EVALUATING THE BOND STRENGTH OF DIFFERENT REPAIR MATERIALS UNDER HARSH ENVIRONMENTS

by

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EVALUATING THE BOND STRENGTH of REPAIR MATERILS UNDER HARSH ENVIRONMENTAL LOADING

Master of Engineering, 2017

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When considering aging infrastructure, repair paths are often taken as a cheaper solution to extend the life the structure. Repair materials are selected for their sustained capacity to withstand the load. This study evaluated the durability of repair materials, based on the principles of engineered cementitious composites against traditional concrete mixes. The durability of the repair materials was evaluated through a comprehensive testing regime which evaluated the performance of the materials in isolation as well as in combination with a prescribed substrate. While the SCM based repair mixes withstood durability tests comparability and did outperform the reference concrete, the improvement wasn't significant enough to justify the costs associated. The slant shear method may not be the optimal way to measure bond strength as a valid result is greatly dependent on the ratio of bond to compressive strength for the mix in question. Additional testing is recommended.

Acknowledgments

I owe the success of this work, and my success in the industry, to the mentorship of Dr. Shehata. It all started in the third year of my undergraduate degree at Ryerson when he introduced me to this world inside of concrete that I didn't know existed and yet would somehow shape the rest of my life. Ever since he introduced me to this complex puzzle that is concrete Dr. Shehata continually provided me every opportunity to further explore this subject outside of the bounds of the classroom and extended his support into my professional life.

I am also deeply indebted to my supervisor at Canada Building Materials, Philip Zacarias, for his support and mentorship. I would not have been able to complete this thesis, while working fulltime, without him. His fairness as a manager, as well as his guidance as an experienced materials scientist, allowed me to develop both professionally and academically as I grew to learn the practical side of this fascinating material that Dr. Shehata introduced me to all those years ago. I have never meet a more meticulous individual and I will forever be a better engineering professional because of it.

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Chapter 1

Introduction and Objectives

1.1 – Introduction and Significance

As infrastructure begins to reach a critical age, the concrete supporting the structure requires considerable maintenance in order to prolong the ability of that infrastructure to remain in working order. A typical repair strategy involves removing the damaged concrete section and provide a concrete based patch. The primary function of the patch will simply be to protect the steel reinforcement from further deterioration. Furthermore, if the cause of the repair was the result of some chemical attack due to environmental exposure conditions, the repair will have to withstand the same exposure, lest additional repair be required.

Engineered cementitious composites (ECC's) are a new generation of highly durable concrete, capable of withstanding considerable amounts of strain. In addition to their "self-healing" properties which have been well documented [3 to 9], their dense micro-structure makes them considerable durable. While a significant amount of research has gone into evaluating the structural capabilities of this material, their potential to be used in repair applications has not been well explored. Given the durable nature of the material, its potential for repair applications seems quite logical. To have a repair material which not only has the structural capacity to transfer load, but also to withstand the chemical and/or physical attacks which result from the environmental exposure of the structure, would be highly beneficial.

One potential downfall, however, which must be considered if the application of choice is commercial repair, must be the cost of the product. Given the high content of cementitious material in a typical ECC mix, the end result would be quite costly. Therefore, the attempt to reduce the cost can be explored by way of SCM substitution as the cost of blast furnace slag, are quite less than that of Portland cement, and its availability in Ontario is higher that that of low-calcium fly ash. The compromise that would then have to be considered is the balance between performance and cost of the final product.

1.2 – Research Objectives

The first phase of this research program will be to evaluate the physical properties of the conventionally accepted fly ash-based ECC mix. However, the ECC mix used contain normal concrete sand and readily available SCM in an attempt to reduce the cost of the product. While the inspiration of the program is in understanding the interface of ECC with conventional concrete, the focus of this program is in the

interface of the two material, rather than in the materials themselves. As the performance of this interface is a result of the paste content and strength of the two materials, the type of sand used may be irrelevant. The success of a proposed repair material lies in the cost of the material, in as much as it does its performance. Thus, if similar interface performance can be achieved through the selection of a cheaper and more commonly available sand, then it is logical to do so. Therefore, the performance of the Fly Ash based high cement content mix used as the bench mark of this program will be compared to the documented performance of that same mix used with silica sand to determine what sort of performance trade-offs the change in sand provides.

While the testing regime will determine the fresh and hardened properties of the candidate material, a modified slant shear test, using the referenced normal concrete as a baseline, will be used to measure the bond strength at various ages under ideal curing conditions as well as through exposure to freeze/thaw cycles. The development of a modified version of the slant shear test was required as the slant shear test provided by ASTM C882 pertained specifically to the evaluation of epoxy resins to a concrete substrate. Additional modifications to the established procedure were also done to expand the scope of testing to determine the effects of exposure to harsh enviroments. A measure of the durability of the interface can be then evaluated by comparing the bond strength gain under ideal curing condition and that of the bond strength after the freeze/thaw cycles. This phase of testing will also include; the evaluation of a comparably designed slag mix to understand the how the use of a more commonly available supplementary cementing material will compare, the use of the same normal concrete mix as a baseline, and the use of a commercially available repair mix to understand what the performance requirements are for such a product.

The second phase of the program will focus on the performance characteristics provided by varying levels, and types of supplementary cementing materials. Once the performance baselines have been established by the first phase, a parametric study can be completed to optimize some new candidate repair materials with respect to both performance and cost.

1.3 – Outline of Thesis

1. Chapter 1 introduced the disconnect present in modern day concrete research and the need to understand the durability of novel structural applications which use composite materials and how the end performance of those applications can be compromised if the interface between

those materials is not properly evaluated. It further outlines the significance of this research as well as the objectives and different phases of this thesis.

2. Chapter 2 will be an in depth literature review that summarizes and critiques the current body of research in the applicable topics. The topics to be covered are the use of concrete as a repair material, the application and development of ECC's, the performance of the material interface, and the durability issues stemming from environmental exposure. The goal of chapter 2 is to provide relevant background information to illustrate the noted gap in research and to be justify the materials and testing programs implemented in this study.

3. Chapter 3 will summarize the experimental details and materials used in this thesis. Detailed summaries of all test methods are presented here. The goal of this chapter is to outline the test methods and the modifications applied to them.

4. Chapter 4 will present and discuss the results obtained. Each phase of testing will be presented and thoroughly analyzed, well as any models derived from those results. The goal of this chapter is to present and to analysis the results such that conclusions can be drawn.

5. Chapter 5 will present the conclusions of this thesis. The conclusions drawn from each phase of testing will be listed, as well as the overall conclusions for the thesis. Recommendations will then be made which suggest areas for future work that may not have been sufficiently covered by this report.

6. Chapter 6 is a list of the references which were used in this report.

Chapter 2

Literature Review

2.1 – ECC as a Repair Material

Lim and Li [30] investigated the potential for ECC's to be used as a repair material. As the failure of structural concrete members tends to be being via surface cracking, as a result of stresses such as creep, along with deterioration due to various environmental elements, a repair material which exceptional strain resistant properties would be ideal. As noted in section 2.2, ECC's exhibit such properties and, as such, provide a logical candidate for a repair material. This was confirmed in laboratory experiments where the ECC repair system was found to be stronger, more ductile, more energy absorbing and showed better crack control than a typical fiber reinforced concrete repair material.

Kamada and Li [31], followed this application and considered the bonding of ECC, as a repair material, to that of the original concrete. Surprisingly, it was found that the performance of the repair system was improved when the concrete substrate material was sanded down to produce a "smooth surface" as opposed to a "rough" surface. This is presumed to be a function of the high interface fracture toughness of a rough surface which makes it difficult to develop interface cracks. This forces the microcracks to develop into fractures.

2.2 – Development and Applications of ECC

2.2.1 – Composition, Properties, and Mix Methodology

Concrete is a diverse material, having its far-reaching applications extended over the past decades as technological advances are made. However, the main drawback of the material for structural applications has always been its poor performance under tensile stresses. As a result, many new technologies in the development of higher performing composite materials has given way to engineered cementitious composites (ECC's). ECC's draw on the principles of micromechanics-based design theory, in that through an understanding of the material interactions, or matrix, on a microscopic level, the inherent weaknesses such as the materials can be minimized. As such, the design of the material tailors towards the creation of a strain hardening material which can provide resistance against tensile strain in a capacity far superior to typical concrete. [1]

A property of ECC's, which lend itself well to be viewed as a repair material, is its ability to promote autogenous healing. Because of the high ductility, multiple microcracks can develop along the surface of the concrete without its ability to resist stress being depleted. So long as there is moisture in the surrounding environment, water can enter these small cracks and react with any unhydrated cement particles to form new hydration products, thus repairing the damaged matrix. Yang et al [3] investigated this phenomenon and showed that ECC's, when tailored for high tensile ductility up to seven percent and with a self-controlled crack width below 60 microns, the autogeneous healing will occur so long as moisture is present in the environment. However, it was found that the recovery rate for samples older than 90 days was faster than samples less than 3 days. Wu et al [4] expanded on this work and proposed various strategies to promote self-healing. The use of hollow fibers, or high porosity aggregates, provides an internal source of moisture that the cement matrix can draw from. The idea of an internal water source is not a new idea as there has been much research on the performance benefits as a result of extended curing [5-8]. Qian et al [9] focused on the influence of curing conditions, as an indicator for self-healing ehavior. Samples where cured under different conditions; air curing, CO_2 curing, wet/dry cycles, and water curing. It was found that for all curing conditions, deflection capacity can be improved beyond its original, pre-cracked, performance. Flexural strength was also found to increase for samples pre-cracked at the age of 14 days, likely due to the continued formation of hydration products, even without an available external water source.

As the superior ductility of the concrete is primarily a function of the fiber-matrix interaction, it would follow that improving that matrix would improve the performance of the concrete. ECC's are typically produced using polyvinyl chloride (PVC) fibers which, due to static charges, can lead to clumping among fibers during mixing which can lead to poor fiber distribution and, ultimately, poor material performance. Zhou et al [10], supported by Boulekbache et al [11], sought to develop a mixing technique aimed at improving the fiber distribution in a typical ECC mix. The standard mixing methodology generally follows that water is added to aggregate to ensure the aggregate reaches a surface saturated state. The cement is then added, which reacts with the available water to produce the paste. Superplasticizers and other viscosity modifying admixtures can then be added to improve the workability of the blend. At this point fibers can be added and mixed until adequate distribution is achieved. Despite this accepted methodology, it was found that by adjusting the sequence to split the addition of the solids and liquids into two steps, separated by the addition of fibers. By comparing identical mixes, only distinguishable by their unique mixing sequences, it was found that samples produced using the alternate method exhibited better fiber distribution which resulted in improved

tensile strain capacity and an increase in ultimate tensile strength. These improvements where found to be further increased in mixtures where the ratio of water to superplasticizer was increased.

Sahmaran et al [12] sought to further improve upon the issue of fiber distribution and to create an optimized mix whereby the workability was perfectly tailored to promote the distribution of fibers. Through the testing of a variety of material proportions it was found that the water to binder, sand to binder and suplasticizer to binder ratios have considerable effect on the rheology of the mix and were found to be optimized at 0.27, 0.36 and 0.303, respectively. It was also found that the max aggregate size had no significant influence on the rheological properties.

2.2.2 – Influence of Fibers

Although ECC's are typically produced using PVC type fibers, polypropylene (PPE) and polyvinyl alcohol (PVA) type fiber are also commonly used in different concrete applications. Felekoglu et al [13] and Zhang and Zhao [14] experimented with these fiber types in order to determine their effect on the mechanical performance of concrete. Both fiber types were shown to enhance flexural strength material durability. However, it was found that the frictional bond between the fiber and cement paste was found to play a critical role in determining performance. As PVA fibers have a relatively rougher surface, they were found to outperform the PPE based fibers. Neither fibre was found to have any significant effect on compressive strength. Ding et al [15] furthered this investigation by subject concrete samples reinforced with PPE fibers to high temperatures. The enhanced durability provided by the PPE fibers was able to resist the extreme thermal effects and mitigate spalling in the concrete.

In an effort to promote sustainability Meddah and Bencheikh [16] investigated the performance of waste fibers in concrete by recycling the fibers from PPE storage bags. By combining these fibers in varying lengths and amounts, it was shown that the waste fibers still had the ability to enhance the durability and flexural toughness of the concrete up to levels comparable to manufactured fibers.

2.2.3 – Structural Applications

Maalej et al [2] reviewed the potential structural applications of ECC's. The uniqueness of the material lies in its ability to exhibit pronounced tensile strain hardening which is primarily a function of the fibers interacting so completely within the cement matrix. This allows for high tensile strain capacity, especially under uniaxial tension. A weakness of steel reinforced concrete is the event of corrosion as caused by water seeping into the concrete through surface cracks, which then attacks the steel. Therefore, the ability to have a concrete structure resistant to surface cracks would provide a great

advantage. If ECC's are considered as this material, or even as a material to be applied to the surface of the substrate concrete, requirements for low crack width and high strain capacity needed. By modifying the fiber – matrix structure using a hybrid system of PVA and PE fibers, the structural performance is enhanced and, when used as a repair material, the bonding to the substrate concrete is improved.

2.3 – Material Interface and Bonding Capacity

2.3.1 – Interfacial Transition Zone

The development of cement paste through the joining of cement particles and water is a chemical bond which is characterized by its mechanical ability to hold aggregates together. This ability, however, is affected by the physical properties of the aggregate in question. Rao and Prasad [17], along with Elsharief et al [18] investigated the physical properties of specific aggregates to understand their effect on bond strength between the aggregate and paste. A rougher surface was found to produce a better bond strength as the specific surface area of the aggregate was greater, allowing for more exposure to the cement paste. Similarly, it was found that reducing the aggregate size provides improved performance in the interfacial transition zone, as there is a reduced wall effect.

2.3.2 – Effects of Supplementary Cementing Materials

Manipulation of the cement paste structure also provides opportunities for improving the bond between aggregate and paste. Kuroda et al [19] and Wong et al [20] investigated the effects of a fly-ash modified cement mortar and its effects on bond strength. A weakness inherent in concrete as a structural material is the interfacial transition zone which develops between the surface of the aggregate and the paste. This zone is characterized by unhydrated cement particles and presence of calcium hydroxide crystals. As fly ash is a pozzolonic material, its ability to consume calcium hydroxide makes it an ideal solution to this weakness, creating a stronger bond. The subject then is to determine the optimum replacement level. The pozzolonic reaction of fly ash is far slower than the hydration of cement. Although replacement levels of up to 25% have no significant performance effects, high replacement levels show improved performance of flexural strength and fracture toughness past 90 days. However, prior to this time, their performance was less than that of a pure cement mix. Keeping this is in mind, Sahmaran and Li [21] studied ECC's containing high volumes of fly ash. Considering the relatively slow reaction of fly ash, Sahmaran and Li produced samples containing replacement levels of 55% and 70% by weight of total cementing material. Even at such high level, the durability and

mechanical properties of the concrete were not significantly reduced, however the increase of fly ash was found to have a negative effect on the transport properties of the material at early ages.

Zhu et al [22] and Chen et al [23] sought to improve the use of fly ash in ECC's through the incorporation of ground granulated blast furnace slag (GGBFS). As a recycled byproduct from the manufacturing of steel, GGBFS has been used in concrete as a supplementary cementing material, providing higher strength and improved ductility in sustaining high amount of strain. It was found that the inclusion of GGBSF in fly ash based ECCS provided considerable improvement in compressive strength at early ages, as well as reducing drying shrinkage. Specifically, ECC mixtures containing 30% GGBSF and 40% fly ash was found to be an optimal level in reducing drying shrinkage at later ages.

Another pozzolonic material which has shown considerable potential in enhancing the performance of concrete materials is metakaolin. Janotka et al [24] investigated the influence of metakaolin on the rheology, hydration and mechanical properties of concrete. It was found that addition of metakaolin improves the durability of the concrete as the resulting denser pore structure decreases the diffusion of harmful ion leading to the deterioration of the cement matrix. These results have been supported by Ramezanianpour and Jovien [25], through their investigations on the influence of metakaolin on the durability of concrete. On the subject of using this product as a replacement of sand versus a replacement of cement, it was found that as a sand replacement, strength gains were found for all ages up to 90 days. However, as a cement replacement, strength gains were evident after 2 days. Overall, the highest compressive strength was achieved using 10% cement substitution. This property is a result of the highly pozzolonic nature of the material, even higher than that of silica fume. Tafraoui et al [26] found that, compared to silica fume, metakaolin has almost equivalent performance improvements in terms of both mechanical properties and durability. This is confirmed by the review Siddique and Klaus [27] complied on the influence of metakaolin. Karahan et al [28] and Kim et al [29] further studied the effects of this material, although choosing to focus on the interaction with the aggregate type. The results of their work falls in line with studies previous performed in this area.

Chapter 3

Experimental Details and Materials

3.1 – Material

For the mix designs used in this study, the physical parameters are provided for both the aggregate and cementing materials used. This study also dealt with a commercial repair mix. However, as that is a proprietary mix, no material information is provided.

3.1.1 – Aggregate

The material properties for the course and fine aggregate used in this study can be found in Table 3.1. The sieve analysis is shown in figures 3.1 and 3.2.

Material	Description	SSD Density (kg/m3)	Absorption (%)
Fine Aggregate	Concrete Sand	2685	0.5
Course Aggregate	19mm Crushed Limestone	2710	1.5

Table 3.1: Aggregate Data
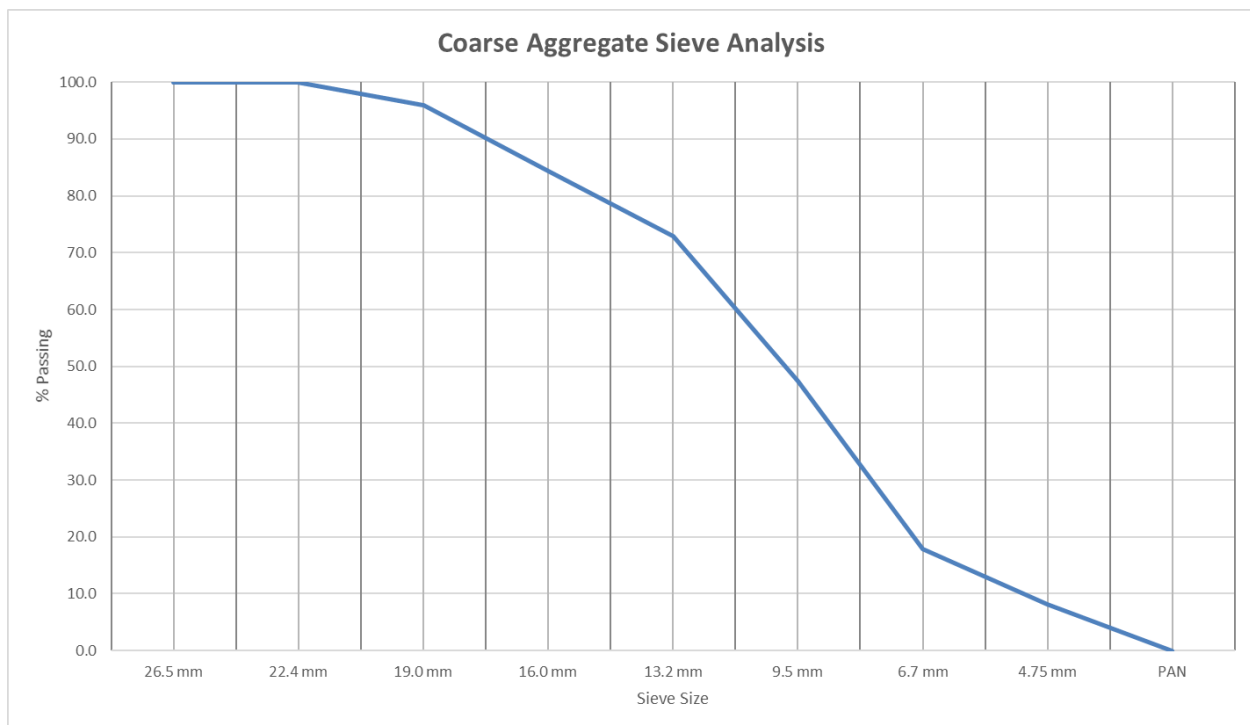
Figure 3.1: Course Aggregate Sieve Analysis
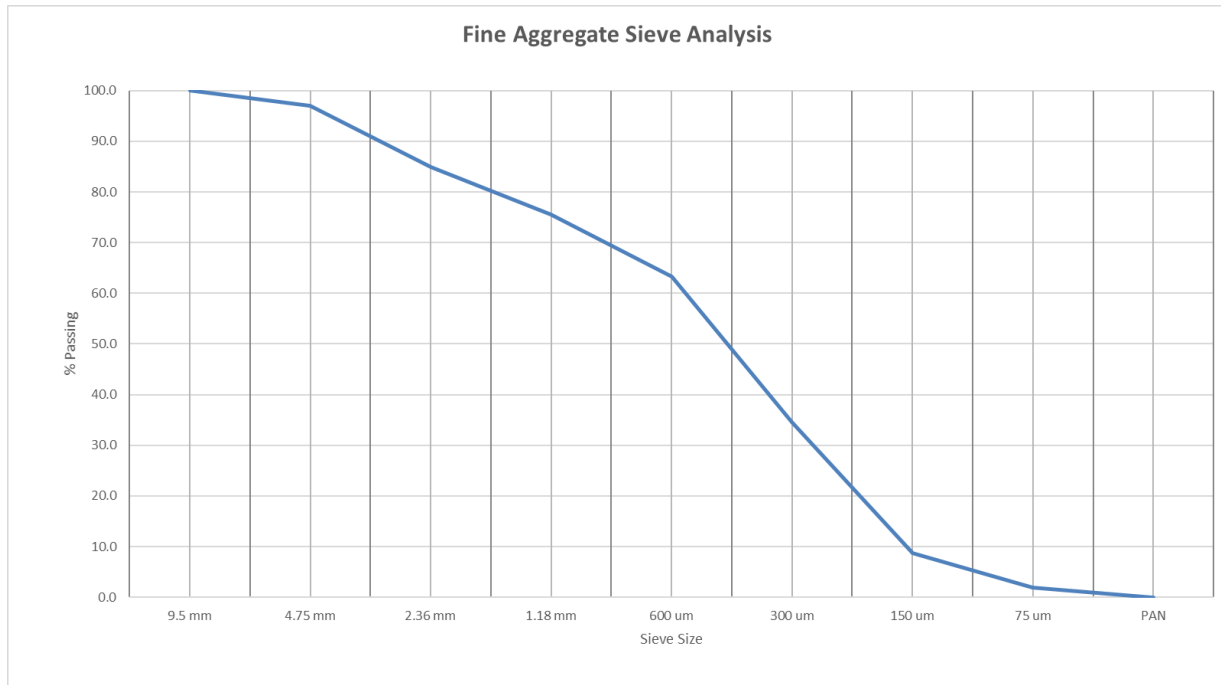
Figure 3.2: Fine Aggregate Sieve Analysis

3.1.2 – Cementing Materials

Chemical and physical data for the cementing materials used in this study are summarized in Table 3.2.

	Portland Cement	Slag	Fly Ash
Physical Density	3150 kg/m^3	2920 kg/m^3	2450 kg/m^3
Fineness (Blaine SA)	382 m^2/kg	519 m^2/kg	
Retained on 45μm Sieve	3.0%	1.02%	24.6%
Loss on Ignition	2.8%		0.59%
Vicat Initial/Finial	133 min / 246 min		
SiO$_2$ Content	19.1%		57.0%
Fe$_2$O$_3$	3.14%		3.5%
SO$_3$	3.51%	2.02%	0.1%
CaO	61.9%		9.5%
AL$_2$O$_3$	5.1%		23.4%
Total Alkali as Na$_2$O Equiv.	0.99%	0.77%	2.89

Table 3.2: Summary of Chemical and Physical Data for Cementing Materials

3.2 – Mix Designs

The designs for the mixes included in this study are summarized in Table 4.4. Proportions shown assume aggregates in saturated surface dry (SSD) condition. Exact proportions required prior to batching were adjusted based on actual moisture content of aggregates.

	C1 Substrate / C1 Repair	Repair Mixes		
		55% Slag	55% Fly Ash	Com. Mix
Target Air Content	5% - 8%	0% - 5%	0% - 5%	
Water to Cement Ratio	0.375	0.270	0.270	Material Data Not Known
Total Cement Content (per m3)	400 kg	1254 kg	1254 kg	
Portland Cement Content (per m3)	260 kg (65%)	569.94 kg (45.45%)	569.94 kg (45.45%)	
Slag Content (per m3)	140 kg (35%)	684.06 kg (54.55%		
Fly Ash Content (per m3)			684.06 kg (54.55%	
Coarse Aggregate Content (per m3)	1072.37 kg			
Fine Aggregate Content (per m3)	708.32 kg	540.27 kg	540.27 kg	
Fiber Content (% of total volume)		2%	2%	
Plasticizer Dosage (mL/100kg of cement)	300	305	325	
Air Entrainer Dosage (mL/100kg of cement)	12			
Target Slump (mm)	120 +/- 30	180 +/- 30	180 +/- 30	
Target Density (kg/m3)	2330.69	2158.86	2038.34	

Table 3.3: Summary of Mix Designs

3.3 – Mixing Procedure and Methodology

This study deals with two classes of cementitious material content; substrate (the more standard stand/stone mixes) and repair (ECC based mixes). Due to such a large discrepancy between the material proportions between the two classes of cementitious materials being mixed, two separate mixing produced have to be employed for each. All mixes were batched using a shear type mixer.

3.3.1 – Substrate Mixes

The mix in the substrate category was intended to represent a typical concrete mixture as produced for outdoor exposure in the specified climate.

Step	Instructions	Time to complete	Total Elapsed Time
0	Material Preparations Prior to batching aggregate should be pre-soaked and homogenized such that the moisture content is greater than the absorption. The mix design is proportioned under SSD conditions. Aggregate is then put into pails, not exceeding a combined mass of 25kg per pail. Lids should be placed on each bin to prevent moisture loss as a result of evaporation.	Unspecified	Unspecified
1	Fine Aggregate Addition Add all fine aggregate in mixing bowl Add 5% to 10% of the design water to the mixing bowl Start the mixer	Unspecified	Unspecified
2	Air Entrainer Once the mixer has started, allow 30 seconds for the fine aggregate and water to mix While the mixer is operational, slowly disperse the required amount of air entrainer into the sand/water slurry and allow an additional 30 seconds for the optimal dispersal of the additive Stop the mixer	60 seconds	60 seconds
4	Cementitious Materials and Coarse Aggregate Place all of the cementitious material into the mixer then place all of the coarse aggregate on top of the cement. Add 40% to 45% of the design water to the mixing bowl Start the mixer. The timer is reset to when the water is added to the mixing bowl	30 seconds	1 minute 30 seconds
5	Initial Mix Allow an initial mixing period of 30 seconds. Add the remaining design water over a period of 30 seconds. Allow an additional mixing period of 3 minutes after all the design water has been added.	4 minutes	5 minutes 30 seconds
6	Super Plasticizer While the mixer is still activated, add the super plasticizer to the mixing bowl Allow a period of 2 minutes for the admixture to disperse	2 minutes	7 minutes 30 seconds
7	Resting Period Stop the mixer and allow a 2 minute rest period. During this time, scrap off any dry material which may have built up in the mixing bowl or around the shear blades of the mixer.	2 minutes	9 minutes 30 seconds
8	Final Mix After the rest period has ended, start the mix and allow for the a final mixing period of 1 minute and 30 seconds	1 minute 30 seconds	11 minutes

Table 3.4: Batching Procedure for Substrate Mixes

3.3.2 – Repair Mixes

The mixes in the very high cement content represented the candidate repair compounds. Due to the very high content of cementitious materials, very low water to cement ratio, and a high proportion of fibers, a revised mixing procedure had to be employed.

Step	Instructions	Time to complete	Total Elapsed Time
0	Material Preparations Prior to batching aggregate should be pre-soaked and homogenized such that the moisture content is greater than the absorption. The mix design is proportioned under SSD conditions. Aggregate is then put into pails, not exceeding a combined mass of 25kg per pail. Lids should placed on each bin to prevent moisture loss as a result of evaporation.	Unspecified	Unspecified
2	Fine Aggregate Addition Add all fine aggregate in mixing bowl Add 5% to 10% of the design water to the mixing bowl Start the mixer	Unspecified	Unspecified
3	Air Entrainer *If the mix design does not include air entrainer, proceed to the next step* Once the mixer has started, allow 30 seconds for the fine aggregate and water to mix While the mixer is operational, slowly disperse the required amount of air entrainer into the sand/water slurry and allow an additional 30 seconds for the optimal dispersal of the additive Stop the mixer	*0 seconds* 60 seconds	*0 seconds* 60 seconds
4	Cementitious Materials Place all of the cementitious material into the mixer. Add 40% to 45% of the design water to the mixing bowl Start the mixer. The timer is reset to when the water is added to the mixing bowl	30 seconds	1 minute 30 seconds
5	Initial Mix Allow an initial mixing period of 30 seconds. Add the remaining design water over a period of 30 seconds. Allow an additional mixing period of 3 minutes after all the design water has been added.	4 minutes	5 minutes 30 seconds
6	Super Plasticizer While the mixer is still activated, add the super plasticizer to the mixing bowl Allow a period of 2 minutes for the admixture to disperse	2 minutes	7 minutes 30 seconds
7	Resting Period	2 minutes	9 minutes

	Stop the mixer and allow a 2 minute rest period. During this time, scrap off any dry material which may have built up in the mixing bowl or around the shear blades of the mixer.		30 seconds
8	Fiber Addition Add of the fibers into the mixing bowl Start the mixer and allow for a mixing period of 1 minute and 30 seconds to allow the fibers to disperse into the slurry Stop the mixer	1 minute 30 seconds	11 minutes
9	Final Mix In a shear mixer, fibers may have the tendency to clump in the middle even after a prolonged mixing period. If this observed, use a scoop to manually disperse the clump to the outer edges of the mixing bowl. Allow a final mixing period of 1 minute to ensure optimal dispersion.	1 minute	12 minutes

Table 3.5: Batching Procedure for Repair Mixes

3.3.3 – Design Adjustments

After completing the mixing procedure for either the normal or the very high cement class, the fresh concrete may not have meet the slump specifications for the design. If, after performing a slump cone test on the mixed product, the achieved slump falls outside of the design value then adjustments to the mix can be made. Of course, if the achieved slump is greater than the upper limited of the specified range, then the concrete must be discarded. However, if the achieved slump is less than the lower limit of the specified range, then an additional mixing procedure may be implemented.

Step	Instructions	Time to complete	Total Elapsed Time
10/11	Slump Correction Making an educated estimate, add some amount of superplasticizer to the concrete in the mixing bowl. Start the mixer. Allow for an additional 60 second mixing period.	60 seconds	11/12 minutes
11/12	Slump Check Stop the mixer and perform another slump test. If the achieved slump still falls below the specified range, or has now exceeded that range, discard the mix.	Unspecified	Unspecified

Table 3.6: Procedure for Slump Adjustment During Batching

3.4 – Testing Methodology and Procedures

3.4.1 – Compressive Strength

3.4.1.1 – Objective

The value of compressive strength is the most common indication of performance for a given concrete mix. As this research program seeks to replicate conventional concrete designs in order to validate their performance characteristics, the measure of compressive strength will have to be known. It will also validate the claim that all substrate material used in the program, though batched separately, are statistically similar. This measure of performance will also be evaluated for the very high cement "repair" mixes being compared.

While compressive strength is typically taken at some time interval, under ideal curing conditions, this provides the maximum potential strength that the concrete can reach over time. Realistically, however, concrete does not remain in an environment of 23 degrees Celsius and 100% relatively humidity, while in the field. Over time, the concrete will be exposed to a range of environmental factors including: freeze thaw cycles and shrinkage. Therefore, in order to get a measure of the "true" performance of the material, all samples cast for this testing program will be done so in duplicate. By having one set curing in ideal conditions, and having another set undergo an intensive regime of environmental attack, a measure of durability can be determined by evaluating the differences in performance between the two sets.

3.4.1.2 – Sample Preparation

After completion of the batch procedure, as outlined in Section 3.1, and the verification of the validity of that batch by confirming target slump and air content values, as outlined in Section 3.2.2 and 3.2.3, specimens for compressive strength testing will be prepared as follows. Note that the procedure outlined is in accordance with the ASTM C39.

- Step 1: Have the plastic cylinder moulds measuring 100mm by 200mm prepared by lightly coating the insides with a release agent.
- Step 2: Using a scoop, fill the mould with the fresh concrete to one third the height of the mould.

- Step 3: Using the small tamper rod, rod the concrete 20 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly 1 inch from the bottom.

- Step 4: Using a scoop, fill the mould with the fresh concrete to a level of two thirds the height of the mould.

- Step 5: Using the small tamper rod, rod the concrete 20 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly half way through the first layer.

- Step 6: Using a scoop, fill the mould with the fresh concrete such that the mould is overfilled with material.

- Step 7: Using the small tamper rod, rod the concrete 20 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly half way through the second layer.

- Step 8: Using the flat edge of the tamper rod, remove the excess concrete from the mould by using a firm, circular, sawing motion.

- Step 9: Remove any excess concrete from the outside of the mould by hand, close the lid of the mould, and place it in the curing room.

- Step 10: After a period of 24 +/- 8 hours, as outlined in ASTM C192, the hardened concrete is removed from the moulds, labelled, and returned to the curing room to await future testing.

3.4.1.3 – Testing Procedure

The compressive strength testing procedure is divided into two separate series, based on the exposure conditions being evaluated. The first series represent the ideal curing conditions based on an environment maintaining 100% relative humidity and a temperature of 23 degrees Celcius. Samples in this series will be tested at 2 intervals, 28 and 84 days, with all samples being testing in duplicate.

The second series represents the effects of aggressive environmental deterioration mechanisms. After casting, the samples will be allowed a curing period of 7 days in an environment maintaining 100% relative humidity and a temperature of 23 degrees Celcius. Samples will then be transported to a humidity chamber which will maintain a relative humidity of 50%. All samples in this series will remain in this environment for an additional 21 days. At the 28th day, samples designated for testing will be removed from the chamber and prepared for compressive strength testing. The remaining samples will be transported to a salt bath to be prepared for the second phase of environmental exposure. The salt

baths will be prepared by filling 20 L pails with 10 kg of water. Each pail will then be filled with 400 g of sodium chloride, such that a concentration of 4% by weight is achieved. The sodium chloride is then dissolved in solution by affixing a metal paddle to a drill and mixing the solution for a period of 60 seconds. A rest period of 30 seconds is allowed, such that any material that has not dissolved, settles. A finally mixing period of 60 seconds is then repeated in order to ensure that all material is in solution. Each of the 20 L pails can hold 4 of the concrete specimens. Once all salt baths have been prepared, allow an initial period of 24 hours for the specimens to saturate. After the initial period has concluded, transfer all of the samples into a freezer without covering. The freezer being used must be able to maintain a maximum temperature of -30 ^{0}C, such that a specimen in any given location within the freezer will be able to reach an internal temperature of -18^{0}C within the allotted cycle time. The first freezing cycle will be a period of 16 to 18 hours. This will then be followed by a thawing cycle, where the samples are returned to the salt baths, for a period of 6 to 8 hours. This process will be repeated until a time of 56 days from the initial saturation period has been reached. At this time, all samples will be removed and allowed a minimum drying period of 2 hours until compressive strength testing can be performed. Note that, over time, the sodium chloride will exit solution and settle at the bottom of the pail. Therefore, every 7 days, provide an additional mixing period of 60 seconds in order to return the solid particles to solution and maintain the targeted concentration of 4%.

All samples will remain in their designated environment until the testing date has been reached. Samples should be removed from the curing environment approximately 4 hours prior to performing the test procedure, such that any moisture absorbed by the sample can evaporate leaving the specimen in a dry condition.

Prior to testing, both end of the specimens must be smoothed and levelled. This can be done using a concrete cylinder end grinding machine.

The compressive strength of the specimen is then measured in accordance with ASTM C39.

3.4.2 –Modulus of Elasticity (Young's Modulus)

3.4.2.1 – Objective

When a material undergoes loading, the response of that loading by the material is characterized by two main functions; stress and strain. Where stress is generally a question of how much loading can be resisted until the material can no longer maintain some level of performance, and where strain is a

function of how the material deforms while still resisting that applied load. Young's modulus, or the modulus of elasticity defines the relationship of these two functions.

There are a variety of methods for determining the Young's modulus of a material depending on the loading conditions being applied. For this research program, this value will be determined compressive strength testing applied to cylinders while deformation is measured. As material resist different types of stress in different ways, a complete understanding of how a given material responds to stress under different conditions is critical. Each of the two methods of testing will also provide answers to two of the fundamental problems of this research program. First, how do the proposed substitute ECC mixes compare to the established mixes as presented in previous research programs and, secondly what is the nature of the function between the young's modulus of two materials and their ability to transfer stress when bonded together? The effects of environmental deterioration on the Young's modulus will also be addressed.

3.4.2.2 – Sample Preparation

Two types of specimens will be prepared for the Young's modulus testing program. The first set will be cylinders that were cast, as outlined in Section 3.3.1. Testing for compressive strength can be performed, in tandum, with the Young's modulus testing program. For this test however, only the specimens designated for testing at 84 days will undergo the procedure. The second type of specimen will be flexural beams. After completion of the batch procedure, as outlined in Section 3.1, and the verification of the validity of that batch by confirming target slump and air content values specimens for compressive strength testing will be prepared as follows. Note that the procedure outlined is in accordance with the ASTM C78.

- Step 1: Have the steel beam moulds, measuring 150mm by 150 mm by 500mm prepared by lightly coating the insides of the mould with a release agent.
- Step 2: Using a scoop, fill the mould to one third of the height with fresh concrete.
- Step 3: Using the large tamper rod, rod the concrete 75 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly 1 inch from the bottom.
- Step 4: Using a rubber mallet, firmly strike the sets of the mould 12 times.
- Step 5: Using a steel spade trowel, spade the insides of the mould.
- Step 6: Using a scoop, fill the mould to two thirds of the height with fresh concrete.

- Step 7: Using the large tamper rod, rod the concrete 75 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly half of the depth of the first layer.

- Step 8: Using a rubber mallet, firmly strike the sets of the mould 12 times.

- Step 9: Using a steel spade trowel, spade the insides of the mould.

- Step 10: Using a scoop, fill the mould with fresh concrete, taking care to overfill the mould.

- Step 11: Using the large tamper rod, rod the concrete 75 times taking care not to strike the bottom of the mould but instead to achieve a depth of penetration of roughly half of the depth of the second layer.

- Step 12: Using a rubber mallet, firmly strike the sets of the mould 12 times.

- Step 13: Using a steel spade trowel, spade the insides of the mould.

- Step 14: Place the filled mould on a vibrating table, set the vibration intensity to a low-medium setting, allow the fresh concrete to better consolidate.

- Step 15: While the mould is still on the vibrating table, use the flat edge of the tamper rod, to remove the excess concrete from the mould by using a firm, circular, sawing motion.

- Step 16: To achieve a final finish on the surface, use a moisten wooden trowel to trowel the surface of the concrete.

- Step 17: Remove any excess concrete from the outside of the mould by hand, close the lid of the mould, and place it in the curing room.

- Step 18: After a period of 24 +/- 8 hours, as outlined in ASTM C192, the hardened concrete is removed from the moulds, labelled, and returned to the curing room to await future testing.

3.4.2.3 – Testing Procedure

To test the modulus of the concrete through the flexural strength, allow the beams to cure for 86 days. On the final day, remove the beams from the curing room and test for flexural strength using the third point loading method. Ensure that the loading apparatus is set for the deflection controlled technique, in that the displacement rate of the load being applied is controlled. Apply displacement until the load fails and collect the flexural stress vs. strain data for analysis.

For the compressive strength samples, complete the procedure for compressive strength as outlined in Section 3.3.1. This testing procedure will only be formed on the samples designated for 86 days. Prior to completing the compressive strength testing procedure, the designated cylinders must be affixed with a

strain gauge, such that both the stress and strain data can be collected during the test. Using a 60mm strain gauge, affix the gauge to cylinder through the following method:

- Step 1: Once the cylinder has been removed from the testing conditions, allow the sample to air dry in the testing room.

- Step 2: Placing the cylinder on its side, locate a small patch of surface approximately 65mm by 5mm that is smooth and free of defects/indentations/scaling.

- Step 3: Using a wet cloth, lightly clean the designated area in order to remove any dust or debris from the concrete surface.

- Step 4: Remove the strain gauge from its packaging and, holding the wire connection, place the gauge on the surface designated in the previous step. Use a small piece of tape to affix one end of the gauge wire to the concrete surface. Take care to avoid touch the underside of the gauge.

- Step 5: Apply a small amount of isopropyl alcohol to a dry rag and gently wipe the designated surface. Perform the wiping motion in one direction, starting near the affixed end of the gauge and moving out.

- Step 6: Apply a small amount surface conditioner, a technique of wet abrasion which uses a mild acid, to a dry rag and gently wipe the designated surface. Perform the wiping motion in one direction, starting near the affixed end of the gauge and moving out.

Figure 3.3: Strain Gage Set-up

- Step 7: Apply a neutralizing agent to the designated area in order to bring the surface pH back to an optimal level.

- Step 8: Apply a catalyst to the underside of the gauge, which will accelerate the adhesion of the glue to the concrete.

- Step 9: Apply the glue to the prepared surface and carefully apply the gauge to the surface. The glue will be begin to set quickly so take care to place the gauge in a straight line, perpendicular to the smooth end of the cylinder. Also take care to smooth out the gauge in order to remove any air pockets which may have formed during placement.

- Step 10: After firmly holding down the gauge for a period of 60 seconds, remove pressure. Allow a 30 minute curing period for the glue to completely set. Figure 3.1 show a compressive strength cylinder with the strain gauge applied.
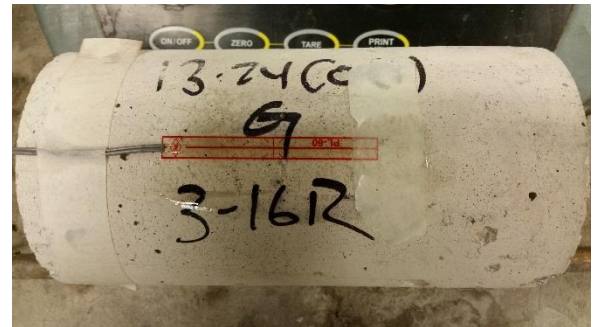
- Step 11: Prior to proceeding with the normal testing procedure for compressive strength, place a load cell on the testing platform and connect both the strain gauge and load cell to a data logger.

3.4.3 – Drying Shrinkage

3.4.3.1 – Objective

Due to the presence of water that remains in the capillaries formed during hydration, a decrease in the relative humidity in the environment can result in a length change or shrinking of the specimen as the pore water is drawn out, and the walls of the capillaries narrow. In natural climates, this process can take years and if the concrete is unrestrained, the resulting change in dimension will have no severe effects on the performance of the material. However, if the concrete is restrained, the resulting length change from this phenomenon will create a buildup of stresses along the interface between the concrete and the restraining material. This will result in a reduced ability to carry any service loads being transferred between the concrete and the restraining material.

Such an effect is particularly significant in the subject of repair materials. While each unique formulation of concrete will have a unique response to drying shrinkage, the matter of repair implies that the age of the two materials will differ. For each repair scenario there will exist some substrate which has existed for some number of years, and the repair material which has just been applied. Therefore, in order to understand how the rate of shrinkage between two different materials at two different ages can affect the bond between these two materials, the unique rate of shrinkage for each must be considered.

3.4.3.2 – Sample Preparation

The effects of differential rates of shrinkage between two materials will be tested in two in different ways. The direct effect of these shrinkage rates will be assessed in the environmental exposure condition for bond strength via slant shear testing that will be outlined in Section 3.3.5. While that test a measurement for how the bond between two given materials will effected in such an environment which promotes drying shrinkage, the exact rates of shrinkage for each material will determined using the standard test method for determining the length change of concrete as follows. Note that the procedure outlined is in accordance with ASTM C157.

- Step 1: Have the steel beam moulds, measuring 75mm by 75 mm by 285mm prepared by lightly coating the insides of the mould with a release agent. Ensure that the gauge studs are screwed into the mould after the application of the release agent.
- Step 2: Place the mould on a vibrating table. Set the table to a medium vibration intensity.
- Step 3: Using a scoop, fill the mould with fresh concrete to approximately half the height of the mould.
- Step 4: Using a plastic tampering device, evenly tamp the surface of the concrete, taking special care to work the concrete into the corners of the mould as well as underneath and around the gauge studs.
- Step 5: Using a scoop, fill the mould with fresh concrete such that the mould is filled beyond capacity.
- Step 6: Using a plastic tampering device, evenly tamp the surface of the concrete.
- Step 7: Using a steel trowel, remove any excess concrete from the mould and then continue until a smooth finish is achieved.
- Step 8: Remove any excess concrete from the outside of the mould by hand, close the lid of the mould, and place it in the curing room.
- Step 9: After a period of 24 +/- 8 hours, as outlined in ASTM C192, the hardened concrete is removed from the moulds, labelled, and returned to the curing room to await future testing..

3.4.3.3 – Testing Procedure

After the initial curing period, use a length comparator to take an initial measure of the specimen. The prisms will then be returned to the curing room and allowed a curing period of seven days. After this period has concluded, the prisms are to be removed from the curing room and its length measure again. The prisms will then be transported to a humidity chamber which can maintain a relative humidity of 50 +/- 4%. The prism will be stored in this chamber and measured for length change every seven days until the testing program has concluded. Make note of the "top" and "bottom" of the prisms such that a consistent orientation is achieved during each measurement. This will remove any small errors between testing.

3.4.4 – Bond Strength via Slant Shear Test

3.4.4.1 – Objective

The focus of this research program is qualify the repair application of a specific class of material. While the tests discussed in this chapter explore the material characteristics which may impact the ability for one material to transfer some load to another, ultimately the bond strength between those two materials must be evaluated. The measurement of bond strength through the slant shear test will provide a direct measurement of stress by casting the candidate substrate, or parent, material and, after some curing or pre-exposure process, cast the "repair" material directly on top. Then, after some additional curing or exposure process has been completed, the bond strength can be measured by testing the composite sample for compressive strength and dividing the load over the contact surface area between the two materials. For this program, the substrate material will not receive any surface preparation, such as sand-blasting, to promote bond strength. Instead, the substrate will simply be saw cut to ensure that any change in strength from one repair material to the next is a function of the composition of the paste being evaluated rather than some mechanical factor.

As with the exposure program described in Section 3.3.1, the bond strength via slant shear test will follow the same dual condition exposure. Ultimately, by comparing the results of these two exposure conditions, as well as accounting for the results of the tests described in this chapter, the key parameters which most significantly impact the efficacy of a material can be isolated and studied.

3.4.4.2 – Sample Preparation

As this test requires a composite sample of two separate materials of two different ages, the sample preparation will be performed in two phases; preparation of substrate, and preparation of repair. The substrate will be cast according to the preparation of compressive strength specimens, as described in Section 3.3.1. The application of the repair material will then be described.

Preparation of Substrate

- Step 1: After the fresh concrete has been prepared, follow steps 1 through 10 as outlined in Section 3.3.1.2.
- Step 2: After allowing an initial curing period of sixth days, remove the samples from the curing room and cut them in half using a concrete saw. The cut should be on a diagonal such that a 30 degree inclination along the cut face is achieved. There should also be an equal offset of the

inclined face achieved between the two halves. Figure 3.2 illustrates the dimension of the cut specimen. Return the specimens to the curing room.

- Step 3: On the seventh day, remove the samples from the curing room and transport all of them to the drying chamber described in Section 3.3.3. Allow a 21 day exposure period.

- Step 4: After the drying exposure period has been completed remove the samples from the chamber.

- Step 5: Make measurement of the dry mass of the substrate specimen, the measurement of the length of the smoothed elliptical face, and a measurement of the offset of the face.
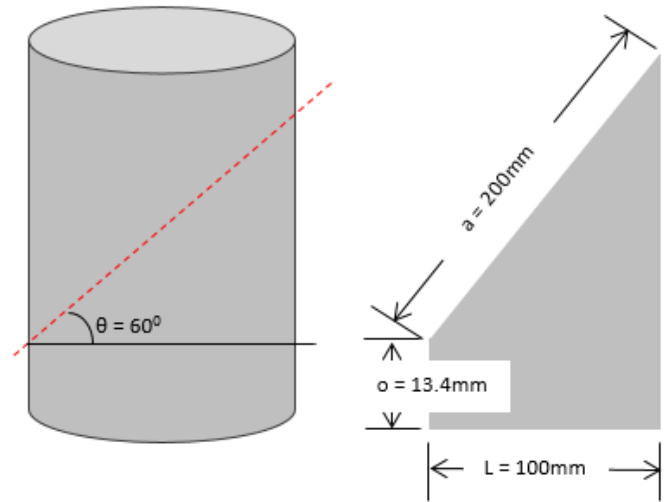
Figure 3.4: Slant shear sample preparation

Preparation of Repair

- Step 1: In order to create the composite samples, use the 100mm x 200mm compressive strength moulds. Use a saw to remove the base of the mould, such that a plastic sleeve is all that remains. One of the substrate specimens into the sleeve.

- Step 2: After the fresh concrete of the candidate repair material has been batched, use a scoop to fill the mould containing the substrate specimen to one third the height of the void left in the mould.

- Step 3: Using a small tamper rod, rod the concrete 20 times. Take care not to strike the substrate specimen.

- Step 4: Use a scoop to fill the mould containing the substrate specimen to the two thirds the height of the void left in the mould.

- Step 5: Using a small tamper rod, rod the concrete another 20 times. Again, take care not to strike the substrate specimen.

- Step 6: Use a scoop to fill the mould containing the substrate specimen with concrete such that mould is overfilled.

- Step 7: Using a small tamper rod, rod the concrete a final 20 times. Again, taking care not to strike the substrate specimen.

- Step 8: Using the sides of the small tamper rod, strike the sides of mould along the filled space to ensure the concrete has full consolidated and that no voids are left between the substrate specimen and the fresh concrete.

- Step 9: Using the flat edge of the tamper rod, remove the excess concrete from the mould by using a firm, circular, sawing motion.

- Step 9: Remove any excess concrete from the outside of the mould by hand, close the lid of the mould, and place it in the curing room.

- Step 10: After a period of 24 +/- 8 hours, as outlined in ASTM C192, the hardened concrete is removed from the moulds, labelled, and returned to the curing room to await future testing.

3.4.4.3 – Testing Procedure

The testing program for the bond strength via slant shear will be identical to the procedure described in Section 3.3.1.3. After the composite samples have completed a seven day (after the casting of the repair material) curing period. Half the samples will remain in the curing room as the control condition and be tested for bond strength at 28 and 84 days. The second half of the samples will undergo the environmental exposure conditions and then be tested for bond strength at 28 and 84 days.

To measure the bond strength, when the prescribed exposure period for the sample has end, remove sample from the exposure condition and leave it to air dry for a minimum period of at least 2 hours. Just as the compressive strength specimens had to have their ends grinded for testing, these bond strength specimens must receive the same treatment as the testing procedure and apparatus are the same. Once the samples have been fully prepared and have had sufficient time to air dry, measure the mass of the specimen as well as its height. Complete the testing procedure as outlined in Section 3.3.1.3 to determine the maximum loading which the composite sample can achieve. Also note the failure mechanism. As this is a composite sample, failure will be a result of one of four options:

1. Failure of substrate
2. Failure of repair
3. Failure of bond
4. Combination failure

While the objective of this research program is to evaluate bond strength, failure mechanisms are not so simple. If bond produced by the interface of the two materials is relatively strong, but one material is significantly stronger than the other then failure will be a result of the weaker material reaching it's

critical stress first. Alternatively, if the two material have comparable properties and the bond produced is quite strong, the two materials may act as one and fail simultaneously while still maintaining bond. These failure mechanisms will have to be noted in order for a valid analysis to be made. The results of the other material testing programs, outlined in this chapter, can then also be made to evaluate the significance of that parameter as it relates to bond strength or durability.

Chapter 4

Results and Discussion

4.1 – Compressive Strength Testing Results and Analysis

4.1.1 – Scope of Compressive Strength Testing

This section of the study is devoted to establishing the level of performance for each of the mixes addressed. Section 4.4 will provide the results of the Bond Strength via Slant Shear testing for each of the exposure conditions outlined. By understanding how the individual materials act in isolation, conclusions can be drawn concerning the interaction of the two materials. In this case, when considering the possible failure mechanisms for the slant shear testing procedure, one of three results can typically be expected;

1) Bond Failure
2) Substrate Material Failure
3) Repair Material Failure

As the test is performed under compressive loading conditions, the second and third failure conditions will be a direct result of the ultimate compressive strength capacity of either the proposed substrate or repair material. Therefore, in order to make any valid conclusions, these values must be known.

4.1.2 – Compressive Strength Testing Results

Figure 4.1 provides the compressive strength information for the Type C1 substrate material used in this phase of the program. Substrate testing was done on the 56th and 112nd day, instead of the 28th and 84th days as was done with the repair materials, as the substrate samples had to batched 28 days prior to the repair batching into to be adequately prepared for future testing. As all testing in this program is done to measure the various parameters in relation to slant shear testing, all test programs and significant test dates coorespond to dates for slant shear testing.
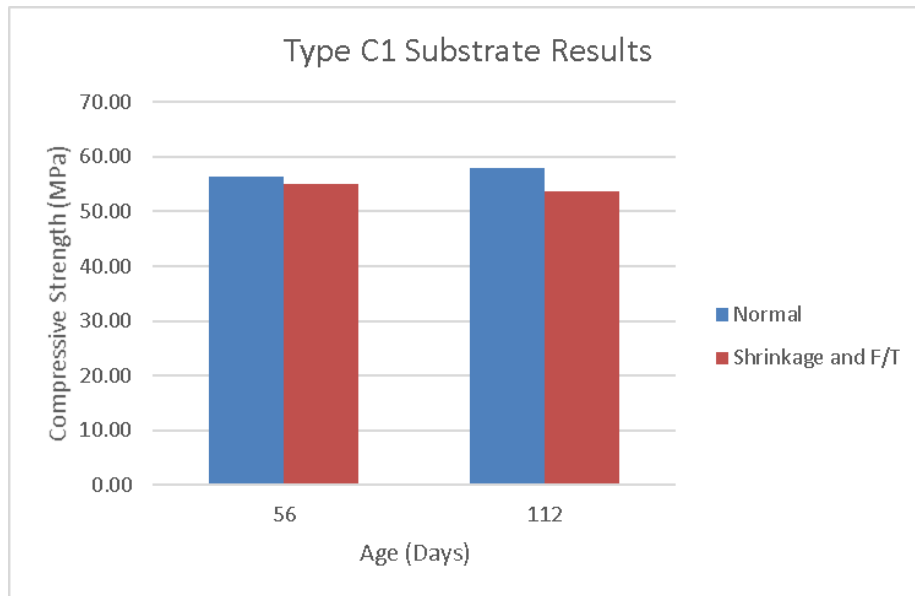
Figure 4.1: Type C1 Concrete Substrate Results

Figures 4.2 and 4.3 provide the compressive strength information for the candidate repair materials used in this phase of the program, for the 28 day results and the 84 day results, respectively. The companion substrate mix, C1 Substrate, performs comparably to the results provided in Figure 4.1. Despite begin cast at a later date, the companion substrate mix does perform marginally better than its baseline companion. Overall, the effects of the environmental exposure for the 28 day results do not so any significant changes in strength as compared to the reference set. Initial exposure in this program was a 7 day curing period followed by 21 days in a humidity chamber. As this samples are homogenous (one material), it follows that any volume change should have no negative consequences in regards to the compressive performance. That being said, the fly ash based repair, 55% FA, and the commercial repair mix, Com. Mix, do show improvements of 9.9% and 11.6%, respectively. As the volume of the sample is reduced, the occupied void space is also reduced, thus an increase in strength may follow.
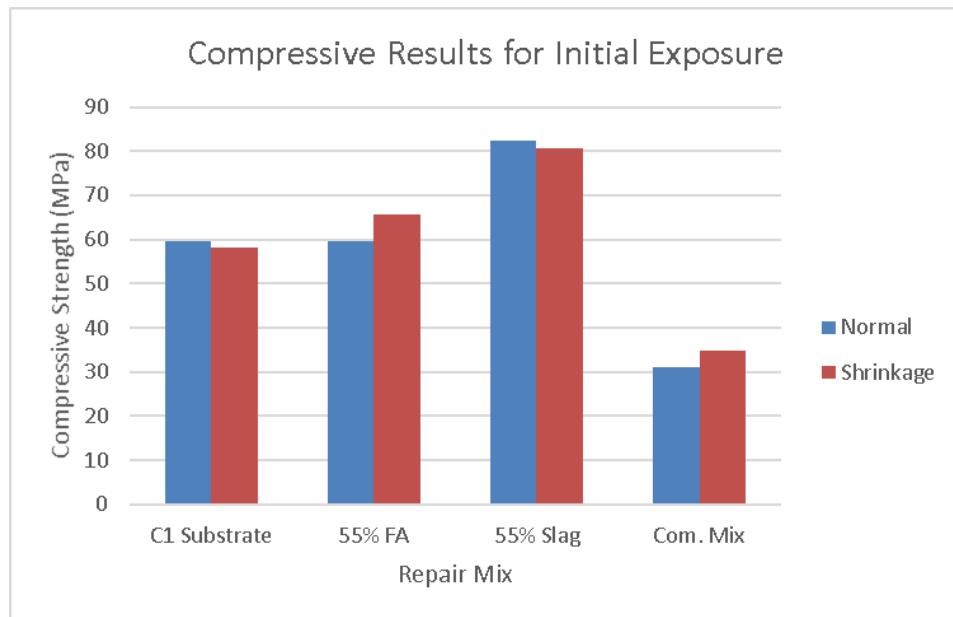
Figure 4.2: Type C1 Substrate Companion Mixes- Compressive Strength Results at 28 Days

The second stage of the environmental exposure was the freezing and thawing cycles, as outlined in Section 3.2.1.3. While the slag based repair mix performed the best overall by a considerable margin, it also experienced the most significant deterioration as a result of the combined environmental exposure with a reduction of 11.8%.
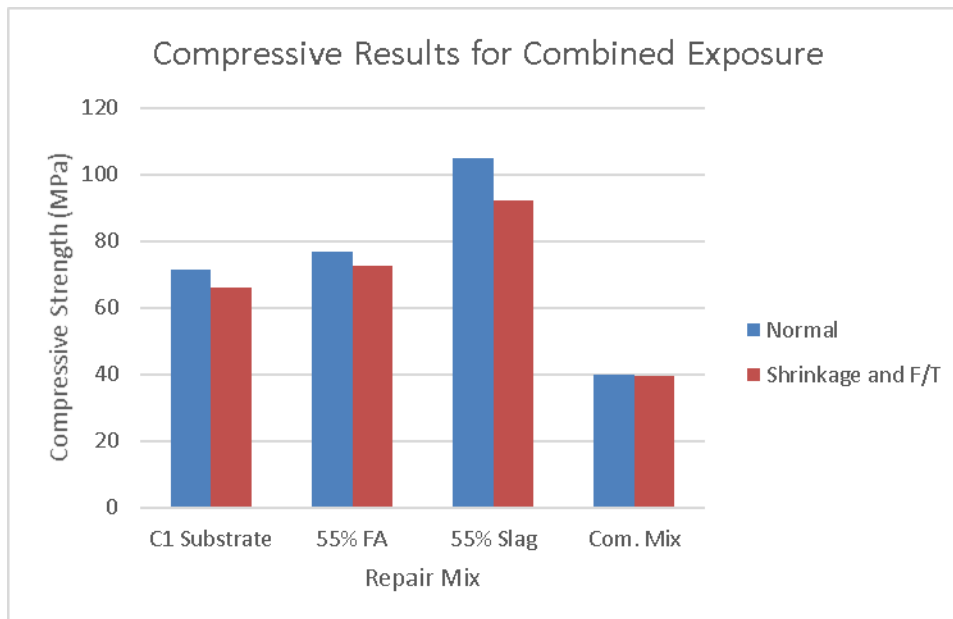

Figure 4.3: Type C1 Substrate Companion Mixes – Compressive Strength Results at 84 Days

4.2 – Young's Modulus Testing Results and Analysis

4.2.1 – Scope of Young's Modulus Testing

In the study of material performance, there are two key parameters that need to be understood in order to qualify a material for use; the amount of loading that can be withstood, and the physical response of that material when a given load is applied. The relationship between these two parameters, of stress and strain, is referred to as the Young's modulus. A material may be able to withstand a high degree of loading, but if its physical response is an excessive amount of deflection, than that material may not be suitable for a particular use. When considering the interaction of two different materials, acting together, to resist a shared loading, the comparative moduli between them becomes particularly critical. If one material has a higher degree of rigidity or stiffness, than the material that it is bonding to, the differential degree of deformation occurring at the interface will produce internal stresses that will compromise the overall integrity of the composite material.

This stage of testing will evaluate the modulus of both the referenced substrate material as well as each of the candidate repair materials part of the phase one testing program. By understanding how each material responds to load, individually, as well as how that response is effected by environmental stress, the significance that this parameter has in regards to how it can transfer loading, can be quantified. This testing will be performed through two separate methods. Third point loading will be performed on beams using a constant deflection rate. This will provide a direct comparison to the M45 mix referenced in Section 1.3. The second method of testing will through measuring the displacement occurring while the testing for compressive strength is taking place. This will provide a reference similar to the slant shear testing that will take place. Cylinders designated this testing will be subject to the same environmental exposure conditions outlined in Section 3.2.1.3, but will only be measured for modulus testing on the 84th day.

4.2.2 – Young's Modulus Testing Results

The first phase of testing evaluated the flexural strength of a select number of materials, in order to provide a comparison between the materials used in this study, and the Fly Ash based M45 mix referenced in the literature. Flexural testing was done using the third point loading method, where the rate of displacement applied was fixed at 0.005mm of vertical displacement per second.

Before proceeding into a deeper analysis, the results illustrated in Figure 4.4 allow some preliminary assumptions to be validated, but all provide insight into the behavior of the materials selected for this
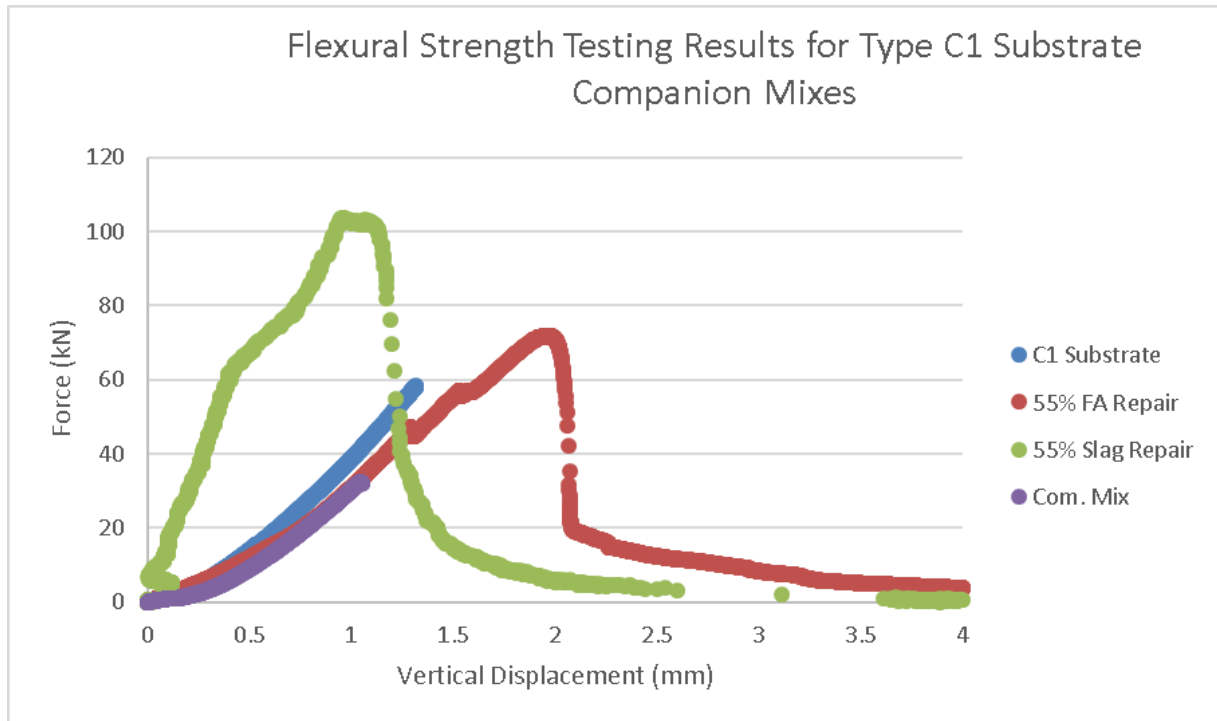

Figure 4.4: Flexural Testing Results for Type C1 Substrate Companion Mixes

phase of the study. While the fly ash based repair mix achieve a maximum flexural strength of 9.59 MPa compared to the slag based repair mix of an equal cement replacement value which achieved 13.83 MPa the Fly Ash was able to achieve a strain value at the ultimate loading 4 times greater than that of the Slag based repair mix. This is expected as the molecular nature of the Fly Ash particles which produces a far more ductile matrix, as opposed to Slag based mixes which tend to exhibit a higher degree of brittleness. While the slag based mix did experience significant deformation after the ultimate load was achieved, this was largely due to the high volume of fibers contained within the mix. Additionally, the Fly Ash based repair mix did significantly outperform both the slag containing substrate mix and the commercial mix.
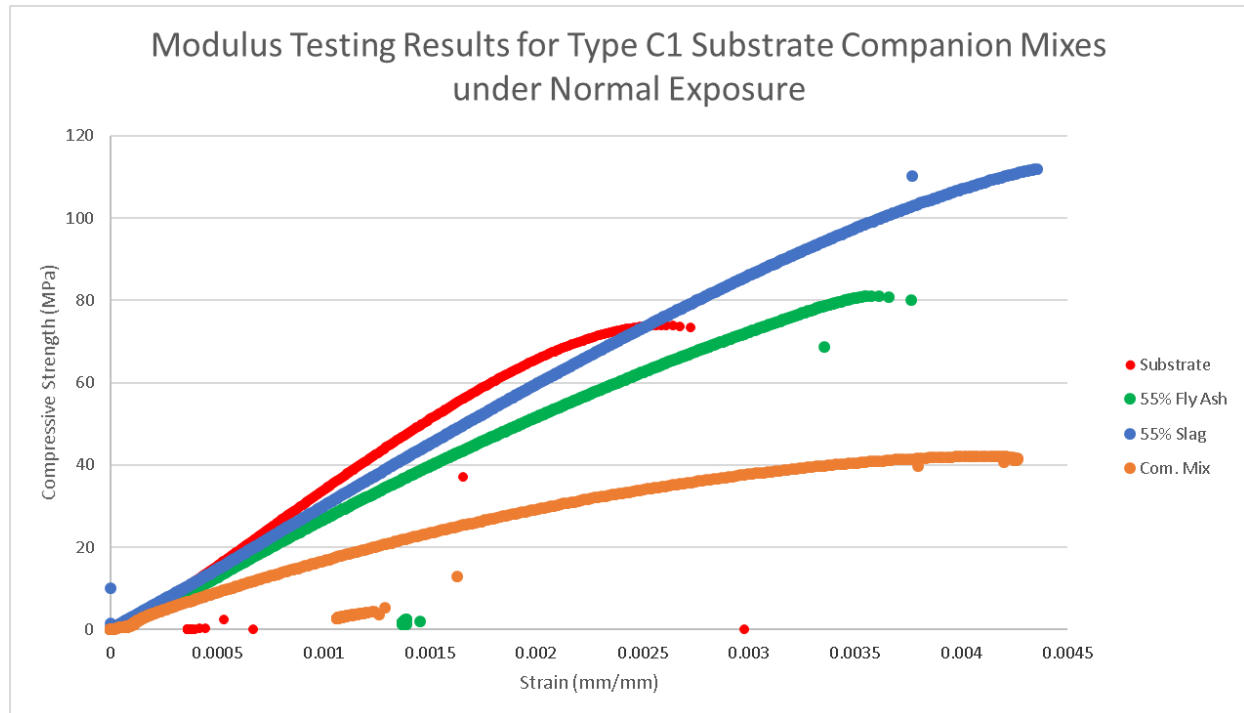

Figure 4.5: Modulus Testing Results for Type C1 Substrate Companion Mixes under Normal Exposure
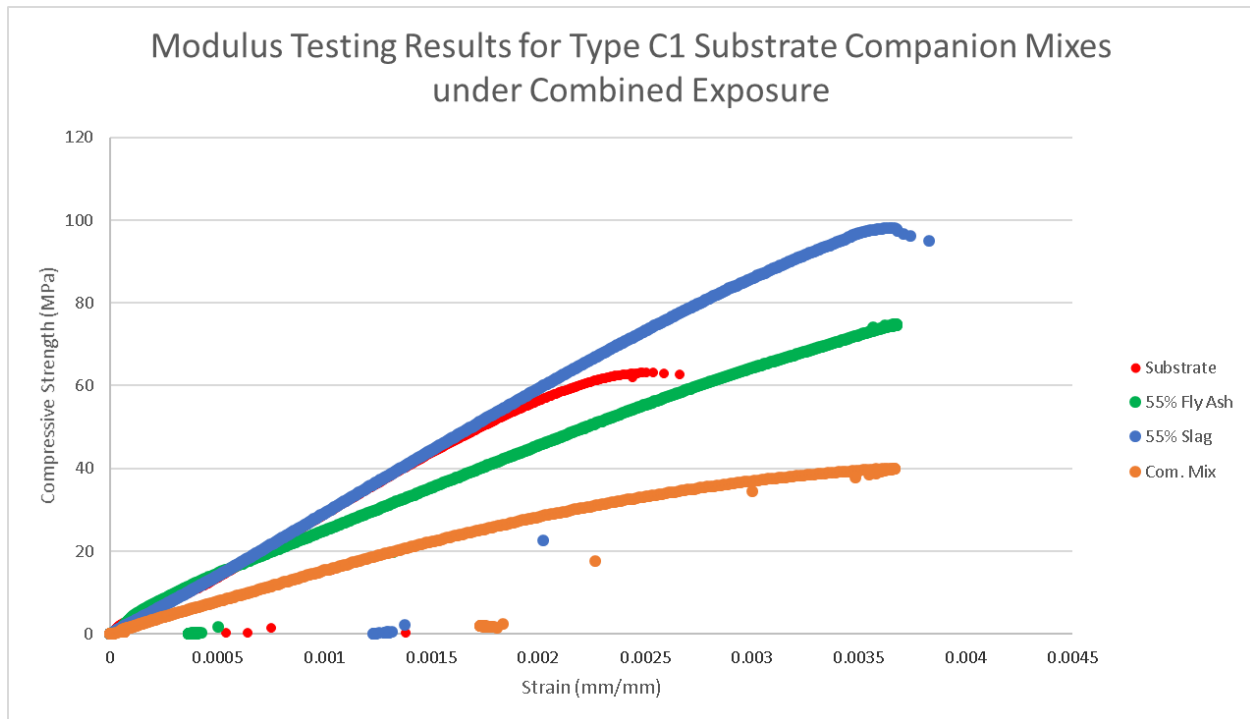
Figure 4.6: Modulus Testing Results for Type C1 Substrate Companion Mixes under Combined Exposure

To provide a more direct analysis of the young's modulus under comparable loading conditions to those achieved during the slant shear testing, graphs for loading vs. deformation were produced using traditional compressive strength cylinders. Testing was expanded to include results for normal exposure as well as environmental exposure in order to evaluate the how the modulus of elasticity is impacted by environmentally produced deterioration mechanisms.

Mix	Ultimate Compressive Stress (MPa)		Strain at Ultimate Stress $x10^{-3}$(mm/mm)		Modulus of Elasticity @ 45% Max Stress (GPa)		
	Normal	Shrinkage + 56 F/T Cycles	Normal	Shrinkage + 56 F/T Cycles	Normal	Shrinkage + 56 F/T Cycles	Change
Substrate	73.8	63.1	2.59	2.49	34.6	27.7	-19.9%
55% Fly Ash	81.0	74.9	3.56	3.67	26.7	23.6	-11.6%
55% Slag	111.9	98.2	4.34	3.64	30.0	29.6	-1.3%
Com. Mix	42.1	40.0	4.10	3.65	16.4	15.1	-7.9%

Table 4.1: Type C1 Substrate Companion Mixes – Effects of Environmental Exposure on Youngs Modulus

Figures 4.5 and 4.6 illustrate the results of the modulus testing performed for the companion mixes listed. The effect of environmental exposure on the modulus is evident when comparing the nature of the graph produced during a normal curing regime, against what is produced after the material has been subjected to a more aggressive environmental exposure. Table 4.1 provides a more succinct comparison of the two testing programs. Values for Young's Modulus were calculated using the zero-loading condition and the ultimate loading conditions. While all materials did experience a decrease in compressive strength, only the Fly Ash based mix was able to withstand a higher degree of strain upon reaching ultimate loading conditions. As a result, the modulus of the material was effectively reduced after undergoing, what was intended to be, a deleterious testing regime. Of all the materials, the substrate did experience the most significant reduction in modulus, while the Slag based repair mix remained, effectively, unchanged. It is interesting to note that the commercial repair mix exhibited a much higher degree of ductility than either of the ECC based repair mix, despite the absence of fibers.

4.3 – Drying Shrinkage Testing Results and Analysis

4.3.1 – Scope of Drying Shrinkage Testing

Once concrete reaches its hardened form, there is moisture present within the capillaries that have formed during hydration. Over time, this internal moisture can allow of an extended period of hydration as any unhydrated cementing products may react with this moisture to form additional calcium silicate hydrate. However, should this internal moisture remain present, the concrete specimen can experience a volume change. When the relative humidity of the outside environment drops below the internal relative humidity, the moisture in the capillaries will be forced out of the matrix. As these capillaries are very narrow, the surface tension produced by the moisture exiting the system causes capillaries to contract which produces an overall volume change in the specimen. If the specimen is in an unrestricted environment, then this volume will have no detrimental effects. However, if the specimen is restricted then the volume change will result in a buildup of internal stresses.

As the focus of this study is the evaluation of ECC based repair materials, it is critical to understand the nature of the volume change that these materials undergo during such drying conditions. Section 4.4 will evaluate the performance of these materials in a restrained condition. As the first phase of the environmental exposure program is the subjection of the materials to drying conditions while restrained, the relative volume change (and rates of volume change) between the candidate repair material and the established substrate will need to be evaluated. Another influencing factor will be the time frame between which this testing will take place. While all material in this study will have samples prisms measured for drying shrinkage, as per Section 3.2.3, for a period of at least 112 days, the focus of this testing will assess the relative volume change due to drying shrinkage between the dates the companion samples are undergoing the same exposure conditions.

To better replicated field condition, the substrate samples will have an extended period of drying exposure before the candidate repair materials are prepared. The rate of drying shrinkage in concrete decreases over time, therefore should any repair material be applied to a given substrate, that substrate is unlikely to experience significant additional volume change due to drying shrinkage. Therefore, this study will focus on the amount of volume change undergone between days 35 and 56 for the substrate materials, and between days 7 and 28 for the candidate repair materials. The amount of differential

shrinkage between the two materials can then be obtained by subtracting the total amount of shrinkage which occurred during the considered period.

4.3.2 – Drying Shrinkage Testing Results

Results for all samples included in phase one are provided in Figure 4.7. Note that "C1 Substrate" represents the substrate mix used for this testing phase where as "C1 Repair" represents the same mix, expect where used as reference with the other candidate repair materials. As "C1 Substrate" had to be cast 28 days prior to the repair mixes, the dates provided below represent the time the samples spent in the humidity chamber and so are not all representative of the same date. Therefore, considering the time period where the repair mix was batched, and applied to the substrate mix, the influence time frame to consider is between days 28 and 49 for the substrate mix, and between days 0 and 21 for the repair mixes.
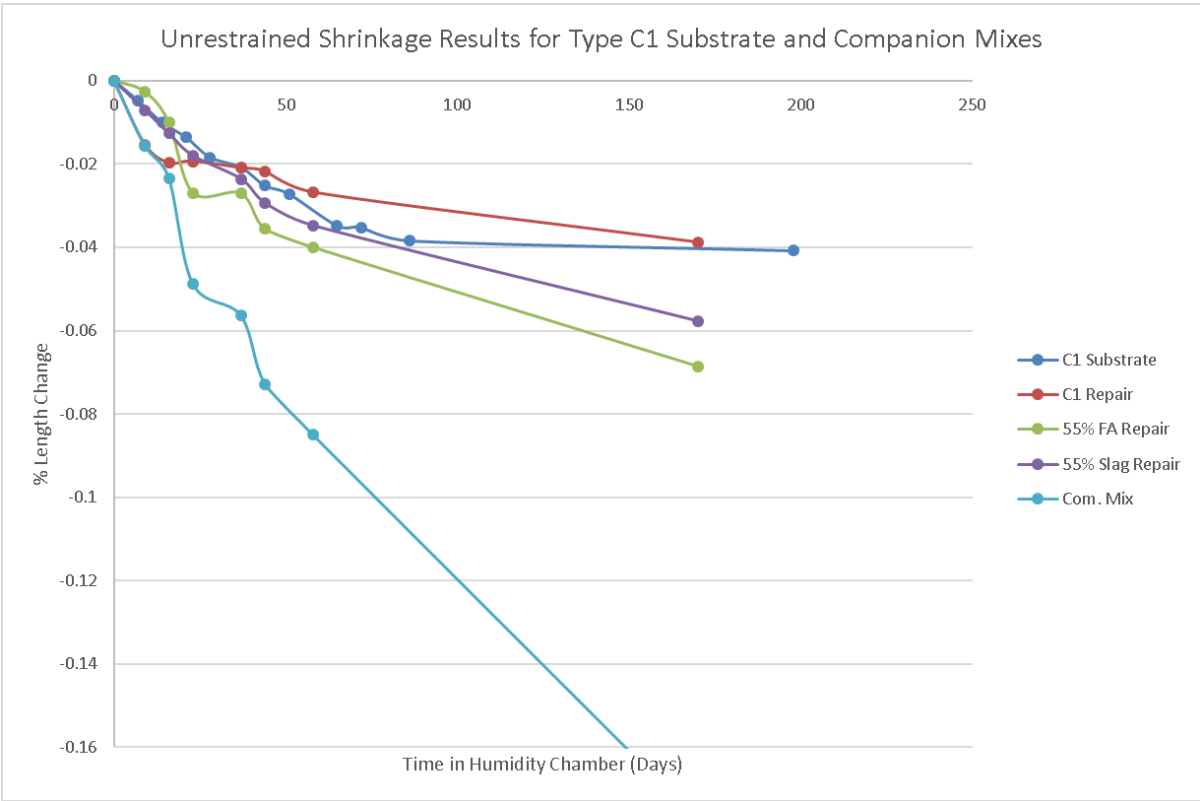

Figure 4.7: Unrestrained Shrinkage Results for Type C1 Substrate and Companion Mixes

As expected, the Fly Ash and Slag based repair mixes experience considerably more volume change than the C1 mix, due to the total cement content being nearly three times greater, and smaller aggregate size and content. The C1 mix also contains 19mm coarse aggregate, a material not found in any of the other repair mixes. As a result, the coarse aggregate provides increased resistance to the volume change which occurs in the paste. The Slag and Fly Ash repair mixes experienced comparable levels of volume change. While the proportioning of their mix structure are identical, Fly Ash proved to be more susceptible to the exposure conditions. Interestingly, the commercial repair mix, demonstrate the highest level of volume change.

4.4 – Bond Strength via Slant Shear Testing Results and Analysis

4.4.1 – Scope of Bond Strength Testing

Now that key performance measures have been evaluated for each individual material, the final stage of the test program will measure the how the proposed repair material perform. The end criteria for the evaluation of the repair capacity of a material has to be how that material interfaces with a given substrate. Furthermore, the durability of that interface must also be evaluated. This section will present the bonding capacity of the proposed repair materials as a function of the slant shear strength. These results will then be evaluated against various the various material parameters for both the repair and substrate samples.

Referencing Section 4.1.1, the different possible failure mechanisms for composite samples were described. As the failure will occur in the weakest component, a failure of either the substrate or the repair simply indicates that one material is significantly stronger than the other one, and the maximum strength achieved is not a true measure of the bond capacity of the two material, instead primarily a function of the maximum compressive strength of the weaker material. Therefore, only composite samples which exhibit failure along the interface, can be used to better understand the significant parameters governing the bonding capacity of two materials. Should the sample fail along the interface, further analysis of the compressive modulus of the two materials, as well as the differential shrinkage rates, will assess the significance of these parameters which can lead to a buildup of stresses along the interface. It has been discussed that the modulus describes how a given material deforms under stress. Should the moduli of the two materials differ greatly, the sample of the material experiencing greater deformation will develop stresses along the interface has it is restrained from movement. Similarly,

differential shrinkage rates will lead to a buildup of similar stresses. However, these stresses will develop overtime whereas the stresses produced by different moduli will only develop under significant loading.

4.4.2 – Bond Strength Testing Results

Figure 4.8 and 4.9 provide the slant shear results under both the normal exposure and the combined shrinkage and freeze/thaw exposure conditions for the Type C1 substrate group, respectively. Note that the maximum stress values displayed are a function of the maximum compressive load withstood by the sample and the area of the diagonal saw cut plane.
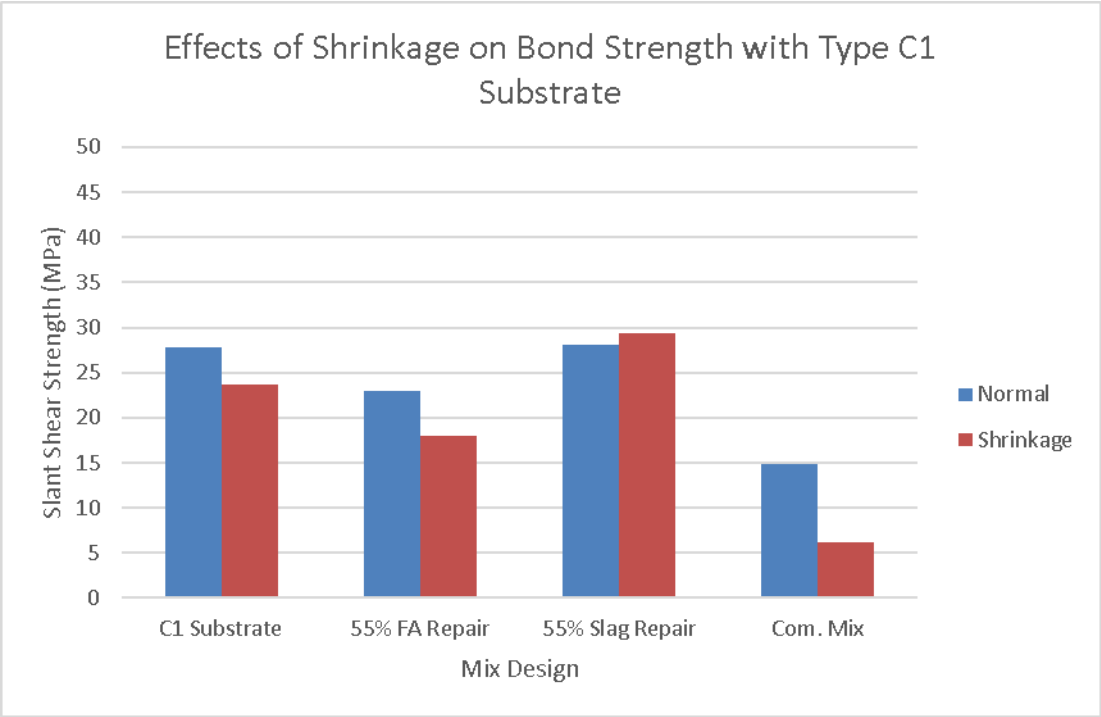

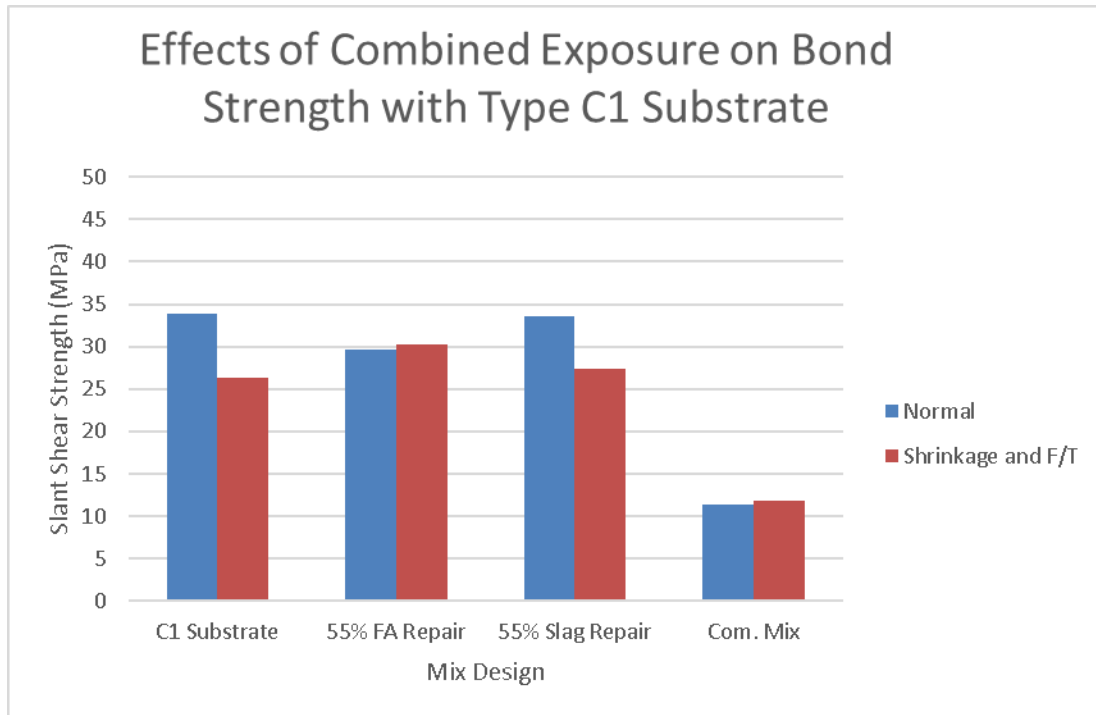Figure 4.8: Effects of Shrinkage on Bond Strength with Type C1 Substrate

Figure 4.9 - Effects of Combined Exposure on Bond Strength with Type C1

Investigating the results of the initial exposure conditions, under drying shrinkage, the commercial mix showed the greatest reduction in bond strength of 58% followed by a reduction of 21% which was seen in the 55% Fly Ash repair mix. Interestingly, the 55% Slag Repair material saw an increase in ultimate loading of %5. However, the failure cause for all the 55% Slag Repair samples were in the substrate. Therefore, any reduction in bond strength which may have occurred to this exposure condition, still maintained a greater strength than the ultimate compressive strength of the substrate material.

The combined effects of both exposures conditions can be evaluated in Figure 4.9. The greatest reduction in bond strength seen in the substrate to substrate reference samples. The most common failure cause at this age was failure at the shear plane so the reduction in ultimate loading is due to a decrease in bond as a results of the combination of deleterious exposure conditions. To evaluate just the effects of freeze thaw under salt exposure, Figure 4.10 compares the 28 days environmental exposure results (drying shrinkage) and the 84 day environmental exposure results (drying shrinkage and freeze thaw cycles). Despite the rigorous exposure conditions after being removed from the humidity chamber, most samples were still able to see an improvement in bond strength.
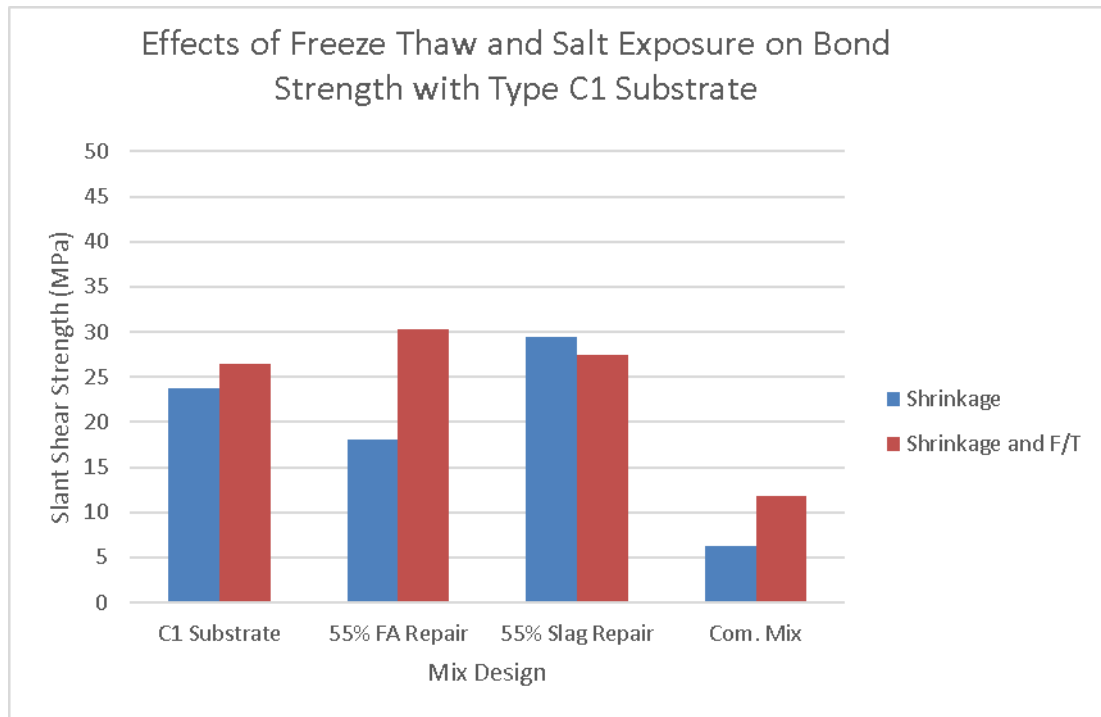
Figure 4.10: Effects of Freeze Thaw and Salt Exposure on Bond Strength with Type C1 Substrate

Chapter 5

Discussion of Results, and Recommendations for Future Research

5.1 –Discussion of Results

While the intention of this research study was to evaluate the potential for an ECC based repair mix, a review of the results presented in Section 4.4 illustrated that there is only marginal advantage in using a specialize repair mix over a concrete material identical to that of the substrate being considered, though arguably not one which could justify the cost between the two sets of materials. While the performance of the fly ash based repair mix was comparable, if not superior, to the substrate to substrate condition, the cost of the ECC repair mix far exceeds that of the conventional substrate design. Therefore, any marginal improvements in performance resulting from the use of an ECC based mix could not be financially justified. However, it is interesting to note the performance improvement experienced by the Fly Ash based repair mix after exposure to freeze thaw. The results shown in Figure 4.10 suggest that the exposure to the freezing and thawing cycles actually improved the bond strength. While the same figure shows an improvement for the commercial mix, the overall lower values obtained suggest less significance in the results. Even if the results were significant, the extremely high shrinkage that the material undergoes, as shown in Figure 4.7 show a clear detrimental effect to the bond as shown in Figure 4.8.

It seems that the freezing and thawing cycles had a negligible impact on the samples. One of the reasons could be that the thawing period was relatively short for such samples of such a low permeability. There is a possibility that the brine solution did not saturate the whole samples; hence, freezing occurred on samples that are not 100% saturated having minimal damaging effect. On the other hand, the thawing cycle could have served as additional curing to some samples, namely the fly ash and slag, leading to enhanced bond strength.

Ultimately, the use of slant shear testing as a tool to evaluate the feasibility of ECC based repair materials creates limitations on the scope of mixes that can be testing. As the goal of this study was to access bond strength, slant shear samples had to be produced such that failure would occur at the bond. This mode of failure will only occur when the compressive strength of both the substrate and repair material are comparable, and must be stronger than the bond itself. By their nature, ECC mixes, even

when altered from their optimized design, are still quite resilient and far exceed the strength of a traditional subgrade concrete. In order to bypass this disconnect, the substrate produced for this study had to be considerably stronger than what would be typically encountered in a repair scenario, otherwise no meaningful data would have been produced. While this still serves as a valid evaluation of bond strength, the testing then loses its connection to the proposed real world applications.

5.2 – Recommendations for Future Research

The intention of this research study was evaluate the potential for applying the design philosophy of ECC mixes to repair applications. While this idea was explored, the lessons learned in this study should be reviewed and applied to a more comprehensive, restructured, research program. First, any doubt from the data produced by this study must eliminated in order to draw accurate conclusions from the work completed. Once firm conclusions can be made, the work should be repeated using substrates which better reflect the performance of traditional 35 MPa C1 concrete mixes, as well as adjusted repair materials with a reduced total cement content. In order to isolate the bond capacity of any materials being studied, the compressive strength of the proposed repair material should closely match that of the substrate to ensure that failure from slant shear testing does occur at the bond. Furthermore, in such repair applications, it is not necessary to have a repair product with a compressive strength significantly higher than that of the substrate. A reduced cement content will also reduce the overall cost of the mix, thus making the materials proposed application that much more practical.

Additional testing should also be performed to better evaluate the bond strength under different exposure conditions. The slant shear method may not be the most accurate measure of bond strength, and exposure to different environmental conditions, such as extended cycles of freezing and thawing, may be better evaluated through different methods.

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