# Best Practices of Using Shotcrete for Wall Fascia and Slope Stabilization (Phase 1 Study)

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# BEST PRACTICES OF USING SHOTCRETE FOR WALL FASCIA AND SLOPE STABILIZATION
**(Phase I Study)**

by

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16. ABSTRACT
Shotcrete has become attractive and holds potential to replace cast-in-place (CIP) concrete for elements like retaining walls and slope stabilization. However, this practice is still limited due to concerns of drying shrinkage cracking, long-term durability, and debonding from reinforcing bars or existing structures. To provide best practices of shotcrete for wall fascia and slope stabilization, a comprehensive review on the state of knowledge of shotcrete is first provided. A desirable shotcrete mixture and a CIP concrete mixture from WSDOT benchmarks are tested for their basic mechanical properties, early age shrinkage, and long-term durability performance. The restrained ring test procedures adopted from AASHTO T334 are identified to be capable of evaluating early-age shrinkage cracking tendency of shotcrete, and the fracture energy test procedures based on three-point bending beam are considered to be more sensitive than the dynamic modulus of elasticity test in screening degradation effect of materials under rapidly repeated freezing and thawing action.  Prolonged watering provide best practices to mitigate shrinkage cracking. In comparison with CIP concrete, the “before shooting” shotcrete mixture studied in Phase I exhibits better early age shrinkage resistance as well as long-term freeze-thaw resistance. The Phase II study will be conducted for evaluating “after shooting” shotcrete and their early age shrinkage and long term durability performance.

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## TABLE OF CONTENTS

## LIST OF TABLES

Page

## LIST OF FIGURES

# EXECUTIVE SUMMARY

Shotcrete fascia walls are structural earth retaining components for soldier pile and soil nail walls. This method of construction has become attractive and holds potential to replace cast-in-place (CIP) concrete for elements like retaining walls and slope stabilization, if its economic benefits and good long-term performance are demonstrated. However, this practice could also possibly be limited due to early age drying shrinkage cracking and debonding from reinforcing bars or existing structures, and long-term durability concerns. Research including early age shrinkage and long term durability investigation, best curing practices, and acceptance guides for shotcrete is highly needed.

The goal of this Phase I project aims to conduct some preliminary study on performance characterization of shotcrete and compare their performance with those of CIP, in order to shed some light on best practices of shotcrete for wall fascia and slope stabilization. A comprehensive review on the state of the knowledge of shotcrete is first presented, including its production and mix design, mechanical properties, short- and long-term performance, related quality assurance methods, and comparisons with CIP concrete. From the literature review, the critical issues related to early age shrinkage cracking and long term durability are identified. Two types of mixtures (a desirable shotcrete mixture and a CIP concrete mixture) are chosen for the following performance comparisons: material properties in the fresh (e.g., slump, air content, and unit weight) and hardened (e.g., compressive strength, modulus of elasticity, and flexural strength) states; early age free shrinkage and restrained shrinkage performance; and long-term freeze-thaw resistance through dynamic modulus of elasticity and fracture energy tests.

Based on the comparative evaluation of basic material properties, early age shrinkage, and freeze-thaw resistance for shotcrete and CIP concrete, the following finding/conclusions are drawn:

(1) From the literature review, the early age shrinkage and long-term durability issues and their related test methods are identified when using shotcrete for wall fascia and slope stabilization. The shrinkage cracking tendency of shotcrete is related to both its tensile strength and free shrinkage properties. Watering shotcrete surface at early age is remarkably important to minimize its shrinkage cracking since it presents relatively low free shrinkage strain. Internal air-void system (air content and spacing factor) of hardened shotcrete has significant influence on durability of shotcrete. Addition of air entraining admixture results in well-distributed entrained air rather than entrapped air. Freeze-thaw resistance of shotcrete is improved with increasing of air content and decreasing of spacing factor. Inclusion of silica fume in the mix generally reduces the mass of scaling residues and improves the durability of shotcrete due to lower permeability.

(2) Following the ASTM standard test procedures for concrete and cementitious material characterization, the rheological property tests (e.g., slump, air content, and unit weight) of freshly mixed shotcrete are conducted to achieve desirable mix design with acceptable workability (i.e., pumpability and shootability) by adjusting the contents of air entraining admixture (AEA) and high-range water reducing admixture (HRWRA). The average slump and air content for the desirable "before shooting" shotcrete are 5 inch and 10.2%, respectively, which are much higher than those of CIP concrete.

(3) To achieve best curing practices of shotcrete to mitigate early age shrinkage cracking, a few curing regimes are considered in terms of prolonged watering and curing compound. In detail, four curing regimes with prolonged watering of 1 day (Regime I), 4

days (Regime II), 7 days (Regime III) and 10 days (Regime IV) and one curing regime with curing compound (Regime V) are applied for evaluation of shrinkage properties. Both the early-age free shrinkage test using prismatic specimens with dimensions of 4 × 4 × 11.25 inch in accordance with ASTM C157 and the restrained shrinkage test for cracking tendency via rings in accordance with AASHTO T334 are performed. Based on the free shrinkage test, the shotcrete with prolonged watering is found to shrink the most, followed by CIP concrete, while the shotcrete with curing compound shrinks the least. CIP concrete considerably exhibits lower free shrinkage than shotcrete since less cementitious materials in CIP concrete are used. Using curing compound to seal all surface of shotcrete specimens greatly prevents internal moisture from loss even without external moisture supply, and the shotcrete exhibits 48% of free shrinkage compared to that without curing compound. Prolonged watering also has significant influence on free shrinkage of shotcrete as drying shrinkage is almost suspended/postponed till the stop of watering, and it is also found that the longer the shotcrete is kept wet, the lower free shrinkage it has. From the restrained shrinkage ring test, it is also observed that CIP concrete cracks the earliest (at 7.6 days), followed by shotcrete with prolonged watering (at 12.73 days, 16.80 days, 31.97 days, and 40.47 days, respectively, for curing regimes I, II, III, and IV); while shotcrete with curing compound does not crack (no cracking is observed up to 45 days). The cracking of a ring specimen can be characterized as combined effects of free shrinkage and tensile strength. Prolonged watering postpones shrinkage cracking due to lower free shrinkage at early age, and the longer of watering action is applied to shotcrete rings, the longer it takes for shrinkage cracking. Even though CIP concrete exhibited lower free shrinkage than that of shotcrete, the ring specimens of CIP concrete crack earlier as it has lower tensile strength (as characterized by flexural strength) than shotcrete. Using curing compound (Regime V) to prevent specimens from drying provides the best practice; however, it may be difficult to be implemented thoroughly to structures in the field.

(4) Long-term freeze-thaw durability of shotcrete are evaluated based on standard and non-standard approaches. The rapidly repeated freeze-thaw tests in accordance with ASTM C666 Procedure A are performed on 3 × 4 × 16 inch prisms. The non-destructive method, i.e., vibration-based dynamic modulus of elasticity test, is conducted following the ASTM C215 on two groups of specimens subjected to freezing and thawing conditioning cycles. In parallel, a destructive method, i.e., fracture energy test of shotcrete, is performed using the three-point bend test of notched beams. It is demonstrated that both the dynamic modulus of elasticity and fracture energy tests can evaluate concrete material deterioration due to accumulative freeze-thaw damage. Mass loss due to frost action is visually observed as scaling of paste and mortar at the bottom surfaces and ends of the specimens. Both the dynamic modulus of elasticity and fracture energy for both shotcrete and CIP concrete mixtures keep decreasing with the freeze-thaw conditioning cycles. After 300 (ASTM benchmark) freeze-thaw cycles, the relative dynamic modulus of elasticity of shotcrete and CIP concrete are 94.15% and 87.82%, respectively, of those of virgin samples; while the fracture energy values of shotcrete and CIP concrete are 83.81% and 74.92%, respectively, compared to those of virgin samples. Apparently, shotcrete is more durable than CIP concrete based on the comparisons of relative dynamic modulus of elasticity and relative fracture energy, and it deteriorates at a slower rate than CIP concrete under frost action. In addition, the fracture energy of CIP concrete decreases faster than that of shotcrete, and the decreasing rates of fracture energy for both shotcrete and CIP concrete are much faster than

those based on the dynamic modulus of elasticity test. In other words, the durability factors determined from fracture energy test show larger changes from the benchmark values than those from dynamic modulus of elasticity test, indicating that the fracture energy test is more sensitive to screen the rate of aging or degradation and capable of capturing material deterioration subjected to rapidly repeated freeze-thaw action as well as other types of accumulative damage.

The results of this study are limited to the mix design and test methods used to explore proper use of shotcrete for wall fascia and slope stabilization. In particular, early age shrinkage and long-term durability related properties are mainly emphasized. Based on the experimental program conducted in this study, the following recommendations are suggested to better understand the performance of shotcrete:

(1) More viable mix designs of shotcrete by adjusting water/cement ratio, proportions of cementitious materials (e.g., cement, silica fume, ground granulated blast-furnace slag, fly ash, etc.) should be evaluated since only one shotcrete mixture with water/cement ratio of 0.34 and compressive strength higher than 6,000 psi is used in the present study.

(2) All specimens of "before shooting" shotcrete are prepared for evaluation and testing of shotcrete mechanical properties in this Phase I study; however, they cannot be identically equal to those obtained from "after shooting" concrete. The comparisons of the mechanical properties and durability of "before shooting" and "after shooting" types of shotcrete should be more considered.

(3) More laboratory evaluations should be conducted to reveal air-void characteristics since the air-void system in hardened shotcrete has significant influence on mechanical properties and long-term durability performance. The comparisons and correlations of air-

void characteristics between “before shooting” and “after shooting” types of shotcrete are needed.

(4) Early age shrinkage due to loss of moisture and shrinkage cracking tendency with a risk of decreasing quality and durability of shotcrete should be completely understood. Some other potential shrinkage-associated mitigation strategies, such as using shrinkage reducing admixtures (SRA), accelerators, expansive cementitious materials, silica fume, steel fiber, etc., should be proposed to reduce shrinkage cracking tendency.

(5) Other methods are recommended to screen internal damage process of pore structures and reveal failure mechanisms of shotcrete subjected to freeze-thaw action, such as micro/nano X-ray computed tomography (nano-CT) and scanning electron microscopy (SEM), etc., so that long-term durability of shotcrete can be better understood at the small scale of material characterization.

(6) Besides frost attack, combined frost and chemical attacks should be investigated for durability evaluations of shotcrete due to frequent use of salty deicers to melt snow and ice and improve traffic safety in cold regions.

(7) Bond strength and debonding mechanism at interface area between shotcrete and substrate should be investigated to ensure application of shotcrete as a repairing material and in slope stabilization application.

In summary, to provide best practices and durability evaluation of shotcrete for wall fascia and slope stabilization, a desirable shotcrete mixture as well as a benchmark CIP concrete mixture from WSDOT are tested for their related mechanical properties, with an emphasis on evaluation of early age shrinkage and long term durability performance. The restrained shrinkage ring test is identified to be capable of evaluating early-age shrinkage cracking tendency of shotcrete, and the fracture energy test is considered to be more sensitive than the dynamic modulus of elasticity test in term of screening degradation/aging effect of material under freezing and thawing cyclic conditioning. Prolonged watering curing methods are beneficial to mitigate shrinkage cracking. Curing compound is potentially beneficial to mitigate shrinkage cracking, but more field practice experience and thorough application of curing compound in field are needed to achieve better outcomes. As shown in this study, the shotcrete mixture exhibits better early age shrinkage resistance and long-term freeze-thaw resistance than the evaluated CIP concrete.

# Chapter 1 INTRODUCTION

## 1.1 Background and Problem Statement

Shotcrete fascia walls (see Figure 1.1) are structural earth retaining components for soldier pile and soil nail walls. This method of construction has become attractive in many states due to its inherent cost and construction time saving potentials. However, this practice could also possibly reduce the 75-year life expectancy of walls due to potential for lack of homogeneous consolidation, inadequate air content, higher permeability, possible early rebar corrosion, premature failure of admixed synthetic fiber, etc. Further, shotcrete is prone to early-age drying shrinkage cracking (Figure 1.2) and debonding from reinforcing bars or existing structures (Figure 1.3), compounding long-term durability concerns. There is also a potential that shotcrete is considered to replace cast-in-place (CIP) concrete for elements like retaining walls and soil nail/soldier pile fascia walls, if its economic benefits and good long-term performance are demonstrated in comparison with CIP concrete.

Figure 1.1 Shotcrete retaining fascia walls

Figure 1.2 Observed early-age shrinkage cracking in shotcrete structures

(https://www.troublefreepool.com/threads/50350-Cracks-in-Gunite-should-I-be-worried)

Figure 1.3 Debonding issues of shotcrete (Drover and Villaesusa, 2015)

Currently, the state of knowledge regarding proper shotcrete mix design, construction, curing practices, quality assurance (Q/A), durability performance, condition assessment/testing, maintenance, and repair/rehabilitation is scattered in published domain or undocumented. Most of the evaluation and test methods commonly developed for concrete could not be readily applied or are not suitable for characterization of shotcrete. Studies including durability investigation, best curing practices, and field Q/A acceptance testing criteria are highly needed.

There is currently very limited information available to evaluate curing practices, construction, long-term durability, and acceptance guides for shotcrete. AASHTO “Guide Specifications for Shotcrete Repair of Highway Bridges” (1998) documented the practice for durable shotcrete repair of bridges, but it is only applicable for bridge repairing application. Zhang et al. (1999) evaluated durability of polypropylene fiber-reinforced shotcrete via freezing and thawing cyclic tests. Bindiganavile and Banthia (2000) studied effect of mineral admixtures on long-term durability and mechanical performance of shotcrete. Jolin et al. (2002) tested several dry-mix shotcrete mixtures to quantitatively assess performance consistency of shotcrete in practice. Leung et al. (2006) developed a new testing configuration to evaluate shrinkage cracking of shotcrete. Wenzlick (2007) of MODOT found that shrinkage cracking and lack of bond to existing structures were pronounced for shotcrete as a repairing material and recommended that silica fume should be included in the pre-bagged mix to improve bond strength and a 7-day moisture cure of shotcrete is needed to decrease shrinkage cracking. In summary, most of the existing studies and available guides and specifications were primarily focused on shotcrete repair of bridges. There are no studies available for shotcrete in wall fascia and slope stabilization and its related mix design performance, curing practices, long-term durability issues, acceptance criteria, performance and cost comparisons with CIP concrete, etc.

## 1.2 Research Objectives

The goal of this proposed project aims to provide a thorough review of the state of academic and industrial knowledge to ensure proper use of shotcrete for wall fascia and slope stabilization. With the increasing emphasis on using shotcrete for accelerated construction and rapid renewal, such a synthesis would be an extremely useful resource to help highway agencies achieve construction quality and durability of structures using shotcrete. Thus, there is an urgent need to document the use of shotcrete for wall fascia and slope stabilization by highway agencies, assess the condition of such existing inventory, develop test methods to evaluate critical performance issues facing shotcrete, and identify best practices during various stages of the life cycle of such structures. In particular, the proposed research will investigate adequacy of shotcrete consolidation, permeability, early age shrinkage and associated cracking, potential and long-term durability. Also, development of best curing practices and Q/A test methods for field-placed shotcrete and their cost and performance comparisons with cast-in-place (CIP) concrete will be addressed by this study.

# Chapter 2 LITERATURE REVIEW

The review focuses on the past studies on characterizing and understanding performance and durability of shotcrete as well as the advantages of using admixtures and their effects on properties of shotcrete. Recent developments regarding phenomena of shrinkage has been also considered. In addition, studies on developing better curing practices and other quality assurance methods are reviewed.

## 2.1 Production and Mix of Shotcrete

### 2.1.1 Production

Shotcrete is regarded as a special construction technique to place and compact concrete rather than a special mixture design (Beaupre, 1994). Shotcrete is a concrete which is conveyed through a pressurized hose to a nozzle at a high velocity onto the receiving surface to form a structural or non-structural component of buildings, and it is a process of simultaneous compaction, condensation and hardening of concrete. Shotcrete is possibly applied to surfaces using either dry or wet mix method. The dry mix process contains a premixed blend of Portland cement and damp aggregate, which is pumped through the hose to the nozzle. Water is added from a separate hose in the nozzle and completely mixed with the dry mixture blend just as both streams are being sprayed onto receiving surface (Figure 2.1a). The final quality of shotcrete is strongly affected by experience of nozzleman (Crom, 1981). While in the wet mix concrete, all mix constituents are mixed with water and then pumped through the hose (Figure 2.1b). To achieve a high speed of pumping, additional compressed air is added in the nozzle. Compared with the dry mix process, the mixing water of wet mix shotcrete is more accurately controlled by delivery equipment, and the wet mix shotcrete is applied at much higher production rate. Some finishes can be subsequently applied to fresh shotcrete structure; for example, thin surface coating component can be directly sprayed onto the surface to avoid internal moisture loss.

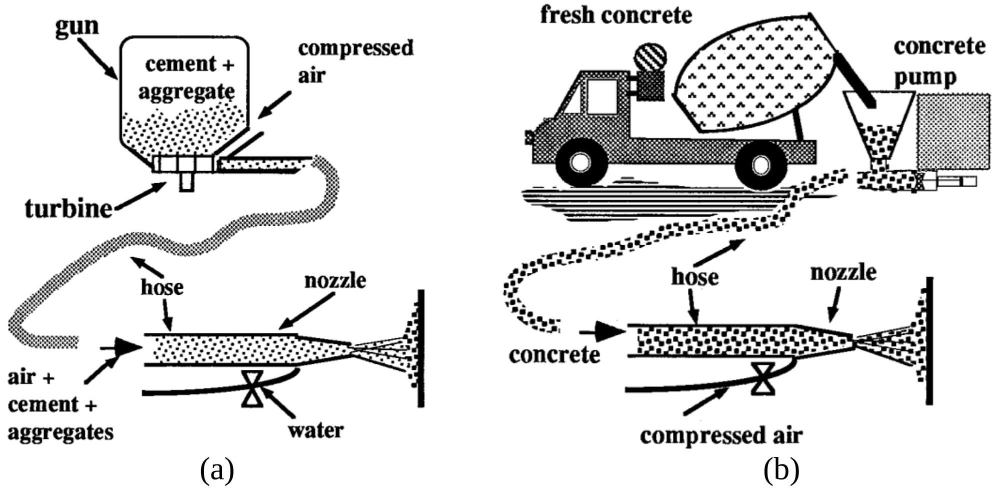



Figure 2.1 Schematic of shotcrete production: (a) Dry-mix process; and (b) Wet-mix process (Beaupre, 1994)

### 2.1.2 Mix

The mix constituents of normal concrete primarily consist of Portland cement, aggregates, and water. However, some other ingredients are added to improve the mechanical properties, workability, and pumpability of shotcrete in some application, and they include silica fume, ground granulated blast-furnace slag (GGBFS), air-entraining admixtures, water-reducing admixtures, accelerators, fibers, etc.

The water cement/ratio of shotcrete depends on field application but generally varies from 0.3 to 0.6, and a typical wet mix design for shotcrete is shown in Table 2.1 (Jolin, 2003a). A relatively lower water/cement ratio is required in production of high performance shotcrete. Normal types of cement, river sand and coarse aggregate can be used to produce shotcrete. The nominal maximum aggregate size is usually 3/4 inch or smaller. The ACI Committee 506 (2005) has recommended the grading limits for shotcrete to minimize drying shrinkage and rebound (Table 2.2). Shotcrete produced with finer aggregates exhibits greater drying shrinkage, while with coarser aggregate results in more rebound.

Table 2.1 Typical wet-mix shotcrete composition (Jolin, 2003a)

| Material | Quantity for 1 $m^3$ |
| --- | --- |
| Portland Cement | 400 kg (880 lb) |
| Silica Fume | 40 kg (88 lb) |
| Fine Sand | 1110 kg (2447 lb) |
| Coarse Aggregate (max 10 mm [3/8 in.]) | 460 kg (1014 lb) |
| Water | 180 kg (396 lb) |
| Water-Reducing Admixture | 1500 ml (51 fl oz.) |
| Superplasticizer | 5000 ml (170 fl oz.) |
| Air-Entraining Admixture | 2500 ml (84 fl oz.) |
| w/c | 0.41 |

Table 2.2 Grading limits for aggregate of shotcrete (ACI 506)

| Sieve Size | Percent by Mass Passing Individual Sieves | | |
| --- | --- | --- | --- |
| | Grading No. 1 | Grading No. 2 | Grading No. 3 |
| 3/4 in. | - | - | 100 |
| 1/2 in. | - | 100 | 80-95 |
| 3/8 in. | 100 | 90-100 | 70-90 |
| No. 4 | 95-100 | 70-85 | 50-70- |
| No. 8 | 80-100 | 50-70 | 35-55 |
| No. 16 | 50-85 | 35-55 | 20-40 |
| No. 30 | 25-60 | 20-35 | 10-30 |
| No. 50 | 10-30 | 8-20 | 5-17- |
| No. 100 | 2-10 | 2-10 | 2-10 |

Silica fume, a waste byproduct of silicon metal and alloy production process, has been widely utilized to improve strength, durability and sustainability of concrete and shotcrete (Morgan and Wolsiefer, 1992; Zhang et al., 1999; Sawoszczuk et al., 2013). The replacement ranges from 7 to 15 percent by mass of cement (US Army Corps of Engineers, 1993).

GGBFS, a waste byproduct of iron production process, has been widely utilized to achieve certain performance of shotcrete, including slower setting time, lower heat generation during hydration, and higher chloride-ion resistance (Sawoszczuk et al., 2013). Thus, the addition of GGBFS may exhibit some interaction issues with use of accelerators.

Air-entraining admixtures are essential to improve the pumpability and freeze-thaw durability of shotcrete. Small air bubbles are initially created during mixing and most of bubbles will be lost during pumping and shooting. Therefore, the air content of fresh shotcrete after mixing is recommended higher than 12% to compensate these losses (Morgan, 1989).

Water-reducing admixtures are important to improve workability of shotcrete, especially for high performance shotcrete to allow lower water-cement ratio to be used (Zaffaroni et al., 2000).

Accelerators (accelerating admixtures) are used extensively in shotcrete when rapid section buildup and early strength development are required, such as in tunnel construction. However, accelerators may decline due to increasing use of silica fume (Prudencio, 1998).

Fibers in shotcrete have been used to enhance its ductility, toughness, and fatigue resistance and reduce crack propagation (Verma, 2015).

## 2.2 Performance of Shotcrete

### 2.2.1 Air content and mechanical properties

Pumpability and shootability of fresh wet-mix shotcrete are important rheological parameters, and they can be determined by slump and air content tests (Yun et al., 2015a; Yun et al., 2015b). Related air-void system is an essential parameter that affects the mechanical properties and freeze-thaw durability of shotcrete (Morgan, 2003; Fonseca and Scherer, 2015; Choi et al., 2016). The ingredients used in shotcrete can have a significant effect on air content. From the point of view of fresh shotcrete, the pumpability and shootability can be achieved by adjusting the amounts of water-reducing admixtures and air-entraining admixtures from an optimal mix design test. It is usually considered that a slump of 4-8 inch and an air content of 10-20% are acceptable. The air content of hardened shotcrete is excessively affected by production procedures, construction practices and weather, such as the method of batching, time and speed of mixing, transportation and delivery, pumping and shooting, temperature, etc. (Portland Cement Association, 1998; Choi, 2008; Zhang, 2012).

There are no specific testing methods for fresh or hardened shotcrete. All tests considered for conventional concrete are applicable to be applied for shotcrete. Similar to conventional concrete, the properties of shotcrete are mainly controlled by mixture design parameters, i.e., water/cement ratio, content and type of cement, size and type of aggregate, admixtures used, energy and duration of mixing process, and curing conditions (US Army Corps of Engineers, 1993). The proper use of silica fume, GGBFS, accelerators, and fibers can significantly improve certain properties of shotcrete. In addition, the shooting method used (dry or wet mix) influences its properties, and the higher air content of shotcrete after shooting, the lower strength it achieves.

Compressive strength ranges from 4,000 psi (27.5 MPa) to 10,000psi (68.9 MPa) at 28 days have been commonly reported in field construction (Zhang, 2014). The early age strength of shotcrete can be higher than conventional concrete, reaching 1,000 psi in 5 hours and 3,000 psi in 24 hours (Heere et al., 2002; Jolin et al., 2003b). The strength of shotcrete tends to increase with decreased air content and decreased spacing factor, when compared the same mixture without shooting. The shotcrete after shooting exhibits 6~10% loss of air content and 20-70% increase of strength (Choi et al., 2016). The addition of silica fume and GGBFS usually improves the mechanical properties and durability since they can improve bond strength between cement paste and aggregates. Won et al. (2013) found that some mineral-based accelerator shows higher early-age strength while some exhibit better long-term strength. Banthia et al. (1994), Zhang et al. (1999) and Verma (2015) showed that the use of fibers in shotcrete significantly improves the ductility and flexural strength, while slightly improves the compressive strength. Accelerators are commonly used to increase early strength and achieve rapid set (Prudencio 1998). Hot environment may benefit strength growth and subsequent integrity at early age (Lee et al., 2013).

Considering shotcrete is sprayed on existing structures (hard rock, slopes, rebar, etc.) as a support system, adhesion strength between shotcrete and existing structures is one critical property of shotcrete. Bryne et al. (2014a; 2014b) developed a pull-out test method to evaluate early age adhesion strength from several hours after shooting. At very early time after spraying, the physical properties and adhesion strength depend on the set accelerator and the formed micro-structure. The failure location of the shotcrete layer is another aspect to be considered. Malmgren et al. (2005) observed that failure is more likely to occur where the shotcrete layer is thinner than or equal to 20 mm and with a low adhesion strength. Karlsson (1980) found that among only 32% of the 238 tests the whole failure occurred at the contact area from a field study. Malmgren et al. (2005) also found that relatively less cracks occurred at the contact between shotcrete and substrates from the restrained shrinkage tests, which indicated that restrained shrinkage could destroy the bond between shotcrete and substrates. The type of surface preparation also has significant influence on long-term bond strength of shotcrete (Talbot et al., 1994). Improvement of the adhesion strength showed a reliable relation with the growth of compressive strength.

### 2.2.2 Shrinkage

Shrinkage in shotcrete exhibits due to loss of moisture from mixture. Several types of shrinkage associated with shotcrete are plastic, autogenous, drying, and carbonation, which are results of rapid loss of water after placing, cement hydration, evaporation of water, and carbon-dioxide reactions, respectively. Shrinkage would not lead to any tensile stress if without any restraints and has no effect on structure response. However, shotcrete is commonly employed to produce layers or linings with large ratios of surface area to volume, and restrained shrinkage cracking is hence an important concerning issue (Leung et al., 2006). Watering is important to minimize shrinkage cracking tendency since it reduces the shrinkage at early age but has no significant effect on strength development. Long waiting without watering before producing a second layer will increase risk of shrinkage cracking in shotcrete (Ansell, 2010). In cooperation with steel fibers in shotcrete can reduce shrinkage cracking and develop crack distribution since it has better tensile strength (Malmgren et al., 2005; Bryne et al., 2014c).

Several testing methods have been employed to investigate the restrained shrinkage cracking of shotcrete. ASTM C1581 (2016) (Figure 2.2) and AASHTO T334 (2012) provide a standard testing set-up for restrained shrinkage cracking of concrete, with a ring specimen cast around a stiff steel ring. However, this method is not accurate to shotcrete since it cannot prepare representable material (Bryne et al., 2014c). Leung et al. (2006) proposed an alternative testing configuration, consisting of a shotcrete specimen bonded to a steel I-section at the bottom and angles at ends to provide shrinkage restraints (Figure 2.3). The degree of constraints and weight of steel members were analyzed by a finite element method, and the results showed that this method is a practical approach for investigating the shrinkage cracking behavior of shotcrete. Bryne et al. (2014c) also introduced a similar test set-up to investigate of shrinkage cracking of shotcrete, but a solid granite slab was used to replace the steel slabs to simulate a realistic restraint in field.

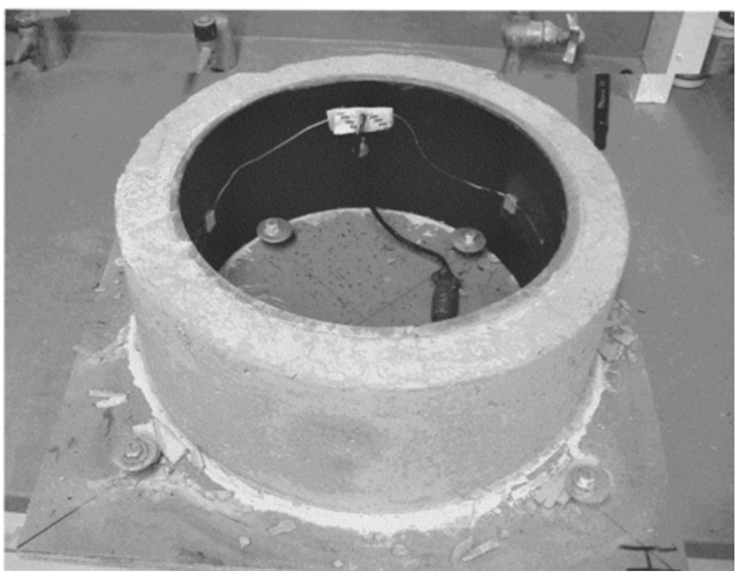


Figure 2.2 Restrained shrinkage test of concrete with steel ring (ASTM C1581)

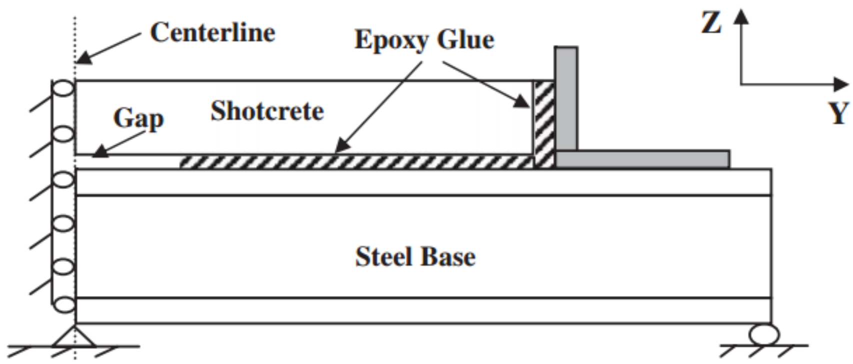



Figure 2.3 Model with hinge support for the calculation of upper bound values of restraint (Leung et al., 2006)

### 2.2.3 Freeze-thaw durability

Shotcrete infrastructures located in cold climates frequently suffer from the freeze-thaw cycles as well as deicer salts attack during winter seasons. Both frost damage and salt scaling can reduce the strength and modulus of elasticity and eventually lead to structural damage or loss in serviceability. Many studies have been conducted on durability of shotcrete (Beaupre et al., 1994; Lamontagne et al., 1996; Jolin et al., 1997; Morgan, 2003; Mainali et al., 2014; Wang et al., 2015a&b). Resistance of shotcrete to freeze-thaw can be determined in accordance with ASTM C 666 (2015), and the air content of fresh shotcrete and the air content and spacing factor of hardened shotcrete specimens can be determined following ASTM C231 (2014) and ASTM C 457(2012), respectively. Some other methods were adopted to study pore structure and permeability of shotcrete, such as X-ray diffraction, acoustic emissions (AE), thermogravimetry-differential scanning calorimetry (TGA-DSC), scanning electron microscopy (SEM), etc. A typical damage process of shotcrete after suffering sulfate attack and drying-wetting cycles is shown in Figure 2.1. Since the use of shooting technology, some differences of internal structure and durability were shown between shotcrete and ordinary concrete (Niu et al., 2015; Jiang et al., 2015).

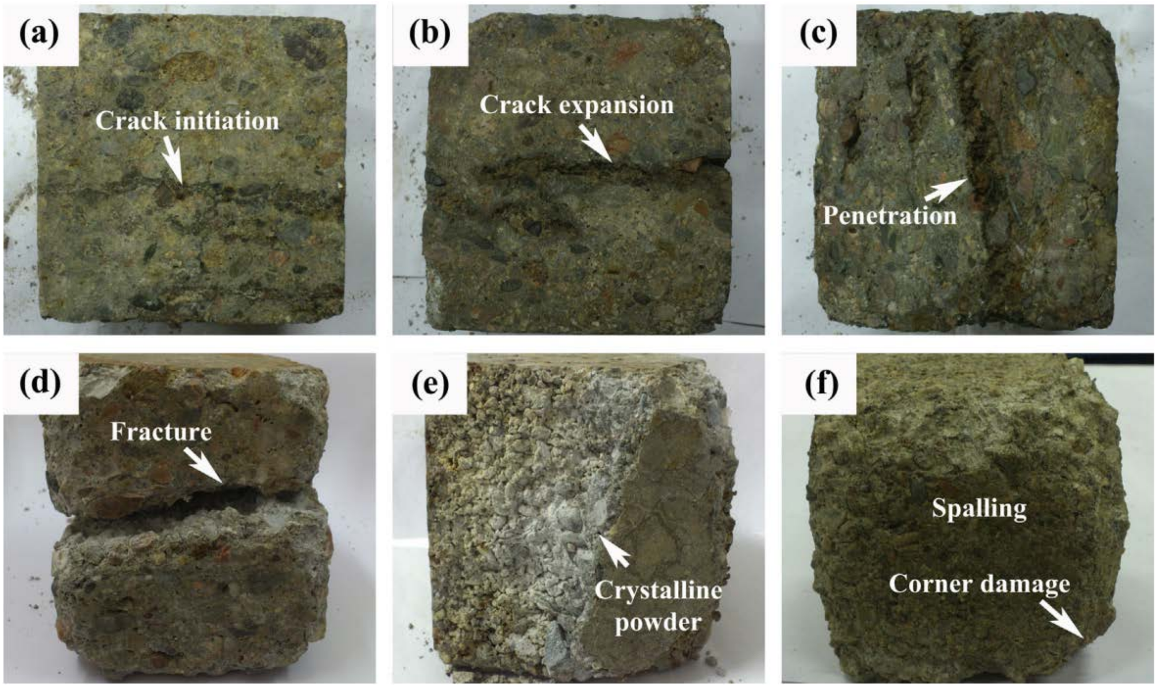



Figure 2.4 Appearances of damage process after suffering sulfate attack and drying–wetting cycles: (a) shotcrete, 30 days; (b) shotcrete, 60 days; (c) shotcrete, 90 days; (d) and (e) shotcrete, 140 days; and (f) ordinary concrete, 140 days. (Niu et al., 2015)

Internal air-void system of hardened shotcrete has significant influences on the durability of shotcrete (Choi et al., 2016). Air entraining admixtures are important to ensure freeze-thaw and deicer salt scaling resistance (Lamontagne et al., 1996; Chen et al., 2015). Deicer salt scaling resistance of both dry and wet mix shotcrete improves with increasing of air content and decreasing of spacing factor, and use of silica fume generally reduces the mass of scaling residues and improves the durability of shotcrete (Morgan and Wolsiefer, 1992; Beaupre et al., 1994; Choi. et al., 2016). Some accelerators improved durability of shotcrete due to its excellent strength, permeability and freeze-thaw cycle resistance (Park et al., 2008).

## 2.3 Effects of Admixtures

Yun et al., (2015b) studied effects of various admixtures on rheological properties of high-performance wet-mix shotcrete (HPWMS), e.g., silica fume, air-entraining admixtures, superplasticizer, synthetic fiber, powdered polymer, etc. The yield stress and plastic viscosity of HPWMS with various types and amounts of admixtures were measured using an IBB rheometer to determine pumpability and shootability. Air-entraining agent tended to proportionally reduce both flow resistance and torque viscosity of HPWMS. Superplasticizers showed a relatively greater influence on flow resistance than torque viscosity. Silica fume increased flow resistance while slightly reduces torque viscosity. Silica fume improved shootability and pumpability of shotcrete greatly.

Park et al. (2008), Won et al. (2013), Won et al. (2015) compared the mechanical properties of shotcrete containing different content of high-strength cement based mineral accelerator (HS-CM) with shotcrete containing 5% of normal cement-based mineral accelerator (CM). They found that shotcrete containing more than 6% HS-CM with respect to cement weight was slower at initial set but faster at final set than that made with CM. HS-CM accelerated shotcrete had approximately the same compressive and flexural strength at early age but higher compressive and flexural strength at 7 days and 28 days than CM accelerated one. Based on microstructural analysis through scanning electron microscope (SEM), X-ray diffraction (XRD) and nitrogen adsorption tests, they also found that shotcrete made with HS-CM showed better frost and chemical resistance than that made with CM. Alkali-silica reaction of accelerating admixtures for shotcrete is also another phenomenon being investigated. Length change of cement pastes made with various accelerating admixtures under sulfate solution were measured to characterize the expansion caused by alkali-silica reaction. Paglia et al. (2003) observed that accelerated cement pastes showed more expansion up to 6 months than unaccelerated ones. Won et al.

(2012) showed that expansion of accelerated shotcrete increased with the total equivalent alkali content of the specimens.

## 2.4 Curing, Construction Practices and Quality Assurance for Shotcrete

The quality control and assurance procedures of shotcrete, regarding materials, equipment, methods, etc., should be clearly conducted to assure performance of final production. In general, the US Army Corps of Engineers (1993) discussed some technical aspects of shotcrete that should be incorporated into shotcrete production, as shown in Table 2.1. Quality assurance activities, such as submittals, mixture proportion evaluation, nozzleman certification and performance testing should be assigned to a shotcrete production.

Some preparatory work of substrate is required before applying shotcrete. For rock of poor, loose, carbonated or penetrated by chlorides, they should be removed from substrate. Pre-wet of substrate should be performed to improve bond strength before shotcrete is sprayed.

Reduction of rebound material losses and improvement of material properties are the major concerns of shotcrete industry due to its significant effects on costs and wastage of materials (Ginouse and Jolin, 2016). Materials (i.e., air pressure, cement content, water content, nominal maximum size and grading of aggregate, amount of reinforcement, etc.), thickness of layer, nuzzling techniques and procedures of applying greatly affect the quality of shotcrete and the amount and composition of rebound. Mixtures with small aggregates result less rebound than those with large-aggregates. It was found that when shotcrete is applied horizontally, no uniform distribution would be achieved, and poor nozzling techniques lead to entrapment of rebound materials. Ginouse and Jolin (2014) and Ginouse et al. (2014) found that wet mix process produces better uniformity than dry mix process.

Table 2.3 Technical aspects of shotcrete

| Preproduction Phase | Production Phase |
|---|---|
| (a) Submittals:<br>(1) Cementitious materials;<br>(2) Aggregates;<br>(3) Admixtures and curing compound;<br>(4) Fibers and reinforcement;<br>(5) Mixture proportions;<br>(6) Accelerator compatibility test;<br>(7) Nozzleman certification;<br>(8) Equipment;<br>(9) Curing and protection.<br>(b) Test panel fabrication, testing, and evaluation. | (a) Materials:<br>(1) Cementitious materials;<br>(2) Aggregates (Quality, Grading, and moisture content);<br>(3) Admixtures and curing compound;<br>(4) Fibers and reinforcement;<br>(b) Surface preparation;<br>(c) Shotcrete:<br>(1) Strength (testing panels, in-place samples);<br>(2) Mixture proportions;<br>(3) Air content;<br>(4) In-place thickness;<br>(5) Rebound testing;<br>(6) Curing and protection;<br>(7) Nondestructive testing (impact hammers or probes, ultrasonic equipment, and pull out devices, etc.);<br>(8) Delamination testing;<br>(9) Surface tolerances;<br>(10) Visual inspection. |

Proper curing of shotcrete is extremely important to assure strength gain and long-term durability and to mitigate shrinkage cracking. The curing procedures of ACI 308R (2001) should be followed, and the surface of shotcrete should be kept continuously moist condition for at least 7 days after placement to ensure that the tensile strength gained is sufficient to resist shrinkage-induced stress. Compound, cellulose, or membrane curing is immediately carried out after initial moist curing, and they should be removed before applying the next layer. Shehata and Klement (2005), and Shehata et al. (2006a; 2006b) tested different curing methods: air-curing, curing compound, misting and curing compound, and cellulose. Cellulose cured shotcrete showed enhanced pore structure and higher quality of surface compared to other traditional methods. In addition, cellulose curing mitigates shrinkage cracking.

## 2.5 Comparison with CIP Concrete

Shotcrete is pneumatically conveyed and sprayed at high velocity to existing structures without external vibration. Processes of pumping and shooting greatly affect the behavior and properties of shotcrete when compared with cast-in-place (CIP) concrete. These properties include fresh concrete/shotcrete related properties (i.e., slump, air-void system, setting time, etc.) and hardened concrete/shotcrete properties (strength, chloride permeability, rate of water absorption, durability, etc.). Hover and Phares (1996) and Choi (2016) concluded that shotcrete had lower air content and smaller spacing factor than CIP concrete with the same mixture (e.g., approximate 10% of air content was loss after shooting). Wang et al. (2015b), Choi (2016), and Zhang (2016) also found that shotcrete exhibited higher compressive and splitting tensile strength, better permeability and durability due to lower air content after shooting.

# Chapter 3 MATERIALS AND EXPERIMENTAL TESTING PROGRAM

The goals of this study are to evaluate effect of curing practices on early shrinkage behavior of shotcrete and develop test methods for long-term performance and durability, in comparisons with cast-in-place (CIP) concrete. The testing results for CIP concrete can be found from previous reports of WSDOT projects: WSDOT T4120-08 “Mitigation Strategies for Early-Age Shrinkage Cracking in Bridge Decks” (Qiao et. al., 2010) and WSDOT 13A-3815-5188 “Concrete Performance Using Low-Degradation Aggregates” (Qiao et. al., 2012). In the following sections, the materials and experimental testing program for both shotcrete and CIP concrete mixtures in this study are presented.

## 3.1 Materials

The cementitious materials, including Portland cement Type I-II, silica fume (SF), and ground granulated blast-furnace slag (GGBFS), were provided by Lafarge NA-PNW District. Coarse aggregate and fine sand were provided by the Pre-mix, Inc., a local concrete company in Pullman, WA. The nominal maximum size of coarse aggregate is 3/8 inch in this study. The grain size distributions of coarse aggregate and fine sand from sieve analysis in accordance with ASTM C136 (2014) are presented in Table 3.1. The coarse aggregate and fine sand for shotcrete meet the requirements of AASHTO #8 and WSDOT Class 2 Sand. The fine sand for CIP concrete meets the requirements of WSDOT Class 1 Sand. The corresponding specific gravity and water absorption are determined in accordance with ASTM C127 (2015) and ASTM C128 (2015), respectively, and their values are also given in Table 3.1.

Table 3.1 Grain size distribution of aggregates (sieve analysis)

| Type | Shotcrete, Cumulative % Passing | | CIP, Cumulative % Passing | |
|---|---|---|---|---|
| Sieve Size | Coarse aggregate | Fine aggregate | Coarse aggregate | Fine aggregate |
| 1/2 | 100 | -- | 100 | -- |
| 3/8" | 99.1 | 100.0 | 98.5 | 100 |
| 1/4" | 37.3 | 99.5 | 67.8 | 99.5 |
| #4 | 6.9 | 85.7 | 37.3 | 97.7 |
| #8 | 3.2 | 58.5 | 3.0 | 84.3 |
| #16 | 1.8 | 35.6 | 0.4 | 61 |
| #30 | 1.2 | 16.0 | | 42.2 |
| #50 | 0.9 | 4.8 | | 17.7 |
| #100 | 0.8 | 2.1 | | 4.1 |
| #200 | -- | -- | | 2.2 |
| Specific Gravity | 2.69 | 2.64 | 2.68 | 2.65 |
| Absorption Capacity, % | 1.21 | 1.89 | 1.20 | -- |

Two types of commercially available chemical admixtures are used to produce shotcrete: air entraining admixture (AEA) and high-range water reducing admixture (HRWRA), and both are produced by BASF Construction Chemicals, LLC. 1000 air-entraining admixture from Grace Construction Products is used to produce proper air content in the concrete mixes. Glenium 3030 NS, a polycarboxylate-based HRWRA is used to achieve the desired workability and pumpability. The volume contents of AEA and HRWRA for shotcrete are determined based on the measurements made on the fresh mixed shotcrete/CIP concrete in the trial mix design tests.

## 3.2 Mix Designs

Two mix designs considered for this study for the shotcrete and CIP concrete batches are summarized in Table 3.2 along with the benchmark mix design of shotcrete from the WSDOT (See Appendix).

Table 3.2 WSDOT mix designs

| Mixture | Cement ($lb/yd^3$) | Silica Fume ($lb/yd^3$) | GGBFS ($lb/yd^3$) | Coarse ($lb/yd^3$) | Sand ($lb/yd^3$) | w/cm | Water (lbs) |
|---|---|---|---|---|---|---|---|
| Shotcrete | 705 | 50 | 40 | 2120 | 790 | 0.34 | 267 |
| CIP Concrete | 564 | -- | -- | 1830 | 1270 | 0.48 | 272 |

## 3.3 Sample Preparations

Pumping and shooting are two of basic operation procedures in shotcrete constructions, whenever wet-mix shotcrete or dry-mix shotcrete is used. In previous studies, evaluation of shotcrete usually regards two terms: known as “before shooting” and “after shooting”, or known as “without shooting” and “with shooting”. Since the goals of this phase of the study is to provide best practices for shotcrete mainly with emphasis on shrinkage and durability issues, the effect of pumping and shooting is not investigated.

Mixing of constituents to produce shotcrete specimens is performed at the concrete laboratory of Washington State University by a concrete drum mixer with a volume of 3.5 cubic feet. The mixing procedures are briefly described as follows:

1. All the materials are batched by weight.

2. Two pounds of water and two pounds of cement are mixed together and then used to wet the inside drum of the concrete mixer. Then, the paste is dumped.

3. All the pre-weighted aggregates and sand are added into the mixer, and they are mixed for 1/2 minute.

4. All the pre-weighted cementitious materials (cement, silica fume and/or GGBFS) are added into the mixer. The air-entraining admixture (AEA) is added into half of the water, and the water solution is then added into the mixer. They are mixed for 3 minutes.

5. The rest water is added, and they are mixed for 2 minutes.

6. High Range Water reducing admixture (HRWRA) and SRA are added separately, and they are then mixed for 3 minutes.

7. The mix is rested for 2 minutes.

8. The mix is mixed for the final 2 minutes.

9. The slump test is first conducted.

10. The air content test is then conducted.

11. Necessary adjustments of HRWRA and AEA are made until the targeted slump and air content are achieved.

As soon as the mixing is completed, the fresh shotcrete is poured into oiled wooden/steel molds to cast specimens in accordance with ASTM C192 (2016). Specimens are externally vibrated for approximately 10 seconds using a vibrating table. The curing of all specimens consists of two phases: initial curing after casting and standard curing prior to testing. All specimens in the molds are initially cured in a vibration-free fog room with temperature 73.5 ± 3.5 °F (23.0 ± 2.0 °C) from the time of casting. After approximate 24 hours, specimens are demolded and began standard curing period. Specimens for mechanical tests are soaked in lime-saturated water storage tanks until testing age, while specimens for shrinkage tests are cured at a curing room with temperature of 73 ± 3°F (23

± 2°C) and relative humidity of 50 ± 4%.

### 3.4 Experimental Testing Plan

A series of tests are conducted to evaluate the properties of shotcrete/CIP concrete in fresh and hardened states. Slump and air content are tested to evaluate workability and pumpability of fresh shotcrete and ensure durability of hardened shotcrete. Similar or same to the test methods in hardened concrete, the hardened shotcrete properties tests included three categories. The Category 1 is related to the mechanical properties of shotcrete at different ages, such as compressive strength, flexural strength, and modulus of elasticity, etc. The Category 2 is related to the early-age shrinkage and shrinkage cracking tendency of shotcrete under different curing conditions, which is one of critical concerns in field construction and goals for producing best curing practices for shotcrete construction. The corresponding tests include free shrinkage tests and restrained ring tests under different curing methods. The Category 3 is related to the long-term durability of shotcrete under rapid freeze-thaw (F/T) actions, and the corresponding tests include dynamic modulus of elasticity test and cohesive fracture test to characterize degradation of material properties after different numbers of F/T cycles. The procedures for each test in the three categories above are briefly discussed in the following sections, and the tests considered in this study are summarized in Table 3.3 along with their corresponding ASTM/AASHTO standard test method designations. For all tests, at least three replicates are tested.

Table 3.3 Experimental testing program

| Properties | Test Methods | Condition |
|---|---|---|
| Fresh Properties of Shotcrete | | |
| Slump | ASTM C143 | Fresh |
| Air content | ASTM C231 | Fresh |
| Unit Weight | ASTM C138 | Fresh |
| Hardened Properties of Shotcrete | | |
| Air content | ASTM C457 | Hardened concrete<br>@ > 28 days |
| Compressive Strength | ASTM C39 | 6''*12'' cylinder<br>@3, 7, 14, 28, and 56 days |
| Flexural Strength | ASTM C78 | 3''*4''*16'' prism<br>@3, 7, 14, 28, and 56 days |
| Modulus of Elasticity | ASTM C469 | 6''*12'' cylinder<br>@3, 7, 14, 28, and 56 days |
| Free Shrinkage | ASTM C157 | 4''*4''*11.25 prism<br>Begin after initial curing of 1 days |
| Autogenous Shrinkage | ASTM C157 | 4''*4''*11.25 prism<br>Begin after initial curing of 1 days |
| Restrained Shrinkage | AASHTO T334 | Begin after casting |
| Freezing/Thaw Durability & Dynamic Modulus & Fracture Energy | ASTM C666<br>ASTM C215<br>RILEM 50-FMC | 3''*4''*16'' prism<br>F/T Begins after initial curing of 28days; @ 0, 60, 120, 180, 240, 300, and 600 cycles |

### 3.4.1 Properties of fresh shotcrete

The slump test (Figure 3.1) was performed following the procedures of ASTM C143 (2015) "Standard Test Method for Slump of Hydraulic Cement Concrete". Based on the pressure method, a Type-B Air Meter is used to measure air content, which follows ASTM C231 "Standard Test Method for Air Content of Freshly-mixed Concrete by the Pressure Method" (Figure 3.2). In the meantime, the unit weight of fresh shotcrete is determined following the procedures of ASTM C138 (2016) “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete”. Pumpability and shootability of fresh wet-mix shotcrete are important rheological parameters for construction practices (Yun et al., 2015a; 2015b). Air content of fresh wet-mix shotcrete is also critical for improving the air-void system and freeze-thaw durability of shotcrete (Morgan, 2003; Fonseca et al., 2015; Choi et al., 2016). After transportation and delivery, pumping and shooting, air content of in place shotcrete will decrease a lot (US Army Corps of Engineers, 1993; Choi, et al., 2016). It is usually recommended that slump of 4 in. to 8 in. and air content of 8-20% is acceptable for fresh shotcrete. Thus, the amounts of HRWRA and AEA are adjusted to achieve a slump target (i.e., 5 inch) and a target air content (i.e., 10%).

Figure 3.1 Slump test


Figure 3.2 Air content test by pressure method

### 3.4.2 Mechanical properties of hardened shotcrete

Three basic mechanical properties for the hardened shotcrete/CIP concrete are evaluated at different ages: compressive strength, modulus of elasticity, and flexural strength.

The compressive strength test is conducted on 6 inch × 12 inch cylinders following the procedures of ASTM C39 (2017) "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (Figure 3.3). The compressive test is conducted under a specific stress rate, 35 ± 7 psi/s. Therefore, the required loading rate is calculated corresponding to the size of the specimen, i.e., 60000 ± 12000 lbf/min.

The modulus of elasticity test is conducted following the procedures of ASTM C469 (2014) "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" (Figure 3.4). The load is applied corresponding to a specific stress rate, 35 ± 7 psi/s, until it reached 40 % of the average ultimate load of the 6 inch × 12 inch cylindrical specimens.

The flexural strength test is performed in accordance with ASTM C78 (2016) "Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with

Third-Point Loading)” (Figure 3.5). A constant loading rate is applied under a specific tensile stress rate within the range of 125 to 175 psi/min, i.e., 5,000 to 7,000 lbf/min for the 3 inch × 4 inch × 16 inch prisms.

Figure 3.3 Compressive strength test


Figure 3.4 Modulus of elasticity test


Figure 3.5 Flexural strength test (3 inch × 4 inch × 16 inch prism, span: 12 inch)

### 3.4.3 Shrinkage

#### *3.4.3.1 Curing regimes*

Shrinkage in shotcrete exhibits due to rapid loss of water after placing, cement hydration, evaporation of water, etc. In field construction, keeping watering shotcrete structures is important to minimize shrinkage cracking since it reduces shrinkage at early age as well as slightly accelerates strength growth. To achieve best curing practices of shotcrete, it is of great significance to evaluate impact of different curing conditions on early-age shrinkage and shrinkage cracking tendency. Apart from standard curing condition (i.e., drying from 1 day), a few curing regimes are also considered to minimize shrinkage and mitigate shrinkage cracking in this study. Prolonged moisture or watering curing for more than one day and up to as long as 10 days are first recommended since the drying shrinkage rate is very high at early age. In addition, sealing structure surface using curing compound to prevent water evaporation is proposed due to its more convenient operation than prolonged watering. More details are summarized in Table 3.4.

Table 3.4 Curing conditions (regimes) for best curing practices

| Curing Regimes | Condition |
|---|---|
| I: Drying from 1 day (Standard Curing) | - Daily watering for 1 day from casting |
| II: Drying from 4th day | - Daily watering for 4 days from casting |
| III: Drying from 7th day | - Daily watering for 7 days from casting |
| IV: Drying from 10th day | - Daily watering for 10 days from casting |
| V: Curing compound after 1 day | - Daily watering for 1 day from casting<br>-Seal all surface with curing compound |
| CIP concrete | - Daily watering for 1 day from casting |

Shrinkage characteristics of shotcrete concrete is a concern for crack control in design of concrete structures. Two types of shrinkage tests are conducted in this study: free shrinkage and restrained shrinkage tests. The free shrinkage test mainly provides the basic moisture related shrinkage characteristics of shotcrete without any restraint. However, in most cases, structures are under different boundary conditions and shrinkage-induced tension stress may cause cracking issues. Both the ASTM and AASHTO standards provide test methods for restrained shrinkage measurement and suggest the ring test to determine the relative cracking tendency among different concrete mixtures under a certain drying condition. These two test methods are based on the same theory and testing procedures; however, the dimensions of the concrete ring and allowable nominal sizes of coarse aggregate show some differences.

### *3.4.3.2 Free shrinkage test*

The shrinkage test of shotcrete is conducted in accordance with ASTM C157 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete". The geometry of prism specimens is 4 inch × 4 inch × 11.25 inch, which meets the requirements of ASTM C157. The length change of specimens is measured after 24 hours from casting by a linear variable differential transformer (LVDT) glued at two ends and automatically collected by DASYLAB software (Figure 3.6). After 1 day of initial moist curing, all specimens are continued to be cured following the regimes in Table 3.4. For curing regimes II ~ VI as shown in Table 3.4, the specimens are kept watering daily until certain days. For the curing regime V, specimens are sealed with a thin layer of curing compound on the surface to prevent moisture loss, which is similar to autogenous shrinkage test. After the curing regimes end, they are cured at a curing room with temperature of 73 ± 3°F (23 ± 2°C) and relative humidity of 50 ± 4%.

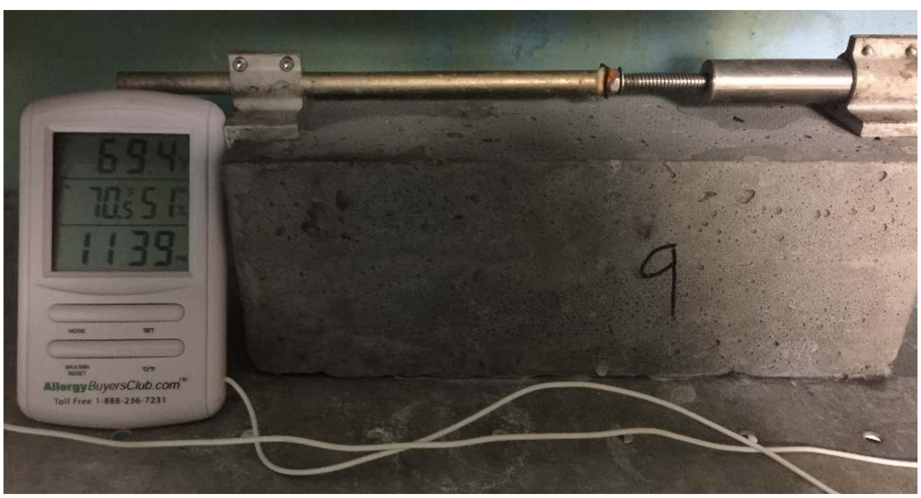



Figure 3.6 Free shrinkage test of shotcrete

### *3.4.3.3 Restrained shrinkage test*

In this study, the restrained shrinkage test is performed in accordance with AASHTO

T334 (2016) "Standard Method of Test for Estimating the Cracking Tendency of Concrete". The inside steel ring is cut from a steel tube with industry (allowable in AASHTO standard), and it has an outer diameter of 12.75 inch, a wall thickness of 1/2 ± 1/64 inch, and a height of 6 inch (Figure 3.7a). The outside ring is made of a plastic board with a thickness of 0.25 inch and an inner diameter of 18 inch, and it is supported around by plywood. The shotcrete ring is cast intermediately after mixing and covered with wet burlap followed with plastic sheet to prevent moisture loss from specimens for the first day. After this initial curing, the outer plastic board is demolded and the top surface is coated with a thin layer of paraffin wax to prevent moisture loss (see Figures 3.7b and 3.7c). The ring specimens are only allowed to present water evaporation through the outside surface. The steel strains are measured by four strain gages equidistantly mounted on the inner surface of the inside steel ring and automatically recorded by SmartStrain software at an interval of 1 second (Figure 3.7d). Shrinkage-induced cracking is visually inspected every 12 hours. Figure 3.7e shows a typical shrinkage-induced cracking of shotcrete after several days of drying.

(a) Restrained steel ring setup

(b) After casting with shotcrete

(c) Coating the top surface with paraffin wax

(d) Data acquisition system

(e) Typical shrinkage cracking

Figure 3.7 Restrained shrinkage test of shotcrete

### 3.4.4 Freeze-thaw durability

Evaluation of frost resistance of shotcrete includes both standard and non-standard approaches to characterize material degradation. Apart from non-destructive standard test protocol (e.g., ASTM C215 [2014]) to measure the dynamic modulus of elasticity of the conditioned samples, fracture energy test is accordingly conducted at different defined freeze-thaw cycles.

#### *3.4.4.1 Rapid freeze and thaw test*

The shotcrete prism samples are conditioned using the rapidly repeated freeze-thaw test in accordance with ASTM C666 Procedure A (2015), which is originally designed to evaluate the potential frost resistance of concrete in cold climates. The condition chamber used in this study is shown in Figure 3.8. The temperature range of $0^{o}$F to $40^{o}$F of the specimens is conditioned in the freeze-thaw cycles, and the conditioning machine runs six freezing-thawing (F/T) cycles per day.

Figure 3.8 Freeze-thaw conditioning chamber

### *3.4.4.2 Dynamic modulus test*

The dynamic modulus of elasticity of prismatic concrete samples is obtained at every 30 freeze-thaw cycles through the transverse frequency test in accordance with ASTM C215 (2014). Figure 3.9 shows the test setup for dynamic modulus of elasticity measurement, which is explained in detail in previous WSDOT research report "Concrete Performance Using Low-Degradation Aggregates" (Qiao et. al., 2012).

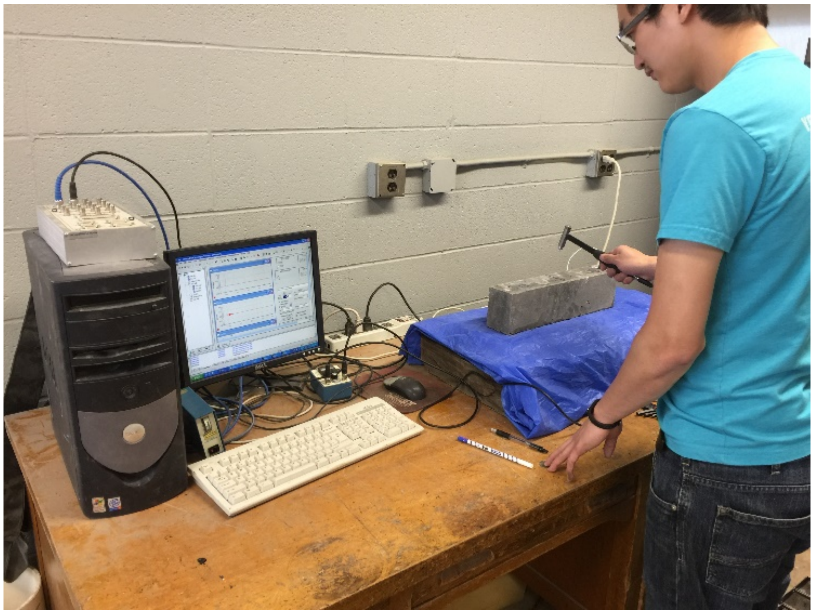


Figure 3.9 Dynamic modulus test setup at WSU

The dynamic modulus of elasticity, $E$, in Pascal (Pa) can be determined from the fundamental transverse frequency, mass, and dimensions of the test sample, and the equation is defined as:

$$E = CMn^2 \tag{3.1}$$

where: $M$ is the mass of the sample;

$n$ is the fundamental transverse frequency;

$C = 0.9464T\frac{L^3}{bt^3}$ for a prism;

*L* is the length of the sample;

*t* and *b* are the thickness and width of the sample, respectively.

*T* is a correction factor that depends on the ratio of the radius of gyration to the length of the specimen and the Poisson's ratio, 1.41 in this study.

The dynamic modulus of elasticity values of the concrete samples at different cycles are compiled and compared. The relative dynamic modulus of elasticity is calculated as the ratio of initial dynamic modulus at 0 cycle to that at certain number of freeze-thaw cycles. The decrease of the dynamic modulus of elasticity over the accelerated freeze-thaw cyclic conditioning indicates the degradation of concrete materials. It is not recommended that samples be continued in the test after their relative dynamic modulus of elasticity has fallen below 60%.

***3.4.4.3 Cohesive fracture test***

Cohesive fracture tests for both shotcrete and CIP concrete samples are conducted to evaluate the fracture energy of samples at different F/T cycles. The fracture energy is a material property that is as important as normal strength or modulus properties, and it is considered to characterize the material degradation under rapid freeze-thaw attacks (Chen and Qiao, 2015). The evaluation of fracture energy is performed based on a notched three-point bending beam (3PBB) with dimension of 3 inch × 4 inch × 16 inch, as shown in Figure 3.10. In this study, the depth of the notch is fabricated as half of the depth of the specimen using a diamond saw. More related information can be found in Qiao and Chen (2013).

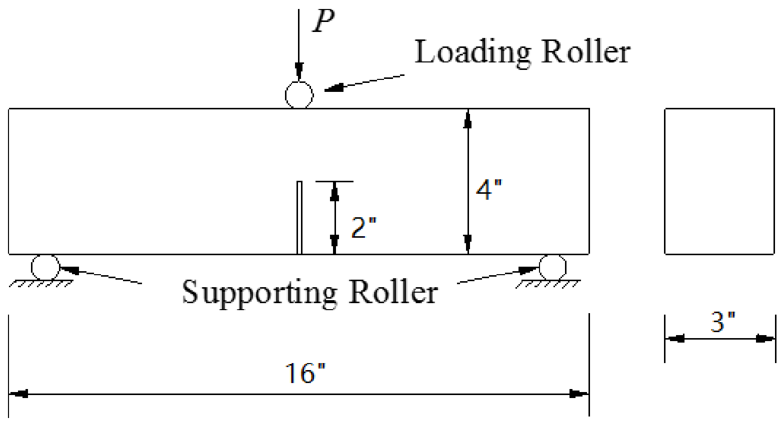



Figure 3.10 Sketch diagram of cohesive fracture test under three point bending

All the fracture tests are performed on an MTS servo-hydraulic testing machine using the test setup shown in Figure 3.11. The tests are conducted under displacement-controlled mode, i.e., at a loading rate of 0.0236 in./min. Two Linear Variable Differential Transducers (LVDTs) oppositely mounted in the beams are used to measure the mid-span deflection (MSD, $\delta$) of the test sample. The loading and mid-span deflections are simultaneously recorded by the machine.

Figure 3.11 Testing equipment setup for fracture test

Figure 3.12 illustrates a typical load-deflection ($P$-$\delta$) curve from a cohesive fracture test, in which $P$ is the measured load and $\delta$ is the average mid-span deflection of two LVDTs. The additional load $P_1$ is the self-weight of the specimen. Accordingly, the total work energy $W$ can be calculated using Equation 3.2.

$$W = W_0 + W_1 + W_2 \tag{3.2}$$

where $W_0$ is the area under the load-deflection curve; $W_1 = P_1\delta_0$ is the energy absorbed by the sample's self-weight, where $\delta_0$ is the deflection when the measured load is zero; and $W_2$ is the residual energy that need to fully separate the fractured sample into two halves after the measured load drops to zero, approximately equal to $W_1$. Therefore, the fracture energy can be calculated by:

$$G_F = \frac{W_0 + 2P_1\delta_0}{A_{lig}} \quad (3.3)$$

where $A_{lig}$ is the fractured area of the sample.

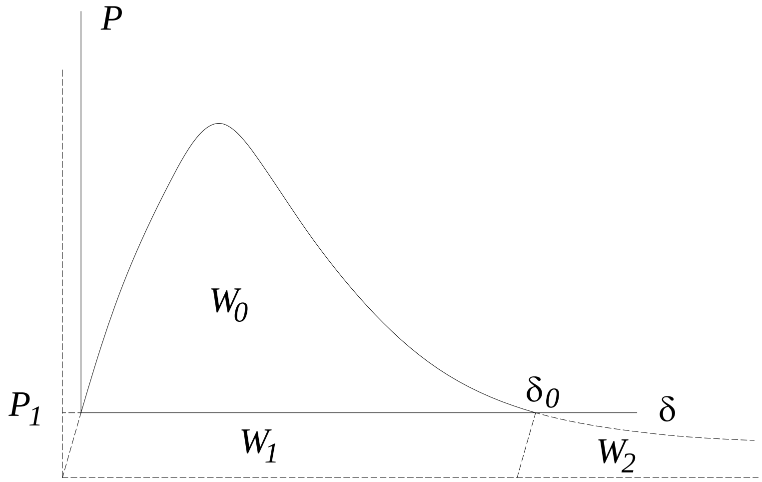



Figure 3.12 Typical load-deflection curve of cohesive fracture test

# Chapter 4 TEST RESULTS AND ANALYSIS

In this chapter, the results from the tests introduced and discussed in the previous chapter are presented and analyzed.

## 4.1 Test Results of Fresh and Hardened Shotcrete/CIP concrete

Three rheological properties are evaluated for the freshly mixed shotcrete/CIP concrete to achieve desirable mix designs: slump, air content, and unit weight. Afterwards, three basic mechanical properties are evaluated for the hardened shotcrete/CIP concrete of these desirable mix designs: compressive strength, modulus of elasticity, and flexural strength.

### 4.1.1 Slump, air content and unit weight tests

Slump and air content tests are conducted on fresh shotcrete to evaluate its workability and durability properties with adjustment of the dosages of HRWRA and AEA. Both the slump and air content tests for each batch are conducted three times. As illustrated in Table 4.1, the average measured slump and air content for the desirable shotcrete are 5 inches and 10.2%, respectively. It is obviously noticed that the air content of shotcrete is much higher than CIP concrete, resulting in lower unit weight. This is reasonable since a lot of entrained air is lost after pumping and shooting, and the unit weight increases as well.

Table 4.1 Slump, air content and unit weight of shotcrete and CIP concrete

| Mixtures | Slump (in.) | Air Content, % | Unit Weight, lb/ft$^3$ |
|---|---|---|---|
| Shotcrete | 5.0 | 10.2 | 137.7 |
| CIP | 4.0 | 4.8 | 148.8 |

### 4.1.2 Compressive strength and modulus of elasticity

The modulus of elasticity and compressive strength are measured at 7 days, 14 days, 28 days, and 56 days to study both stiffness and strength developments with age. Three replicates of specimens are tested for all the tests. The averaged test results for the compressive strength and modulus of elasticity are shown in Tables 4.2 and 4.3, respectively. Due to a lower water/cement ratio, shotcrete exhibits higher compressive strength and modulus of elasticity than CIP concrete.

Table 4.2 Compressive strength (unit: psi)

| Age | Shotcrete | STDEV | COV | CIP | STDEV | COV |
|---|---|---|---|---|---|---|
| 7 | 4549 | 190 | 4% | 3461 | 134 | 4% |
| 14 | 5354 | 320 | 6% | -- | -- | -- |
| 28 | 6665 | 220 | 3% | 4432 | 143 | 3% |
| 56 | 6887 | 370 | 5% | -- | -- | -- |

Table 4.3 Modulus of elasticity (unit: ksi)

| Age | Shotcrete | STDEV | COV | CIP | STDEV | COV |
|---|---|---|---|---|---|---|
| 7 | 2769 | 73 | 3% | 2950 | -- | -- |
| 14 | 3105 | 26 | 1% | -- | -- | -- |
| 28 | 3501 | 162 | 5% | 3400 | -- | -- |

### 4.1.3 Flexural strength (Modulus of rupture)

Shrinkage-induced cracking tendency of shotcrete is related to its tensile properties. Flexural beam bending tests is a standard method to evaluate the tensile strength of shotcrete. Flexural strength tests on 3 inch × 4 inch × 16 inch prisms are performed at 3 days, 7 days, 14 days, 28 days and 56 days to investigate the tensile strength gain versus time. The averaged testing results for the flexural strength are listed in Table 4.4 and also plotted in Figure 4.1. At 28 days, shotcrete and CIP concrete exhibited flexural strength of 772 psi and 748 psi, respectively. By comparing these two groups, shotcrete has approximately 5%-20% higher flexural strength than those of CIP concrete.

Table 4.4 Flexural strength (unit: psi)

| Age | Shotcrete | STDEV | COV | CIP | STDEV | COV |
|---|---|---|---|---|---|---|
| 3 | 530 | 46 | 9% | 412 | 35 | 9% |
| 7 | 588 | 18 | 3% | 499 | 30 | 6% |
| 14 | 683 | 12 | 2% | 594 | 98 | 17% |
| 28 | 772 | 24 | 3% | 748 | 6.4 | 1% |
| 56 | 820 | 30 | 4% | -- | -- | -- |

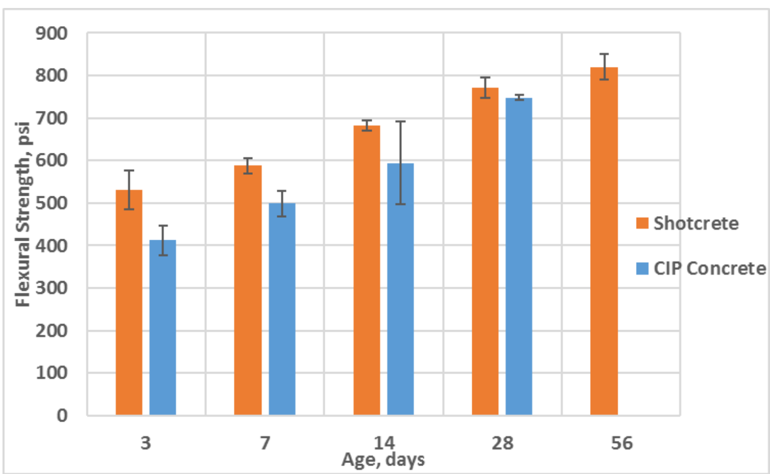



Figure 4.1 Comparison of flexural strength

## 4.2 Evaluation of Shrinkage

To evaluate effect of curing regimes on the shrinkage properties, two tests are performed for shotcrete and CIP concrete: free shrinkage and restrained shrinkage. The curing effect on shrinkage is only conducted for shotcrete.

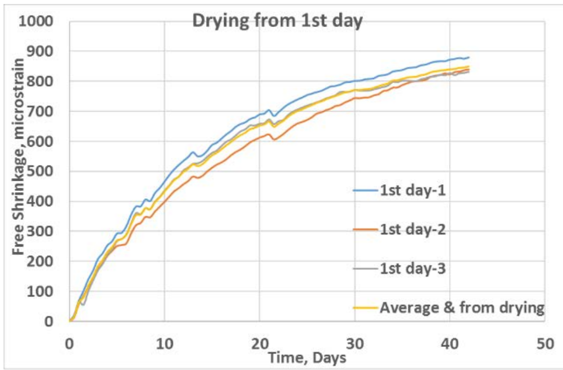
### 4.2.1 Free shrinkage test results

Free shrinkage of all specimens is automatically measured using LVDTs (Linear

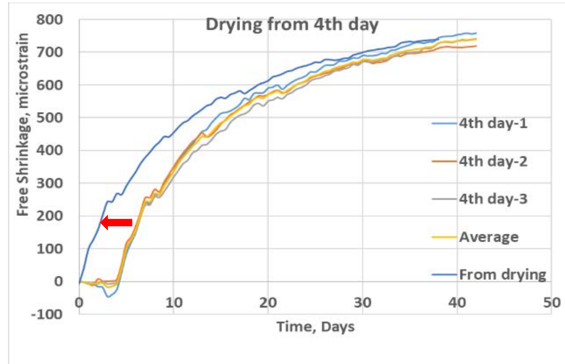
Variable Differential Transducers) immediately after demolding. All specimens are kept in a curing room with temperature of 73 ± 3°F (23 ± 2°C) and relative humidity of 50 ± 4%. The only difference for curing regimes is the surface treatment method, i.e., keep watering for certain days and seal surface with curing compound. However, the frequent watering actions at early days increases the relative humidity of the curing room.

Figure 4.2 provides the free shrinkage tendency diagrams of shotcrete under different curing regimes as shown in Table 3.4 and CIP concrete as well. To better understand the influence of prolonged watering on the shrinkage properties of shotcrete, the average shrinkage tendency of “from measuring” and “from drying” are comparatively depicted in Figure 4.3, where “from measuring” indicates original test data, while “from drying” indicates the test data is left shifted from the day of demolding to the day of stop watering. In addition, the average shrinkage values at the representative days (i.e., 7 days, 14 days, and 28 days) are listed in Tables 4.5 and 4.6 for “from measuring” and “from drying”, respectively.

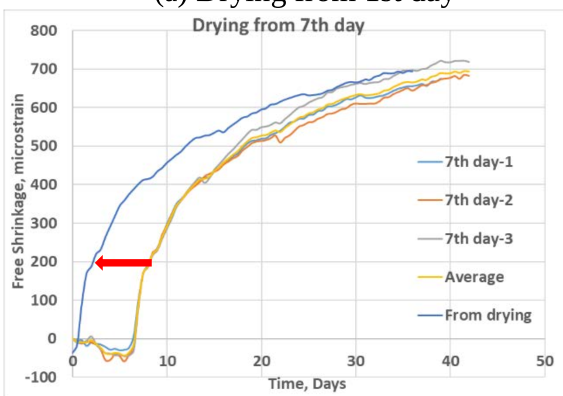
It can be seen from all the data in Table 4.6 and Figure 4.3b that the shotcrete with one day prolonged watering (curing regime I) shrinks the most, followed by CIP concrete; while shotcrete with longer watering curing and curing compound shrinks less. CIP concrete considerably exhibits lower free shrinkage than shotcrete because less cementitious materials are used in CIP concrete. When curing compound is applied to seal the surface of specimens to prevent internal moisture loss but without external moisture supply, the free shrinkage at 28 days is considerably reduced by 48%, compared with that of curing regime I. Thus, curing compound holds the great potential for shrinkage mitigation of shotcrete construction for wall fascia and slope stabilization.



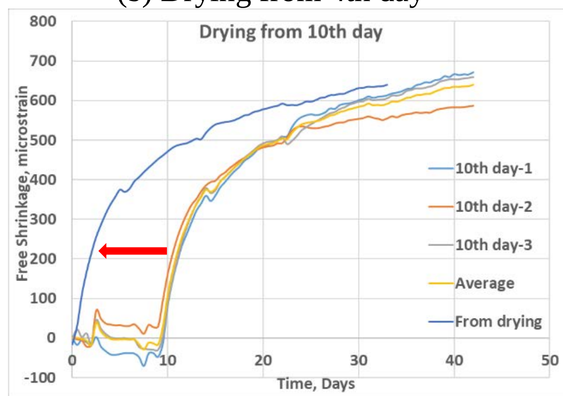

(a) Drying from 1st day



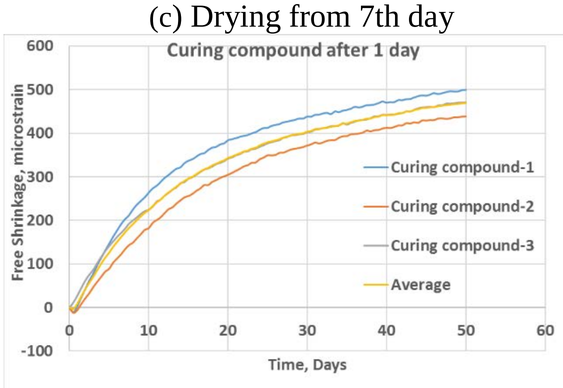

(b) Drying from 4th day



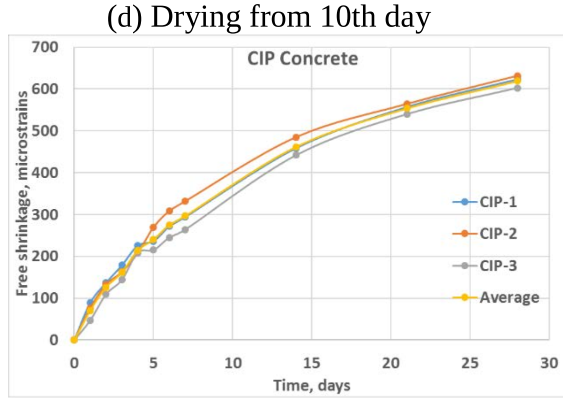

(c) Drying from 7th day




(d) Drying from 10th day

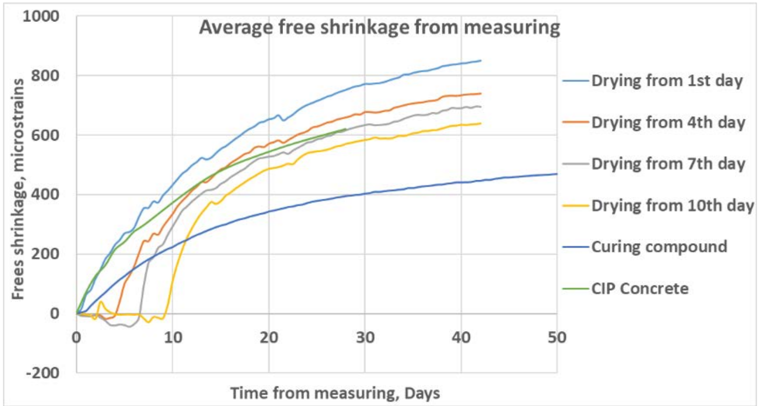



(e) Seal with curing compound after 1 day

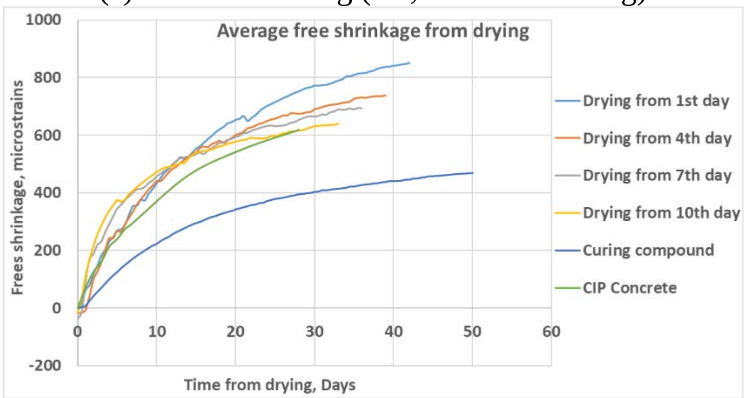



(f) CIP concrete-Drying from 1st day

Figure 4.2 Free shrinkage of shotcrete with different curing regimes and CIP concrete




(a) From measuring (i.e., since demolding)




(b) From drying (i.e., stop watering)

Figure 4.3 Comparison of free shrinkage

Table 4.5 Comparison of average free shrinkage values from measuring (unit: με)

| Age | 1st day | 4th day | 7th day | 10th day | Curing compound | CIP |
|---|---|---|---|---|---|---|
| 7 | 354 | 243 | 93 | -16 | 173 | 297 |
| 14 | 524 | 454 | 415 | 375 | 285 | 461 |
| 28 | 752 | 658 | 615 | 570 | 395 | 619 |

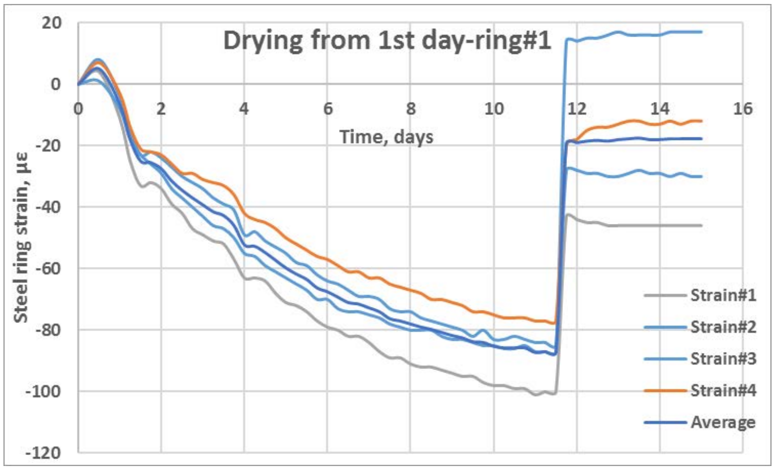
Table 4.6 Comparison of average free shrinkage values from drying (unit: με)

| Age | 1st day | 4th day | 7th day | 10th day | Curing compound | CIP |
|---|---|---|---|---|---|---|
| 7 | 354 | 336 | 402 | 407 | 173 | 297 |
| 14 | 524 | 525 | 527 | 518 | 285 | 461 |
| 28 | 752 | 675 | 654 | 616 | 395 | 619 |

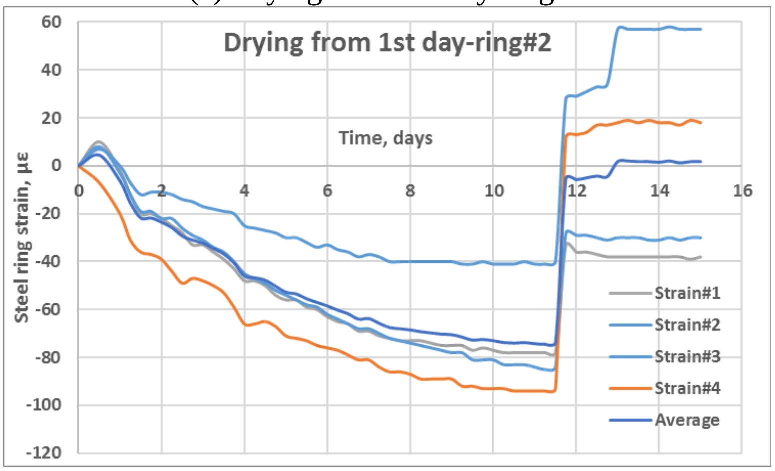
Prolonged watering also had significant influence on free shrinkage of shotcrete. The drying shrinkage is almost suspended/postponed until watering is stopped. From Figure 4.3a and Table 4.5, for curing regime I, II, III and IV, their free shrinkage at 28 days are 752, 658, 615, 570 macrostrains, respectively, indicating the longer shotcrete being kept moist, the smaller free shrinkage it induces. Based on Figure 4.3b and Table 4.6, it could be found that the longer moist cured specimens result in smaller ultimate shrinkage strains at long period but slightly higher shrinkage rate at early days. Therefore, prolonged watering to keep shotcrete from drying is highly recommended for practice.

### 4.2.2 Restrained shrinkage test results

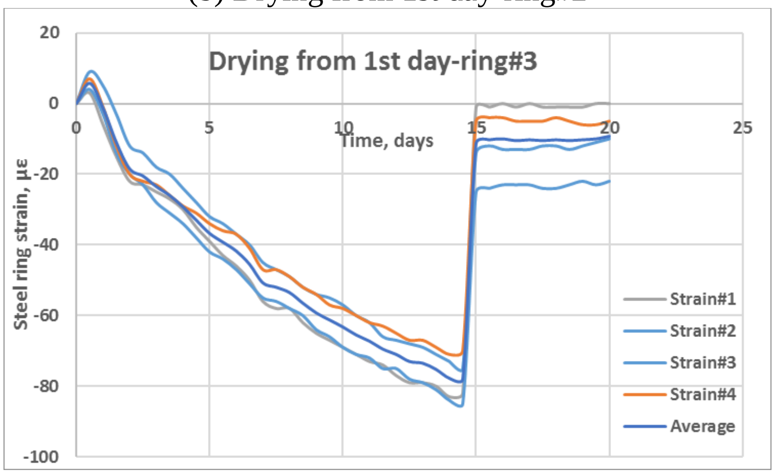
In parallel with free shrinkage test, the restrained shrinkage test is conducted to compare the shrinkage cracking tendency of shotcrete by different curing methods as well as mixtures. Figures 4.4 to 4.8 depict the testing results of restrained shrinkage performed on shotcrete following five different curing regimes in this study, where the measured steel strain versus test age are plotted. Figure 4.9 presents the testing results of restrained shrinkage performed on CIP concrete following the curing regime I in Table 3.4. Sudden jump in a shrinkage strain-time curve indicates the time of cracking of ring taking place. If no sudden jump is observed in the shrinkage strain curve in the given age (time), no cracking then occurs in the ring.




(a) Drying from 1st day-ring#1

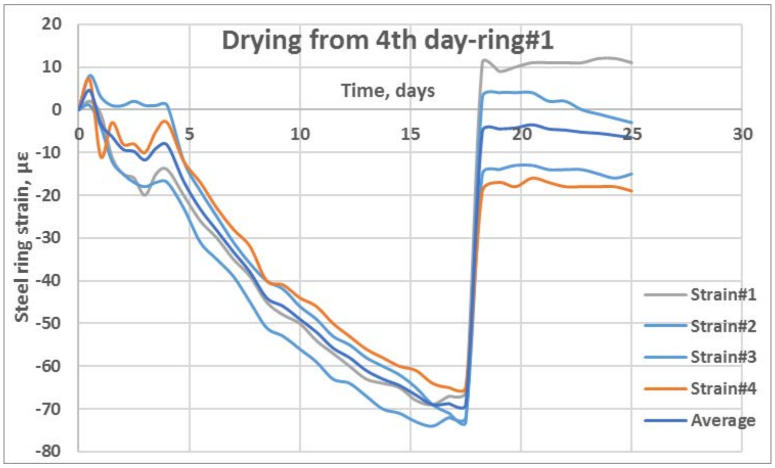



(b) Drying from 1st day-ring#2

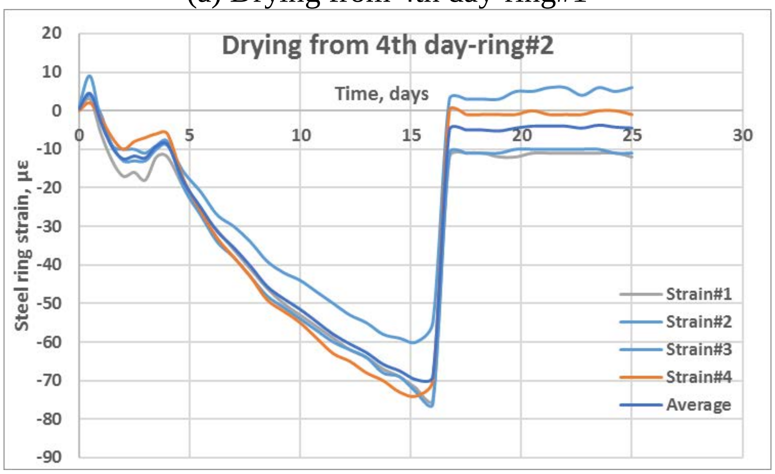



(c) Drying from 1st day-ring#3

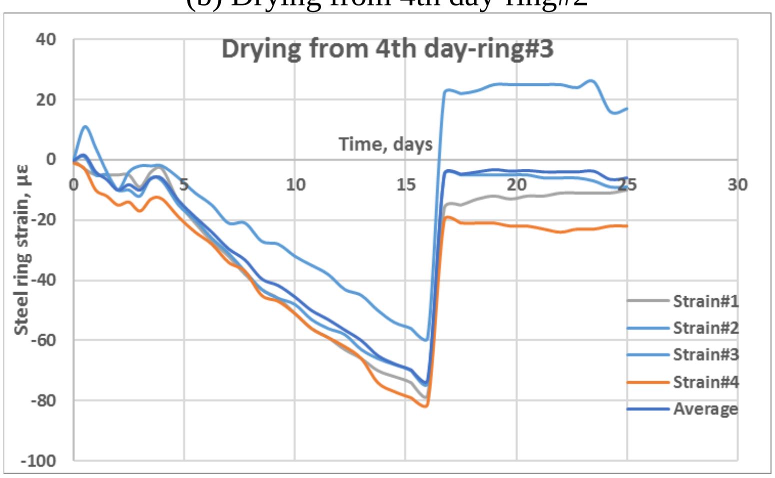
Figure 4.4 Restrained shrinkage of shotcrete under curing regime I




(a) Drying from 4th day-ring#1

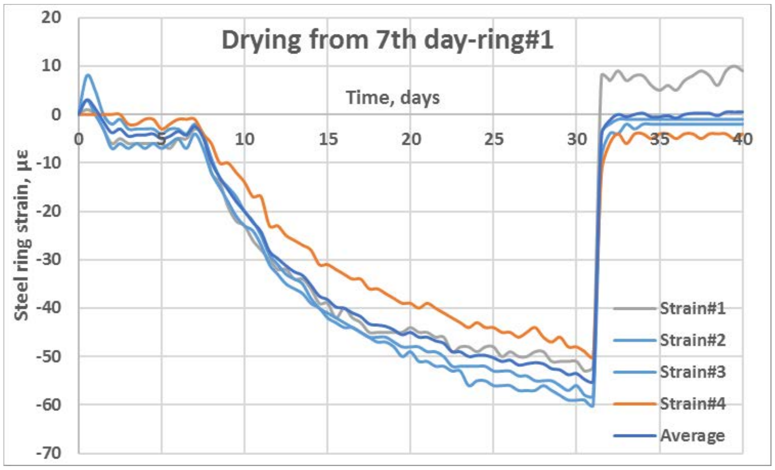



(b) Drying from 4th day-ring#2

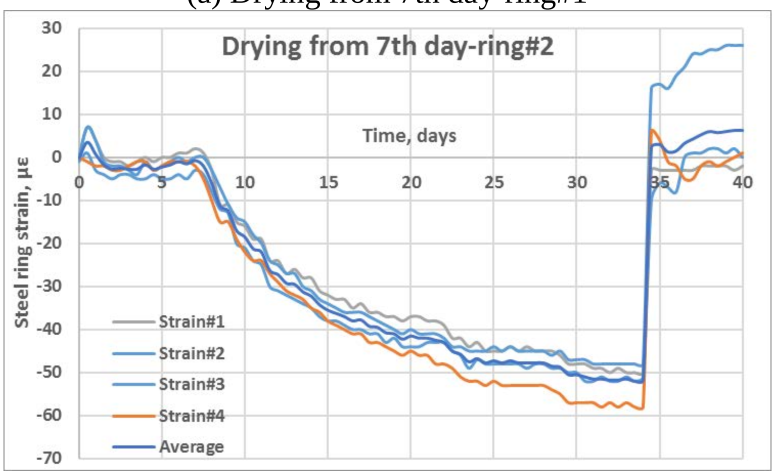



(c) Drying from 4th day-ring#3

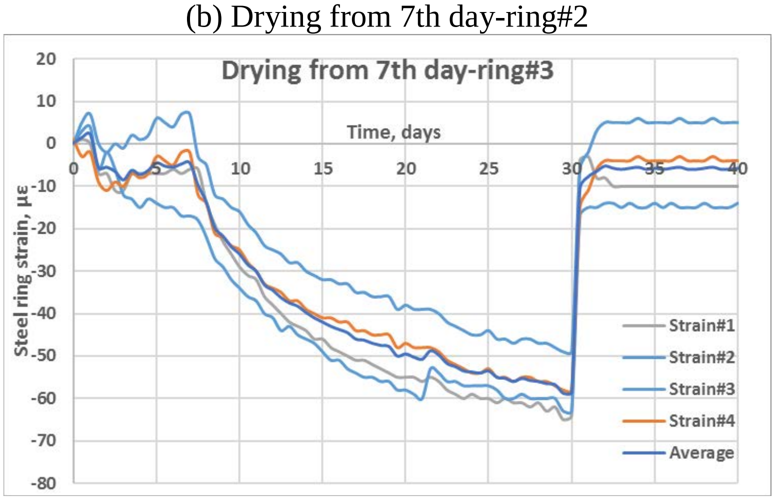
Figure 4.5 Restrained shrinkage of shotcrete under curing regime II




(a) Drying from 7th day-ring#1

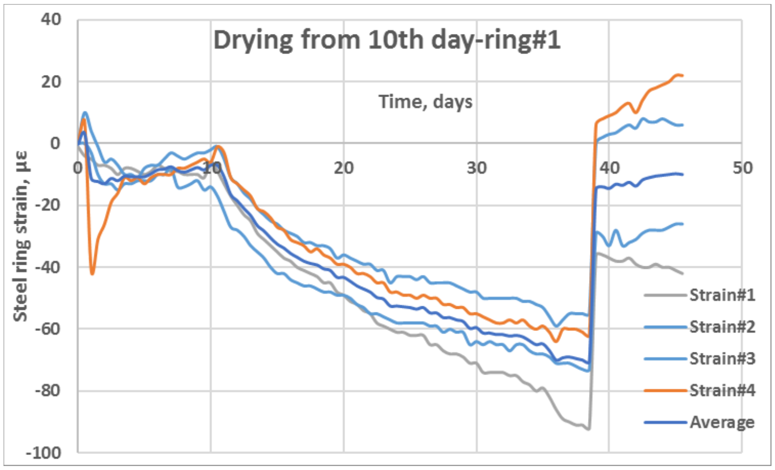



(b) Drying from 7th day-ring#2

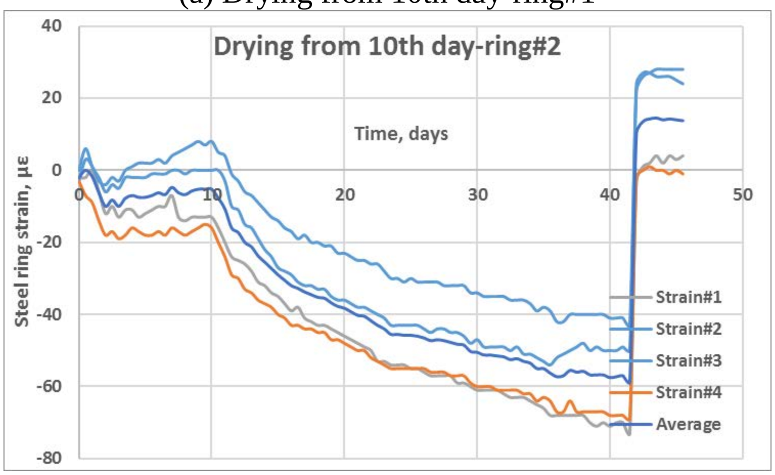



(c) Drying from 7th day-ring#3

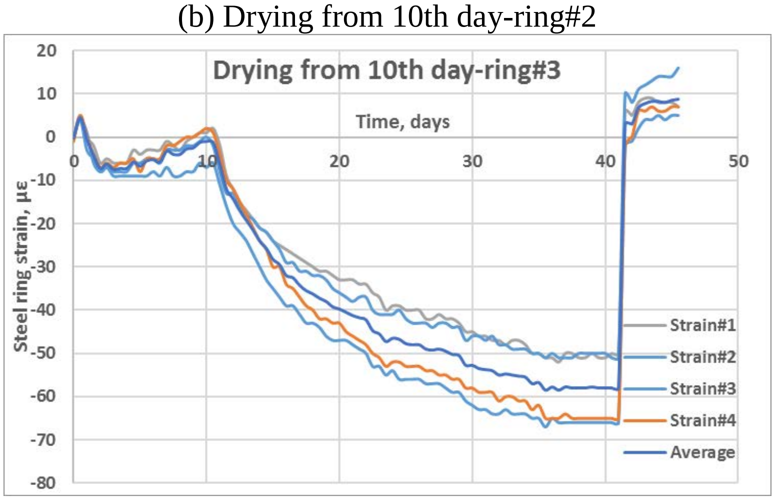
Figure 4.6 Restrained shrinkage of shotcrete under curing regime III



(a) Drying from 10th day-ring#1

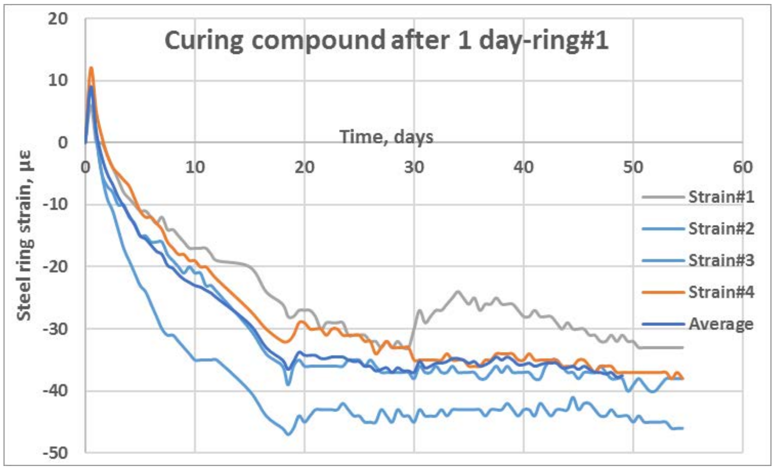


(b) Drying from 10th day-ring#2

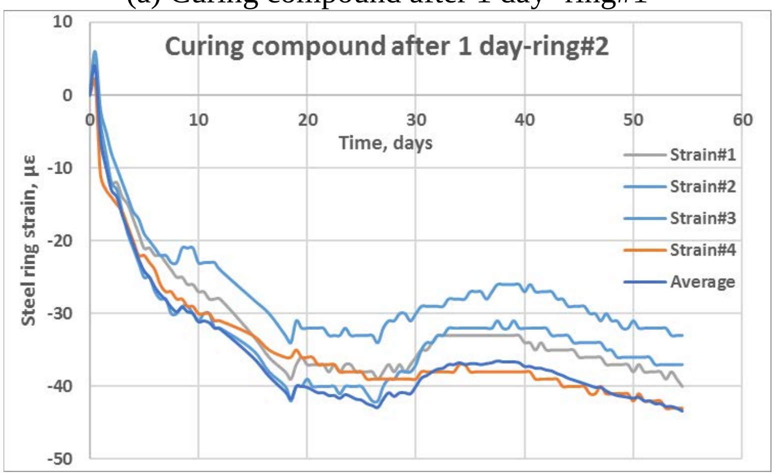


(c) Drying from 10th day-ring#3

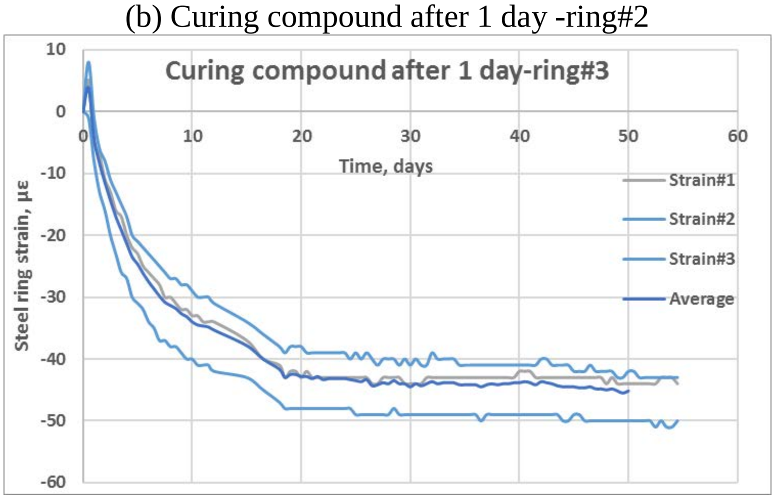
Figure 4.7 Restrained shrinkage of shotcrete under curing regime IV



(a) Curing compound after 1 day -ring#1

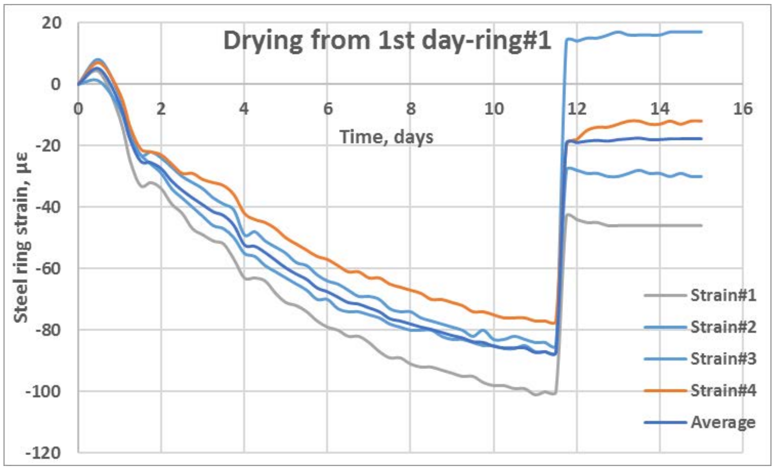


(b) Curing compound after 1 day -ring#2

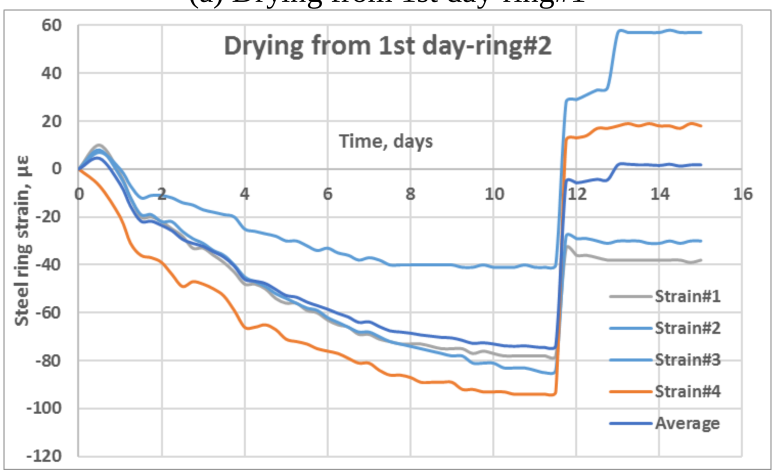


(c) Curing compound after 1 day -ring#3

Figure 4.8 Restrained shrinkage of shotcrete under curing regime V




(a) Drying from 1st day-ring#1




(b) Drying from 1st day-ring#2

Figure 4.9 Restrained shrinkage of CIP concrete under curing regime I

Based on the ring strain monitoring data from the ring test illustrated in Figures 4.4 to 4.9, the cracking ages of all ring specimens are listed in Table 4.7 and shown in Figure 4.10. It can be seen that CIP concrete crack the earliest (i.e., 7.6 days), followed by shotcrete with increasingly prolonged watering (i.e., 12.73 days, 16.80 days, 31.97 days, and 40.47 days for curing regimes I, II, III, and IV, respectively), whereas shotcrete with curing compound does not crack.

Table 4.7 Comparison of restrained shrinkage cracking ages from ring tests

| Condition | ID | Age at cracking | Average | Age from drying |
|---|---|---|---|---|
| Shotcrete-Regime I | Ring#1 | 11.64 | 12.73 | 11.73 |
| | Ring#2 | 11.57 | | |
| | Ring#3 | 14.98 | | |
| Shotcrete-Regime II | Ring#1 | 18.08 | 16.80 | 12.80 |
| | Ring#2 | 16.02 | | |
| | Ring#3 | 16.29 | | |
| Shotcrete-Regime III | Ring#1 | 31.33 | 31.97 | 24.97 |
| | Ring#2 | 34.17 | | |
| | Ring#3 | 30.41 | | |
| Shotcrete-Regime IV | Ring#1 | 38.57 | 40.47 | 30.47 |
| | Ring#2 | 41.78 | | |
| | Ring#3 | 41.05 | | |
| Shotcrete-Regime V | Ring#1 | No Crack | -- | -- |
| | Ring#2 | No Crack | | |
| | Ring#3 | No Crack | | |
| CIP Concrete-Regime I | Ring#1 | 6.7 | 7.6 | 6.6 |
| | Ring#2 | 8.5 | | |

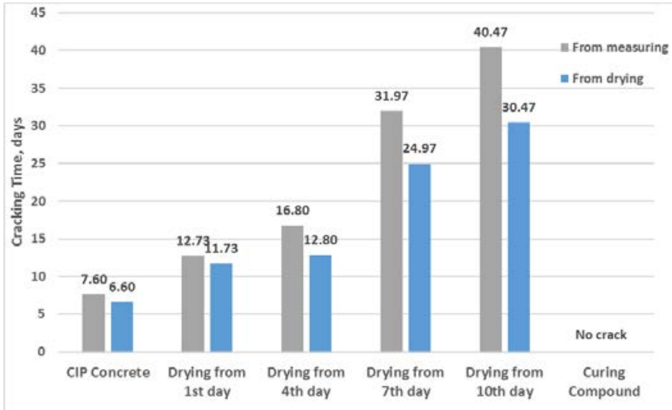


Figure 4.10 Comparison of restrained shrinkage cracking ages from ring tests

The cracking of a ring specimen is related to both free shrinkage and tensile properties of shotcrete. Based on the free shrinkage test results, the hypothetical free shrinkage values at the average cracking age of ring specimens of six groups are listed in Table 4.8, and they are 474, 532, 667, and 647 microstrains, for shotcrete under curing regime I, II, III, and IV, respectively, and 280 microstrains for CIP concrete.

Table 4.8 Comparison of average free shrinkage strain values at cracking (unit: με)

| Curing Regime | 1st day | 4th day | 7th day | 10th day | Curing compound | CIP |
|---|---|---|---|---|---|---|
| Shrinkage strain | 474 | 532 | 667 | 647 | -- | 280 |

Prolonged watering significantly postpones occurrence of shrinkage cracking since it prevents the shotcrete from drying at early age. Comparing the restrained shrinkage test results of shotcrete ring under curing regimes I, II, III, and IV, it can be found that the longer the watering action is applied to shotcrete, the slower the shrinkage cracking occurs. In addition, the hypothetical free shrinkage strain at cracking age increases if longer watering action is applied since it also has higher tensile strength at later period. When curing compound is applied to seal the surface of shotcrete ring specimens to prevent internal moisture loss but without external moisture supply, it leads to excellent shrinkage cracking resistance in comparison with other curing regimes. Since the shrinkage-induced tensile stress does not exceed the tensile strength, no crack is observed during the measuring period. This phenomenon coincides well with the free shrinkage test results, that is, when the free shrinkage values are low, the shrinkage-induced tensile stresses on specimen due to restraints are low. Even though CIP concrete exhibits lower free shrinkage than that of shotcrete, the ring specimens of CIP concrete still cracks earlier as it has lower flexural strength than shotcrete. Among these curing regimes for shotcrete, prolonged watering curing methods are beneficial to mitigate shrinkage cracking. Curing compound is potentially beneficial to mitigate shrinkage cracking, but more field practice experience and cost effect should be considered.

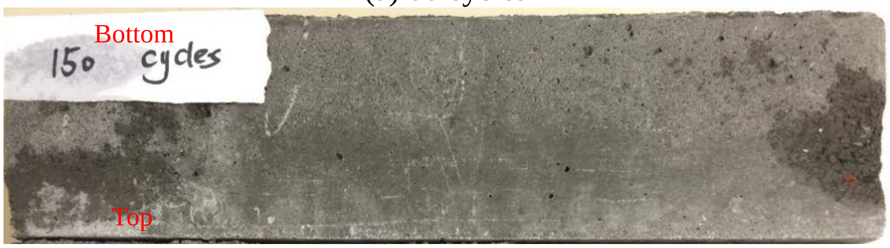
## 4.3 Evaluation of Freeze-Thaw Durability

A group of shotcrete beams are cast from the same batch for evaluation of freeze-thaw durability. After initial wet curing of 28 days, they are conditioned to investigate its long-term freeze-thaw durability in cold climates. The measured data, including mass loss and visual inspection of specimen appearance, transverse frequency, and fracture energy, are given in the following sections. The length change information of specimen is excluded due to lack of measuring equipment.

### 4.3.1 Surface scaling process and mass loss

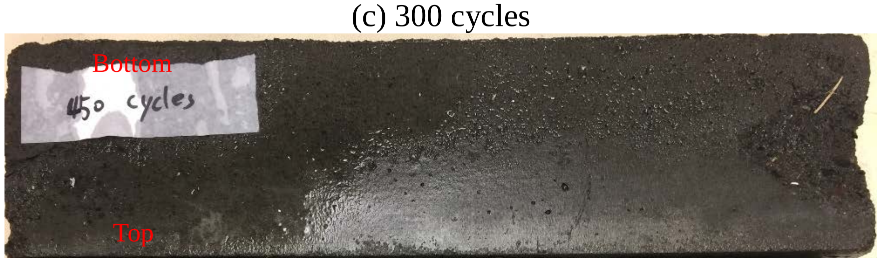
The appearances of a typical shotcrete sample at 0, 150, 300, 450, and 600 freeze-thaw cycles are illustrated in Figure 4.11. The mass reduction due to frost actions is mainly observed as the scaling of paste and mortar at the bottom surfaces and ends. The surface scaling in shotcrete becomes more and more serious with the increasing freeze-thaw cycles. Several small pieces of shotcrete at the ends are spalled after 600 cycles.


(a) 00 cycles

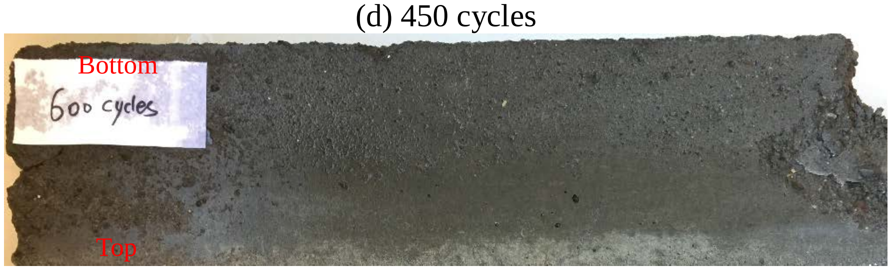



(b) 150 cycles


(c) 300 cycles



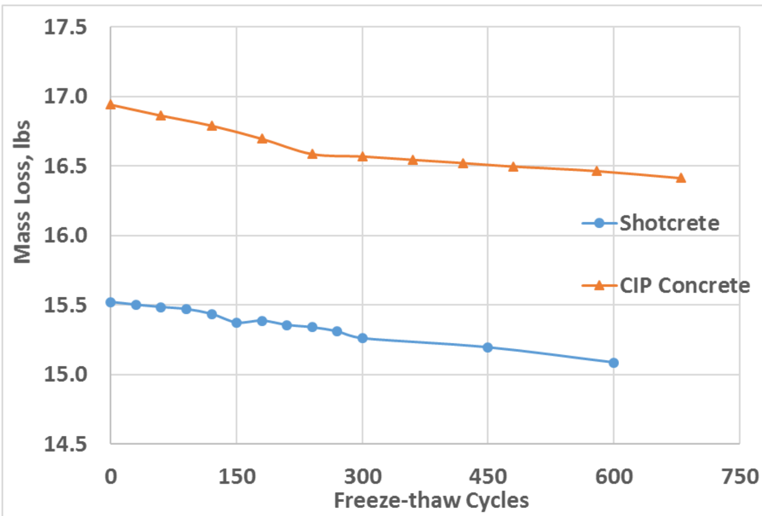

(d) 450 cycles



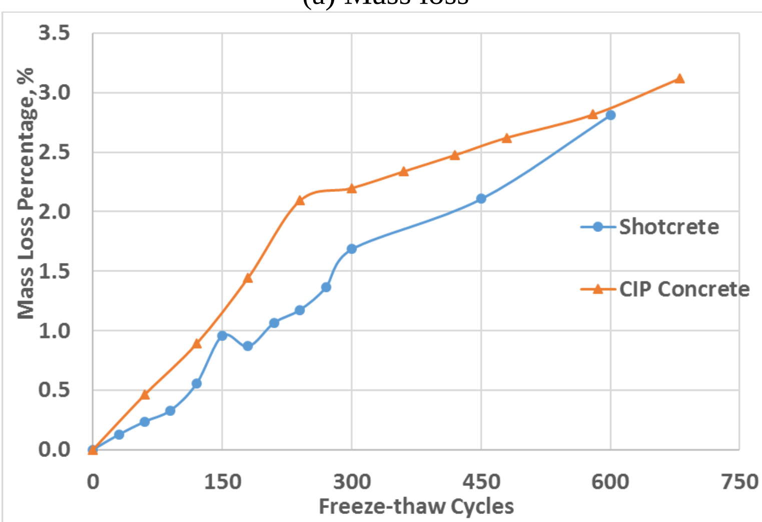

(e) 600 cycles

Figure 4.11 Appearances of shotcrete under rapidly repeated freeze-thaw actions

Mass reduction of concrete is mainly resulted from the scaling of paste and small mortar at the bottom surfaces and ends. The mass loss and loss percentage of two groups with respect to the freeze-thaw cycles are comparatively shown in Figure 4.12. Again, the initial mass of the shotcrete specimens with absent of pumping and shooting is lower than that of CIP concrete. It can be seen from Figure 4.12 that the mass of specimens keeps decreasing due to accumulative frost actions. The mass loss percentage are 1.68% and 2.20% after 300 freeze-thaw cycles for shotcrete and CIP concrete, respectively, and they are 2.81% and 2.90% after 600 freeze-thaw cycles for shotcrete and CIP concrete, respectively. Shotcrete exhibits less mass loss and lower mass loss percentage than CIP concrete, indicating that shotcrete has less severe frost damage.




(a) Mass loss




(b) Mass loss percentage

Figure 4.12 Comparison of mass loss due to freeze-thaw cycles

### 4.3.2 Dynamic modulus of elasticity

The vibration-based dynamic modulus of elasticity test using impact hammer is conducted on two groups of specimens subjected to freezing and thawing conditioning cycles. The natural frequencies from the transverse vibration test are initially measured at every 30 freeze-thaw cycles, as shown in Figure 4.13. Subsequently, the dynamic modulus of elasticity is calculated from the transverse frequencies through Equation 3.1. The dynamic modulus of elasticity and the relative dynamic modulus of elasticity for both groups with respect to the number of freeze-thaw cycles are comparatively illustrated in Figure 4.14. As shown in Figure 4.13 and Figure 4.14a, it is unexpected that shotcrete shows lower natural frequencies as well as smaller dynamic modulus of elasticity than those of CIP concrete. However, the relative dynamic modulus is necessary to compare the material degradation.

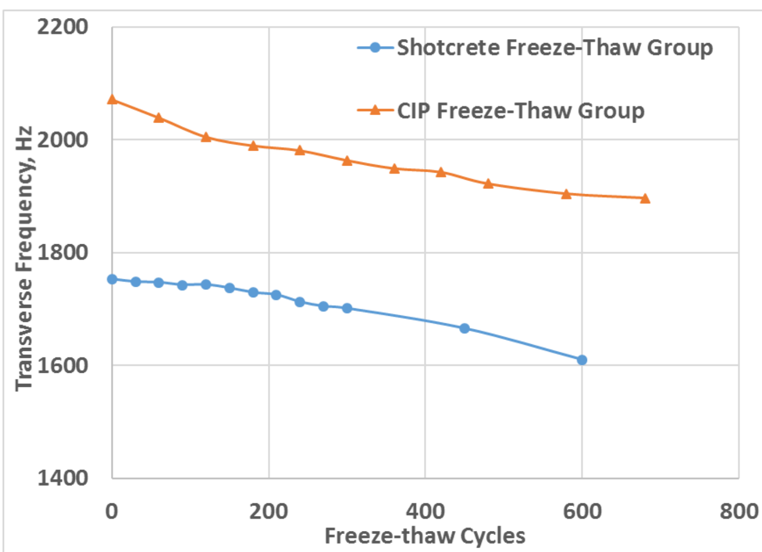
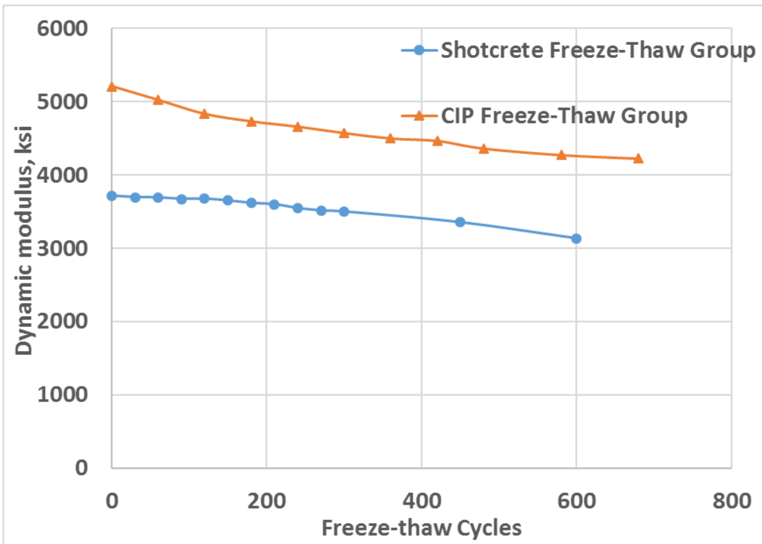


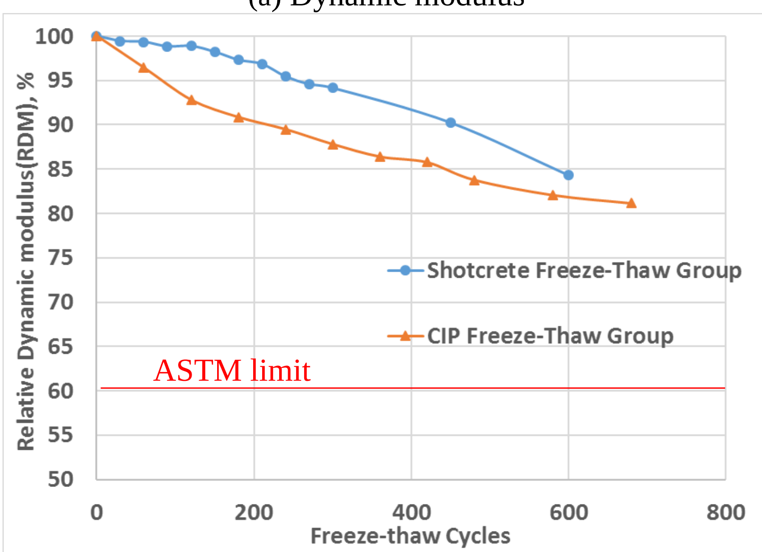

Figure 4.13 Comparison of transverse frequency

From Figure 4.14b, it can be observed that the relative dynamic modulus of shotcrete is much higher than those of CIP concrete. The relative dynamic modulus of shotcrete and

CIP concrete, known as the durability factor according to ASTM C666, are 94.15% and 87.82% after 300 freeze-thaw cycles, respectively, and they are 84.33% and 81.98% after 600 freeze-thaw cycles, respectively. The durability factors for both groups are still above the ASTM limit (i.e., 60% at 300 freeze-thaw cycles), which implies no frost failure occurs after as more as 600 cycles. In comparison with CIP concrete, shotcrete seems to be more durable in cold climates.




(a) Dynamic modulus



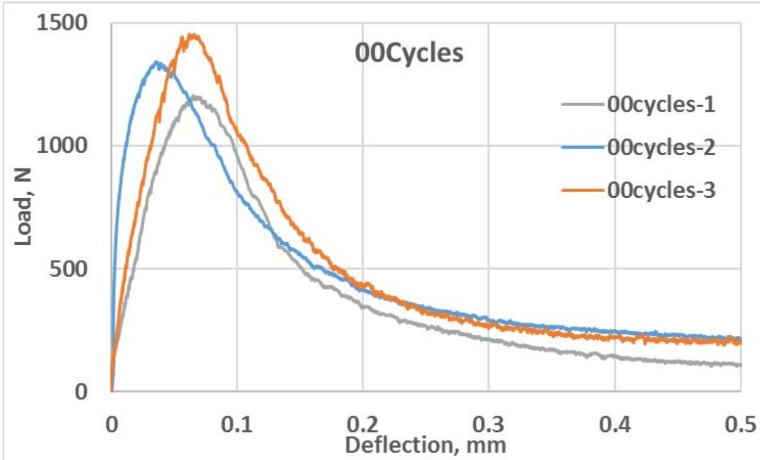

(b) Relative dynamic modulus

Figure 4.14 Comparison of dynamic modulus

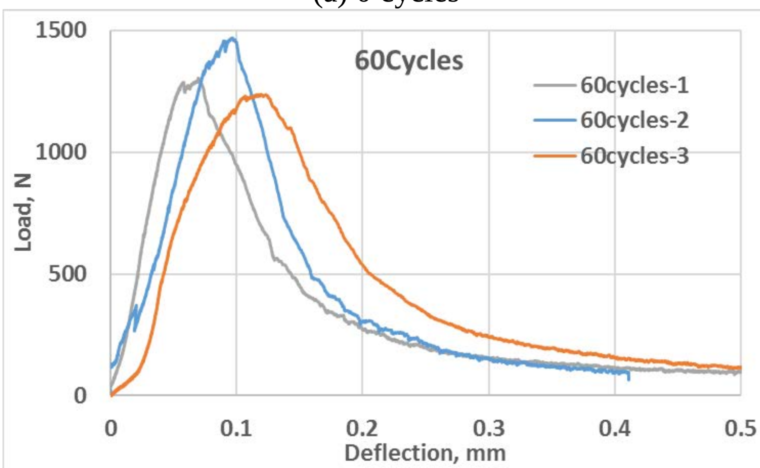
### 4.3.3 Fracture energy

In parallel with the non-destructive dynamic modulus approach, cohesive fracture test is conducted on two groups of concrete beams at different freeze-thaw cycles. More than 24 specimens with dimensions of 3 inch × 4 inch × 16 inch are cast from the same batch and conditioned in the chamber prior to test age. They are perpendicularly notched at the central span and then tested at every 60 cycles up to 300 cycles (i.e., 00, 60, 120, 180, 240, 300), and then tested at 450 and 600 cycles. At least three specimens are tested for each mentioned number of freeze-thaw cycles. The applied load and mid-span deflection are simultaneously recorded by the machine to obtain the load-deflection ($P$-$\delta$) curve for each sample. The load-deflection ($P$-$\delta$) curves for all specimens at given number of freeze-thaw cycles are plotted in Figure 4.15, where the applied load is read from the load cell while the deflection is the average mid-span deflection of two LVDTs.

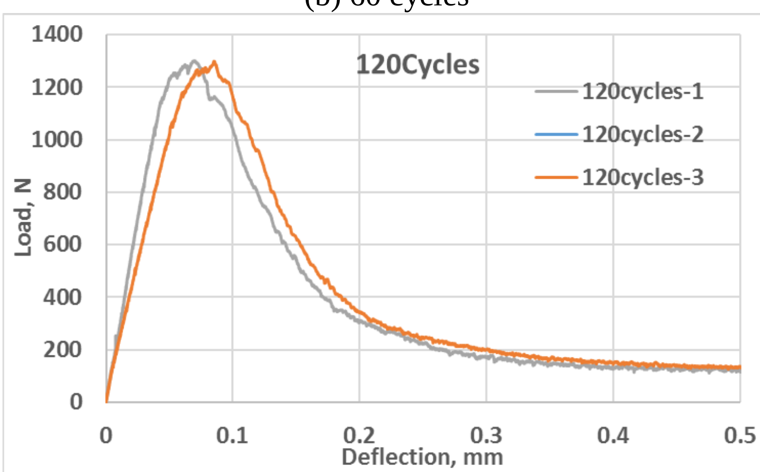
Based on the load-deflection curves, the total absorbed fracture energy values of all samples are then calculated through Equations 3.2 and 3.3. The peak load at fracture and total fracture energy of two groups of samples with respect to the number of freeze-thaw cycles are depicted in Figures 4.16 and 4.17, respectively. Similarly, to better compare the material degradation in terms of peak load and fracture energy, their relative percentages to the virginal (0 cycle or unconditioned) ones are also illustrated.



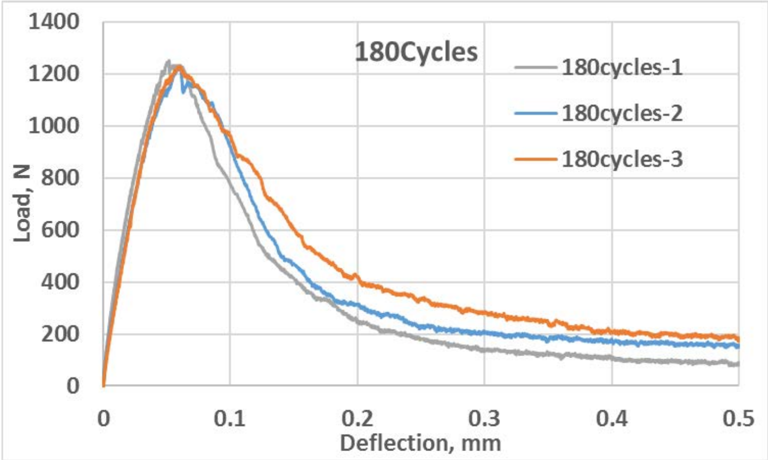

(a) 0 cycles



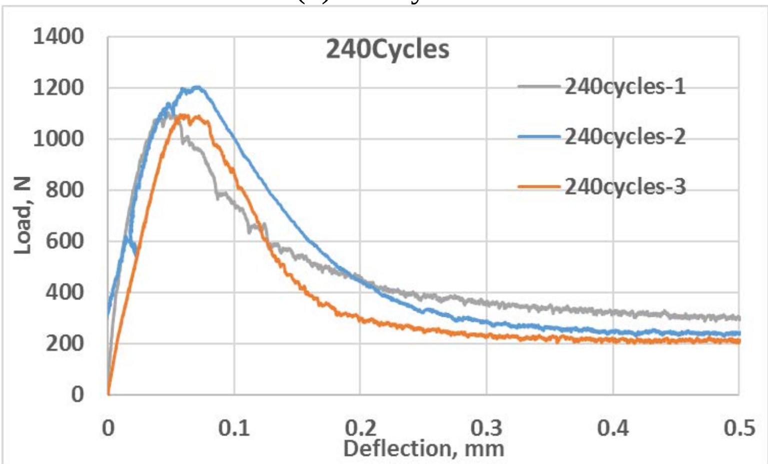

(b) 60 cycles



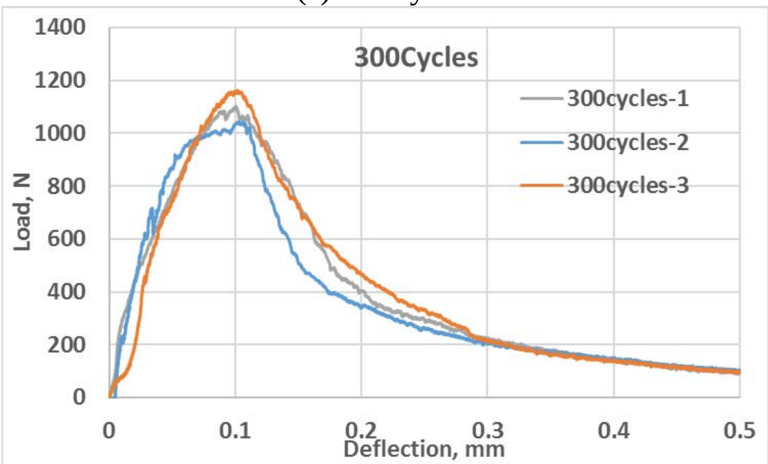

(c) 120 cycles



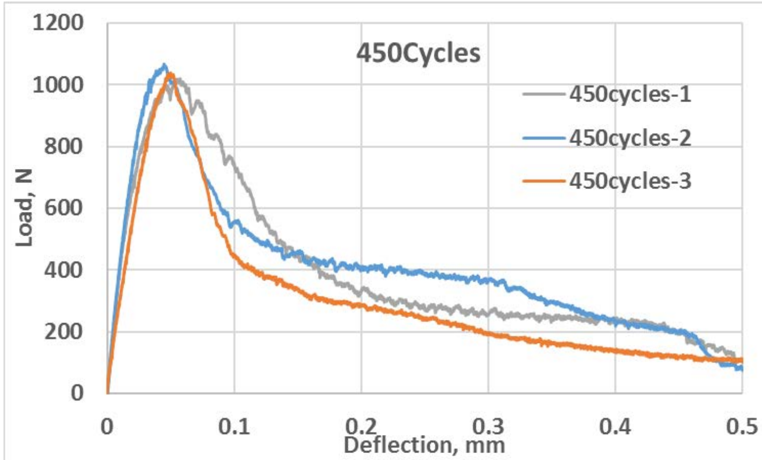
(d) 180 cycles



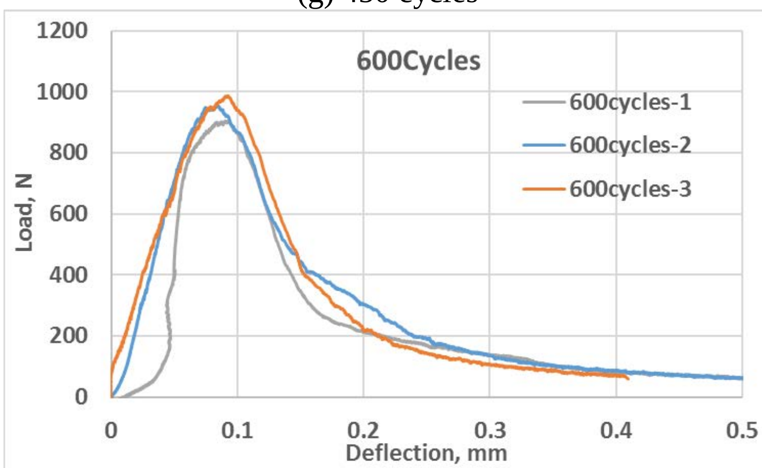
(e) 240 cycles



(f) 300 cycles

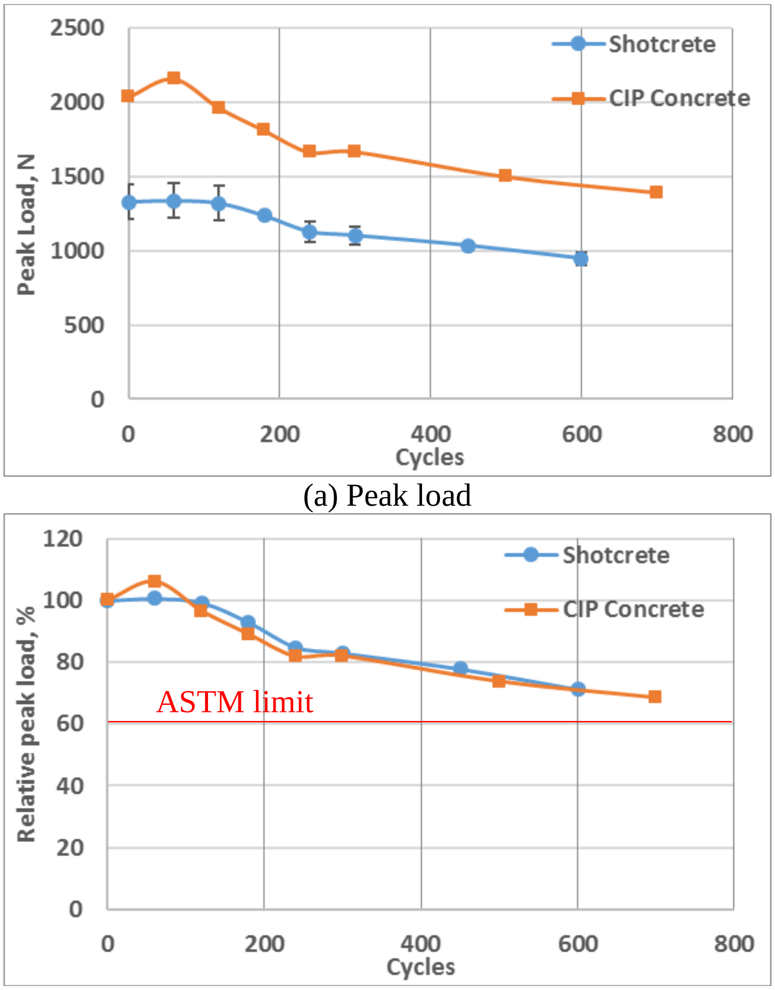


(g) 450 cycles



(h) 600 cycles

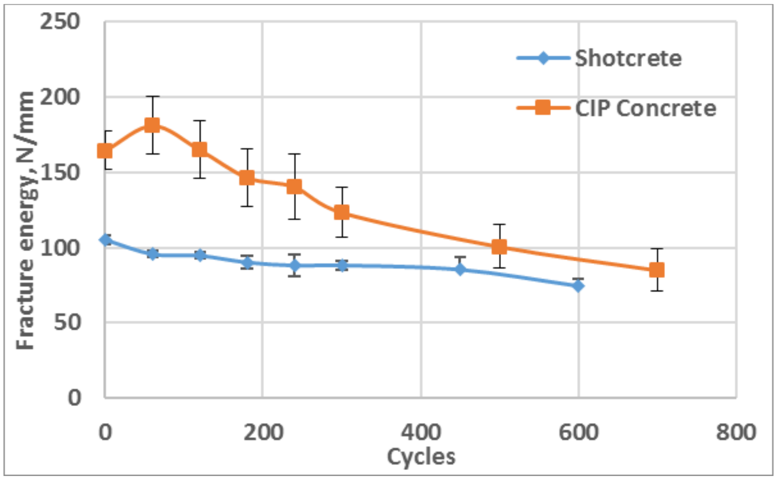
Figure 4.15 Load-deflection curves of shotcrete at different freeze-thaw cycles



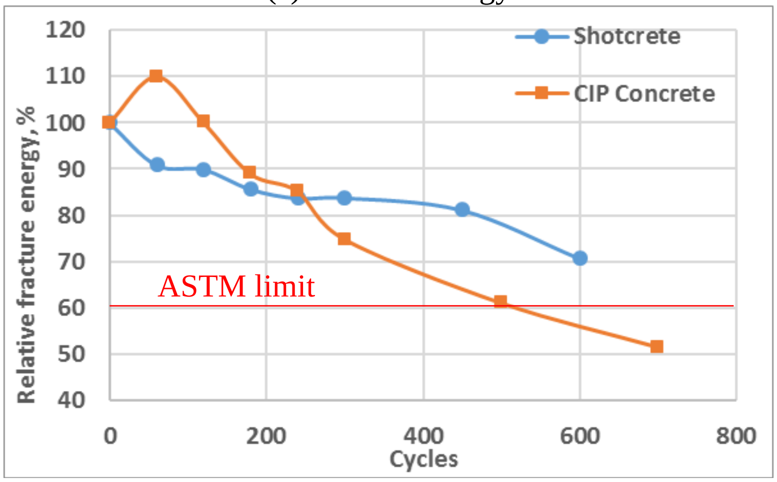
(a) Peak load

(b) Relative peak load

Figure 4.16 Comparison of modulus of elasticity




(a) Fracture energy




(b) Relative Fracture energy

Figure 4.17 Comparison of fracture energy

As shown in Figures 4.16a and 4.17a, the average flexural peak loads of shotcrete and CIP concrete samples keep decreasing due to accumulative freezing and thawing actions. An unexpected phenomenon can also be observed that the average flexural peak load and fracture energy of shotcrete samples are lower than those of CIP concrete samples at the same freeze-thaw cycle, so comparison of relative values should be emphasized.

As shown in Figure 4.16b, the relative peak load of shotcrete has very close decreasing trend (rate) with that of CIP concrete, which indicates that shotcrete has comparable freeze-thaw resistance. However, it is generally known that the peak load is only a sole point in a load-deflection curve while the total fracture energy considers the whole fracture work process separating the specimen. Thus, the fracture energy may be more representative than the peak load to characterize material degradation. It can be seen in Figure 2.17b that the decreasing trend of the total fracture energy is quite different between shotcrete and CIP concrete, that is, the relative decreasing ratio of fracture energy of CIP concrete is much larger than those of shotcrete. At 300 (ASTM benchmark) freeze-thaw cycles, the relative fracture energy decreasing ratios of shotcrete and concrete samples are 83.81% and 74.92%, respectively, compared to those of virginal samples. At 600 freeze-thaw cycles, the relative fracture energy decreasing ratio of shotcrete and concrete samples are 70.71% and 55.54%, respectively, compared to those of virginal samples. Obviously, shotcrete is more durable than CIP concrete based on the comparison of relative fracture energy.

### 4.3.4 Comparison of "Durability Factors"

The durability factor of concrete is an important parameter for material design to ensure its long-term life service. According to ASTM C666 (2015), the durability factor refers to the relative dynamic modulus of elasticity at 300 cycles or the specified number of cycles that freeze-thaw exposure is terminated. In this study, in comparison with dynamic modulus of elasticity, the facture energy is also considered to evaluate the freeze-thaw resistance of shotcrete and CIP concrete. Table 4.9 shows the durability factors of both groups at 300 and 600 cycles as determined from the dynamic modulus and facture energy tests.

Table 4.9 Comparison of durability factors of different test methods

| Method | | Durability Factor | |
|---|---|---|---|
| | | Shotcrete | CIP Concrete |
| @300 Cycles | Dynamic Modulus | 94.15% | 87.82% |
| | Fracture Energy | 83.81% | 74.92% |
| @600 Cycles | Dynamic Modulus | 84.33% | 81.98% |
| | Fracture Energy | 70.71% | 55.54% |

By comparing the durability factors from two test approaches in Table 4.9, it can be obviously found that the durability factors from relative fracture energy are much smaller than those from relative dynamic modulus, indicating that fracture energy test is a more sensitive test method than the dynamic modulus of elasticity one to capture material deterioration when subjected to rapidly repeated freezing and thawing actions as well as other types of accumulative damage and manifest degradation and aging effect of materials. More importantly, the fracture energy is associated with the full fracture of concrete cross section, and it better represents damage or degradation taking place both inside and on/near surface.

# Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Summary and Conclusions

The goal of this proposed project aims to provide best practices of shotcrete for wall fascia and slope stabilization. A comprehensive review of the state of academic and industry knowledge of shotcrete is first conducted, including its production and mix design, mechanical properties, short- and long-term performance, related quality assurance methods, and comparisons with CIP concrete.

From the literature review, the shrinkage cracking and durability issues are identified as two important performance aspects for best practices and quality assurance of shotcrete. Two types of mixtures (a desirable shotcrete mixture and a CIP concrete mixture) from the WSDOT are chosen for performance comparisons, including material properties in the fresh (e.g., slump, air content, and unit weight) and hardened (e.g., compressive strength, modulus of elasticity, flexural strength, shrinkage, and freeze-thaw actions) states. In particular, early age shrinkage and restrained shrinkage performance, and long-term freeze-thaw resistance through dynamic modulus of elasticity and fracture energy tests are emphasized.

Based on the comparatively experimental evaluation of basic material and mechanical properties, shrinkage and freeze-thaw resistance for shotcrete conducted in this study, the following finding/conclusions are drawn.

(1) Based on the literature review, the early age shrinkage and long-term durability issues and their related test approaches are identified when using shotcrete for wall fascia and slope stabilization. The shrinkage cracking tendency of shotcrete depends on a combined factor related to its tensile strength and free shrinkage property. As a key curing

regime, watering shotcrete surface at first several days is important to minimize its shrinkage cracking since it presents relatively low free shrinkage strain. Internal air-void system (air content and spacing factor) of hardened shotcrete has significant influences on durability of shotcrete. Addition of air entraining admixture results in well-distributed entrained air rather than entrapped air. Freeze-thaw resistance of shotcrete is improved with the increasing of air content and decreasing of spacing factor. The participation of silica fume in shotcrete mixture generally reduces mass of scaling residues and improves durability of shotcrete due to lower permeability.

(2) Following the ASTM standard test procedures for concrete and cementitious material characterization, the rheological properties tests (e.g., slump, air content, and unit weight) of freshly mixed shotcrete are conducted to achieve desirable mix design with acceptable workability (i.e., pumpability and shootability). Adjustment of the amount of air entraining admixture (AEA) and high-range water reducing admixture (HRWRA) are considered when producing shotcrete. The average slump and air content for the desirable "before shooting" shotcrete are 5 inch and 10.2%, respectively, which are much higher than those of considered CIP concrete.

(3) To achieve best curing practices of shotcrete to mitigate early age shrinkage cracking, a few curing regimes are applied in terms of prolonged watering and curing compound. In detail, four curing regimes with prolonged watering of 1 day, 4 days, 7 days and 10 days and one curing regime with curing compound are considered for evaluation of early-age shrinkage properties. The early-age free shrinkage test using prismatic specimens with dimensions of 4 × 4 × 11.25 inch in accordance with ASTM C157 and shrinkage cracking tendency test via rings in accordance with AASHTO T334 are performed.

(4) Based on the free shrinkage test, shotcrete with watering is found to shrink the most, followed by CIP concrete, while shotcrete with curing compound shrink the least. CIP concrete considerably exhibits a lower free shrinkage than shotcrete since less cementitious materials are used, leading to a higher water/cement ratio. Using curing compound to seal all surface of shotcrete specimens greatly prevents internal moisture loss even without external moisture supply, and it exhibits only 48% of free shrinkage compared to that without curing compound being applied. Prolonged watering also has significant influence on free shrinkage of shotcrete as drying shrinkage is almost suspended/postponed till the stop of watering, and it is also found that the longer shotcrete is kept wetting, the smaller free shrinkage it has.

(5) From the restrained shrinkage ring test, it is also found that the CIP concrete ring cracks the earliest (@ 7.6 days), followed by shotcrete with prolonged watering (at 12.73 days, 16.80 days, 31.97 days, and 40.47 days for curing regime I, II, III, and IV as shown in Table 3.4, respectively); while shotcrete with curing compound does not crack at all. Cracking of a ring specimen is characterized as the combined effects of free shrinkage and tensile strength. As expected, prolonged period of watering postpones shrinkage cracking due to lower free shrinkage at early age. The longer the watering action being performed on shotcrete rings, the slower shrinkage cracking occurs. Even though CIP concrete exhibits lower free shrinkage than that of shotcrete, the ring specimens of CIP concrete still crack earlier as it has lower tensile strength than shotcrete. Using curing compound to prevent specimens from drying provides the best practice; however, lack of field application experience, cost reasons, etc. may deter its application in the field.

(6) The long-term freeze-thaw durability of shotcrete and CIP concrete are evaluated using standard and non-standard approaches. The rapidly repeated freeze-thaw tests in accordance with ASTM C666 Procedure A are performed on 3 × 4 × 16 inch prisms. The non-destructive method, vibration-based dynamic modulus of elasticity test, is conducted following the ASTM C215 on two groups of specimens subjected to freeze-thaw conditioning cycles. In parallel, the destructive method, fracture energy test of shotcrete, is conducted by means of three-point bend test on notched beams. It demonstrates that both the dynamic modulus of elasticity and fracture energy tests are capable of determining the material deterioration due to accumulative freeze-thaw damage.

(7) The mass loss due to frost actions is visually observed as the scaling of paste and mortar at the bottom surfaces and ends. Both the dynamic modulus of elasticity and fracture energy for both shotcrete and CIP concrete mixtures keep decreasing with the freeze-thaw conditioning cycles. After 300 (ASTM benchmark) freeze-thaw cycles, the relative dynamic modulus of shotcrete and CIP concrete are 94.15 and 87.82, respectively; while the fracture energy of shotcrete and CIP concrete samples are 83.81% and 74.92%, respectively, compared to those of virgin samples. Obviously, shotcrete is more durable than CIP concrete based on the comparison of relative dynamic modulus and relative fracture energy.

(8) The decreasing trends or relative ratios are quite different between the two test methods, i.e., dynamic modulus of elasticity and fracture energy tests. The relative decreasing ratios of fracture energy are much larger than those of dynamic modulus of elasticity. In other words, the durability factors determined from relative fracture energy are much smaller than those from relative dynamic modulus of elasticity, indicating that

the fracture energy test is a more sensitive test than the dynamic modulus of elasticity one to screen material deterioration over time and capture accumulative material damage subjected to rapidly repeated freezing and thawing actions.

In summary, to provide best practices of shotcrete for wall fascia and slope stabilization, a desirable shotcrete mixture and a CIP concrete mixture from WSDOT benchmarks are tested for their related mechanical properties and evaluation of shrinkage and durability performance. The restrained ring test procedures follow AASHTO T334 are identified to be capable of evaluating early-age shrinkage cracking tendency of shotcrete; while the fracture energy test procedures are validated again to be more sensitive than the dynamic modulus of elasticity test in screening material deterioration /aging effect under freeze-thaw cyclic conditioning. As demonstrated in the laboratory testing, prolonged watering curing methods are beneficial to mitigate shrinkage cracking. Curing compound is potentially beneficial to mitigate shrinkage cracking, and more field practice experience is needed. The "before shooting" shotcrete studied in Phase I exhibits better early age shrinkage resistance and long-term freeze-thaw resistance than the considered CIP concrete.

## 5.2 Recommendations

The results of this study are limited to the mix designs and test methods used to explore proper use of shotcrete for wall fascia and slope stabilization. In particular, the early age shrinkage and long-term durability properties are mainly characterized. Based on the experimental program conducted in this study, the following recommendations are suggested for Phase II and/or future study to better understand performance of shotcrete:

(1) Only one mix design of shotcrete with water/cement ratio of 0.34 and compressive strength higher than 6,000 psi is considered and tested in this study. More mix designs by

adjusting the water/cement ratio, proportions of cementitious materials (i.e., cement, silica fume, GGBFS and Fly ash, etc.) are needed according to “Class of Concrete” in “Standard Specifications for Road, Bridge, and Municipal Construction” by Washington State Department of Transportation.

(2) All specimens of “before shooting” shotcrete are prepared for evaluation and testing of shotcrete mechanical properties; however, it cannot be identically equal to those from “after shooting” shotcrete. The comparisons of the mechanical properties and durability of “before shooting” and “after shooting” types of shotcrete should be considered.

(3) It is well known that the air-void system in shotcrete has significant influence on the mechanical properties and long-term durability performance. In this study, the air content is controlled as 10.2% before shooting, and its air-void system of hardened shotcrete, even after shooting, are still not clear. More laboratory evaluations should be performed to reveal the air-void characteristics.

(4) Early age shrinkage due to loss of moisture and shrinkage cracking tendency on shotcrete surface with a risk of decreasing quality and durability need to be completely investigated. Some other potential mitigation strategies, such as using shrinkage reducing admixtures (SRA), accelerators, expansive cementitious materials, silica fume, steel fiber, etc., can be proposed to reduce shrinkage cracking tendency.

(5) To better characterize long-term durability of shotcrete, other methods are recommended to screen damage process of pore structures and reveal failure mechanisms of shotcrete subjected to freeze-thaw actions, such as micro/nano X-ray imaging scanning, scanning electron microscopy (SEM), etc.

(6) In this study, only frost action is considered for durability evaluation of shotcrete. However, salty deicers are commonly used in cold regions to melt snow and ice and improve traffic safety, and resistance of shotcrete structures under more severe and combined frost and chemical attacks should be investigated. In addition, possible corrosion of reinforced bars cannot be neglected.

(7) Lack of bond to existing structures is pronounced for shotcrete as a repairing material and for slope stabilization. The bond strength and debonding mechanism at the interface area between shotcrete and substrates should be investigated.

(8) Most of the test methods commonly used to characterize shotcrete material properties and performance are adopted from the standard test methods (either ASTM or AASHTO or both) employed for concrete materials. There is a need to develop effective test methods specifically for characterization of shotcrete. Due to relative lack of study for shotcrete materials and structures, further study is needed to systematically develop best curing practices, recommendations for Q/A test methods, and guide specifications for shotcrete in retaining wall Fascias and slope stabilization.

(9) Based on laboratory accelerated test data (e.g., under rapidly cyclic freeze-thaw actions) and correlating them with field data, there is a need to develop life prediction methodologies for shotcrete using damage mechanics principles and statistical tools.

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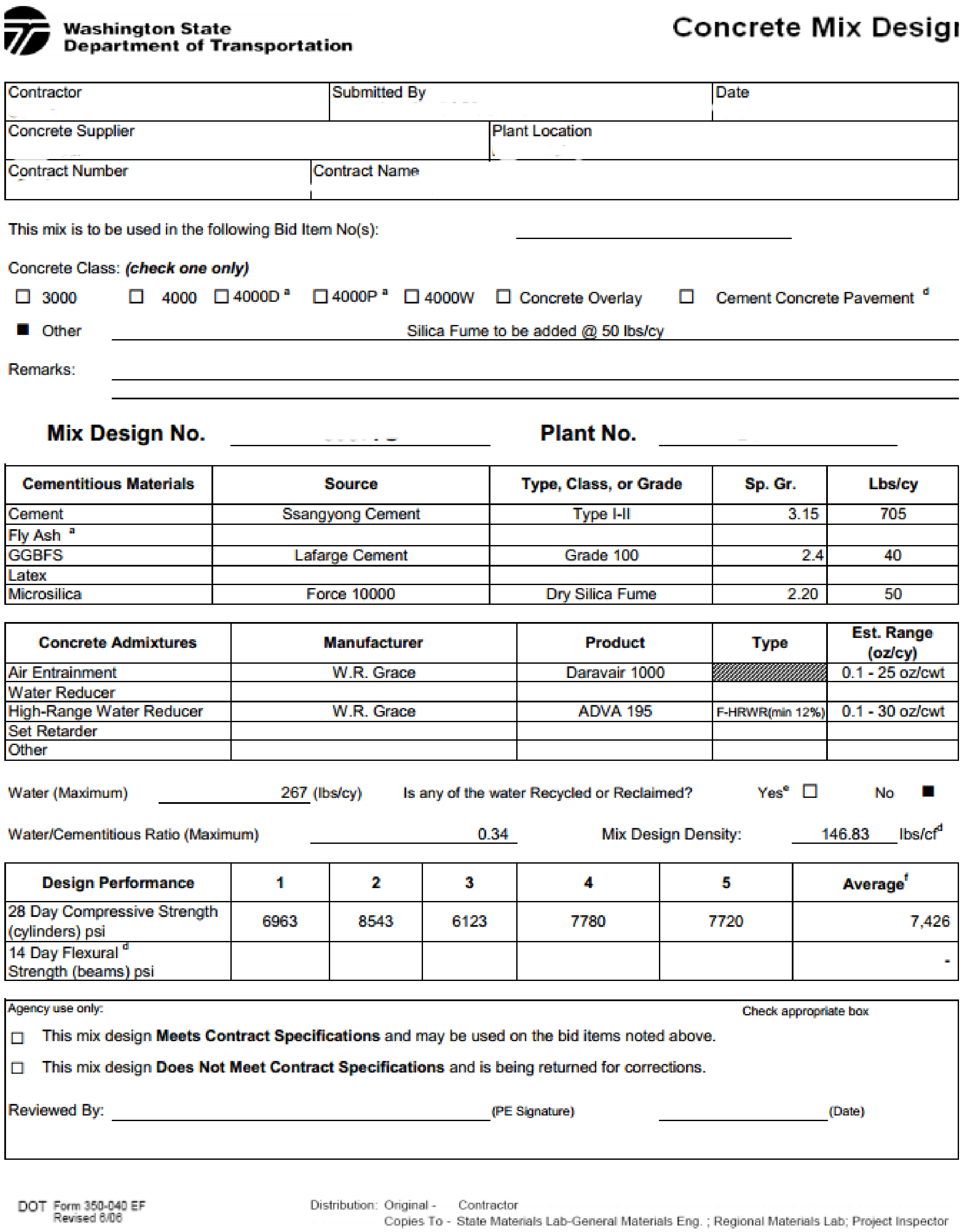
# APPENDIX

Appendix: Mix design for shotcrete



Washington State Department of Transportation

**Concrete Mix Desigı**

| Contractor | Submitted By | Date |
|---|---|---|
| Concrete Supplier | Plant Location | |
| Contract Number | Contract Name | |

This mix is to be used in the following Bid Item No(s): ____________

Concrete Class: ***(check one only)***

☐ 3000 ☐ 4000 ☐ 4000D [a] ☐ 4000P [a] ☐ 4000W ☐ Concrete Overlay ☐ Cement Concrete Pavement [d]

■ Other Silica Fume to be added @ 50 lbs/cy

Remarks: ____________

**Mix Design No.** ____________ **Plant No.** ____________

| Cementitious Materials | Source | Type, Class, or Grade | Sp. Gr. | Lbs/cy |
|---|---|---|---|---|
| Cement | Ssangyong Cement | Type I-II | 3.15 | 705 |
| Fly Ash [a] | | | | |
| GGBFS | Lafarge Cement | Grade 100 | 2.4 | 40 |
| Latex | | | | |
| Microsilica | Force 10000 | Dry Silica Fume | 2.20 | 50 |

| Concrete Admixtures | Manufacturer | Product | Type | Est. Range (oz/cy) |
|---|---|---|---|---|
| Air Entrainment | W.R. Grace | Daravair 1000 | | 0.1 - 25 oz/cwt |
| Water Reducer | | | | |
| High-Range Water Reducer | W.R. Grace | ADVA 195 | F-HRWR(min 12%) | 0.1 - 30 oz/cwt |
| Set Retarder | | | | |
| Other | | | | |

Water (Maximum) 267 (lbs/cy) Is any of the water Recycled or Reclaimed? Yes[e] ☐ No ■

Water/Cementitious Ratio (Maximum) 0.34 Mix Design Density: 146.83 lbs/cf[d]

| Design Performance | 1 | 2 | 3 | 4 | 5 | Average[f] |
|---|---|---|---|---|---|---|
| 28 Day Compressive Strength (cylinders) psi | 6963 | 8543 | 6123 | 7780 | 7720 | 7,426 |
| 14 Day Flexural [d] Strength (beams) psi | | | | | | - |

Agency use only: Check appropriate box

☐ This mix design **Meets Contract Specifications** and may be used on the bid items noted above.

☐ This mix design **Does Not Meet Contract Specifications** and is being returned for corrections.

Reviewed By: ____________ (PE Signature) ____________ (Date)

DOT Form 350-040 EF
Revised 6/06

Distribution: Original - Contractor
Copies To - State Materials Lab-General Materials Eng. ; Regional Materials Lab; Project Inspector

## Combined Gradation Chart

| Concrete Aggregates | Component 1 | Component 2 | Component 3 | Component 4 | Component 5 | Combined Gradation |
|---|---|---|---|---|---|---|
| WSDOT Pit No. | PS-X-125 | PS-X-125 | | | | |
| WSDOT ASR 14-Day Results (%)[b] | ☐ Yes ☐ No | ☐ Yes ☐ No | ☐ Yes ☐ No | ☐ Yes ☐ No | ☐ Yes ☐ No | |
| Grading [c] | WSDOT Class 2 BLD_SAND | AASHTO #8 AGG_3/8 | | | | |
| Percent of Total Aggregate | 73 | 27 | | | | 100% |
| Specific Gracvity | 2.69 | 2.74 | | | | |
| Lbs/cy (ssd) | 2120 | 790 | | | | |

**Percent Passing**

| | | | | | | |
|---|---|---|---|---|---|---|
| 2 inch | 100.0 | 100.0 | - | - | - | 100.0 |
| 1-1/2 inch | 100.0 | 100.0 | - | - | - | 100.0 |
| 1 inch | 100.0 | 100.0 | - | - | - | 100.0 |
| 3/4 inch | 100.0 | 100.0 | - | - | - | 100.0 |
| 1/2 inch | 100.0 | 100.0 | - | - | - | 100.0 |
| 3/8 inch | 100.0 | 87.0 | - | - | - | 96.5 |
| No. 4 | 100.0 | 20.0 | - | - | - | 78.3 |
| No. 8 | 92.0 | 1.0 | - | - | - | 67.3 |
| No. 16 | 68.0 | - | - | - | - | 49.5 |
| No. 30 | 43.0 | - | - | - | - | 31.3 |
| No. 50 | 13.0 | - | - | - | - | 9.5 |
| No. 100 | 3.0 | - | - | - | - | 2.2 |
| No. 200 | 0.9 | - | - | - | - | 0.7 |

Fineness Modulus: 2.86 (Required for Class 2 Sand)

ASR Mitigation Method Proposed[b:] ________________________________

Notes:

a Required for Class 4000D and 4000P mixes.

b Alkali Silica Reactivity Mitigation is required for sources with expansions over 0.20% - Incidate method for ASR mitigation.
For expansion of 0.21% - o.45%, acceptable mitigation can be the use of low alkali cement or 25% type F fly ash.
Any other proposed mitigation method or for pits with greater than 0.45% expansion, proof of mitigating measure, either ASTM C1260 / AASHTO T303 test results must be attached.
If ASTM C 1293 testing has been submitted indicating 1-year expansion of 0.04% or less, mitigation is not required.

c AASHTO No. 467, 57, 67, 7, 8; WSDOT Class 1, Class 2; or combined gradation. See Standard Specification 9-03.1.

d Required for Cement Concrete Pavements.

e Attach test results indicating conformance to Standard Specification 9-25.1.

f Actual Average Strength as determined from testing or estimated from ACI 211.

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