sand consumed in the preliminary set-up, a new 389cc Honda GX390 4000 PSI BE pressure washer, an industrial heavy duty wet sandblasting kit from ATPRO Powerclean Equipment, sandblasting tank with plywood cover and an industrial floor lamp were equipped in the sandblasting system (Figure 32).



Figure 32 BE pressure washer, wet sandblasting kit and system set up

4.3.3 Sandblasting operation

Because of the upgrade of the sandblasting system, a desirable surface roughness after 28 days was likely to be obtained. However, due to time frame limitations of this project, 7-day curing was considered adequate. In order to try to minimize the roughness variability among the different samples, an operational procedure was followed to ensure uniformity. The total sandblasting time for each sample ranged from 15 to 20 minutes at full pressure and at a distance from the gun between 10cm during the first 10 minutes to 15cm until the end of the process. The angle that the gun swiped at was roughly between -30 degrees to 30 degrees, as shown in Figure

33 below. A 20-minute sandblasting will consumed about half bag of sand. Although the roughness of each sample surface was not able to be fully controlled at the same level, the difference was maintained within an acceptable range.



Figure 33 Sandblasting operation schematic [41]

4.4 Surface roughness choice and quantification

With good sandblasting techniques, a certain roughness should be decided upon to ensure that sufficient restraint could be developed at the interface for shrinkage testing. The main principle of restrained shrinkage testing, as per the work of Gupta [13, 14], is to provide an extremely restrained condition at the interface so that the overlay may crack easily when it shrinks. As explained in previous chapters, due to limitations of the dimension, the standard substrate with protuberances was not able to be used. Thus, a preliminary study was performed to explore what degree of roughness would have full fixity and could be replicated easily. After a certain roughness was decided upon, the level of roughness was quantified using laser profilometer was conducted.

4.4.1 Preliminary studies

As plain mortar mix provides the best visibility to see cracks during shrinkage tests, the preliminary study used plain mortar as the overlay material. Three samples with different roughness were prepared by sandblasting and the plain mortar overlay was cast on top of all three samples in the same batch. Then, all three samples were transferred into the environmental chamber to be subjected to hot air at 50C for 2 hours. Samples were demolded and the chamber continued to run for another 22 hours.

Surprisingly, within these three samples, no cracks were found in the one which was lightly sandblasted (right), but both the moderately (middle) and strongly sandblasted (left) samples had

cracks on their surfaces, as shown in Figure 34. But the strongly sandblasted sample had bigger cracks (approximately 0.31mm), than the moderately sandblasted sample, which was approximately 0.14mm. Also, in consideration of the ease with which a replicable roughened surface could be obtained, the roughness of the strongly sandblasted (left) sample was chosen. As seen in Figure 34, on the right, the surface roughness is visually consistent.



Figure 34 Sandblasted surface and shrinkage preliminary test

In order to further prove the shrinkage results, more samples with similar roughness were cast and very similar and replicable cracks with close crack width, at around 0.29mm were obtained, as shown in Figure 35.



Figure 35 Replicable cracks in samples with similar roughness

4.4.2 Roughness quantification

A detailed roughness quantification is presented here to help better understand the extent of the sandblasting treatment. In practical applications, there is still no standardized method to quantify

the surface roughness. The most acceptable way of quantification is to use the concrete surface profiles proposed by the International Concrete Repair Institute (ICRI), shown in Figure 36. This method is, to some extent, somewhat based on empirical visual inspection.

Another common way to assess the surface roughness is through the so-called Sand Patch Test, as shown in Figure 36 [42], by spreading a certain amount of normal size sand on the surface and measuring the total area covered by the sand. The mean texture depth is determined by

$$MTD = \frac{4V}{\pi D^2}$$

where V is the volume of the sand and D is the diameter of spread sand.



Figure 36 Concrete surface profiles and Sand Patch Test

However, in terms of accuracy, advanced methods such as the non-contact laser profilometer are available which can allow getting exact measurements of the roughness profile and topography. The *fib* Model Code 2010specifies a mean roughness R_a as a roughness quantification indicator defined as the average deviation of the profile from a mean line (\overline{y}), shown in Figure 37 [33].

$$R_a = \frac{1}{l} \cdot \int_0^l |y(x) - \bar{y}| \cdot dx \approx \frac{1}{n} \sum_{i=1}^n |y_i - \bar{y}|$$
$$\bar{y} = \frac{1}{l} \int_0^l y(x) \cdot dx \approx \frac{1}{n} \sum_{i=1}^n y_i$$

where:

l is the assessment length

y(x) is the profile height at position x



Figure 37 Average roughness R_a [33]

In the testing program shown in Figure 38, a Microtrak II Laser Triangulation Sensor LTC 120-20 was used as the main laser scanning instrument, with a 10mm measurement range and 120mm standoff distance. A dogbone machine carried the laser head to move horizontally with a constant velocity of around 0.085mm/s controlled by a Dayton DC speed controller. MT2 remote control software was used to collect distance data from the laser head to the specimen surface. In each sample, 4 lines (85mm) along the length of the specimen and 4 lines (47mm) along the width of the specimen were scanned several times to guarantee that there was no out-of-range value in each scanned line. There is an indicating LED light on the laser head to help see whether or not the measurement was out of range. Each line was scanned a few times to make sure all data remained within range, by repeatedly and slightly changing the position and orientation of the specimen. The velocity of the moving laser head could be accurately monitored by the speed controller from DasyLab 9 software communicating with it. The set-up is shown in Figure 38. Constrained by the time frame of this testing program, 3 specimens were chosen to be tested to represent the roughness of all specimens.



Figure 38 Laser scan set up

Once the data was gathered for each specimen, Excel and MountainsMap 7 was used to process the data. MountainsMap 7 is a professional surface imaging & metrology software, developed by Digital Surf that is used to analyze data, automatically and accurately, from all 2D profilometers, according to ISO 4287 and other related standards. According to ISO 3274, with the surface profile raw data, the form of the profile needs to be removed first, and based on proper filter method and cut-off values, the roughness and waviness profile can be extracted automatically from the software.

Following the procedures specified in ISO 3274, first the form of raw data was removed and the curve was given, as below in Figure 39.



Figure 39 Form removed curve

After the form was removed, a Gaussian filter with cut-off distance at 5mm was applied to filter the roughness and waviness curves, shown in Figure 40.



Figure 40 Roughness and waviness profile after filtering

With the help of MountainsMap, all related roughness and waviness parameters from ISO 4287 were then easily obtained. R_a and W_a are known to be the most simple and distinct parameter to

depict the roughness and waviness of a profile. It was found that $R_a = 0.0248$, $W_a = 0.92$ for Sample 1 and $R_a = 0.0217$, $W_a = 0.772$ for Sample 2, as shown in Figure 41. All other factors were also found to be close in measurement based on such accuracy. The findings were conclusive enough to say that the roughness of different samples was quite consistent and within acceptable range.

ISO	ISO 4287				ISO 4287						
Amp	Amplitude parameters - Roughness profile				Amplitude parameters - Roughness profile						
Rp	0.0477	mm	Gaussian filter, 0.8 mm		Rp	0.0416	mm	Gaussian filter, 0.8 mm			
Rv	0.0527	mm	Gaussian filter, 0.8 mm		Rv	0.0427	mm	Gaussian filter, 0.8 mm			
Rz	0.100	mm	Gaussian filter, 0.8 mm		Rz	0.0843	mm	Gaussian filter, 0.8 mm			
Rc	0.102	mm	Gaussian filter, 0.8 mm, ISO 4287 w/o amendme		Rc	0.0878	mm	Gaussian filter, 0.8 mm, ISO 4287 w/o amendme			
Rt	0.561	mm	Gaussian filter, 0.8 mm		Rt	0.481	mm	Gaussian filter, 0.8 mm			
Ra	0.0248	mm	Gaussian filter, 0.8 mm		Ra	0.0217	mm	Gaussian filter, 0.8 mm			
Rq	0.0299	mm	Gaussian filter, 0.8 mm		Rq	0.0264	mm	Gaussian filter, 0.8 mm			
Rsk	-0.156		Gaussian filter, 0.8 mm		Rsk	-0.103		Gaussian filter, 0.8 mm			
Rku	2.39		Gaussian filter, 0.8 mm		Rku	2.37		Gaussian filter, 0.8 mm			
Amp	litude pa	ram	eters - Waviness profile		Ampl	itude pa	aram	eters - Waviness profile			
Wp	2.61	mm	Gaussian filter, 0.8 mm		Wp	1.76	mm	Gaussian filter, 0.8 mm			
Wv	2.24	mm	Gaussian filter, 0.8 mm		Wv	1.75	mm	Gaussian filter, 0.8 mm			
Wz	4.84	mm	Gaussian filter, 0.8 mm		Wz	3.52	mm	Gaussian filter, 0.8 mm			
Wc	2.49	mm	Gaussian filter, 0.8 mm, ISO 4287 w/o amendme		Wc	2.31	mm	Gaussian filter, 0.8 mm, ISO 4287 w/o amendme			
Wt	4.84	mm	Gaussian filter, 0.8 mm		Wt	3.52	mm	Gaussian filter, 0.8 mm			
Wa	0.920	mm	Gaussian filter, 0.8 mm		Wa	0.772	mm	Gaussian filter, 0.8 mm			
Wq	1.10	mm	Gaussian filter, 0.8 mm		Wq	0.916	mm	Gaussian filter, 0.8 mm			
Wsk	0.380		Gaussian filter, 0.8 mm		Wsk	-0.249		Gaussian filter, 0.8 mm			
Wku	2.24		Gaussian filter, 0.8 mm		Wku	2.09		Gaussian filter, 0.8 mm			

Figure 41 Roughness and waviness parameter comparison of the two samples

The Abbott-Firestone curve in Figure 42 is a commonly used method to describe surface texture. It is defined as the cumulative probability density function of the height of the surface profile. The curves that were established were similar using this measure.



Figure 42 Abbot Curve comparison of two samples

4.5 Shrinkage testing execution

Based on previous preliminary tests, a proper base with a consistent roughness was confirmed. Following UBC testing technique [3], five different EDCC fiber mixes and one plain control mix were tested one by one, in the single channel environmental chamber, each time three specimens were put at the exact marked position to keep the testing consistent. The mixing was completed within 10 minutes and the casting and finishing were done very quickly within 5 minutes. Then 3 specimens with the mold were straightaway transferred to the chamber and exposed to hot air for 2 hours. Then the specimens were demolded and kept in the chamber for another 22 hours. The chamber maintained a temperature of 50 degrees and 5% relative humidity was controlled by a temperature and humidity sensor. The chamber configuration is shown in Figure 43 and 44.



Figure 43 Single channel environmental chamber schematic [13]



Figure 44 Single channel shrinkage chamber set-up

It needs to be noted that before the overlay was cast on top of the substrate, the interface was carefully pre-moisturized to make sure of as little water exchange as possible. If the interface were too dry, water from the overlay near the interface would have moved out and changed the local water cement ratio to create a weak link along the interface. On the other hand, if the interface were too wet, water would have moved to the repair mix and changed the water-cement

ratio, thus once again creating a weak interface. This measure though essential is also difficult to control and needs to be handled very cautiously. Usually, a saturated surface dry condition is ideal to minimize the moisture transportation. As suggested by people from the repair industry, a surface which is damp without standing water could be regarded as SSD condition, as in Figure 45. A paper towel could be used to dry and check if standing water exists.



Figure 45 Pre-moisturized surface

Going back to our experiment, after 24 hours, a visual inspection was conducted for all 6 different mixes, to see if cracks had developed on their surfaces, as shown in Figure 46. If cracks were observed, further crack measurements were performed, if not, specimens were moved to the curing room for moisture curing, until they matured.

As expected, only plain mix cracks and no cracks were found in all fiber mixes. One percent fiber should be more than enough to bridge any shrinkage cracks. All fiber mixes were cured to maturity and freeze and thaw tests and bond tests for each mix were performed to further evaluate the durability performance of this material.



4.6 Crack measurements

As no fiber mix acquired cracks, only cracks on the plain mix were measured. Two methods were used to do the measurements: portable magnifier and image analysis software. Each specimen was marked with 13 points and the crack widths were measured at each point, as shown in Figure 25. After the crack widths were measured, total crack area $[A_{total}]$ was subsequently calculated with the following simple formula:

$$A_{total} = \sum_{i=1}^{n} w_i l_i$$

where,

 $w_i = average \ crack \ width \ of \ the \ i^{th} \ crack$ $l_i = length \ of \ the \ i^{th} \ crack$ $n = number \ of \ cracks \ observed \ in \ a \ test$

Figure 47 shows how the crack width was measured under a portable magnifier using scaling measurement and under a microscope using image analysis software. A 0.297mm average crack width and a 26.864 mm² total crack area for one crack were measured from image analysis for better accuracy, as shown in Figure 48.



Figure 47 Crack measurements under optical magnifier and under microscope with image analysis software



Figure 48 Measurements with image analysis software

4.7 Shrinkage test results and discussion

All EDCC mixes with fibers showed very good shrinkage resistance without any visual cracks. For the plain mix without fibers, cracks with up to 0.3mm width were identified after 24-hour hot air exposure. And this is found to be much smaller compared to the data from Gupta [3] and it is because the restraints here produced by sandblasting are lower than the restraints produced by the protrusions. It can be concluded that all 5 EDCC fiber mixes exhibited very good shrinkage resistance by taking advantage of fiber bridging effect, but the bond strength after the shrinkage exposure attack needs to be further investigated. Although no cracks were observed, some micro-delamination may have occurred at the non-visible interface which may cause a loss of bond and this will be further validated in the bond chapter.

5. Freeze and thaw resistance of EDCC

5.1 Introduction

In Canada, freeze and thaw resistance is essential from the durability perspectives of concrete structures because freeze and thaw cycles occur seasonally in all parts of Canada. Hence, before any new material can be applied in the industry, the freeze and thaw resistance of this material must be well understood. This chapter will show the research done with all six different EDCC mixes having been subjected to up to 90 freeze and thaw cycles to evaluate their freeze and thaw resistance.

5.2 Test set-up

Basically, this test follows ASTM C666, although some differences do exist due to testing instruments, testing plan, testing variables, etc. Quantification of the freeze and thaw damage was accomplished through measurements of ultra-sonic pulse velocity and loss of mass at every 10 cycles. For each mix, 3 samples were cast, and then, in order to see how freeze and thaw cycles would impact the bond strength, the 3 samples were subjected to 30, 60 and 90 cycles respectively. The few differences from ASTM C666 standard are listed below,

- (1) Samples' curing period: The standard requires 14 days of moisture curing before running the freeze and thaw cycles, but so as to evaluate the bond more realistically in field applications, a 28-day full curing period was applied in our case, because, within 14 days, the bond was not fully developed.
- (2) Cycle duration: Due to the inefficiency of this rapid freeze and thaw cabinet, many trials and adjustments were conducted to make sure that samples were properly frozen and thawed. A 6-hour cycle was chosen, although this is beyond the requirement of the 2 to 5 hours requirement of the standard.
- (3) Number of cycles: According to the standard, 300 cycles or cycles at which the dynamic modulus is reduced to 60% should be done. However, considering the time frame of this project and the bond strength assessment after the freeze and thaw cycles were completed, a maximum 90-cycle testing was chosen. On the other hand, there would be no point for successive bond strength evaluation if the bond strength drops too much after certain cycles.

(4) Damage quantification method: In this testing, instead of using the standard recommended parameter of dynamic modulus, pulse velocity was used for damage quantification because of a machine issue in the dynamic modulus testing apparatus.

5.3 EDCC characterization

5.3.1 Air content

A proper air void system can effectively protect cementitious materials from freeze and thaw attack. Hence, before continuing the freeze and thaw tests, the air content of fresh EDCC mortar was characterized following ASTM C143 [46] and the results are shown in the table below. As we can see in Table 7, all fiber mixes contain more than 6.8% air in the fresh state, which should be more than enough to guarantee integrity during the freeze and thaw cycles. It should be noted that no air-entraining agent was incorporated into any of the fiber mixes for consistency sake and the plain mix was decided not to be air entrained as well, although only 3% air content was detected, which is less than the normal frost resistance requirement.

EDCC Air Content							
1% PET	6.80%						
1% PET+1%PVA	7.80%						
1% PVA	7.50%						
2% PET	8.50%						
2% PVA	10.50%						
Plain mortar	3.00%						

5.3.2 Workability

Proper workability was sought to facilitate casting and better compaction to guarantee good quality. So, based on the EDCC original mix, the superplasticizer dosage was adjusted for each mix with different fiber content, as shown in Table 8.

Mix	Superplasticizer dosage	Slump
1% PET	3kg/m3	80
1% PET+1%PVA	4kg/m3	70
1%PVA	3kg/m3	75
2% PET	4.5kg/m3	70
2% PVA	4kg/m3	80
Plain mortar	2kg/m3	100

Table 9 Superplasticizer dosage and slump of EDCC

5.3.3 Compressive strength

Compressive strength is a good technique for quality control, so for each mix, three 75×150 mm (D×H) cylinders were are cast and tested after the 28-day standard moisture curing. All the samples of the same mixes showed similar strength; this indicates good quality control within the mixes (see Table 9). It was found that by increasing the fiber addition, the compressive strength increased as well, which is a unique material property compared to normal fiber reinforced concrete, which often displays the opposite trend.

Sample No.	Age/day	Compresssive Strength /MPa	Average /Mpa	COV	
1% PET_1	28	47.80			
1% PET_2	28	47.39	47.86	0.89%	
1% PET_3	28	48.38			
1% PVA_1	28	45.68			
1% PVA_2	28	45.04	45.33	0.59%	
1% PVA_3	28	45.26			
2% PET _1	28	59.77			
2% PET_2	28	59.32	59.33	0.61%	
2% PET_3	28	58.89			
2% PVA _1	28	54.99			
2% PVA_2	28	55.25	54.58	1.41%	
2% PVA_3	28	53.50			
1% PET&1% PVA_1	28	58.82			
1% PET&1% PVA_2	28	61.04	60.15	1.59%	
1% PET&1% PVA_3	28	60.58			
Plain mix_1	28	40.36			
Plain mix_2	28	41.21	40.80	0.85%	
Plain mix_3	28	40.82			

Table 10 EDCC compressive strength

5.4 EDCC overlay dimension control

As explained in previous chapters, because of the composite assembly overlap design, the substrate is smaller than the mold and if the base is not properly fixed, the base will move during vibration and cause quality problems for future testing. So, as shown in Figure 49, small mortar spacers were placed in the gap between the molds and the base, to help stabilize the base in place. Because the spacers will eventually be cast into the composite beam, in order not to let the

spacers exert any impact on the succeeding tests, the spacers are made from exactly the same mix design as the plain mortar.



Figure 49 Plain mortar spacers to fix the substrate

5.5 Freeze and thaw test execution

The rapid freeze and thaw cabinet is manufactured by Humboldt construction materials testing equipment provider. This cabinet can fit 18 standard $405 \times 76 \times 105$ samples at the same time. A freeze and thaw control specimen was used to control cycling temperature in the chamber, so only 17 specimens can be tested at the same time, as shown in Figure 50. Two thermocouples were embedded inside the control specimen sealed with playing putty and its location was changed every 20 cycles. Water needed to be added to all trays to keep all specimens submerged in 1/8 inch water on each side due to moisture evaporation taking place with the cycles going on. Two cut 1/8 inch wires were placed at the bottom of each tray, as well, to keep the specimen from directly touching the tray.



Figure 50 Freeze and thaw cabinet

After every 10 cycles, the cabinet temperature maintained at around 4C and all specimens were taken out to test for pulse velocity at the pre-marked location from both sides along the length

direction with the Proceq TICO ultrasonic velocity tester, shown in Figure 51. Two transducers covered the top half of the side surface and each time, three readings were taken from the tester and recorded.



Figure 51 Ultrasonic pulse velocity tester

5.6 Freeze and thaw test results

As discussed in previous chapters, the first two groups of specimens subject to shrinkage exposure and moisture curing immediately after casting the repair overlay are exposed to 30, 60 and 90 freeze and thaw cycles. Below are the results of all the different EDCC mixes based on pulse velocity curves and mass loss curves. All the values given in the vertical Y axis are the ratio of the pulse velocity or mass after certain freeze and thaw cycles and the initial pulse velocity and mass without any freeze and thaw exposure. Values for the X axis are number of freeze and thaw cycles.

5.6.1 1% PVA freeze and thaw resistance

As we can see from Figure 52 and 53 pulse velocity curve, within 90 cycles no obvious drop or even a sudden increase around of 15% in the pulse velocity occurred. This indicates that no damage occurred during the EDCC repair, and also according to the mass loss curve, nearly no mass loss occurred. It could be concluded that based on ASTM C666, the freeze and thaw resistance of 1% PVA mix is adequate for at least 90 cycles. However, the bond strength between the repair and substrate, after a certain amount of freeze and thaw cycles, still remained unknown and will be discussed in next chapter. Also, no damage, such as scaling, was identified visually.



Figure 52 1% PVA Mass loss curve (FT only)



Figure 53 1% PVA pulse velocity curve (FT only)

5.6.2 1% PVA (with shrinkage exposure) freeze and thaw resistance

Figure 54 and 55 show that no damage was found from mass and pulse velocity loss curve (change within 5-10%). The mass and pulse velocity even increased due to water saturation after 10 cycles. Also, there was no damage, such as scaling as identified visually.



Figure 54 1% PVA mass loss curve after shrinkage exposure



Figure 55 1% PVA pulse velocity curve after shrinkage exposure

5.6.3 1% PET freeze and thaw resistance

No damage was found from mass and pulse velocity loss curve (change within 2-6%), as seen in Figures 56 and 57. Little damage, such as scaling, was identified.



Figure 56 1% PET Mass loss curve (FT only)



Figure 57 1% PET pulse velocity curve (FT only)

5.6.4 1% PET (with shrinkage exposure) freeze and thaw resistance

No damage within 60 cycles was found from mass and pulse velocity loss curve (change within 3%) as shown in Figures 58 and 59. A sudden drop occurred at 90 cycles in pulse velocity and this will be further validated in the bond test. Little damage, such as scaling, was identified visually.



Figure 58 1% PET Mass loss curve with shrinkage exposure



Figure 59 1% PET pulse velocity curve after shrinkage exposure

5.6.5 2% PVA freeze and thaw resistance

No damage was found to have occurred over the course of 90 cycles from mass (change within 1%) and pulse velocity loss curve (even depicted an increase from 10% to 15%), as seen in Figures 60 and 61. Nearly no damage was visually identified.



Figure 60 2% PVA Mass loss curve (FT only)



Figure 61 2% PVA pulse velocity curve (FT only)

5.6.6 2% PVA (with shrinkage exposure) freeze and thaw resistance

Figure 62 and 63 showed that no damage was found from mass (change within 5%) and pulse velocity loss curve (change within 5-7%) within 90 cycles. Nearly no damage was visually identified.



Figure 62 2% PVA Mass loss curve with shrinkage exposure



Figure 63 2% PVA pulse velocity curve after shrinkage exposure

5.6.7 2% PET freeze and thaw resistance

No damage was found within 60 cycles from mass (change within 2%) and pulse velocity loss curve (change within 5-10%) as shown in Figure 64 and 65. But when running into 90 cycles, however, the pulse velocity dropped over 15% and some damage was seen around the surface.



Figure 64 2% PET Mass loss curve (FT only)



Figure 65 2% PET pulse velocity curve (FT only)

5.6.8 2% PET (with shrinkage exposure) freeze and thaw resistance

No damage was can be found from mass (change within 2%) and pulse velocity loss curve (change within 5-10%) within 60 cycles, as shown in Figure 66 and 67. However, at 90 cycles, the pulse velocity dropped over 15% and some damage on the surface was visually identified.



Figure 66 2% PET Mass loss curve with shrinkage exposure



Figure 67 2% PET pulse velocity curve after shrinkage exposure

5.6.9 1% PVA&1% PET freeze and thaw resistance

No damage was found from mass (change within 1%) and pulse velocity loss curve (change within 2%) as shown in Figure 68 and 69 within 90 cycles. Nearly no damage was visually identified.



Figure 68 1% PVA&1% PET Mass loss curve (FT only)



Figure 69 1% PVA&1% PET pulse velocity curve (FT only)

5.6.10 1% PVA&1% PET (with shrinkage exposure) freeze and thaw resistance

No damage was can be found from mass (change within 2%) and pulse velocity loss curve (change within 6%) from as seen in Figure 70 and 71 within 90 cycles. Little damage was visually identified.



Figure 70 1% PVA&1% PET Mass loss curve with shrinkage exposure



Figure 71 1% PVA&1%PET pulse velocity curve after shrinkage exposure

5.6.11 Plain mortar freeze and thaw resistance

Plain mortar specimens are also tested as control specimens, but unfortunately, after 20 to 25 cycles, all specimens had to be removed from the freeze and thaw chamber because of serious damage and the bond dropped to zero. The whole specimen became crumbly and broke into pieces, as shown in Figure 72. Simply compared with all other fiber mixes, plain mortar mix had a poor freeze and thaw resistance.



Figure 72 Plain mortar after 30 freeze and thaw cycles

5.6.12 Plain mortar (with shrinkage exposure) freeze and thaw resistance

Compared to plain mortar without previous shrinkage exposure, specimens after shrinkage exposure could resist more cycles, even though some cracks had developed on the surface as shown in Figure 73. After 50 cycles, however, all three specimens had to be removed as well due to serious damage of much wider crack width and materials peeling off. The detachment appeared after 50 cycles and the bond strength was expected to drop to zero. The bond strength needed to be tested at 30 cycles, to see if it performed better than the specimens without shrinkage exposure.



Figure 73 Plain mortar with shrinkage exposure after 60 freeze and thaw cycles
5.7 Freeze and thaw test results discussion

One of the major limitations in these six series of tests is that only up to 90 freeze and thaw cycles were executed as compared to 300 cycles required by the standard arguably it would be of little significance to test the bond strength after all specimens are seriously damaged. Still, it would be unsafe to simply suppose that all fiber mixes would have good freeze and thaw resistance and durability after 300 cycles dictated by ASTM C666, without performing the test to that point.

However, judging from all freeze and thaw tests done so far, from simply observing the UPV and mass loss data, little or nearly no damage was noted on all EDCC fiber mixes but severe damage was observed in the plain mix. It can be concluded that fiber addition does greatly increase the freeze and thaw resistance, but the impact of freeze and thaw cycles on the bond between the overlay and substrate remains unknown until the bond test is done. The damage caused by freeze and thaw cycles was essentially due to internal cracks induced by the freezing of ice. The fibers appear to help bridge and tighten the cracks and stop crack propagation and augment freeze and thaw resistance. However there is no experimental evidence of such mechanism. The reason could be due to the high air content of EDCC mixes over plain concrete.

6. Bond durability of EDCC

6.1 Introduction

The bond between the repair system and the substrate is reported to be the weakest link, creating many durability problems. When evaluating the durability performance of repair material, one of the most important aspects is the durability of the bond. The bond of this EDCC material is still unknown. As one of the main components of this project, bond performance of EDCC and concrete substrate, after a certain amount of environmental deterioration, is investigated in this chapter.

The widely used bond test is the direct pull-off bond test which is easy and fast to conduct although some limitations do exist. One is due to different failure modes, such as substrate failure and repair failure. Therefore, it is very difficult to ascertain the real interfacial bond strength value through this test. However, by reasonably changing the design of the assembly, the likelihood of ascertaining interfacial failure can be greatly increased. This will be further discussed in this chapter. Based on aforementioned reasons, the pull-off bond test, following the ASTM C1583 was chosen in this testing scheme.

Five EDCC fiber mix repair materials and one plain mix control repair mortar were used for this test. For each mix, four series of bond tests were conducted as: bond without applying environmental deterioration, bond after shrinkage exposure, bond after freeze and thaw exposure and bond after both shrinkage and freeze and thaw exposure. A development curve indicating the relationship between bond strength and freeze and thaw cycles was drawn to determine the bond performance of each mix and by comparing the residual bond strength after deterioration.

6.2 Bond test design

One of the main disadvantages of this pull-off test is that it is very difficult to ascertain the interfacial bond strength because the failure mode cannot be controlled. But in this composite assembly design with a high strength concrete base and an EDCC repair overlay, with a tensile strength exceeding 3MPa, it is expected that most of the failure will occur at the interface. Previous research that was done in this lab by Wang [30] showed that the tensile strength of different EDCC fiber mixes is over 3MPa, as shown in Table 10. In her research, closed-loop pure uniaxial tensile tests were performed on 4 different EDCC fiber mixes.

Mixture ID	First-crack strength, MPa	Ultimate tensile strength, MPa	Tensile strain capacity, %
2% PVA	3.22	4.43	3.89
2% PET	1.42	1.57	0.45
1% PVA	2.54	3.32	0.57
1% PVA&1% PET	3.12	3.78	1.67

Table 11 Tensile strength of EDCC [30]

As discussed in Chapter 5, nearly no damage was identified by the UPV test after up to 90 freeze and thaw cycles, so it is reasonable to assume that the overlay EDCC would retain a certain tensile strength depicted in Table 10.

Based on these arguments, we can be quite confident to expect most of the failure to occur at the interface instead of in the substrate on repair overlay. Actually over 80% of the specimens fail in the interface which is a good indicator of the real bond strength of EDCC and concrete substrate.

6.3 Pull-off test preparation and set-up

6.3.1 Bond test preparation

Each specimen was drilled (with a diamond impregnated bit) with a 40mm deep circular cut, located 10 to 15mm below the interface, as shown in Figure 75. For each specimen, three cores were drilled. The drilling process was carried out in automatic mode, with a very low drilling speed to minimize damage to the interface. It is worthwhile to mention that when the bits were drilled into the substrate, external manual force was needed to help accelerate the process. This is because the drill cannot penetrate into the high strength concrete substrate in automatic mode.

After the cores were drilled, the standing water was removed with a rag, the surface was cleaned of any debris with sandpaper and sample was left to dry. After the surface was cleaned and dried, a 50mm in diameter steel disk was attached to the circular cut with Epoxy (Devcon 2 Ton) and the epoxy was allowed to cure for 24 hours for full strength development.

Some limitations should be noted here, one being that the standard requires the center of the cores to more than one diameter away from the free side of the specimen, unfortunately due to the narrow width of the specimens, there was only a 37.5mm distance from the center to the free side. But the limitation here is not expected to affect the results much.



Figure 74 Bond test coring preparation

6.3.2 Bond test set-up

There were also some other challenges and limitations while conducting the bond strength test on small composite beam specimens. As the beam is only 100mm wide, three legs of the pull-off tester are not able to sit on the beam surface. The test set-up was therefore changed by putting two steel bases on either side of the specimen to extend the surface area so that the pull-off tester was able to sit on the surface in some way. Another challenge was to make sure the tester was leveled before and during the testing until failure. Two clamps were used in this case, to make sure that the surface that the tester was sitting on was leveled, as shown in Figure 76. At the beginning only one clamp was used to stabilize the base on the desk. Two steel bases were just put beside the specimen without clamping them with the specimen. It was found that the tester was always tilting during the testing. By adding the second clamp, the tester could remain leveled during the entire loading process.

The pull-off tester has a circular level on top of the machine itself and another level was used before and during the whole testing process to ensure the machine would remain leveled. Also, some copper shims were cut and inserted between the leg and the specimen to make sure of the levelness.



Figure 75 Pull-off bond test set-up

6.4 Pull-off test bond strength results

A Proceq made DY-216 automated pull-off tester was used. Right after the specimens were are properly prepared, as described in 6.3, the draw bolt of the tester was secured to the test disc and he draw bolt was fitted to the coupling and the test was started. The loading rate was automatically controlled at constant 0.2MPa/s. After each core was tested to failure, the peak load and failure mode was recorded. In each EDCC fiber mix, specimens with and without shrinkage exposure after 30, 60 and 90 cycles were tested and specimens only subject to shrinkage and without any freeze and thaw exposure were then tested and compared. In all curves, series 1 refers to samples after shrinkage exposure and series 2 refers to samples without shrinkage exposure.

6.4.1 1% PVA bond strength

Mix	Cycle	1	2	3	Average	STDV	COV
1% PVA	0	1.70	1.58	1.83	1.70	0.10	5.99%
1% PVA FT_30	30	1.54	1.13	1.32	1.33	0.17	12.60%
1% PVA FT_60	60	1.19	1.38	1.15	1.24	0.10	8.09%
1% PVA FT_90	90	0.83	0.99	1.08	0.97	0.10	10.70%
1% PVA SHK_1	0	2.11	1.51	1.77	1.80	0.25	13.67%
1% PVA SHK FT_30	30	1.70	1.50	1.25	1.48	0.18	12.41%

Table 12 1% PVA bond strength value (Unit: MPa)



Figure 76 1% PVA bond strength degradation curve

6.4.2 1% PET bond strength

Mix	Cycle	1	2	3	Average	STDV	COV
1% PET	0	1.31	1.22	1.88	1.47	0.29	19.88%
1% PET FT_30	30	0.49	0.39	0.44	0.44	0.04	9.28%
1% PET FT_60	60	0.40	0.37	0.35	0.37	0.02	5.50%
1% PET FT_90	90	0.39	0.39	0.26	0.35	0.06	17.68%
1% PET SHK_1	0	1.83	1.60	1.14	1.72	0.29	16.73%
1% PET SHK FT_30	30	0.98	1.38	1.27	1.21	0.17	13.94%
1% PET SHK FT_60	60	0.60	0.64	0.34	0.53	0.13	25.25%
1% PET_SHK_FT_90	90	0.21	0.21	0.21	0.21	0.00	0.00%

Table 13 1% PET bond strength value (Unit: MPa)



Figure 77 1% PET bond strength degradation curve

6.4.3 2% PET bond strength

Table 14 2% PET	bond strength	value (Unit: MPa)	
	bond strength		

Mix	Cycle	1	2	3	Average	STDV	COV
2% PET	0	1.48	1.62	1.18	1.55	0.18	11.84%
2% PET FT_30	30	0.88	0.77	0.69	0.78	0.08	9.99%
2% PET FT_60	60	0.62	0.61	0.51	0.58	0.05	8.56%
2% PET FT_90	90	0.67	0.54	0.60	0.60	0.05	8.81%
2% PET_SHK_1	0	2.02	2.21	2.10	2.11	0.08	3.69%
2% PET SHK FT_30	30	1.52	1.51	1.91	1.65	0.19	11.31%
2% PET SHK FT_60	60	0.68	0.59	0.38	0.55	0.13	22.85%
2% PET SHK_FT_90	90	0.28	0.39	0.28	0.32	0.05	16.38%



Figure 78 2% PET bond strength degradation curve

6.4.4 2% PVA bond strength

Mix	Cycle	1	2	3	Average	STDV	COV
2% PVA	0	2.06	2.02	2.11	2.06	0.04	1.78%
2% PVA FT_30	30	1.84	1.78	1.08	1.57	0.34	22.02%
2% PVA FT_60	60	1.48	1.32	1.42	1.41	0.07	4.69%
2% PVA FT_90	90	1.33	1.37	1.06	1.25	0.14	10.99%
2% PVA FT_SHK_1	0	2.12	1.90	2.10	2.11	0.10	4.71%
2% PVA SHK FT_30	30	2.50	1.44	2.03	2.27	0.43	19.15%
2% PVA SHK_FT_60	60	2.23	1.56	2.37	2.05	0.35	17.22%
2% PVA SHK_FT_90	90	1.64	1.47	1.25	1.45	0.16	10.99%

Table 15 2% PVA bond strength value (Unit: MPa)



Figure 79 2% PVA bond strength degradation curve

6.4.5 1% PVA&1% PET bond strength

Mix	Cycle	1	2	3	Average	STDV	COV
1+1	0	1.60	1.53	1.70	1.61	0.07	4.33%
1+1 FT_30	30	1.76	1.46	1.44	1.55	0.15	9.42%
1+1 FT_60	60	1.73	1.72	2.04	1.83	0.15	8.12%
1+1 FT_90	90	1.29	1.17	1.13	1.20	0.07	5.68%
1+1_SHK_1	0	2.26	1.41	1.10	1.84	0.49	26.72%
1+1 SHK_FT_30	30	2.07	1.51	0.88	1.79	0.28	15.64%
1+1 SHK FT_60	60	1.52	1.49	1.56	1.52	0.03	1.88%
1+1 SHK_FT_90	90	1.19	1.11	1.17	1.16	0.03	2.94%

Table 16 1% PVA&1% PET bond strength value (Unit: MPa)



Figure 80 1% PVA&1% PET bond strength degradation curve

6.4.6 Plain mortar bond strength

Mix	Cycle	1	2	3	Average	STDV	COV
0.00	0	1.96	2.10	1.21	2.03	0.07	3.45%
0%_SHK_1	0	1.70	1.47	1.40	1.52	0.13	8.41%
0%_SHK_1_30	0	1.02	0.99	0.67	0.89	0.16	17.73%

Table 17 Plain mortar bond strength value (Unit: MPa)

6.5 Pull-off test bond strength results discussion

As mentioned before, over 80% of the failures occur at the interface, which makes the results more convincing. It was easily found that the PET fiber EDCC mix had poor bond durability. Although the bond strength was very high before freeze and thaw cycles, it experienced a sudden drop after a certain amount of freeze and thaw cycles. However, for the PVA mixes, even though the bond strength was reduced after a certain amount of freeze and thaw cycles, it still maintained a certain level of bond strength, which indicates better bond durability as compared to the PET fiber mix, as shown in Figure 81 (Series 1: residual bond strength after 90 FT cycles, Series 2: residual bond strength after both shrinkage and 90 FT cycles). As for plain mortar mix after 20 to 50 cycles, specimens did not keep integrity and had to be removed from the chamber. The bond strength dropped to nearly zero, so it has not been drawn in the figure.



Figure 81 Residual bond strength

Interestingly, in all five EDCC fiber mixes, specimens with shrinkage exposure exhibit slightly higher bond strength after freeze and thaw cycles. This is contrary to intuition that specimens with both shrinkage and freeze and thaw exposure would end up with lower bond strength than those only subject to freeze and thaw cycles. Instead of introducing more damage to the bond, the heat applied during shrinkage tests appears to increase the bond. Because shrinkage cracks appeared in the plain mortar mix after shrinkage exposure, the bond strength was much lower than that without shrinkage exposure.

Also, we can appreciate the data of both the plain mix and the fiber mix. Without any shrinkage exposure, actually the plain mix showed very good bond strength of up to 2.03MPa. However, from the durability perspective, the fiber mix was much more durable than the plain mix, especially after the freeze and thaw cycles.

By comparing different EDCC mixes, it was found without a doubt that 2% PVA was the best option, especially in terms of bond durability and 1% PVA&1% PET also performed very close to 2% PVA. When considering the cost of fiber, 1% PVA&1% PET is the best option.

7. Bond performance of sprayed EDCC

7.1 Introduction

EDCC is also designed and optimized for a faster repair placement using the spray process. Due to the high speed of spraying out the materials from the nozzle, EDCC is sprayed and attached to the substrate through pneumatic compaction, unlike normal vibration compaction through hand application. Due to a different compaction method, the bond quality between EDCC and substrate needs to be tested and confirmed. From the cost perspective, the faster process is more economical because it can reduce the labor cost incurred in the process. In this chapter, an experimental test program was conducted by spraying EDCC with 1% PET and 1% PVA fiber onto brick and concrete masonry substrate. The bond was tested after the specimen was cured 5 days in the field and then moisture-cured in the curing room for 51 days. This test also served as a comparative study of the differences between hand application and spraying.

7.2 Spray procedures

Trials were performed before the spray process was finally working. At the beginning, the materials got clogged at the tip of the gun, due to the design of the gun itself. Other factors, such as fresh properties of the EDCC are also important in spray as reflected in the cohesiveness and workability of the material. If the material is too dry, it is unlikely that it will be sprayed from the tip of the gun, but if the material is too flowable, the material will experience a serious sloughing off. So, the workability should be controlled very carefully. The cohesiveness really affects the fiber dispersion, which will have a significant impact on the spray processand prevent the fiber from balling and clogging the gun tip.

After many trials, the spray process was developed and achieved through two different set-ups. One was through the spray machine with the spray gun which was suitable for larger batches and for long trips for material transportation. The other set-up was by using the hopper and the gun itself, which is better for relatively small batches as shown in the photos below.

7.3 Testing set-up

Two different substrates were chosen to be tested - concrete and clay masonry blocks. Due to the high speed of the spray process, when the materials first arrive at the edge of the substrate, an edge effect will influence the quality of the materials in the local area around the edges. So a wood frame was built to eliminate this edge effect, as shown below in Figure 82. Due to higher

efficiency and easier clean-up, the hopper spray method was adopted. The mixing procedure for the large batch was adopted, as well, to ensure that there would be no clogging during the spray process. The surface was pre-moisturized in a similar fashion to the hand application.



Figure 82 Spray set-up

After the specimens were are sprayed and with advance knowledge of the limitations of the bond testing that would occur afterwards, which would require the surface to be leveled, the surface was slightly flattened manually. With the aim of simulating actual field conditions, the specimens were then placed vertically in the lab for another 5 days. After that, the specimens were transferred to the curing room for another 51 days, before the bond tests were conducted. The long curing time is required because of the high volume of fly ash in the EDCC mix gain is slower.

7.4 Specimen coring

After all the specimens were fully cured, the drilling and coring process was performed according to ASTM C1583 standard, in Figure 83. In the brick specimens, all coring was carried out covering the relatively weak mortar joints, as shown in Figure 83. In the concrete specimens, three middle cores were covering weak mortar joints, as shown in Figure 84.



Figure 83 Brick substrate coring layout (right figure source from reference [1])



Figure 84 Concrete substrate specimen coring layout (right figure source from reference [1])

7.5 Spray process and quality control

The spray process was conducted with the hopper and the redesigned spray gun, Figure 85. The amount of materials spraying from the gun could be controlled by the operator himself.

The quality of the spray is mainly determined by two aspects, rebound and sloughing off. In this spray process, very little sloughing off was observed because of the better cohesiveness of the EDCC mix. A reasonable amount of rebound was observed because of the high speed and pressure. It was found that the main component of the rebound was fiber, which may be bad for bond performance and long term durability. A fan was also operating during the whole procedure to help blow away the rebound materials.



Figure 85 Spray process

7.6 Bond strength results

Following the same procedures as in previous bond tests, pull-off tests were carried out in a total of 24 cores drilled within 4 concrete specimens and 18 cores in 3 brick specimens. However, because all EDCC was sprayed onto the substrate, it was fairly difficult to make the surface flat and some of the cores had to be discarded due to the poor surface flatness and difficult to level the machine.

In the concrete specimens, 2 specimens were drilled with 9 cores on each and 2 specimens were drilled with 4 cores on each. For the brick specimens, 3 specimens were drilled with 6 cores on each. Bond strength results are shown in Table 17 and 18. The thickness of the sprayed EDCC was roughly controlled at 30mm to 35mm.

Masonry	1			2	3	4				
	1.01	1.24	0.98	1.12	1.28	1.13				
Bond	1.16	1.04	1.25	1.08	0.87	1.1				
strength (MPa)	0.85	1.33	1.09	1.2						
	0.99	0.91	1.1							
Average		1.09								

Table 18 Concrete specimen bond strength

Brick	1			2	3							
Bond strength (MPa)	1.5	1.7	1.68	1.77	1.75	1.65						
	1.37	1.88	1.65	1.85	1.44	1.72						
	1.47		1.74		1.32							
Average			1.	63		1.63						

Table 19 Brick specimen bond strength

For failure mode, it is found that most of the cores fail in the substrate for brick specimens but fail at the interface for most concrete specimens, as shown below in Figure 86.



Figure 86 Pulled cores

7.7 Bond strength results comparison with hand applied data

As reported in reference [1], the bond strength for hand-applied concrete specimen was 1.52 MPa compared with the findings of 1.06 MPa for sprayed specimens. However, for brick specimens, the hand-applied bond strength was measured at 1.36 MPa, as compared with 1.63 MPa for sprayed specimens. So, a 30% drop happened for concrete specimens but a 20% increase for brick specimens, as shown in Figure 87.



Figure 87 Bond strength comparison with reference [1]

From these data, it can be concluded that the spray process functions better for brick specimens than the concrete specimens. This is further supported by different failure modes for the two substrates.

Possible reasons are listed below:

- (1) The thickness of EDCC on top of the concrete specimens was approximately 5mm thicker than were the brick specimens, which may lead to poorer bond performance. It was also found by Yan [1] thesis that with the increase of the repair thickness, a decrease of bond strength occurred between the repair and substrate.
- (2) Because specimens were sprayed one at a time from brick to concrete specimens, moisture on the masonry surface may have evaporated before it was sprayed which may cause a poorer bond strength.

8. Conclusions and recommendations for future work

This study aims to investigate the durability performance of EDCC as a repair material and to ensure the long-term durability of EDCC in seismic retrofitting applications. Based on the overlay substrate composite assembly to simulate a real in-situ repair scenario, three main durability factors were taken into consideration. These factors were: restrained shrinkage resistance, freeze and thaw resistance and bond strength durability. The author is hopeful that the conclusions drawn from the test results will be helpful for future application of this repair material.

From a strength perspective, unlike traditional fiber reinforced concrete, incorporation of fibers from 1% to 2% by volume in this application, the compressive strength increased by more than 10% and up to at least 45MPa, which suffices for most applications. It is worthwhile mentioning that very rigorous control of the quality of the mix is needed by proper mixing procedures to guarantee the strength.

In terms of restrained shrinkage resistance, as expected, all 5 EDCC fiber mixes survived the harsh and hot extreme exposure for 24 hours and no cracks were observed visually or even under the microscope. However, for the plain mortar without fiber, up to 0.3mm cracks were identified on the surface. It could be concluded that the fiber addition to the matrix really helps increase the shrinkage resistance.

In terms of freeze and thaw resistance, constrained by the limited number of freeze and thaw cycles as compared to the 300 cycles required by the standard and little significance to test the bond strength after all the specimens had been seriously damaged, only 90 cycles were executed on all five different fiber mixes and one plain mix. Even with these limitations, within 90 freeze and thaw cycles, it became quite evident that all fiber mixes showed much better performance than the plain mix. The plain mix specimens had to be removed from the chamber after only 50 cycles, due to very serious deterioration, while all the fiber mixes kept very good integrity after 90 cycles. Also, it was learned from the mass loss curve and pulse velocity degradation curve, that very little degradation and loss were found in all five fiber mixes.

Although all EDCC fiber mixes showed good shrinkage resistance and freeze and thaw resistance within 90 freeze and thaw cycles, the residual bond strength after these environmental exposures remains of interest. The residual bond strength is crucial to ensure the long-term durability of the repair itself. So the pull off bond test was conducted on specimens after the

environmental exposures of shrinkage and freeze and thaw cycles; and on specimens that did not undergo any of these exposures. By comparing the residual bond strength within different fiber mixes and the bond strength degradation with the increase of the number of cycles, the best EDCC mix could be determined. It was found that 2% PVA and 1% PVA & 1% PET hybrid mix showed the highest residual bond strength and it can be said with confidence that both mixes have very good bond durability. But considering the cost differential between the two, the 1% PVA & 1% PET hybrid mix is the best option.

When it comes to the spray process, it was very successful with very little rebound and nearly no material sloughing off. By comparing the bond strength between the hand-applied process and the spray process, it was found that the brick specimen has higher bond strength in the spray process, while the concrete specimen shows a higher strength in the hand-applied process. More experiments need to be performed to further verify this conclusion. Meanwhile, the spray process is expected to increase the material application speed to further reduce potential high labor cost.

For future recommendations, more specimens should be tested to 300 freeze and thaw cycles to investigate the real freeze and thaw resistance of different EDCC fiber mixes. In the spray process, a better thickness control of the overlay needs to be found. This study found that the thickness affects the bond strength between the overlay and substrate because of the poor compaction in thick overlays. More durability indicating properties, such as chloride diffusion, permeability, soptivity etc. should be assessed to further validate the good durability performance in full manners.

References

[1] Yuan Yan (2016). Investigation into bond strength between EDCC/masonry, MASc thesis – University of British Columbia, Vancouver Canada

[2] "ASTM C666 / C666M – 15, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing), ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C0666_C0666M-15, www.astm.org."

[3] Gupta R (2008). Development, application and early-age monitoring of fiber-reinforced 'crack-free' cementbased overlays, PhD Thesis – University of British Columbia, Vancouver Canada

[4] "ASTM C1583 / C1583M-13, Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method), ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/C1583_C1583M-13, www.astm.org."

[5] Banthia N, and Nandakumar N (2003). Crack growth resistance of hybrid fiber reinforced cement composites, Cement and Concrete Research 25, pp 3-9

[6] ACI evaporation nomograph, ACI 305R-96, 1996

[7] Miroslaw Grzybowski, and Surendra P. Shah (1990). Shrinkage Cracking of Fiber Reinforced Concrete, Materials Journal 87-2, pp138-148

[8] Wang, Y., Wu, H., and Li, V. (2000). "Concrete reinforcement with recycled fibers." J. Mater. Civ. Eng., 10.1061/(ASCE)0899-1561(2000)12:4(314), 314-319.

[9] Hwai-Chung Wu, Yun Mook Lim, V. C. Li (1996). "Application of recycled tyre cord in concrete for shrinkage crack control" Journal of Materials Science Letters 15-20, pp1828-1831

[10] Miroslaw Grzybowski, and Surendra P. Shah (1990). "Shrinkage Cracking of Fiber Reinforced Concrete" Materials Journal 87-2, pp 138-148

[11] ASTM C1581 / C1581M - 09a, Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage, ASTM International, West Conshohocken, PA, 2009, DOI: 10.1520/C1581_C1581M-09A, www.astm.org."

[12] Banthia N, Yan C, and Mindess S (1996); Restrained shrinkage cracking in fiber reinforced concrete: A novel test technique, Cement and Concrete Research 26-1, pp 9-14

[13] Banthia N, and Gupta R (2006); Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete, Cement and Concrete Research 36, pp 1263-1267

[14] Banthia N, and Gupta R (2009); Plastic shrinkage cracking in cementitious repairs and overlays, Materials and Structures 42, pp 567-579

[15] Concrete by Sidney Mindess and J. Francis Young. Prentice-Hall, Inc., Englewood Cliffs, NJ 07632

[16] Y. Li, B.W. Langan, and M.A. Ward (1994), in High-Performance Concrete, ed. V.M. Mahhorta, SP-149, American Concrete Institute, Detroit, MI, pp. 545-560

[17] Y Li, BW Langan, MA Ward (1994), Freezing and thawing: comparison between non-air-entrained and airentrained high-strength concrete, Special Publication

[18] M. D. Cohen, Y. Zhou, and W. L. Dolch (1992). "Non-Air-Entrained High-Strength Concrete--Is it Frost Resistant?" Materials Journal 89-4 pp 406-415

[19] Victor C. Li, Shuxin Wang and Cynthia Wu (2001). Tensile Strain-Hardening Behavior of Polyvinyl Alcohol Engineered Cementitious Composite (PVA-ECC). Materials Journal 98-6 pp 483-492

[20] Victor C. Li (2003). On engineered cementitious composite (ECC) A review of the material and its applications. Journal of advanced concrete technology Vol.1, No. 3, pp 215-230

[21] Gregor Fischer and Victor C. Li (2002). Effect of Matrix Ductility on Deformation Behavior of Steel-Reinforced ECC Flexural Members under Reversed Cyclic Loading Conditions. Structural Journal 99-6 pp 781-790 [22] Mo Li and Victor C. Li (2006). Behavior of ECC/Concrete Layer Repair System Under Drying Shrinkage Conditions. Proceedings of ConMat 2006

[23] Jun Zhang, Yuan Gao, Zhenbo Wang (2013). Evaluation of shrinkage induced cracking performance of low shrinkage engineered cementitious composite by ring tests. Composites Part B: Engineering Volume 52 pp 21-29

[24] Mustafa Şahmaran, Mohamed Lachemi, Khandaker M.A. Hossain, Victor C. Li (2009). Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. Cement and Concrete Research 39-10 pp 893-901

[25] Victor C. Li, G. Fischer, Y. Kim, M. Lepech, S. Qian, M. Weimann and S. WangDurable (2003). Link Slabs for Jointless Bridge Decks Based on Strain-Hardening Cementitious Composites, Research Report RC-1438

[26] VC Li, M Lepech (2004), Crack resistant concrete material for transportation construction, Journal of Pavement Research and Technology

[27] M Şahmaran, E Özbay, HE Yücel, M Lachemi (2013). Frost resistance and microstructure of Engineered Cementitious Composites: Influence of fly ash and micro poly-vinyl-alcohol fiber. Cement & Concrete Composites volume 34 pp 156-165

[28] Shuxin Wang and Victor C. Li (2007). Engineered Cementitious Composites with High-Volume Fly Ash. 104-M25

[29] En-Hua Yang, Yingzi Yang, and Victor C. Li (2007). Use of High Volumes of Fly Ash to Improve ECC Mechanical Properties and Material Greenness. 104-M68

[30] Qiannan Wang, BANTHIA Nemkumar, SUN Wei (2013). Development of engineered cementitious composite with non-oiled polyvinyl alcohol fibers and natural sand. FIBER CONCRETE 2013

[31] Yun Yong Kim, Hyun-Joon Kong, and Victor C. Li (). Design of Engineered Cementitious Composite Suitable for Wet-Mixture Shotcreting. 100-M59

[32] A. Momayez, M.R. Ehsani, A.A. Ramezanianpour, H. Rajaie (2005). Comparison of methods for evaluating bond strength between concrete substrate and repair materials. 35-4 pp 748-757

[33] CEB-FIP MODEL CODE 2010. First complete draft – volume 1. Bulletin 55. In: Comité Euro-International du Béton. Secretariat permanent. Case Postale 88, CH-1015 Lausanne, Switzerland; 2010.

[34] S. Austin, P. Robins, P. Youguang (1999). Shear bond testing of concrete repairs. Cem. Concr. Res., 29 pp. 1067 - 1076

[35] Cristina Zanotti, Nemkumar Banthia, Giovanni Plizzari (2014). A study of some factors affecting bond in cementitious fiber reinforced repairs. Volume 63 pp 117-126

[36] Mahmood Naderi (2008). Effects of Cyclic Loading, Freeze-Thaw and Temperature Changes on Shear Bond Strengths of Different Concrete Repair Systems. The Journal of Adhesion 84-9 pp 743-763

[37] ICRI (International Concrete Repair Institute). Selecting and specifying concrete surface preparation for sealers, coatings, and polymer overlays. Technical Guideline No. 03732, Des Plaines, IL; 1997.

[38] Pedro M.D. Santos, Eduardo N.B.S. Júlio (2013). A state-of-the-art review on roughness quantification methods for concrete surfaces. Volume 38 pp 912-923

[39] ENBS Julio, FAB Branco, VD Silva (2004). Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface. 18-9 pp 675-681

[40] Pedro M.D. Santos, Eduardo N.B.S. Júlio, V1'tor D. Silva (2007). Correlation between concrete-to-concrete bond strength and the roughness of the substrate surface. 21-8 pp 1688-1695

[41] Garbacz, A., Gorka, M., Courard, Luc (2005). Effect of concrete surface treatment on adhesion in repair systems. Magazine of Concrete Research 57-1 pp 49-60

[42] "ASTM C39 / C39M-15a, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C0039_C0039M-15A, www.astm.org."

[43] ASTM C127 – 15, "Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C0127-15, www.astm.org."

[44] ASTM C597 – 16, "Standard Test Method for Pulse Velocity Through Concrete, ASTM International, West Conshohocken, PA, 2016, DOI: 10.1520/C0597-16, www.astm.org."

[45] ASTM C143 – 15A, "Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM International, West Conshohocken, PA, 2016, DOI: 10.1520/C0143_C0143M-15A, www.astm.org."

[46] ASTM C231 / C231M – 14, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method, West Conshohocken, PA, 2016, DOI: 10.1520/C0231_C0231M-14, www.astm.org."