Influences of Fibers on Expansive Shotcrete Mixture Consisting of Calcium Sulfoaluminate, Portland Cement, and Calcium Sulfate

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Mining Engineering

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Abstract

Shotcrete is often used by the mining industry as rock support, tunnel lining, and concrete repair. However, cracking within shotcrete is common, which delays production schedules and increases maintenance costs. To reduce cracking, expansive shotcrete mixtures are often used. While several commercial expansive cements / shotcrete mixtures are available, the ingredients of these products are usually confidential. To optimize the effects and usages of expansive shotcrete mixture, mixture with known compositions should be studied. Possible expansive shotcrete mixtures can be developed by combining calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) in the binder. Furthermore, fibers can be added to the mixture to restrain expansion and impede cracking. The objective of this thesis is to identify expansive shotcrete mixtures consisting of CSA, OPC, and CS, and study the effects of nylon fiber, glass fiber, and steel fiber on the identified mixture so that better crack resistance can be achieved.

In this study, parameters such as density, water absorption, volume of permeable voids, unconfined compressive strength (UCS), splitting tensile strength (STS), and volume change of the mixtures were determined at different time periods (i.e., the mechanical strengths on the 28th day, and the volume changes on the 1st, 7th, 14th, 21st, and 28th days). Five expansive shotcrete mixtures, along with five strength-enhanced mixtures, that contained CSA, OPC, and CS in the binder were identified.

The expansive mixture showing enhanced UCS (mixture with 40%CSA+20%OPC+40%CS) was selected for fiber additions in this study. Results have presented that the addition of fibers improved mixture durability, in the form of decreased water absorption and reduced permeable pore space content. Moreover, the expansion of the CSA-OPC-CS mixture was controlled by fiber reinforcement. Glass fiber restrained up to 50% of the expansion, while nylon fiber restrained up to 43% and steel fiber restrained up to 28% of the expansion. The results showed that STS was improved by 57% with glass fiber addition, 43% with steel fiber addition, and 38% with nylon fiber addition. The UCS also increased at a percentage of 31% after steel fiber addition, 26% after nylon fiber addition, and 16% after glass fiber addition. Based on the results, it is concluded that fiber additions to expansive shotcrete mixtures improve durability and mechanical strengths, while controlling expansion. The results in this thesis provide alternative options of expansive and strength-enhanced shotcrete mixtures consisting of CSA, OPC, CS, and fibers. These options could better mitigate the cracking in shotcrete, thereby reducing the costs on repair and replacement.

Preface

This thesis has identified potential expansive shotcrete mixtures consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS), and then it has investigated the influences of fiber additions on a selected expansive mixture with the greatest potential. In this thesis, I am responsible for concept formations, experimental designs, data collections and analysis, and manuscript compositions.

The introduction in Chapter 1, the literature review in Chapter 2, and the concluding remarks in Chapter 5 of this thesis are original works by me (Hau Yu).

Chapter 3 and part of the content in Chapter 1 of this thesis had been presented as H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Developing Expansive Shotcrete Mixtures from Calcium Sulfoaluminate, Portland Cement, and Calcium Sulfate," at the *CIM 2017 Convention* in Montreal, Canada. I was the principal author responsible for concept formation, data collection, data analysis, paper composition, and paper presentation. L. Wu, W.V. Liu, and Y. Pourrahimian were involved in the concept formation, and contributed to manuscript compositions and edits.

Chapter 4 and part of the content in chapter 1 of this thesis has been under peer-review for the consideration of publication as H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Influence of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate, Portland cement, and calcium sulfate," in *Journal of Rock*

Mechanics and Geotechnical Engineering. I was the principle author responsible for concept formation, data collection, data analysis, and paper composition. L. Wu, W.V. Liu, and Y. Pourrahimian were involved in the concept formation, and contributed to manuscript compositions and edits.

This thesis is dedicated:

To my loving and supporting parents, Chichi Liu and Lien-Chieh Yu

Acknowledgement

I sincerely thank my supervisor, Dr. Wei Victor Liu of the School of Mining and Petroleum Engineering, for providing me with the opportunity to work in an excellent environment and perform research. His motivation, guidance, and support are crucial throughout my M. Sc. studies. Without his help, the completion of my researches and the writing of this thesis would be almost neigh impossible. Thank you.

My gratitude and appreciation go to my advisory committee members, Dr. Yashar Pourrahimian and Dr. Yong Li. They spent much of their precious time on my exam and provide insightful comments, which improved this thesis a lot.

I would also like to thank my colleagues, David Omane, Alex Hu, and Linping Wu, for brainstorming ideas and providing encouragements. It was a pleasure working and sharing much exciting time with them.

Next, I would like to thank Rizaldy Mariano, concrete lab technician, for his supportive attitudes and guidance during my experiments. My gratitude also extends to CTS Cement, for donating calcium sulfoaluminate cement and providing technical instructions.

Finally, I would give all my gratitude to my parents. Their love, encouragement, and support are what make this M. Sc. Study possible. Thanks for being with me.

Hau Yu, August 2017

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List of Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
a/c	Aggregate-Cement ratio
CAC	Calcium Aluminate Cement
CC BY 4.0	Available under a Creative Commons Attribution License
CIA	Concrete Institute of Australia
CS	Calcium Sulfate
CSA	Calcium Sulfoaluminate Cement
HPC	High-Performance Concrete
NIOSH	National Institute for Occupation Safety and Health
OPC	Ordinary Portland Cement
STS	Splitting Tensile Strength
UCS	Unconfined Compressive Strength
w/c	Water-Cement Ratio

List of Nomenclatures

Ø	Diameter of the fiber, (mm)
$Expansion_{free}$	Expansion of Mix1 (%)
$Expansion_{restrained}$	Expansion of Mix1 after fiber addition (%)
Restraint Ratio	Percentage of Mix1's free expansion being restrained (%)
$UCS_{variation}$	UCS variation percentage, compared to 100% Portland cement mixture (%)
$UCS_{reference}$	UCS of the reference 100% Portland cement mixture (MPa)
UCS_{new}	UCS of the sample being compared to the reference mixture (MPa)
V_c	Volume change percentage, compared to the 1st day (%)
V_1	Measured sample volume on the 1st day (m^3)
V_{28}	Measured sample volume on the 28th day (m^3)

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Chapter 1 Introduction

This chapter provides an overview of this thesis, where the background, research scope, research objectives, and the layout of the studies are provided.

*Parts of the content in this chapter has been presented as H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Developing Expansive Shotcrete Mixtures from Calcium Sulfoaluminate, Portland Cement, and Calcium Sulfate," at the *CIM 2017 Convention* in Montreal, Canada, and submitted as a journal manuscript (under review): H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Influence of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate, Portland cement, and calcium sulfate," in *Journal of Rock Mechanics and Geotechnical Engineering.*

1.1 Introduction

Shotcrete, or sprayed concrete, is often used by the mining industry (ACI, 2009; CIA, 2010; Martin et al., 2011); it is a cement-based mixture projected pneumatically in high velocities (ACI, 2013). The flexibility of shotcrete makes it an effective alternative to conventional concrete in terms of rock support, tunnel lining, and concrete repair. The pneumatic projection allows shotcrete to be applied quickly on uneven substrate, acting as excavation stabilization and arch lining in mines (Hofler & Schlumpf, 2006). Moreover, shotcrete has also been successfully used to provide ground supports in underground mines, preserve beams and maintain confinement of the surrounding rock (Morissette et al., 2017). These applications have made the mining industry a major user of shotcrete, at a volume over 700,000 m^3 per year in North America and Australia (Rispin & Brooks, 2001; Stefan, 2009), which creates a huge demand for the cement-based mixtures.

Although shotcrete is widely and frequently used, cracking in shotcrete construction is a common issue, which lead to structural failures, falling rocks, increasing maintenance costs, and delayed production schedule (Drover & Villaescusa, 2015; Lewis et al., 2017; Poisel et al., 2016). Ground movement and shrinkage of shotcrete are the two major sources for cracking. Ground movement around the shotcrete structure exerts tensile forces on shotcrete, causing cracks and fractures (Szwedzicki, 2001). Shrinkage in shotcrete, on the other hand, generates tensile forces exerted by substrate and causes cracking.

The commonly used ordinary Portland cement (OPC) shotcrete mixture can shrink up to 9% due to drying and formation of smaller hydration products (Lagerblad et al., 2010), inducing shrinkage-cracks that are prone to further cracking. That is, the shrinkage generates small cracks in shotcrete, where high stresses are concentrated at the tips of the cracks (Irwin, 1957). These small cracks are hence easily affected by ground movement, developing larger cracks (Campbell, 1999). For example, many complaints about extensive cracking in shotcrete were reported for a large traffic tunnel in Sweden, which prompted the creation of a dedicated research team to explain and reduce the issue (Holmgren, 2010); it was found that large shrinkages were present in the shotcrete due to alkali free accelerators, leading to increased cracking.

Considerable effort has been devoted to repairing and reducing shotcrete cracks in recent years. Among them, shrinkage-compensating shotcrete mixture has been successfully applied at underground mines as ground support of mine openings (e.g., ore pass and rock chute) (King Shotcrete, 2014a; Storrie, 2001). Expansive cement is usually added to the shotcrete mixture for shrinkage compensation, and there are currently many commercial expansive cement products (i.e., CTS Type-K Cement, DENKA CSA#20, and Komponent®) available (CIA, 2010; Huang & Ma, 2011). The expansive cement are categorized into type K, type M, type S, and type G based on their constituents (ACI, 2010). Type K expansive cement consists mainly of OPC, anhydrous tetracalcium trialuminate sulfate (C_4A_3S), calcium sulfate (CS), and lime (CaO); type M includes blended or intergrounded OPC, calcium-aluminate cement, and CS; type S is an OPC containing a high portion of tricalcium aluminate blended with CS; and type G is an OPC that is high in lime content and blended with calcined pozzolans. Besides expansive cements, pre-mixed shrinkage-reduced shotcrete mixtures are also available for application in various mine locations such as ore passes and rock chutes (King Shotcrete, 2014c).

Although there are many expansive cement or shotcrete mixture products on the market, the compositions and ingredients of these commercial products are all confidential information or trade secret. This limits the development and optimization of shrinkage-compensating shotcrete mixtures. To address this issue, expansive mixtures with known compositions and different ingredients should be studied. Several literatures had identified that some shotcrete mixtures with calcium sulfoaluminate cement (CSA), Portland cement (OPC), and calcium sulfate (CS) in the binder would generate expansions (Bizzozero et al., 2014; Chaunsali et al., 2015; Dachtar, 2004). However, the effects of changing CSA-OPC-CS proportions in the binder of the shotcrete mixtures was not studied in these researches. Thus, we proposed to study CSA-OPC-CS mixtures under a systematic control on binder compositions, and develop potential expansive shotcrete mixtures possessing the benefits associated with the utilization of CSA.

One of the advantages of using CSA in the mixture is that the production of CSA releases 49% less CO_2 than that of the OPC, and 3% less than that of the calcium aluminate cement (CAC), a common binder for expansive shotcrete mixtures (Burris et al., 2015). Reduced CO_2 emission would relieve global warming

(Solomon et al., 2009) and could provide financial merits when the carbon tax is implanted in the area of application. Another possible benefit of the CSA-OPC-CS expansive mixture is the enhanced early compressive strength typically associated with CSA (Dachtar, 2004; Péra & Ambroise, 2004), which would allow faster re-entries to the worksite after application.

In addition to shrinkage-compensation, restraint such as rebar and fibers are usually introduced into the expansive mixtures to generate self-compressive stresses in mixture and self-tensile stresses in restraint (ACI, 2010; Scholer et al., 1978). Self-stressing concrete is a product that contains both expansion cement and restraints. Since the 1960s, self-stressing concrete has been widely used in underground applications because it minimizes cracks, frost damage, water leaks, and sulfate attacks (Jabbari & Vallens, 2014; Valentine, 2000). Self-stressing concrete has also been utilized in rock anchoring to enhance pile capacity (Haberfield, 2000). Likewise, there is a potential to develop a self-stressing shotcrete to mitigate cracks and improve durability. However, very little research has been done for self-stressing in the shotcrete area. In particular, the role of fibers as restraint on expansive shotcrete mixtures is still unknown and remains to be elucidated. This is important because fibers are usually added to the mixture under the guide of the Barton's Q-system chart (NGI, 2015; Vandewalle, 1998), and their effects are directly related to the application of expansive shotcrete mixtures.

Different types of fibers (i.e., nylon, glass, and steel) are often added to shotcrete mixtures for various applications. For example, Yun et al. (Yun et al., 2015) suggested that nylon fiber can improve the rheological performances such as yield stress and plastic viscosity. Bryne et al. (Bryne et al., 2014) identified that glass fiber added to shotcrete mixture could reduce shrinkage cracking. Zhu (Zhu, 2013) added steel fiber to shotcrete acting as permanent lining in tunnels, and he found that steel fiber increased tensile strength and crack resistance significantly. In short, fibers can reduce, block, and bridge the cracks in the mixtures, allowing the samples to become tighter and withstand more loads (Dawood & Ramli, 2014; Song et al., 2005).

In this thesis, for the first time, we have identified expansive CSA-OPC-CS shotcrete mixtures and studied the effects of fibers as restraint on the identified mixture are initiated. The influences of fibers on volume change, UCS, and STS were also evaluated. This research provides essential information on mechanical strength and volume change of fiber restrained expansive CSA-OPC-CS mixtures, in comparison with common OPC mixture. Relationships between varying CSA-OPC-CS proportions and expansion / UCS, and the effects of different types of fibers on the mechanical strengths / volume change are also established for future considerations in experimental design.

1.2 Research Scope

This thesis focuses on two parts:

1. The first part is to identify expansive shotcrete mixtures consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS). Successful expansive CSA-OPC-CS mixtures would reduce cracking

due to less shrinkage-induced fractures that weaken the structure. By using a combination of CSA, OPC, and CS, the benefits of CSA (i.e., low CO_2 emission during production and higher early strength) will be transferred to these new mixtures.

2. The second part is to evaluate the effects of fiber addition on a selected CSA-OPC-CS mixture. After the expansive CSA-OPC-CS mixtures were identified, the mixture with the highest unconfined compressive strength (UCS) is reinforced with fibers. The fibers were added to further improve mixture performances (i.e., UCS, tensile strength, durability, expansion restraint) and indirectly enhance crack resistance.

Parameters such as density, water absorption, and volume of permeable voids are evaluated to reflect mixture durability. Next, UCS and splitting tensile strength (STS) are tested to represent mechanical strength. Furthermore, volume change is recorded to identify expansive CSA-OPC-CS mixture and restraining effects of fibers. Combining the results, alternative choices of shrinkage-cracking resistance shotcrete are identified, and the influences of fibers on such mixture are observed so that fiber additions can be decided based on the desired effects. The potential of the fiber-reinforced expansive CSA-OPC-CS shotcrete mixture was preliminarily evaluated in this thesis to advance the development of crack-resistant mixtures in the future.

1.3 Research Objectives

The objectives of this paper are:

1) To identify expansive shotcrete mixtures consisting of Calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) which can mitigate shrinkage cracking, and

2) To study the effects of nylon fiber, glass fiber, and steel fiber on CSA-OPC-CS mixture for further performance improvements.

These results will allow us to suggest alternative choices of expansive shotcrete mixtures, provide design considerations for fiber additions, and initiate development of crack-resistant shotcrete mixtures consisting of CSA, OPC, CS, and fibers.

1.4 Thesis Outline

This thesis is organized into five chapters as described below:

Chapter 1 covers the introduction, the scope of the research work, the objective of the thesis, and the layout of the manuscript.

Chapter 2 includes a literature review on previous research work regarding expansive shotcrete mixtures and fiber reinforcements. This literature review has provided design considerations for the shotcrete mixtures, and the rationale of shotcrete cracking, expansive mixtures, and fiber additions.

Chapter 3 focuses on the identification of expansive shotcrete mixtures consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS), which can reduce shrinkage-cracking. The CSA, OPC, and CS were combined in systematic ratios (the three materials added up to 100% of the binder in weight; each binder material ranged between 0% and 100%, with a minimum increment change at 20%), and the expansion ratios of the mixtures at different CSA-OPC-CS combinations were recorded. Expansive mixtures, strength-enhanced mixtures, unhardened mixtures, and cracked mixtures were identified and grouped. The expansive mixture with the highest unconfined compressive strength (UCS) was selected for further investigation in the next chapter.

Chapter 4 shows the effects of fiber additions on the identified expansive mixture. Three types of fibers (nylon fiber, glass fiber, and steel fiber) were added to the mixture at 1% volume fraction to restrain expansion and impede cracking. Parameters such as density, water absorption, volume of permeable voids, UCS, splitting tensile strength (STS), and volume change of fiber-added expansive mixtures were determined at different time periods (i.e., the mechanical strengths on the 28th day, and the volume changes on the 1st, 7th, 14th, 21st, and 28th days). The effects of fibers on UCS, STS, and volume change are discussed.

Chapter 5 contains the thesis summary, the research conclusions, the results contributions, and the recommendations for future research.

Chapter 2 Literature Review

Chapter 2 contains literature review for topics concerned with this thesis. The usage of shotcrete by the mining industry, the cracking problem associated with shotcrete, the existing expansive shotcrete mixtures, the materials used for creating expansive mixtures, and the effects of fiber additions on shotcrete from past research works are reviewed. The doubts of each of the research work are addressed and the reasons for composing this thesis are concluded.

2.1 Background

This chapter contains a literature review regarding the identification of expansive shotcrete mixtures consisting of calcium sulfoalumiante cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS). Besides, research work on fiber additions to shotcrete mixtures was also reviewed.

2.2 Shotcrete

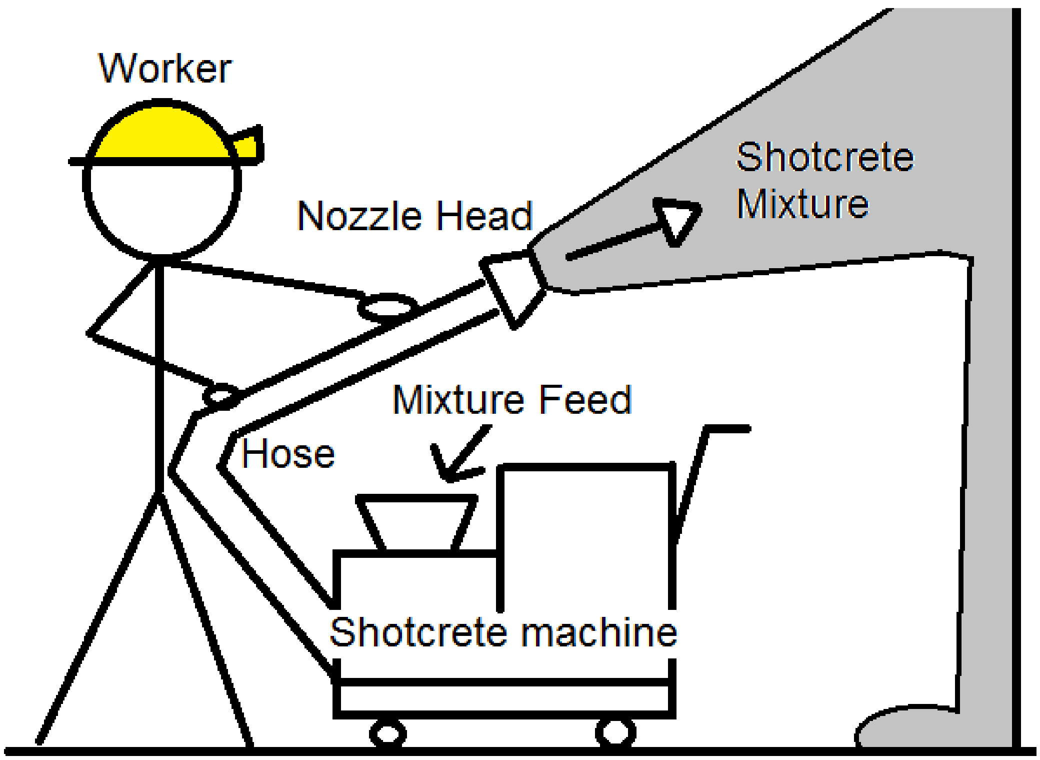


Figure 2.1. Typical shotcreting process

According to the American Concrete Institute (ACI), shotcrete is defined as a cement-based mixture projected pneumatically at high velocities (ACI, 2013). A typical shotcrete application process is shown in Figure 2.1. The high velocity implies that the mixture hit the receiving surface with great force, producing self-compacting material in the process (Jolin, 2000). Because shotcrete has the benefit of easy and rapid application, it is often used as repair materials, linings, and building structures (CIA, 2010). For example, shotcrete had been used to repair a hydro dam in Canada (Heere et al., 1996); the shotcrete repairs performed well and remain generally intact 25 years after application.

2.3 Shotcrete Usage in Mining Operations

Besides using shotcrete for civil constructions, the cementitious mixture is also widely applied in the mining industry (ACI, 2009; CIA, 2010). This is because shotcrete is versatile and easy to apply, making it an excellent choice for the constructions of mining tunnels, shafts, and ground supports. Due to the numerous applications at mines, mining industry has been known to consume shotcrete at a volume over 200,000 m^3 per year in North America (Rispin & Brooks, 2001), and 500,000 m^3 per year in Australia (Stefan, 2009). Some examples of shotcrete usages at mines can be found as below:

- the Diavik diamond Mine (Lewis et al., 2017) in Canada, where shotcrete was installed as ground support in drifts;
- the Coleman-McCreedy East nickel and copper Mine in Canada (King Shotcrete, 2014a), where shotcrete was used to construct an ore pass bin;
- the Mount Isa copper Mine (Li & Cribb, 1999) in Japan, where shotcrete was used as ground support for poor ground conditions;
- the APEX Mine in United States (Guill, 1990), where shotcrete was used to replace rock bolts and mesh as ground support; and,

• the Cluff Lake uranium Mine in Canada (Kiggavik Project EIS, 2011), where shotcrete was applied on walls, ceilings, and roadbeds to reduce gamma radiation in stopes and stope accesses.

2.4 Cracking of Shotcrete

Although shotcrete is widely and frequently favored due to its versatility and faster installation, cracking of shotcrete construction is common. Cracking in shotcrete leads to structure failures and falling rocks, which increases maintenance costs and delays production schedules (Drover & Villaescusa, 2015; Lewis et al., 2017; Poisel et al., 2016). There are two common sources of shotcrete cracking: ground movement and shotcrete shrinkage.

2.4.1 Cracking Caused by Ground Movement

Figure 2.2. Displaced materials at the Copper Cliff mine's 3880 level after an earthquake on 25 March 2008, which shotcrete ground support failed to contain (Morissette et al., 2017), CC BY 4.0

Ground movement around the shotcrete structure exerts tensile forces on shotcrete, causing cracks and fractures (Szwedzicki, 2001). Furthermore, most shotcrete used as ground control suffer some form of cracking after application due to ground movement (Bernard, 2009). For example, a seismic event around the Copper Cliff and the Coleman mines in Canada generated over 635 short tons of displaced materials such as rock and ore, which the shotcrete support cracked and failed to contain (Morissette et al., 2017). The shotcrete was installed as ground support along with rock bolts and rebars, but it failed to prevent the ejection of broken materials caused by ground movement (as shown in Figure 2.2). Significant resources were required for rehabilitation at the Copper Cliff mine, which prompted a revision on the ground support policy. Another example can be found at the Diavik diamond Mine in Canada, where ground movement caused cracking and spalling of shotcrete ground support along secondary drifts (Lewis et al., 2017). The mining operations within the affected mining blocks were halted due to ground movements, and could not resume until assessments and rehabilitations were completed.

2.4.2 Cracking Caused by Shotcrete Shrinkage

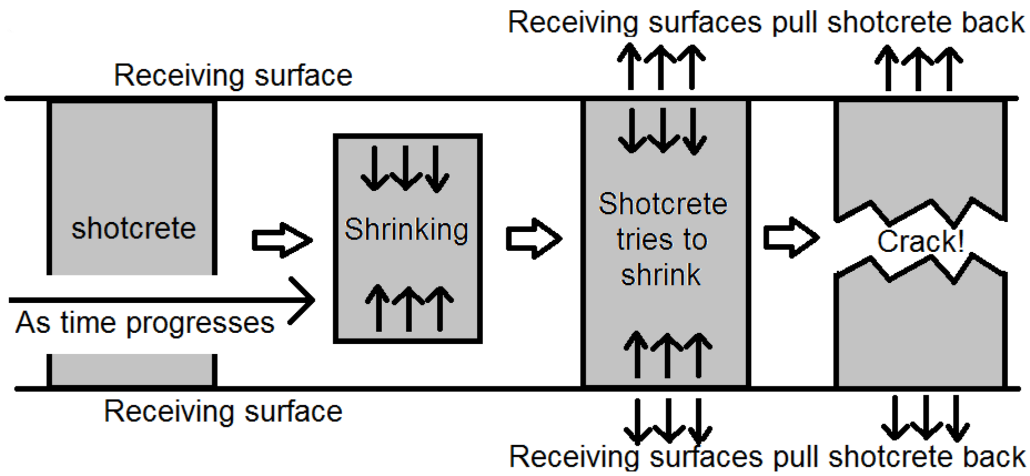


Figure 2.3. Shrinkage cracking mechanism of shotcrete

Besides ground movement, shotcrete shrinkages also lead to cracking. Shotcrete structures have restraints since they are bonded to the receiving surfaces. When shotcrete shrinks, tensile forces are exerted by the restraints, which result in cracking (Bryne et al., 2014). A schematic depicting the mechanism leading to shrinkage cracking is shown as Figure 2.3. Commonly used ordinary Portland cement (OPC) shotcrete mixture was reported to shrink up to 9% due to water evaporation, chemical reaction, and development of cement paste (Lagerblad et al., 2010). This shrinkage induces tensile stresses in the mixture when restrained, which cause cracking. An example of shrinkage cracking can be found at a copper mine in Japan, where shrinkage cracking developed in some locations with poor mix quality, so the mine required new ground support design and replacement (Li & Cribb, 1999).

Shrinkage-cracks may also provoke further cracking. When small cracks are generated, high stresses were concentrated at the tips of these cracks (Irwin, 1957). Since high stresses are concentrated at the already damaged section, these small cracks could develop into larger cracks by ground movement easily (Campbell, 1999). Therefore, shrinkage cracking should be minimized to avoid spending resources on repairing and replacing cracked shotcrete.

2.5 Shrinkage-Compensating Shotcrete Mixtures

Shrinkage-compensating shotcrete mixtures are frequently used at mines to mitigate shrinkage cracking. This would decrease chances of further cracking since less small shrinkage-cracks could occur in the mixture. The usage of shrinkage-compensating shotcrete was found at a nickel and copper mine in Canada, where shrinkage-compensating shotcrete was used to construct an ore pass bin (King Shotcrete, 2014a). A diamond mine in South Africa was also reported to use shrinkage-reduced shotcrete as ground support in a wet shotcrete trial (Storrie, 2001). These shrinkage-compensating shotcrete applications were reported to provide better impact and abrasion resistances, prolonging the life expectancy of the structures constructed.

2.5.1 Common Shrinkage-Compensating Shotcrete Mixtures

Many common shrinkage-compensating shotcrete mixtures are created by adding expansive cement. There are currently many commercial expansive cement products (i.e., CTS Type-K Cement and DENKA CSA#20) available for shrinkage-compensation generation (CIA, 2010; Huang & Ma, 2011). According to the

American Concrete Institute (ACI, 2010), the expansive cement are categorized into the following categories based on their constituents:

- Type K expansive cement consists mainly of OPC, anhydrous tetracalcium trialuminate sulfate (C_4A_3S), calcium sulfate (CS), and lime (CaO);
- Type M expansive cement includes blended or intergrounded OPC, calcium-aluminate cement, and CS;
- Type S expansive cement is an OPC containing a high portion of tricalcium aluminate and CS blend;
- Type G expansive cement is an OPC that has high lime content and blended with calcined pozzolans.

Besides expansive cements, pre-mixed shrinkage-reduced shotcrete mixtures are also available for application in various mine locations such as ore passes, rock chutes, and mine drift supports (King Shotcrete, 2014b, 2014c). Exemplary commercial expansive cements, additives, and mixture blends are summarized in Table 2.1; the volume change and UCS properties of concrete and mortar made with some of the mentioned expansive cement are shown in Table 2.2, along with a pre-mixed shotcrete blend. Note that shrinkage-compensating concrete is defined by ACI (ACI, 2013) as concrete containing expansive components such as calcium aluminate (CAC) and gypsum (CS), which formed calcium sulfoaluminate (CSA or ettringite).

Table 2.1. Common expansive cements, additives, and mixtures (CTS Cement, 2017a, 2017b; King Shotcrete, 2014b, 2014c; Newchem, 2007)

Brand Name	Classification	Application
CTS Type-K Cement	Type-K expansive cement	Replace regular OPC to minimize shrinkage-cracking
DENKA CSA#20	CSA cement	Used for chemically pre-stress concrete
Komponent®	Expansive mineral additive	Mix with OPC to produce shrinkage-compensating mix
RS ArmourGuard	Pre-packaged shotcrete material	Ore pass, ore chute, truck dump
RS-D1	Pre-packaged shotcrete material	Rehabilitation, tunnel lining, slope stabilization, shaft

Table 2.2. Reported volume change and UCS of mortar, concrete and shotcrete (Collepardi & Collepardi, 2004; CTS Cement, 2017b; King Shotcrete, 2014b)

Brand Name	Mixture Created	Volume Change	28^{th} Day UCS
CTS Type K Cement	Shrinkage-compensating concrete	0.045% on the 7^{th} day	31.0 MPa
DENKA CSA#20	Shrinkage compensating mortar	-762 µm / m on the 28^{th} day, or -0.08%	70.8 MPa
King Shotcrete RS-D1	Pre-mixed shotcrete blend	-400 µm / m on the 28^{th} day, or -0.04%	42.0 MPa

2.5.2 Shrinkage-Compensating Shotcrete Mixtures Consisting of CSA, OPC, and CS

Although many commercial expansive cements and expansive shotcrete blends are available in the market, the compositions and components of these products are still unrevealed. This limits the development and optimization of shrinkage-compensating shotcrete mixtures. To address this issue, expansive mixtures with known compositions and different ingredients should be developed and studied.

Studies have provided several expansive shotcrete mixture recipes combining calcium sulfoaluminate cement (CSA), Portland cement (OPC), and calcium sulfate (CS) in the binder (Bizzozero et al., 2014; Chaunsali et al., 2015; Dachtar, 2004). Bizzozero et al. (2014) observed the volume stability of CSA and calcium aluminate cement (CAC) paste respectively, with CS replacement ratios up to 50%. They found that some of these CSA-CS or CAC-CS mixtures demonstrated expansion. It was observed that the expansion of the paste increased as more CSA or CAC was replaced with CS. However, when a critical amount of CS was added, unstable expansions occurred, leading to cracking and deterioration. Therefore, a thershold must be determined to prevent failure when expansive mixtures are obtained by replacing CSA or CAC with CS. Chaunsali et al. (2015) replaced OPC with CSA at a ratio up to 30% for expansion test. Their result showed that an expansion of 4% - 5% occurred with cracking at 30% CSA replacement (as recorded in Figure 2.4). While expansive mixtures can be developed by combining CSA with OPC, it is important to study the ratio of replacement to ensure a controlled expansion. Dachtar (2004) used CSA as a binder for structural concrete. He mixed CSA with OPC and added CS at varying percentages (15% - 25%). The CSA-OPC-CS mixtures tested demonstrate expansion, but some of the mixtures showed rapid expansion toward cracking, which are not suitable for further applications. In short, shotcrete mixtures consisting of CSA, OPC, and CS do expand, but expansion monitoring is required to prevent cracking.

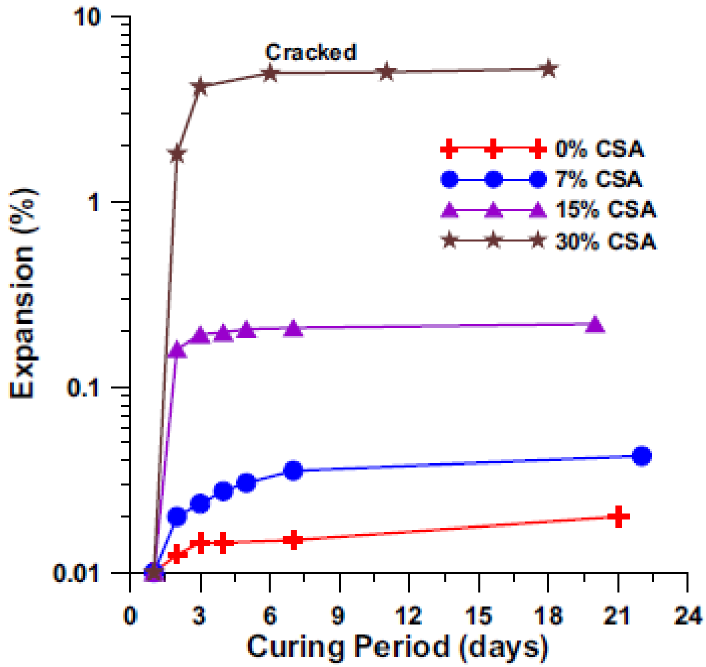


Figure 2.4. Expansion of OPC-CSA blends (Chaunsali et al., 2015), figure usage permission granted by John Wiley and Sons

Although the researches discussed above had identified expansive cementitious mixtures by mixing CAC, CS, OPC, or CSA, no systematc studies were performed on CSA-OPC-CS shotcrete mixtures by combining the binder material compositions in orders. Therefore, we proposed to study CSA-OPC-CS mixtures by a combinaton of various binder compositions, in order to identify potential expansive shotcrete mixtures possessing the benefits associated with the utilization of CSA (e.g., low CO_2 emission during the production of the cement and high early strength).

2.6 Fiber Additions

Besides using expansive mixture, fiber addition is another way to reduce shotcrete cracking. Fiber addition was found to reduce, block, and bridge the cracks in the mixtures, which in turns improve unconfined compressive strength (UCS) and splitting tensile strength (STS) (Dawood & Ramli, 2014; Song et al., 2005; Zhou et al., 2012). Researchers at the National Institute for Occupation Safety and Health (NIOSH) have also stated that steel and polypropylene fibers increase toughness of shotcrete, preserving structure integrity (NIOSH, 2014). Because of the benefits associated with fiber additions, fibers are often added to the mixture during the mixing process.

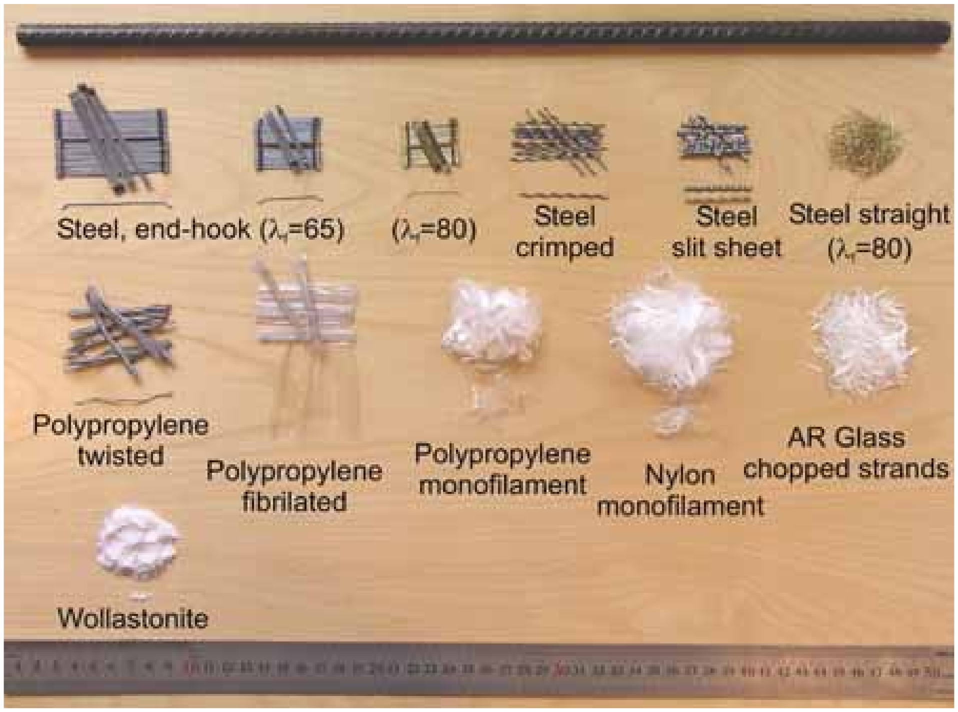


Figure 2.5. Examples of fibers commonly added to concrete (Löfgren, 2005), available under Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities

The fibers commonly added to concrete are shown in Figure 2.5. They are categorized into two main groups (Antona & Johansson, 2011):

1. Natural fibers (e.g., bamboo, cellulose, and asbestos fibers)
2. Manufactured fibers (e.g., metallic, glass, and synthetic fibers).

In addition, typical physical properties of common fibers added to concrete are summarized in Table 2.3. These properties dictate the effects of fibers on concrete performances.

Table 2.3. Physical properties of some fibers, modified after Löfgren (Löfgren, 2005), available under Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities

Type of Fiber	Diameter (μm)	Specific Gravity	Tensile Strength (MPa)	Elastic Modulus (GPa)	Ultimate Elongation (%)
Steel	5 – 1,000	7.85	200 – 2,600	195 - 210	0.5 – 5.0
E Glass	8 – 15	2.54	2,000 – 4,000	72	3.0 – 4.8
AR Glass	8 – 20	2.70	1,500 – 3,700	80	2.5 – 3.6
Carbon (Low Modulus)	7 – 18	1.60 – 1.70	800 – 1,100	38 - 43	2.1 – 2.5
Nylon	20 – 25	1.16	965	5	20.0
Polypropylene (PP)	10 - 200	0.90 – 0.91	310 - 760	3.5 – 4.9	6.0 – 15.0
Bamboo	50 – 400	1.50	350 - 500	33 - 40	N/A
Asbestos	0.02 – 25	2.55	200 – 1,800	164	2.0 – 3.0
Cellulose (Wood)	15 - 125	1.50	300 – 2,000	10 - 50	20.0

Extensive studies were performed in the past on the effects of fiber additions on cementitious mixtures (Bryne et al., 2014; Song et al., 2005; Yun et al., 2015; Zhu, 2013). Yun et al. (2015) suggested that addition of synthetic fibers can improve the rheological performances such as yield stress and plastic viscosity, at the cost of decreasing workability. Alternatively, Bryne et al. (2014) found that fine glass fiber addition to shotcrete mixture could reduce shrinkage cracking without identifying the optimal percentage of fiber for shrinkage-cracking mitigation. On the other hand, Zhu (2013) added steel fiber to shotcrete to act as permanent lining in tunnels, and then reported that steel fiber increased tensile strength and crack resistance significantly. Lastly, Song et al. (2005) incorporated nylon fibers to increase the mechanical strength (UCS and STS) of concrete, and found that UCS and STS were increased by 12.4% and 17.1%, respectively.

In summary, fiber additions to cementitious mixtures were found to mitigate cracking and improve tensile strength. Therefore, fibers were added to the expansive mixtures in this thesis to further improve crack resistance and performances.

2.7 Fiber Addition to Expansive Mixtures

Although the effects of fibers on cementitious mixtures have been discussed in many researches, the effects of fibers identified may not be the same for expansive mixtures. This is because self-stresses are generated when restraints (e.g., rebar, fibers) are added to expansive mixtures, introducing self-compressive stresses in the mixtures and self-tensile stresses in the restraints (ACI, 2010; Scholer et al., 1978). Note that self-stressing concrete are created as the restrained expansion induces compressive stresses at a high enough magnitude, which causes significant compression in the concrete (ACI, 2013). These generated compressive stresses in the mixture would require extra tensile stresses to counter, which indirectly increased tensile strength and provide better resistance to cracking caused by ground movement.

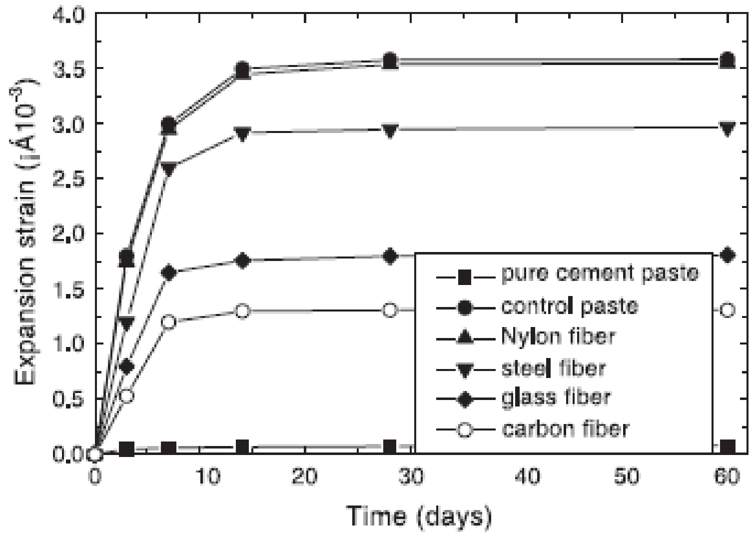


Figure 2.6. Effect of different types of fibers on restraint of paste expansion (Chen & Liu, 2003), figure usage permission granted by Elsevier

Multiple researches have been performed to identify the effects of fiber addition onto expansive cementitious mixture (Chen & Liu, 2003; Sun et al., 2001; Toutanji, 1999). For example, Chen & Liu (2003) studied the influences of fiber inclusions to expansive concrete, in order to promote the usage of expansive fly ash concrete. They focused on evaluating the restraining effect of steel, glass, nylon, and carbon fibers (the expansion of the mixtures tested over time is shown in Figure 2.6). Nylon fiber was found to fail to restrain expansion due to the low elastic modulus, while steel, glass, and carbon fibers did restrain the expansion. On the other hand, Toutanji (1999) investigated the use of polypropylene fiber on silica-fume expansive concrete to develop concrete suitable for the construction of highway pavements and bridge decks. Influences of fibers on workability, bond strength, and permeability were studied. Fiber reinforcements were found to increase bond strength and permeability of the mixture, while also reduce durability. Lastly, Sun et al. (2001) incorporated high-performance concrete (HPC) with expansive agent and hybrid fibers (i.e., steel fibers, polyvinyl alcohol fiber, and polypropylene fiber) to reduce cracking. It was observed that hybrid fibers of different types and sizes reduce cracking. Compared to single fiber incorporation, shrinkage resistance and impermeability were improved when hybrid fibers are used. To sum up, fibers additions to expansive cementitious mixtures could possibly limit expansion and improve crack resistance.

Therefore, by adding fibers to expansive shotcrete mixtures, there is potential to develop shotcrete mixtures with better crack resistance. However, little to no research has been conducted to examine the influences of fibers on expansive shotcrete mixtures consisting of CSA, OPC, and CS. These fiber-reinforced expansive CSA-OPC-CS mixtures could be an alternative choice of crack mitigating shotcrete mix, and requires further investigation.

2.8 Chapter Summary and Conclusions

Cracking in shotcrete is a common phenomenon, which makes repair costly and time consuming. To address the issue, multiple attempts have been made by many researchers. First, shrinkage compensating shotcrete mixtures are developed using different ingredients [e.g., expansive cements, expansive additives, fly-ash, calcium aluminate cement (CAC), calcium sulfoaluminate cement (CSA), and calcium sulfate (CS)], which mitigate cracking. Second, fibers are often added to these expansive mixtures to mitigate cracking and generate self-stresses that can further improve crack resistance.

While the studies reviewed in this chapter provide valuable information on improving the crack resistance of shotcrete, little to no research has been performed on fiber-reinforced expansive CSA-OPC-CS shotcrete mixtures. The author would thus lead off to identify expansive shotcrete mixtures consisting of CSA, OPC, and CS, followed by studying the effects of different types of fibers on above mentioned mixture to develop crack resistant shotcrete. In brief, the objective of this thesis is to develop fiber-reinforced expansive CSA-OPC-CS shotcrete mixtures with better crack resistance.

Chapter 3 Identifying Expansive Shotcrete Mixtures Consisting of CSA, OPC, and CS

Chapter 3 focuses on the identification of expansive shotcrete mixtures composing of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS). CSA, OPC, and CS were combined at different ratios in the binder, and the resulting volume changes were recorded.

*This chapter has been presented as H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Developing Expansive Shotcrete Mixtures from Calcium Sulfoaluminate, Portland Cement, and Calcium Sulfate," at the *CIM 2017 Convention* in Montreal, Canada.

3.1 Introduction

Although shotcrete has been widely applied in the mining industry, shrinkage-induced cracking in the shotcrete is common, which decreases the effectiveness of the concrete mixture application method (Ansell, 2010). The shrinkage-induced cracks in shotcrete may develop into structural failures (Lackner & Mang, 2003), which delays the production schedule due to the additional repair needs.

To reduce shrinkage-induced cracking, expansive shotcrete can be utilized to compensate the shrinkage. Several literatures had identified that some shotcrete mixtures with calcium sulfoaluminate cement (CSA), Portland cement (OPC), and calcium sulfate (CS) in the binder would generate expansions (Bizzozero et al., 2014; Chaunsali et al., 2015; Dachtar, 2004). However, the effect of changing CSA-OPC-CS proportions in the binder of the shotcrete mixtures was not studied in these researches. Thus, we proposed to study CSA-OPC-CS mixtures under a systematic control on binder compositions, and develop potential expansive shotcrete mixtures possessing the benefits associated with the utilization of CSA.

One of the advantages of using CSA in the mixture is that the CO_2 released during the production of CSA is about 49% less than that of OPC and about 3% less than that of calcium aluminate cement CAC, which is a common binder for expansive shotcrete mixtures (Burris et al., 2015). Reduced CO_2 emission would relieve global warming (Solomon et al., 2009) and may provide financial merits when the carbon tax is implanted in the area of application. Another possible benefit of the CSA-OPC-CS expansive mixture is the enhanced early compressive strength typically associated with CSA (Dachtar, 2004; Péra & Ambroise, 2004), which would allow a faster re-entry to the worksite after application.

To assess and optimize the performance of the CSA-OPC-CS mixtures, we tested basic properties such as volume change, unconfined compressive strength (UCS), density, absorption, and volume of permeable voids of various CSA-OPC-CS compositions in this study. The potential of the CSA-OPC-CS shotcrete mixtures was preliminarily evaluated to advance the development of expansive shotcrete mixtures in the future.

3.2 Materials and Methods

3.2.1 Materials

Table 3.1. Basic properties of CSA, OPC, and CS

Ingredient	Specific Gravity	pH when wet	Composition
CSA	2.98	11-12	80-100% of calcium sulfoaluminate cement, with less than 0.1% of silica crystalline
OPC	3.15	12-13	0-15% of limestone, 2-10% of gypsum, 0-5% of calcium oxide, 0-4% of Magnesium oxide, and 0-0.2% quartz
CS	0.56	7.25	85% calcium sulfate dehydrate

Calcium sulfoaluminate cement (CSA), GU Portland cement (OPC), calcium sulfate (CS) in the form of gypsum, and limestone aggregates were combined with local tap water at the Edmonton, Alberta area to create shotcrete mixtures studied in this research. The basic properties of the CSA, OPC, and CS are presented in Table 3.1, and the materials are shown in Figure 3.1. The water used in this study met the chemical, physical, and radiological parameters set by Health Canada for drinking water qualities (Health Canada, 2014) by making the tap water free of impurities and suitable for general experimental purposes. The aggregates were made up in both coarse and fine sizes. The commercial limestone aggregate was available in the lab in large quantities and had an oven-dried (OD) specific gravity of 2.02 and an absorption of 2.38% after tested following the ASTM C127 and ASTM C128 standards (ASTM, 2015b, 2015c). Sieve analysis performed on the aggregate revealed that the aggregates could be classified using the ASTM-C1436 specification to fall within Grading Zone No. 2, and are acceptable to be used in shotcrete mixtures (ASTM, 2013b). The aggregate size distribution and grading zone are shown in Figure 3.2.

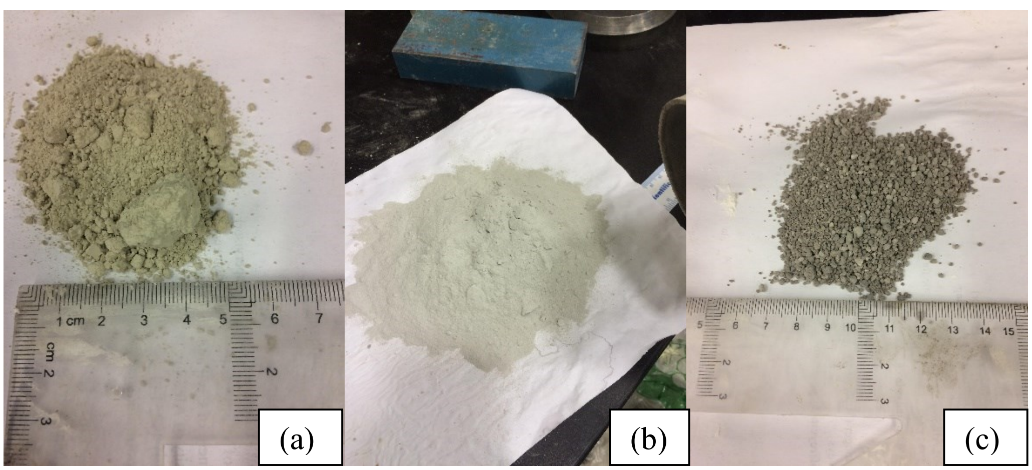


Figure 3.1. Binder materials used in this research: (a) CSA; (b) OPC; and (c) CS

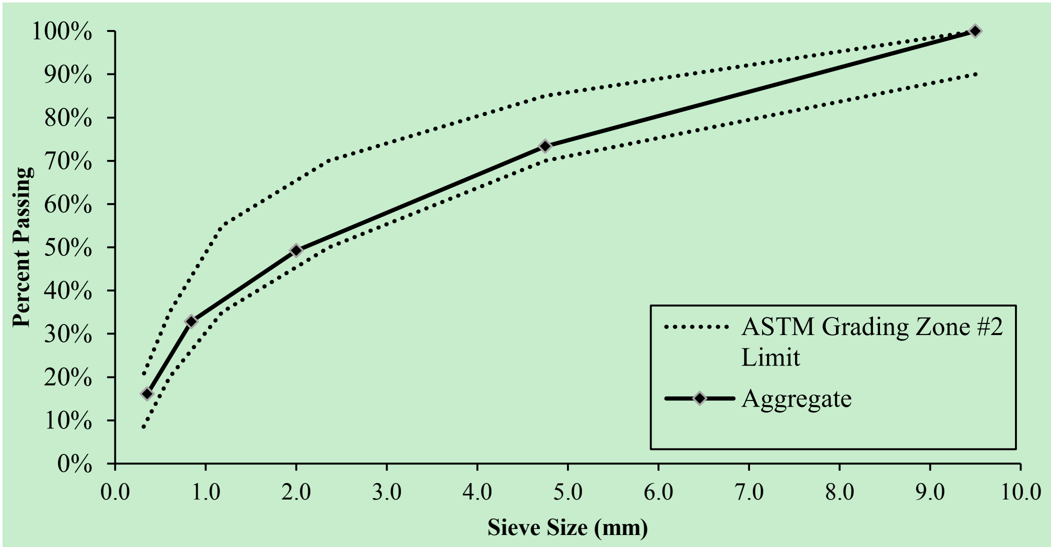
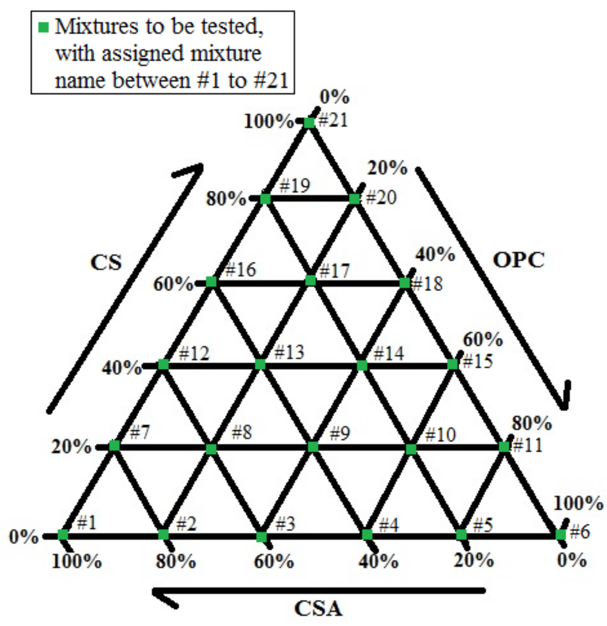


Figure 3.2. Aggregate size distribution and grading limit

3.2.2 Mix Design



Mixture Name	% Material in Binder		
	OPC (%)	CSA (%)	CS (%)
#1	0	100	0
#2	20	80	0
#3	40	60	0
#4	60	40	0
#5	80	20	0
#6	100	0	0
#7	0	80	20
#8	20	60	20
#9	40	40	20
#10	60	20	20
#11	80	0	20
#12	0	60	40
#13	20	40	40
#14	40	20	40
#15	60	0	40
#16	0	40	60
#17	20	20	60
#18	40	0	60
#19	0	20	80
#20	20	0	80
#21	0	0	100

Figure 3.3. Binder composition and design

Table 3.2. Mix design by weight

	Water	Binder	Aggregates	
			Fine Portion	Coarse Portion
Portion by Mass	7.7%	17.2%	53.6%	21.5%
Mixture Proportions	180 kg/m^3	400 kg/m^3	1250 kg/m^3	500 kg/m^3

The shotcrete mixture was designed according to the typical underground wet-mix shotcrete mixture proportions from the ACI 506.5R guideline, and the water/cement (w/c) ratios of the mixtures were kept at 0.45 as per ACI guideline suggested for consistency (ACI, 2009). The shotcrete mixture weight proportions are listed in Table 3.2, with the coarse portion of the aggregates referring to aggregates with a size larger than 4.75 mm (ASTM, 2015a). The binder in Table 3.2 is defined as the material that holds the mixture together, forming the matrix of the mixture (ACI, 2013). CSA, OPC, and CS are all considered binder in this research. Twenty-one shotcrete mixtures with different binder compositions were designed and shown in Figure 3.3, where the mixtures at every intersection in the triangle were assigned a mixture name and tested. The mixture name assigned were between #1 and #21. Effects on the performance of the designed mixtures were tested to verify the effects of different CSA, OPC, and CS ratios. The triangle with the assigned mixture names in Figure 3.3 has the following properties:

(1) The incremental change of the CSA, OPC, and CS percentage is 20% in weight, with each binder material starting from 0% and ending at 100%;

(2) At any point in the tertiary plot, the binder materials must add up to 100%;

(3) The top point of the triangle was consisted of 100% CS in the binder;

(4) The bottom right point was consisted of 100% OPC;

(5) The bottom left point was consisted of 100% CSA; and

(6) When CSA and CS replaced the OPC in the binder, the difference in volume of the mixture was compensated by adjusting the volume of fine aggregate.

3.2.3 Sample Creation and Testing

Figure 3.4. Concrete mixer used for sample creation

Mixture samples were created following procedures stated in ASTM C192 (ASTM, 2016a). Mixture components were mixed using a drum mixer (shown in Figure 3.4) and poured into cylinders of size 75 mm in diameter and 150 mm in height. After casting, samples were immediately transferred to a moisture room with a temperature of 25 ± 2 °C and relative humidity (RH) of 100% for hardening. After

24 hours of hardening, the samples were taken out of the cylinder, and they were cured in the same moisture room until the test dates.

For each mixture, two cylindrical samples were created for the examination of the density, absorption, and volume of permeable voids following the ASTM C642 specification (ASTM, 2013a); these samples were tested after cured in the moisture room for 7 days. Another four cylinder samples were created for each mixture to test for unconfined compressive strength (UCS). Two of the four cylindrical samples were tested on the 1st day, and the remaining two were tested on the 28th day for UCS. The samples were tested for UCS using a loading machine in accordance with ASTM C39 (ASTM, 2016b).

Figure 3.5. Volumetric measurements on cylindrical samples

Volumetric measurements were performed on the samples used for the 28th day UCS test, at the 1st, 2nd, 3rd, 5th, 7th, 14th, 21st, and the 28th days. The volumetric measurements were performed on the samples using a digital caliper, following the length and diameter measuring processes described in the ASTM C496 guideline (ASTM, 2011). The samples were marked on the sides and the tops so that the measurements were performed at the same location for every measurement, as shown in Figure 3.5. To provide a preliminary analysis of the effect of water curing on volume change, two additional cylindrical samples were created and cured in water at a temperature of 19 ± 0.5 °C. These two samples underwent the same volume measurements described above. A summary of the tests performed is recorded in

.

Table 3.3. Summary of tests performed

Material Properties Tested	Test Period	Test Procedure
UCS	1st and 28th day	ASTM C39
Volume Change	1st, 2nd, 3rd, 5th, 7th, 14th, 21st, and 28th day	Caliper Measurements
Density, Absorption, and Volume of Permeable Voids	7th day	ASTM C642

3.3 Results and Discussions

3.3.1 Density, Water Absorption, and Volume of Permeable Voids

Table 3.4. Density, water absorption, and volume of permeable voids results

Mixture Name	OPC (%)	CSA (%)	CS (%)	Oven-dry Bulk Density (kg/m^3)	Water Absorption after Immersion (%)	Volume of Permeable Pore Space (%)
#1	0	100	0	2,550	14.1%	42.5%
#2	20	80	0	2,080	11.4%	29.1%
#3	40	60	0	2,440	12.0%	33.0%
#4	60	40	0	2,670	8.5%	23.7%
#5	80	20	0	2,590	7.8%	21.0%
#6	100	0	0	2,670	6.9%	18.9%
#7	0	80	20	2,340	10.6%	25.8%
#8	20	60	20	2,500	11.3%	30.8%
#9	40	40	20	2,400	11.6%	29.5%
#10	60	20	20	2,360	11.1%	30.3%
#11	80	0	20	2,150	11.2%	26.0%
#12	0	60	40	2,320	9.5%	26.6%
#13	20	40	40	2,530	10.5%	29.9%
#14	40	60	40	2,290	12.9%	33.1%
#15	60	0	40	2,320	10.9%	25.7%
#16	0	40	60	2,410	10.2%	30.3%
#17	20	20	60	2,210	12.3%	29.3%
#18	40	0	60	N/A	N/A	N/A
#19	0	20	80	N/A	N/A	N/A
#20	20	0	80	N/A	N/A	N/A
#21	0	0	100	N/A	N/A	N/A

The oven-dry densities, the water absorption, and the volume of permeable voids of the CSA-OPC-CS (calcium sulfoaluminate cement- ordinary Portland cement-calcium sulfate) mixtures are listed in Table 3.4. The above-mentioned properties were not recorded on mixture #18 to #21 since they failed to harden, due to the retarding ability of excessive CS in the mixtures and the lack of other binding materials (i.e., CSA and OPC); they were recorded as not applicable (N/A) in the table. The oven-dry densities laid between 2,080 kg/m^3 and 2,670 kg/m^3. The water absorptions laid between 6.9% and 14.1%, and the volumes of permeable pore space ranged from 18.9% to 42.5%. It was observed that applying CSA or CS instead of OPC in the shotcrete mixtures would decrease the oven-dry density but at the same time increase the water absorption and the volume of permeable pore space. Of all the tested mixtures, the 100% OPC mixture (mixture #6) demonstrated the highest oven-dry density at 2670 kg/m^3, the lowest water absorption of 6.9%, and the least volume of permeable voids at 18.9%. In contrast, when OPC or CS was utilized over CSA, the water absorption and the volume of permeable voids dropped. The decrease of water absorption and volume of permeable voids could be explained by the CSA's ability to produce ettringite during hydration, which bind a large amount of water in the processes (Zhou et al., 2006).

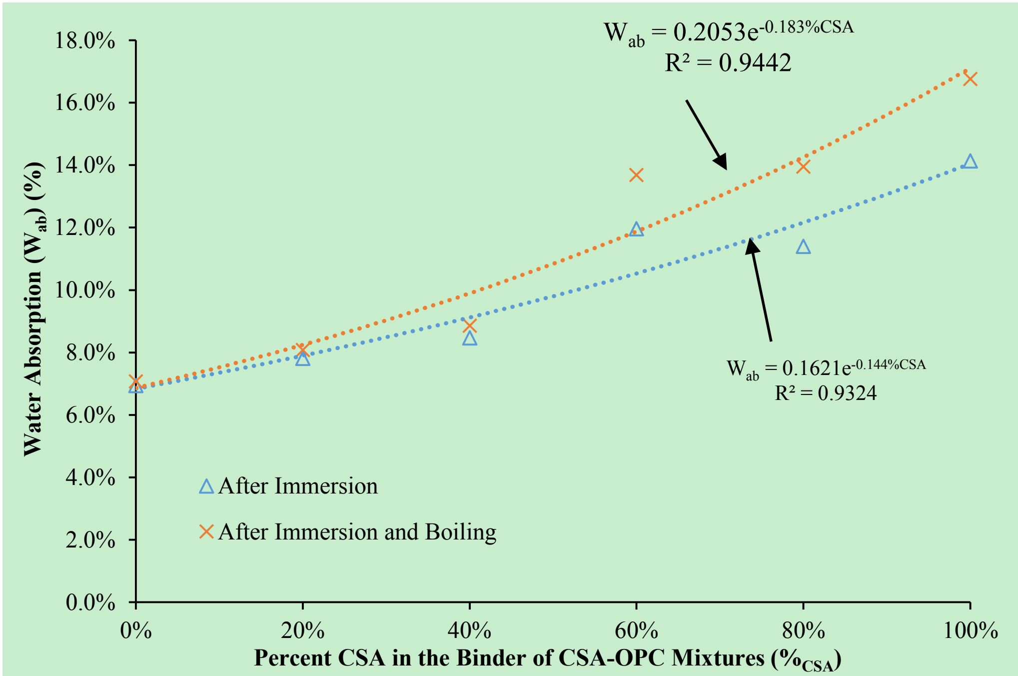


Figure 3.6. Effect of utilizing CSA over OPC on water absorption

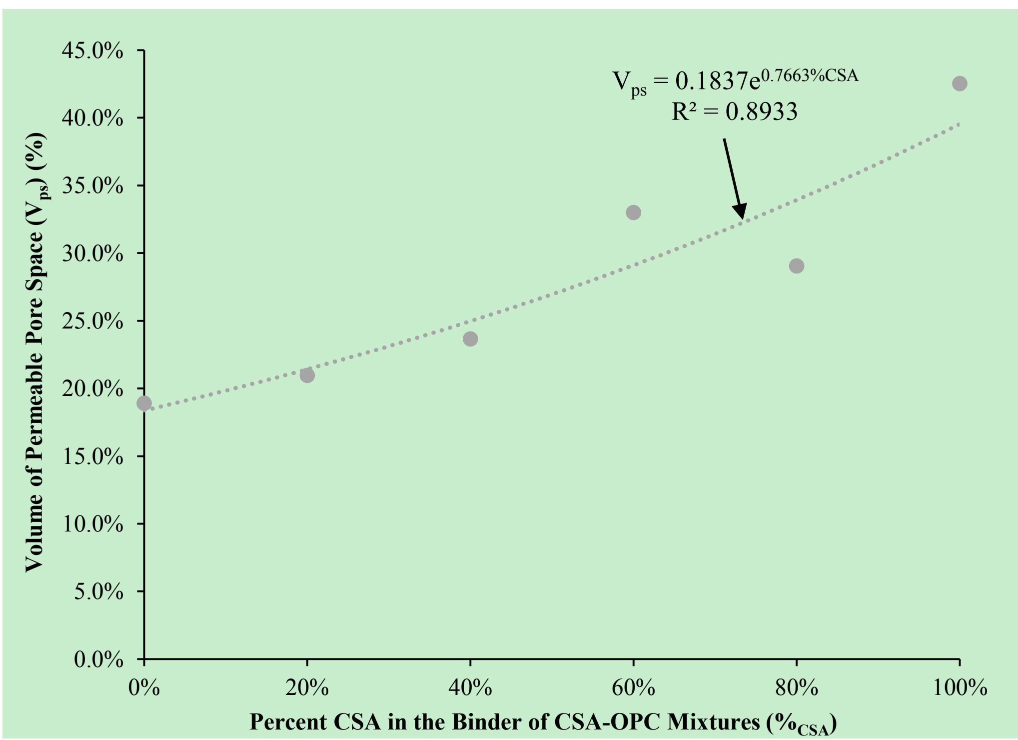


Figure 3.7. Effect of utilizing CSA over OPC on volume of permeable space

As shown in Figure 3.6, the water absorption increased when CSA was utilized over OPC. The immersed water absorption increased from 6.9% to 14.1%, and the immersed and boiled water absorption advanced from 7.1% to 16.8% as the CSA content increased. The relationship between the volume of permeable void space and the CSA-OPC content is shown in Figure 3.7. The volume of permeable void space was the lowest at 18.9% for the 100% OPC mixture, and increased as CSA content increased, which reached 42.5% for the 100% CSA mixture.

3.3.2 Unconfined Compressive Strength

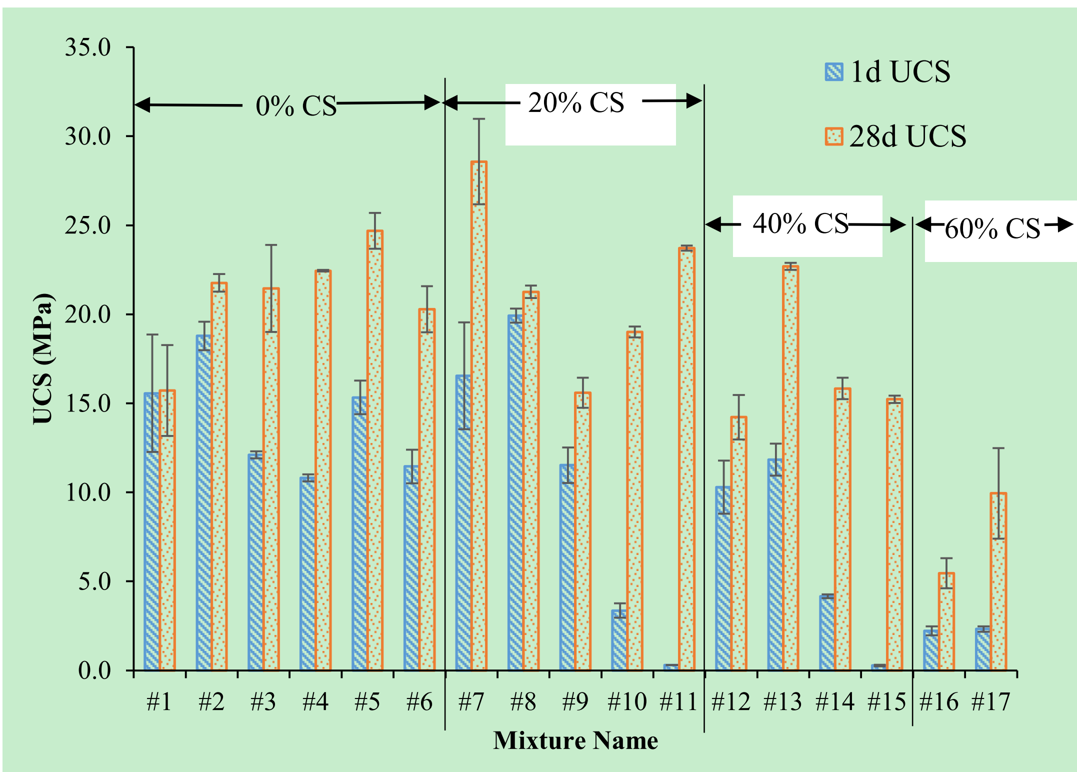


Figure 3.8. UCS Test Results

The compressive strength (UCS) of the shotcrete mixture samples are shown in Figure 3.8. The UCS of the mixtures ranged from 0.3 MPa - 21.3 MPa and 5.5 MPa - 28.6 MPa on the first day and after 28 days, respectively. When 80% or more CS was in the binder the mixture would fail to harden, and thus no UCS could be obtained. The control sample, mixture #6 with 100% OPC in the binder, showed a 28th day UCS of 20.3 MPa. A research testing similar mixture that also used crushed limestone as the aggregate had reported a 28th day UCS of 24.1 MPa, at a w/c ratio of 0.4 (Tavakoli & Soroushian, 1996). The lower UCS may be caused by rougher shape and weaker strength of the limestone aggregate utilized which limited the strength of the mixture. The UCS of aggregates tested in this study should be compared with regular aggregates in the future to confirm the strength contribution of aggregates in mixtures.

In general, results in Figure 3.8 show that the UCS on the 1st day decreased as the proportion of CS increased. When the CS proportion in the binder reached 60%, the compressive strength dropped to 2.2 MPa (mixture #16) and 2.3 MPa (mixture #17). The strength of the 28th day, on the other hand, was lower at 0% CS proportion and increased as the CS content reached 20%, showing the highest UCS of 28.6 MPa (mixture #7). When CS was added over 20%, the UCS on the 28th day dropped as CS content increased, and at 60% CS content all mixtures had less UCS than the plain OPC mixture. Note that this deduction in UCS with high CS content was also found in other research (Fall & Pokharel, 2010), which indicated that the high CS content impeded the hydration of the mixtures and left some components in the mixture unreacted, resulting in lower UCS.

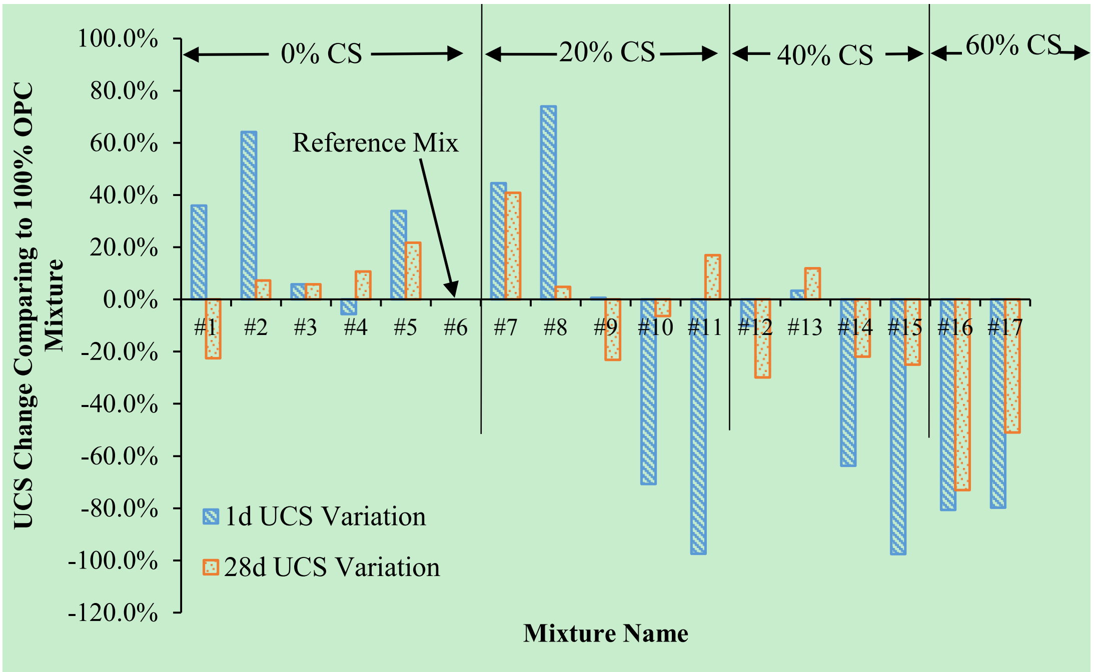


Figure 3.9. UCS Variation Compared to the 100% OPC Mixture

The UCS variations in relation to the commonly used 100% OPC mixture (mixture #6) are summarized in Figure 3.9. The UCS variation was calculated using the following equation (Equation 3.1):

$$UCS_{variation}(\%) = \frac{UCS_{new} - UCS_{reference}}{UCS_{reference}} \times 100\% \qquad \text{Equation 3.1}$$

where

$UCS_{variation}$ is the UCS variation percentage, %

$UCS_{reference}$ is the UCS of the reference 100% Portland cement mixture (mixture #6), MPa

UCS_{new} is the UCS of the sample being compared to the reference mixture, MPa

As seen from Figure 3.9, the UCS variations compared to the 100% OPC mixture laid between -97.6% to 74.0% for the 1st day, and -73.1% to 40.9% on the 28th day. The UCS variation decreased as more CS was added in the CSA-OPC-CS mixtures.

This is because CS lowered the hydration of the mixtures (Fall & Pokharel, 2010). To create CSA-OPC-CS mixtures with improved UCS compared to the reference OPC mix (mixture #6), CS concentration of 20% or less in the binder was recommended. The only exception was found in mixture #13 (40% CSA + 20% OPC + 40% CS), which had a 3.3% UCS increase on the 1st day and an 11.9% UCS increase on the 28th day in comparison to the reference mixture. This composition may be used to act as a UCS-enhanced mixture in the future.

3.3.3 Volume Change Results

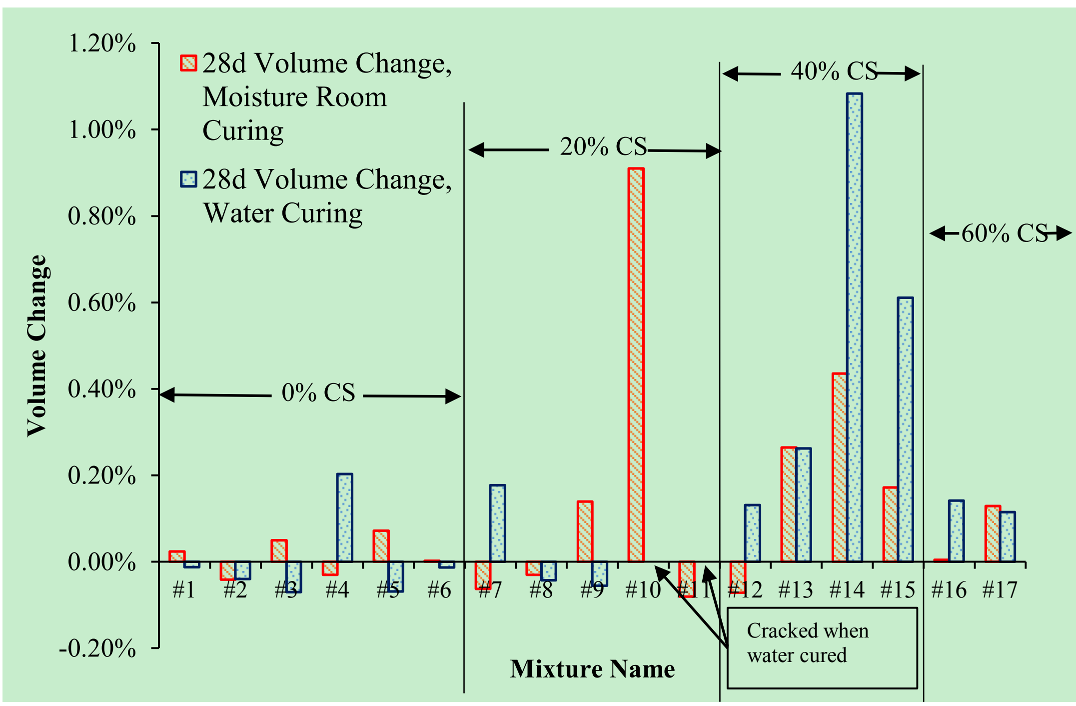


Figure 3.10. Volume Change Results

The volume changes of different mixtures on the 28th day are summarized in Figure 3.10. The volume changes were calculated using Equation 3.2 as shown:

$V_c(\%) = \frac{V_{28} - V_1}{V_1} \times 100\%$ Equation 3.2

Where

V_c is the volume change percentage, %

V_1 is the measured sample volume on the 1st day, m^3

V_{28} is the measured sample volume on the 28th day, m^3

The authors observe from Figure 3.10 that the volume changes of the mixtures ranged between -0.08% and 1.08%. No data was recorded for Mixtures #10 and #11when water cured because they cracked on the 21st day and the 5th day. Before the Mixtures # 10 and # 11 cracked, they had reached an expansion of 1.41% on the 14th day and 0.55% on the 3rd day.

It is noted from Figure 3.10 that the mixtures may expand or shrink under different curing conditions. The Mixtures #3 to #7, #9, and #12 demonstrated different volume change (shrinking and expanding) behaviors when cured in water and moisture room. The liquid water immersion would provide constant and better water contact for the mixtures, influencing the volume change. For the expansive mixtures (mixtures with positive volume changes at both curing conditions), the expansions ranged between 0.11% and 1.08%. These expansive mixtures could compensate shrinkage and therefore reduce the chances of shrinkage-induced cracking. Mixtures #13 to #17 were deemed as the expansive mixtures. We observed from Figure 3.10 that every expansive mixture had at least 40% of gypsum in the binder. The presence of CS in all of the expansive mixtures indicated that gypsum addition would, in general, promote expansion, a trend which was also found in other studies (Bizzozero et al., 2014; Dachtar, 2004; Ioannou et al., 2014).

The expansions generated could be attributed to the formation of ettringite, a hydration product of CS reacting with CSA (Cohen, 1983; Mehta, 1967) or minor CS reacting with OPC (Kovler, 1998).

The authors also observed from Figure 3.10 that the CSA-OPC-CS mixtures were less likely to expand when the CSA content increased. None of the mixtures were expansive when having 60% or more CSA in the binder. The two shrinking mixtures observed had high CSA and low CS content (mixture #2 with 80% CSA and mixture #8 with 60% CSA), and the 28^{th}-day shrinkage was found to be 0.04%. This could be explained by the insufficient amount of CS to react with the CSA for expansion generation. For example, one recent study noted that one part of CSA required 1.27 times as much CS to generate distinctive expansion (Bizzozero et al., 2014).

3.3.4 Preliminary Mixture Classifications

The shotcrete mixtures are classified into expansive, strength-enhanced, cracking and unhardened mixtures. Figure 3.11 shows the binder composition of each class of mixtures. The expansive mixtures demonstrated positive volume changes on the 28^{th} day, the strength-enhanced mixtures shown better UCS both at the 1^{st} and the 28^{th} day than the 100% OPC mixture (mixture #6), and the unhardened mixtures failed to harden 24 hours after mixing. The expansive mixtures identified are candidates for the development of future shrinkage-compensating shotcrete mixtures. The strength-enhanced mixtures identified may be further investigated when shotcrete with higher UCS is required. The cracked mixtures, #10 and #11, cannot be used as shotcrete mixtures even though they generated expansions (1.41% and 0.55% volume change, respectively) before cracking. Moreover, mixtures #18 to #21 failed to harden and are also inadequate for the mining and the construction applications.

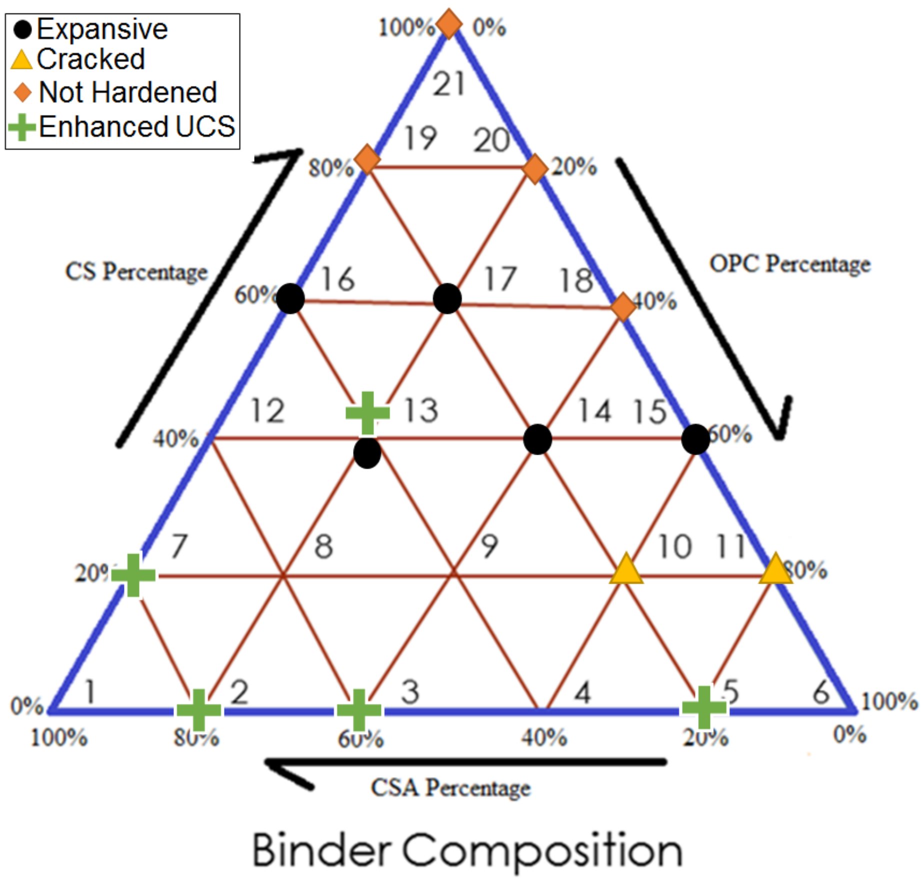


Figure 3.11. Preliminary CSA-OPC-CS Shotcrete Mixture Classification

3.4 Chapter Summary and Conclusions

The authors identified expansive shotcrete mixtures consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) in this chapter. Based on the experiments performed for this chapter, the following conclusions are drawn:

1) A tertiary plot was created depicting CSA, OPC, and CS as the primary, secondary, and tertiary binder materials in the typical shotcrete mixtures. This plot could provide preliminary design considerations for the creation of expansive CSA-OPC-CS shotcrete mixtures.

2) Expansive behaviors were observed on the 28th day from mixture #13 (40%CSA, 20%OPC, and 20%CS) to #17 (20%CSA, 20%OPC, and 60%CS). These mixtures are proposed for further studies as shrinkage-compensating shotcrete mixtures.

3) Strength-enhanced CSA-OPC-CS mixtures (mixture #2, #3, #5, #7, #8, and #13) were identified. These mixtures had higher UCS on the 1st and 28th day when compared to the 100% OPC mixture, and they could be developed as strength-enhanced shotcrete mixtures in the future.

4) It was observed that using CSA or CS instead of OPC in the shotcrete mixtures would decrease the oven-dry density, enhance the water absorption, and increase the volume of permeable pore space.

5) In general, when more CS was utilized as the binder materials of the CSA-OPC-CS mixtures, it is more likely that the expansion would occur on the 28th day. However, as CS content increased, the unconfined compressive strength (UCS) would decrease on the 1st and the 28th day. The expansion could be as much as 1.08%, and the UCS could be as low as 0.3 MPa on the 1st day and 5.5 MPa on the 28th day, respectively.

6) Reducing the water contact would decrease the probability of cracking for the CSA-OPC-CS mixtures. In this study, samples #10 and #11 only cracked when cured in water. In contrast, these mixtures showed no visible cracks on the 28^{th} day when cured in moisture room.

Although the development of expansive shotcrete mixtures using CSA-OPC-CS in the binder is only in the preliminary stage, potential expansive mixtures had been identified in this chapter and would prompt further studies. Besides replacing the limestone aggregate used in this research, it is also recommended to test CSA-OPC-CS mixtures at other binder proportions and investigate the influence of actual shotcreting (pneumatic projection).

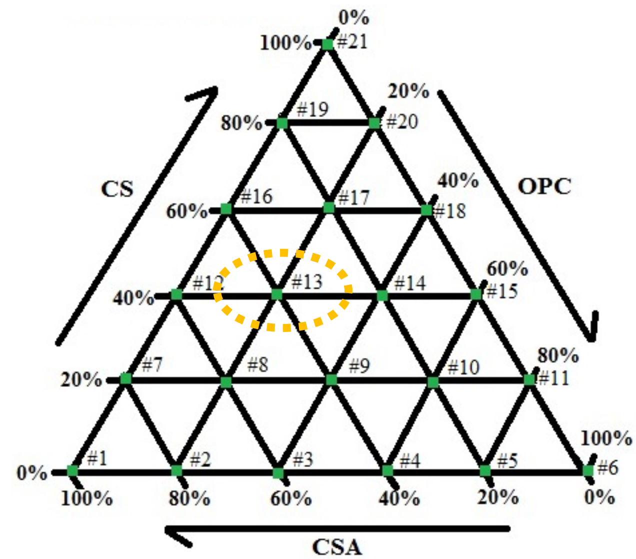
Chapter 4 Effects of Fibers on Expansive CSA-OPC-CS Shotcrete Mixture

Chapter 4 contains the research work performed for evaluating the effects of fibers on expansive CSA-OPC-CS mixture. Nylon fiber, glass fiber, and steel fiber were added at 1% volume fraction, and their effects on restraining expansion and mechanical strength were evaluated.

*The content of this chapter has been submitted as a journal manuscript (under review): H. Yu, L. Wu, W.V. Liu, and Y. Pourrahimian, "Influence of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate, Portland cement, and calcium sulfate," in *Journal of Rock Mechanics and Geotechnical Engineering.*

4.1 Introduction

Mixture Name "#13" was chosen for further investigation in this research.



Mixture Name	% Material in Binder		
	OPC (%)	CSA (%)	CS (%)
#1	0	100	0
#2	20	80	0
#3	40	60	0
#4	60	40	0
#5	80	20	0
#6	100	0	0
#7	0	80	20
#8	20	60	20
#9	40	40	20
#10	60	20	20
#11	80	0	20
#12	0	60	40
#13	20	40	40
#14	40	20	40
#15	60	0	40
#16	0	40	60
#17	20	20	60
#18	40	0	60
#19	0	20	80
#20	20	0	80
#21	0	0	100

Figure 4.1. CSA-OPC-CS mixtures previously tested (Yu et al., 2017)

Shotcrete is often used by the mining industry for ground stabilization. However, cracking within shotcrete is common, which delays production schedules and increases maintenance costs. A possible crack reduction method is using expansive shotcrete mixture consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) that reduces shrinkage. The authors had previously combined CSA, OPC, and CS in systematic ratios to create shrinkage-compensating shotcrete mixtures, where the expansion ratios of the mixtures at different CSA-OPC-CS ratios were identified (Yu et al., 2017). Various mixtures tested in the previous chapter are shown in Figure 4.1, and the binders of these mixtures are best classified as type K expansive cement based on their constituents. The expansive mixture (20%OPC-40%CSA-40%CS) having the highest unconfined compressive strength (UCS) was selected for further investigation in this chapter. Furthermore, fibers were added to the mixture to restrain expansion and impede cracking. The objective of this chapter is to study the effects of nylon fiber, glass fiber, and steel fiber on an expansive shotcrete mixture that can better resist cracking.

4.2 Materials and Methods

4.2.1 Materials

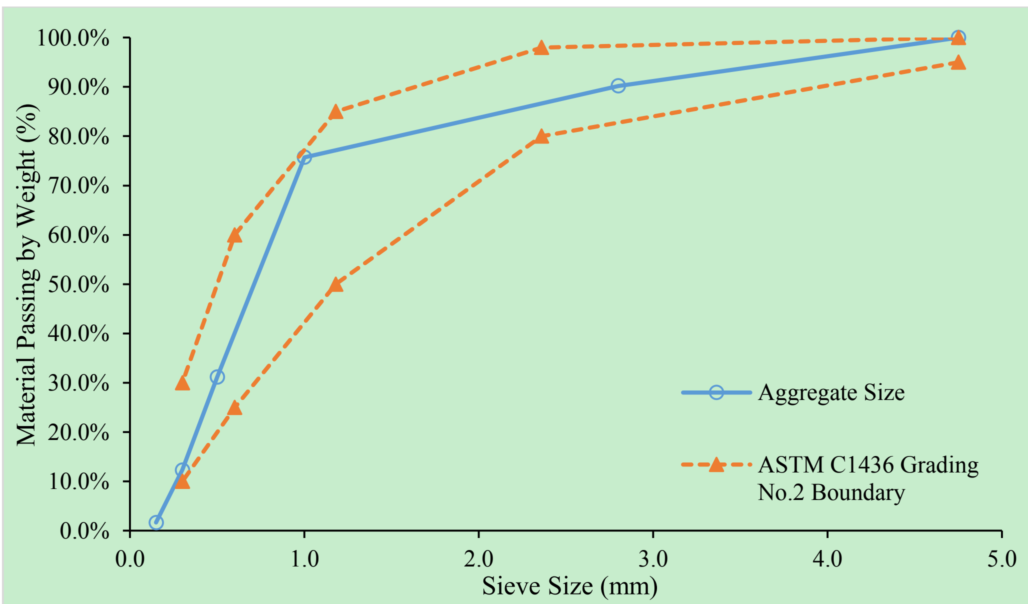


Figure 4.2. Sieve analysis result for the aggregate utilized in this research

The materials used for the creation of the shotcrete mixtures include calcium sulfoaluminate cement (CSA), Type GU ordinary Portland cement (OPC), calcium sulfate (CS) in the form of granular gypsum, fine aggregates, tap water, nylon fiber, glass fiber, and steel fiber. The fine aggregates were in a saturated surface dried (SSD) condition and had an oven-dry (OD) relative density of 1,578 kg/m^3; they were smaller than 4.75 mm and demonstrated a water absorption of 5.1%. The sieve analysis result for the aggregate is shown in Figure 4.2, where the aggregate was found to fit within the ASTM C1436 Grading zone No.2 (ASTM, 2013b) and is suitable for application in shotcrete. All the cementitious materials (CSA, OPC, and CS) and aggregates mentioned above were purchased locally, and the basic properties of the cementitious materials are summarized in Table 4.1. The tap water used for this research was from the Edmonton, Alberta area, in accordance to the parameters set by Health Canada for drinking water (Health Canada, 2014). In other words, the impurities of the drinkable water were under acceptable levels and could be used for the creation of shotcrete mixtures (Hofler & Schlumpf, 2006).

Table 4.1. Basic properties of CSA, OPC, and CS (CTS Cement, 2015; USA Gypsum, 2017)

Ingredient	Specific Gravity	pH when wet	Composition
CSA	2.98	11-12	80% - 100% of calcium sulfoaluminate cement, with less than 0.1% of silica crystalline
OPC	3.15	12-13	0% - 15% of limestone, 2% - 10% of gypsum, 0% - 5% of calcium oxide, 0% - 4% of Magnesium oxide, and 0% - 0.2% quartz
CS	0.56	7.25	19% calcium, 14% sulfur, and 85% calcium sulfate dihydrate

Figure 4.3 shows the three different types of fibers (i.e., nylon, glass, and steel) utilized in this research. The fibers were tested for water absorption following the

absorption calculation process described in the ASTM C642 standard (ASTM, 2013a), and it was found that nylon fiber had a water absorption of 105.0%; glass fiber had a water absorption of 64.9%; and steel fiber had a water absorption of 4.0%. The properties of these fibers are listed in Table 4.2.

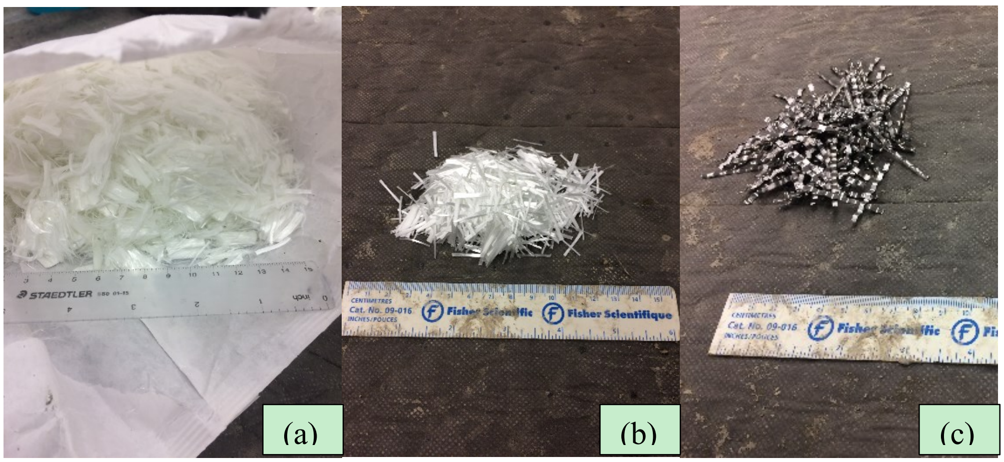


Figure 4.3. Various fibers utilized in the research: (a) nylon fibers; (b) glass fibers; (c) steel fibers

Table 4.2. Basic properties of fibers used (Bon, 2009, 2015; Propex, 2012)

Fiber	Specific Gravity	Tensile Strength (MPa)	Length (mm)	Diameter (mm)	Shape
Nylon	1.14	966	19	0.03	Straight, round
Glass	2.68	1,700	19	0.01	Straight, round
Steel	9.79	966 - 1,242	38	1.14	Wavy

4.2.2 Mix Design

Five CSA-OPC-CS mixtures were found from a previous study (Yu et al., 2017) to be expansive, and their compositions and performances are summarized in Table 4.3. The expansive mixture showing the highest UCS (Mixture Name #13, with 40%CSA+20%OPC+40%CS in the binder) was selected for fiber additions in this chapter, and it was assigned the mixture name of "Mix1". In addition, a 100% OPC mixture was also selected along the expansive CSA-OPC-CS mixture to act as a control sample, which was assigned the mixture name of "Ref."

Table 4.3. Expansive mixtures identified from a previous study (Yu et al., 2017)

Mixture Name	Weight proportion in Binder			28th Day UCS (MPa)	28th day Volume Change
	CSA	OPC	CS		
#13	40%	20%	40%	22.7	0.26%
#14	20%	40%	40%	15.8	1.08%
#15	0%	60%	40%	15.2	0.61%
#16	40%	0%	60%	5.5	0.14%
#17	20%	20%	60%	9.9	0.11%

The shotcrete mixture design proportions are summarized in Table 4.4. The shotcrete mixtures prepared for testing were designed following the ACI 506.5R guideline for typical underground shotcrete proportions (ACI, 2009). Three different types of fibers (i.e., nylon, glass, and steel) were added to Mix1 individually to study their influences. These fibers were added at 1.0% volume fraction, a value that was found effective on restraining expansion (Chen & Liu, 2003). Mixture name "Mix1-N" was assigned to the mixture with nylon fiber reinforcement, "Mix1-G" was assigned to the mixture with glass fiber reinforcement, and "Mix1-S" was assigned to the mixture with steel fiber reinforcement. Note that fibers were added to the mixtures to replace fine aggregates volumetrically, and the aggregate-to-cementitious materials ratio (a/c) was kept at 3.13 as suggested in the ACI 506 guideline for specifying underground shotcrete (ACI, 2009); however, an a/c ratio of 4.35 was then used to investigate the effect of increasing a/c ratio on mechanical strength. The water-to-cementitious materials ratio (w/c) was kept constant at 0.45, following the ACI 506 guideline. Under this w/c ratio, the slumps of Mix1 and Ref were found to fall within the 75 mm to 125 mm desired workability suggested by the ACI 506 guideline.

Table 4.4. Mixture design proportions

Mixture Name	Weight ratio in mix		Weight proportion in Binder			Fiber volume fraction		
	w/c	a/c*	CSA	OPC	CS	Nylon	Glass	Steel
Ref	0.45	3.13	0%	100%	0%	0%	0%	0%
Mix1	0.45	3.13	40%	20%	40%	0%	0%	0%
Mix1-N	0.45	3.13	40%	20%	40%	1%	0%	0%
Mix1-G	0.45	3.13	40%	20%	40%	0%	1%	0%
Mix1-S	0.45	3.13	40%	20%	40%	0%	0%	1%

* a/c ratio was later changed to 4.35 to study the effect of increasing a/c ratio on UCS and STS

The mixtures were prepared according to the ASTM C192 standard for making and curing concrete test samples (ASTM, 2016a). All mixtures were mixed using a drum mixer with a capacity of 0.116 m^3. The fiber volume fraction mentioned in Table 4.4 was added to the cementitious material during the mixing stage. The dry mixture materials with fibers were rotated for 5 minutes before water addition, and then the whole mixture with water was rotated for another 5 minutes. A table vibrator was used for compacting the mixtures in the molds, and a 5 seconds vibration per layer as suggested in the ASTM C192 standard (ASTM, 2016a) was initiated. For each mix, a total of 6 cylinder samples (Diameter, ø: 75 mm; Height: 150 mm) and 2 cube samples (Side dimensions: 5 mm) were created. The cylindrical samples were used to determine UCS and STS, and the cube samples were created to determine density, water absorption, and volume of permeable voids. After the first 24 hours, samples were demolded and transferred to a moisture room with a temperature of 25 ± 2 °C and a relative humidity (RH) of 100% for curing. The mold used to create the cubic samples is shown in Figure 4.4.

Figure 4.4. Mold used to create cubic samples

4.2.3 Sample Creation and Testing

4.2.3.1 Density, water absorption, and volume of permeable voids tests

The density, the water absorption, and the volume of permeable voids were determined following the test methods described in ASTM C642 (ASTM, 2013a).

The oven used for the drying of the sample is shown in Figure 4.5, and the boiling setup is shown in Figure 4.6a.

Figure 4.5. Oven used for the drying of the samples

4.2.3.2 Unconfined compressive strength

The unconfined compressive strength (UCS) of the samples were evaluated using ASTM C39 (ASTM, 2016b), as shown in Figure 4.6b. For each mixture, three cylindrical samples were tested on the 28th day to determine the average UCS.

4.2.3.3 Splitting tensile strength

Splitting tensile strengths (STS) were determined in accordance with ASTM C496 (ASTM, 2011) on the 28th day. Three cylindrical samples were tested per mix for the average values, as shown in Figure 4.6c.

4.2.3.4 Volume Change

Volume changes of the samples were measured using a digital caliper on the cylindrical samples used for the 28^{th} day STS tests. The procedure for the volume determinations were in the form of length measurements and diameter measurements described in ASTM C496 (ASTM, 2011). Samples were marked on the sides and the ends so measurements could be performed on the same locations. A typical dimension measurement is shown in Figure 4.6d. The volumes of the samples were measured on the 1^{st}, 7^{th}, 14^{th}, 21^{st}, and 28^{th} days to monitor volume change.

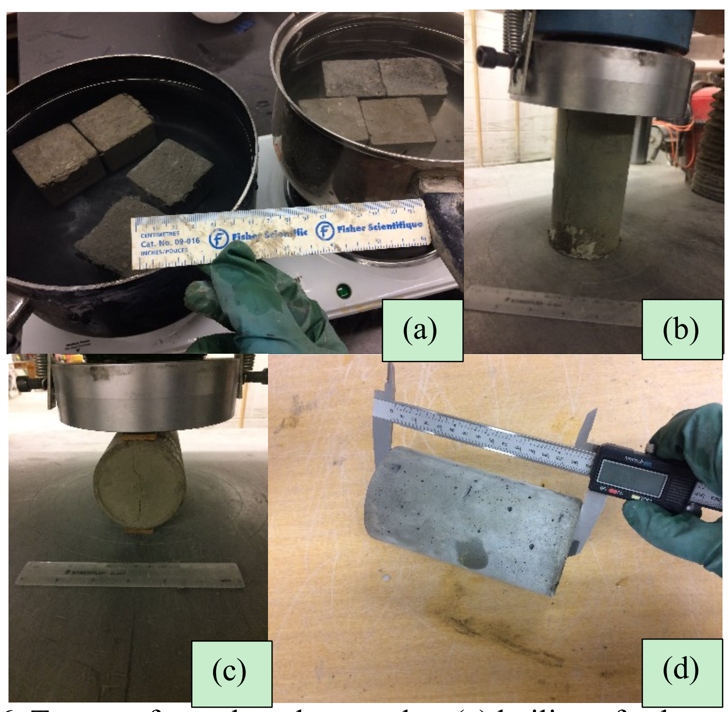


Figure 4.6. Tests performed on the samples: (a) boiling of cube samples for density, absorption, and voids determination; (b) compression of mixture sample; (c) STS determination using a loading machine; (d) measurement of dimension of the sample

4.3 Results and Discussions

4.3.1 Density, Water Absorption, and Volume of Permeable Voids

Table 4.5 shows the oven-dry bulk densities, the water absorptions, and the volume of permeable spaces of the mixtures. The oven-dried densities of CSA-OPC-CS mixtures (Mix1, Mix1-N, Mix1-G, and Mix1-S) ranged between 2,290 kg/m^3 and 2,900 kg/m^3. CSA-OPC-CS mixtures could be best classified as normal weight concrete under the ACI definition (ACI, 2013) since they had densities approximating 2,400 kg/m^3 and were composed of normal-density aggregates. Nylon fiber added to Mix1 showed a significant increase in density at 26.6%, followed by steel fiber addition at an increase of 8.3%, while the addition of glass fiber made little change (1.7%). These increases in oven-dry densities were attributed to the binding provided by the fibers, which allowed more materials to be constrained in the mixture.

Table 4.5. Density, water absorption, and volume of permeable pore space of different mixtures

Mixture Name	Fiber Addition	Oven-dry Bulk Density (kg/m^3)	Water Absorption	Volume of Permeable Pore Space
Ref	None	2,980	9.2%	34.9%
Mix1	None	2,290	16.0%	48.8%
Mix1-N	Nylon	2,900	14.4%	48.3%
Mix1-G	Glass	2,330	14.9%	46.7%
Mix1-S	Steel	2,480	14.3%	45.9%

Table 4.5 also displays the water absorptions of CSA-OPC-CS mixtures, which lay between 14.3% and 16.0%. Compared to a pure OPC mixture (mixture name "Ref"), Mix1 had 73.9% higher water absorption when no fiber was introduced. This can be explained by the greater absorption ratio of CSA in the CSA-OPC-CS mixtures, which is around triple the absorption of the OPC (Dachtar, 2004). Besides absorption, CSA-OPC-CS mixtures also contained more voids than the OPC mixture. CSA-OPC-CS mixtures contained voids ranging between 45.9% and 48.8%, which were 31.5% to 39.8% more than the voids of OPC mixture. The high void content in CSA-OPC-CS mixtures stemmed from their expansion, where larger hydration products replaced smaller constituents (Chaunsali et al., 2015; Mehta, 1973) and created more pore spaces in the process. Fiber additions were found to decrease the volume of permeable voids, enforcing reductions between 1.0% and 5.9%. In brief, fibers provide a binding effect that leads to enhanced density, reduced absorption, and reduced volume of voids.

The water absorption and the volume of permeable pore space listed in Table 4.5 can also be used to indirectly reflect the permeability of shotcrete and its durability (Supit & Shaikh, 2015; Wang et al., 2015). Permeability is defined as the ability to permit liquids or gases passage (ACI, 2013), which allows chemical and water intrusion. Therefore, higher permeability reduces durability and results in more hydration expansion. Based on the results shown in Table 4.5, CSA-OPC-CS mixtures (Mix1, Mix1-N, Mix1-G, and Mix1-S) had higher absorptions and void contents than the OPC mixture (Ref), suggesting worse durability. However, fiber additions to Mix1 group mixtures decreased water absorption and void content (permeability), which would decrease expansion and thus improve durability.

4.3.2 Expansion of CSA-OPC-CS Mixtures

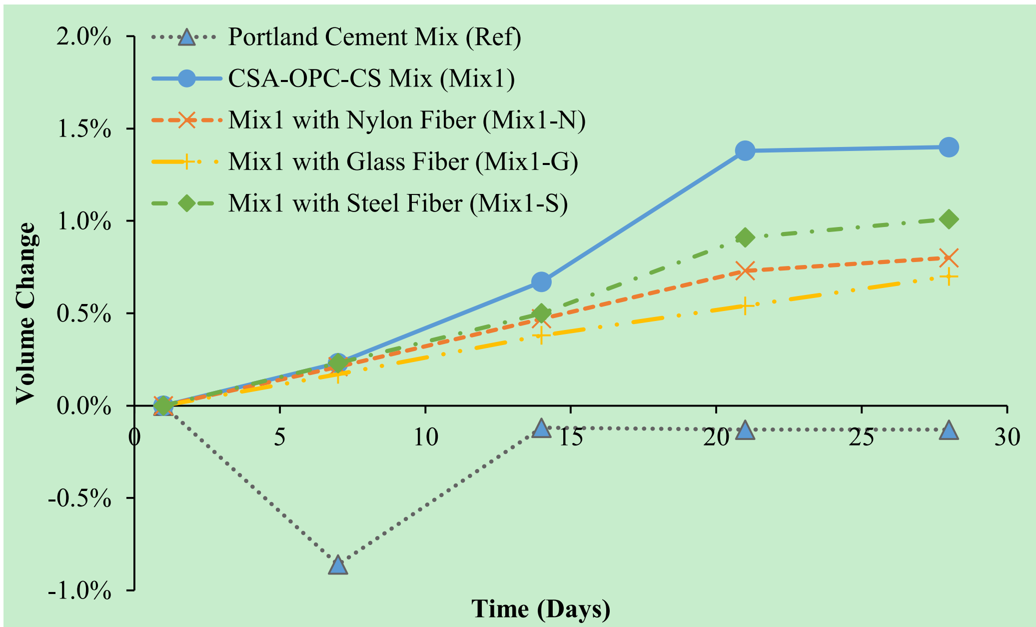


Figure 4.7. Volume changes of mixtures with various fibers over time

The volume changes over time of CSA-OPC-CS mixtures (Mix1, Mix1-N, Mix1-G, and Mix1-S), along with a pure OPC mixture for reference (Ref), are shown in Figure 4.7. The authors found that CSA-OPC-CS mixtures expanded until the 28th day regardless of fiber content, reaching expansions between 0.70% and 1.40%, while OPC mixture shrunk 0.13%. Note that much of the expansion was generated before day 21 and the volume change remained almost constant after that. These expansions were expected because mixture similar to Mix1 was observed to expand up to 0.32% in previous research (Yu et al., 2017). The higher expansion (1.40%) observed in this paper could be attributed to the usage of different fine aggregates and the absence of coarse aggregates, which left Mix1 with smaller size aggregates that allowed greater expansions from better binder-aggregate interaction and possible alkali-aggregate reactions (Farny & Kosmatka, 1997; Zhang et al., 1999). The expansions of CSA-OPC-CS mixtures were generated as CSA, OPC, and CS hydrated, forming ettringite crystals (Dachtar, 2004). As ettringite crystals grew, the volume of the mixture expanded to accommodate the crystals, until the hydration was complete. To verify that ettringite was responsible for the expansion, it is recommended that in the future X-ray powder diffraction (XRD) analysis be conducted on the mixtures over time. This way, the amount of ettringite present can be plotted against expansion, providing evidence for ettringite formation causing expansion.

4.3.3 Influence of Fibers on Expansion of CSA-OPC-CS Mixture

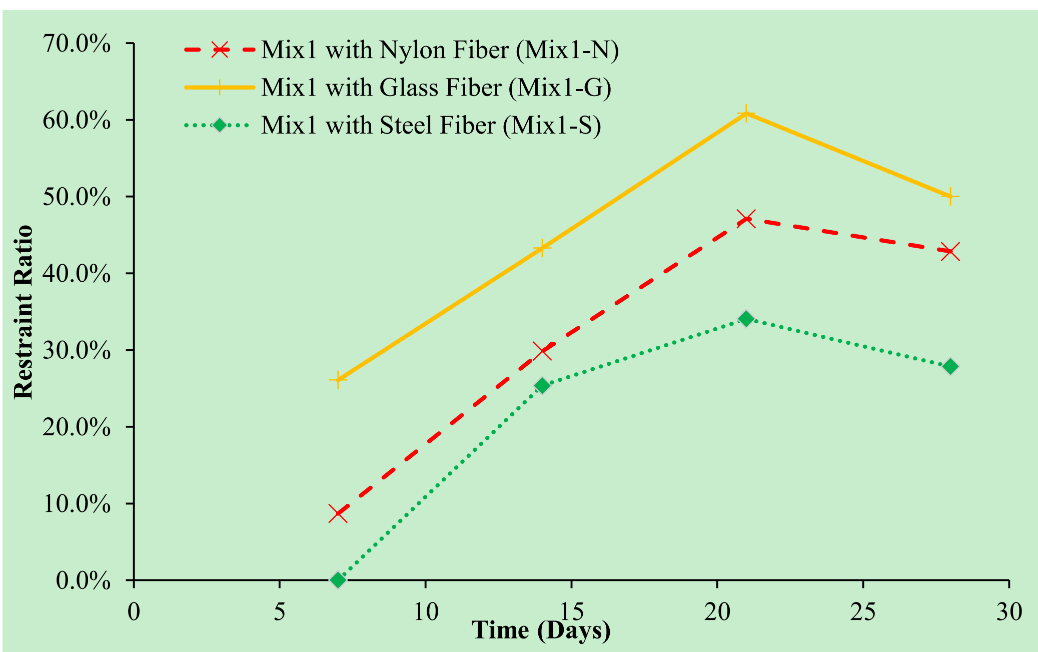


Figure 4.8. Restraint ratio of fiber-reinforced CSA-OPC-CS mixtures over time

The expansion of fiber added mixtures (Mix1-N, Mix1-G, and Mix1-S) in comparison to fiber free mixture (Mix1) after 7, 14, 21 and 28 days, or the restraint ratio, was calculated using the following equation (Equation 4.1) and displayed in Figure 4.8.

$$Restraint\ Ratio(\%) = \frac{Expansion_{free} - Expanion_{restrained}}{Expansion_{free}} \times 100\% \quad \text{Equation 4.1}$$

where

Restraint Ratio is the percentage of Mix1's free expansion being restrained, %

$Expansion_{free}$ is the expansion of Mix1, %

$Expansion_{restrained}$ is the expansion of Mix1 after fiber addition, %

According to Figure 4.8, restraining effects of fibers increased during the first 21 days, and slightly decreased on the 28th day. These trends may be related to self-stresses generated from restrained expansion, which produced tensile stresses in the restraints (Scholer et al., 1978). When more tensile stresses are introduced in the fibers, the fibers provide better restraining effects. The magnitude of stresses generated from restrained volume change increases when more volume change is restrained (Hossain & Weiss, 2004). The fibers demonstrated increasing restraining effects as more and more expansion was restrained in the first 21 days (as shown in Figure 4.7). However, on the 28th day less expansion was restrained when compared to the 21st day, which resulted in slight decreases in the restraining effects of fibers. In order to correlate the self-stresses generated from the fibers' restraining effects in the future, existing strain / stress sensors such as strain gauges, optical fibers, and piezoelectric sensors (Chen & Chung, 1996) could be utilized to monitor self-stresses developments, and compared with restraint ratio.

Although the restraining effects of fibers varied with time, Figure 4.8 shows that different types of fibers had different restraining effects. Glass fiber showed the most restraining effect on the 28th day at 50.0%, followed by nylon fiber at 42.9% and then steel fiber at 27.9%. The better restraining effect of glass fiber was attributed to its smaller size. As seen from the fiber length and diameter shown in Table 4.2, the glass fiber (ø 0.01 mm, where ø resembles diameter) used in this research has a smaller string diameter than the nylon fiber (ø 0.03 mm). Likewise, the nylon fiber bears a smaller string diameter than the steel fiber (ø 1.14 mm). At the same fiber volume fraction (1.0%), a decrease in fiber size allowed more fiber strings to be contained in the unit volume of shotcrete mixture, resulting in more fiber surface area that were in contact with the mixture. The increased contact area between fibers and mixtures was then responsible for the improved restraining effects, as more area was available for bond development. Similar fibers restraining effects were observed in another study (Chen & Liu, 2003), where smaller fiber restrained more expansion. Therefore, to control the expansion of shotcrete mixtures, smaller fibers are recommended for more restraint.

4.3.4 Unconfined Compressive Strength

The 28th day unconfined compressive strength (UCS) of the samples are presented in Table 4.6 along with the percentage UCS increases after fiber additions. The UCS of shotcrete is one of the primary indicators for concrete quality (CIA, 2010), and was tested in this study to represent compressive strength. As can be seen in Table 4.6, OPC mixture (mixture name "Ref") had 42.6% more UCS than the CSA-OPC-CS mixture (mixture name "Mix1") without fiber addition. This is in coherence with other research where CSA-OPC-CS mixtures with high CS content had a worse 28th day UCS than OPC mixture (Dachtar, 2004; Yu et al., 2017). The ettringite formed in CSA-OPC-CS mixtures was responsible for Mix1's lower UCS value, since growth and replacement of ettringite would damage the matrix of the mixture (Stark & Bollmann, 2000) and thus decrease UCS.

Table 4.6. UCS test results

Mixture Name	Fiber Addition	28th Day UCS (MPa)	% UCS Increase
Ref	None	28.8 $\pm$ 1.6	N/A
Mix1	None	20.2 $\pm$ 0.9	0
Mix1-N	Nylon	25.4 $\pm$ 0.4	25.7%
Mix1-G	Glass	23.4 $\pm$ 0.6	15.8%
Mix1-S	Steel	26.4 $\pm$ 0.2	30.7%

As shown in Table 4.6, UCS of the steel fiber reinforced CSA-OPC-CS mixture (Mix 1-S) improved 30.7% over the fibreless mixture (Mix1), followed by the nylon fiber reinforced mixture (Mix1-N) at 25.7%, and the glass fiber reinforced mixture (Mix1-G) at 15.8%. The improvement of UCS after fiber additions agrees with other studies, where fibers increased UCS by as much as 15.8% when added to normal and expansive concrete mixtures (Dawood & Ramli, 2014; Song &

Hwang, 2004; Zhou et al., 2012). The fibers mitigated, blocked, and diverted the cracks in the mixtures, allowing samples to withstand more loads (Burak et al., 2007). On the other hand, fiber additions to expansive mixtures may also reduce UCS. In theory, extra compressive stresses are introduced to the mixtures when expansion are restrained (Scholer et al., 1978); as a result, UCS can be brought down. Therefore, fiber additions could either enhance or weaken the UCS of expansive mixtures, and the effects are dependent on the combination of mechanisms described. Based on the results shown in Table 4.6, fiber additions enhanced UCS of Mix1, suggesting that fiber's crack-bridging effect overcame the generated self-stress.

The UCS of the Mix1 improved the most when steel fiber was added, followed by nylon fiber and then glass fiber. The UCS of steel fiber reinforced mixtures was higher than the nylon fiber reinforced mixture by 3.9%, and outperformed the glass fiber reinforced mixture by 12.8%. These greater increases in UCS may be explained by the fact that steel fiber has less restraining effect than nylon fiber and glass fiber, as seen in Figure 4.8, which generated less self-stress that reduce UCS. Therefore, the improvement of UCS for expansive mixtures by fibers may be dependent on their restraining effect, where more restraining effects lead to less UCS improvements.

4.3.5 Splitting Tensile Strength

Tensile strength is an important quality indicator for shotcrete used as ground support systems in mines (Seymour et al., 2010). Because splitting tensile strength (STS) represents tensile strength better than flexural strength (Lamond & Pielert, 2006), STS of the shotcrete mixtures developed in this study were evaluated. The 28th day STS of the samples are presented in Table 4.7 along with the percentage STS increases after fiber additions. According to Table 4.7, the 28th day STS of the OPC mixtures (Ref) were 38.1% higher than the CSA-OPC-CS mixture (Mix1) when no fibers were introduced. Mix1's low STS may be explained by its ettringite formation. Ettringites were formed as the CSA, CS, and OPC hydrated (Dachtar, 2004), causing expansion of the mixture. The formation of ettringite crystals would consume and replace cementitious materials, generating micro-cracks in the mixtures and decreasing STS (Rocco et al., 2004).

Table 4.7. STS test results

Mixture Name	Fiber Addition	28th Day STS (MPa)	% STS Increase
Ref	None	2.9 $\pm$ 0.0	N/A
Mix1	None	2.1 $\pm$ 0.2	0
Mix1-N	Nylon	2.9 $\pm$ 0.0	38.1%
Mix1-G	Glass	3.3 $\pm$ 0.2	57.1%
Mix1-S	Steel	3.0 $\pm$ 0.1	42.9%

Even though OPC mixtures (Ref) had better STS than fiberless CSA-OPC-CS mixture (Mix1), fiber additions to Mix1 increased STS at levels higher than that of the OPC mix. As seen in Table 4.7, the STS of Mix1 after fiber addition (2.9 MPa – 3.3 MPa) was equal or higher than that of the fiberless OPC mixture (2.9 MPa). Improvement of STS by fibers incorporations was also observed in other research (Balaguru & Shah, 1992; Song et al., 2005), and may be related to several factors. First, fibers bridged the mixture, delaying and reducing crack developments that would weaken the mixture (Burak et al., 2007). Second, fiber additions allowed the transfer of tensile stresses acting on the mixture to the fibers, providing extra supports (Bentur & Mindess, 2007). Finally, self-stresses generated from restrained expansion (Scholer et al., 1978) of Mix1 introduced compressive stresses in the mixture, which required extra tensile stresses to counter and thus indirectly increased STS. Note that because compressive stresses were introduced in the mixtures as self-stress, Mix1 showed more improvement in STS (38.1% – 57.1%) than UCS (15.8% - 30.7%) after fiber additions, regardless of fiber types.

Although all three types of fibers improved STS (as shown in Table 4.7), glass fiber in Mix1 showed the highest STS increase (57.1%), followed by steel fiber (42.9%) and nylon fiber (38.1%). The best STS improvement of glass fiber may be due to its smaller size in comparison to nylon fiber and steel fiber. Potrebowski (Potrebowski, 1983) found that STS is proportional to the number of fibers intersecting the fracture surfaces, which provided bridging. The size of glass fiber (ø: 0.01mm) allowed more fiber string count per unit volume of mixture, which increased its chance to intersect fracture and thus improved STS. For steel fiber, however, shape also played an important role in STS increase (steel fiber: ø = 1.14 mm, curvy shape). Studies have shown that curvy and hooked steel fiber improved STS and flexural strength better than straight fiber (Faisal & Ashour, 1992; Wu et al., 2016), which is attributed to the better mechanical interlock provided by these fiber shapes. Following the same mechanism, the curvy shape of the steel fiber used in this study enhanced mixture (Mix1-S) STS to similar level with the nylon fiber reinforced mixture (Mix1-N).

4.3.6 Influences of Increasing Aggregate Content on Mechanical Strength

Table 4.8. UCS and STS at different a/c ratios

Mixture Name	Fiber Addition	a/c = 3.13 28th Day UCS (MPa)	a/c = 4.15 28th Day UCS (MPa)	% UCS Change	a/c = 3.13 28th Day STS (MPa)	a/c = 4.15 28th Day STS (MPa)	% STS Change
Ref	None	28.8 ± 1.6	20.2 ± 1.9	-29.9%	2.9 ± 0.0	2.6 ± 0.1	-10.3%
Mix1	None	20.2 ± 0.9	11.2 ± 1.1	-44.6%	2.1 ± 0.2	1.2 ± 0.0	-42.9%
Mix1-N	Nylon	25.4 ± 0.4	19.9 ± 0.5	-21.7%	2.9 ± 0.0	2.4 ± 0.5	-17.2%
Mix1-G	Glass	23.4 ± 0.6	17.4 ± 0.2	-25.6%	3.3 ± 0.2	2.4 ± 0.1	-27.3%
Mix1-S	Steel	26.4 ± 0.2	18.2 ± 0.6	-31.1%	3.0 ± 0.1	2.0 ± 0.2	-33.3%

The impacts of increasing the aggregate-to-cementitious-materials (a/c) ratio in mechanical strengths are shown in Table 4.8, including UCS, STS, and differences of mechanical strength in percentage between a/c ratios of 3.13 and 4.15 (change of aggregate content). UCS and STS decreased as the a/c ratio increased from 3.13 to 4.35. For the CSA-OPC-CS mixtures (Mix1, Mix1-N, Mix1-G, and Mix1-S), the

UCS decreased in ranges between 21.7% and 44.6%, and the STS decreased between 17.2% and 42.9%. This decrease in the UCS and STS can be explained by the insufficiency of binding cementitious materials, which resulted in poorly bonded shotcrete matrixes and low mechanical strength (Gündüz, 2008). In other words, increasing a/c ratio means reducing cement content. The reduced cement content contributes to less binding material and decreases bonding in the mixture, leading to lower mechanical strength.

As shown in Table 4.8, drops in UCS and STS values of**Error! Reference source not found.** the fiber inclusive mixtures were less than the fibreless mixtures, after increasing the a/c ratio. The highest reduction occurred in the fibreless mixtures (UCS at -44.6% and STS at -42.9%), and the UCS and STS decrease associated with increasing a/c ratio was reduced after fiber addition. The mitigated UCS and STS drop after fiber additions can be explained by the fibers' ability to bridge the materials together, which provided extra mechanical strength as stresses were transferred from the mixture to the fiber (Dawood & Ramli, 2014; Song & Hwang, 2004). This increased mechanical strength would mitigate the mechanical strength losses due to increasing aggregate content and result in less UCS loss and STS loss.

4.4 Chapter Summary and Conclusions

The authors examined the effects of fiber additions (nylon, glass, and steel) in expansive shotcrete mixtures consisting of calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) in this chapter. Based on the experiments performed for this chapter, the following conclusions are made:

1) Additions of fibers to expansive CSA-OPC-CS shotcrete mixture decreased water absorption and volume of permeable pore space, which indirectly reflected permeability. The reduced permeability would decrease expansion and thus improve durability of the mixture.

2) Fiber additions to expansive CSA-OPC-CS shotcrete mixture restrained expansion. Glass fiber effectively restrained the expansion by 50.0% on the 28^{th} day; nylon fiber restrained 42.9% of the expansion, and steel fiber restrained 27.9% of the expansion. The restraining effect of fiber depended on fiber size: smaller fiber size allowed more contact area and improved the restraining effect.

3) The 28^{th} day unconfined compressive strength (UCS) of expansive shotcrete mixtures increased when fibers were added. Steel fiber addition improved UCS the most, showing a 30.7% increase over the fiberless sample. Nylon fiber addition increased UCS by 25.7%, and glass fiber addition increased UCS by 15.8%. The increase in UCS arose from fiber mitigating and bridging the fractures. However, the UCS improvement was reduced when more expansion was restrained, due to more compressive stresses being generated in the mixture.

4) Fiber additions to expansive shotcrete mixtures increased the 28^{th} day splitting tensile strength (STS). For the expansive CSA-OPC-CS mixtures, glass fiber showed the most STS improvement at 57.1% over the fibreless mixture, followed by steel fiber at 42.9% and then nylon fiber at 38.1%. The

improvement in STS stemmed from both fibers bridging fractures to provide extra support and restraining expansion to generate compressive stresses.

5) Fiber additions to expansive CSA-OPC-CS mixture improved STS more than UCS. This may be due to self-stress generated when expansion was restrained. The restrained expansion introduced extra compressive stresses into the mixture, which indirectly mitigated UCS improvement and further increased STS.

6) Increasing the aggregate-to-cementitious materials ratio (a/c) of the CSA-OPC-CS mixture from 3.13 to 4.35 decreased the UCS by 44.6%, and the STS by 42.9%. However, these reductions in UCS and STS were mitigated when fibers were added. The mitigation effect may originated from fibers providing bridging to fracture and mixtures, which resulted in less mechanical strength loss after aggregate content increased.

The results suggest that fiber additions to expansive shotcrete mixture consisting of CSA, OPC, and CS improved durability and mechanical strengths, while controlling expansion. Moreover, each fiber type had a different effect on UCS, STS, and volume change. These fiber reinforced expansive mixtures provide possible alternative options of crack mitigating shotcrete, which reduce cost and time spent on crack repair.

Chapter 5 Conclusions

Chapter 5 contains the summary of the thesis and research conclusions. The contribution of results and the recommendation for future research works are also discussed.

5.1 Research Summary

Shotcrete is often used by the mining industry as rock support, tunnel lining, and concrete repair. However, cracking within shotcrete is common, which delays production schedules and increases maintenance costs. To reduce cracking, expansive shotcrete mixtures are often used. While many commercial expansive cements / shotcrete mixtures are available, the ingredients of these products are usually confidential. To optimize the performance of expansive shotcrete, mixtures with known compositions are studied and compared. In this thesis, possible expansive shotcrete mixtures are developed by combining calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcium sulfate (CS) in the binder. Furthermore, fibers are added to the expansive CSA-OPC-CS mixture to restrain expansion and impede cracking. The objective of this thesis is to identify expansive shotcrete mixtures consisting of CSA, OPC, and CS, and study the effects of nylon fiber, glass fiber, and steel fiber on the identified mixture so that better crack resistance can be achieved.

In this thesis, the influences of fiber additions on expansive shotcrete mixtures consisting of CSA, OPC, and CS are studied. The first part of the study focuses on the creation of expansive shotcrete mixtures using different combinations of CSA, OPC, and CS, which provided alternative choices for crack resistant shotcrete. CSA, OPC, and CS are combined systematically, with the three ingredients adding up to 100% of the binder. The volume change of each mixture is recorded, and mixtures demonstrating expansion without cracking on the 28th day are identified as expansive mixtures that resist cracking. The second part of this thesis studies the effects of fiber addition (nylon fiber, glass fiber, or steel fiber) on the expansive CSA-OPC-CS mixture, to further improve mixture performances (i.e., UCS, splitting tensile strength (STS), durability, and expansion restraint) and provide future design considerations for fiber additions. The above mentioned properties (UCS, STS, durability, and restraint) are evaluated for the fiber-reinforced expansive CSA-OPC-CS mixtures created. Combining the results, potential crack-resistant expansive mixtures are identified and the advantage of fibers additions are evaluated.

5.2 Research Conclusions

Although the development of fiber-reinforced expansive shotcrete mixtures consisting of CSA-OPC-CS in the binder is only in the preliminary stage, potential mixtures with improved crack-resistance had been identified in this thesis and would prompt further studies. Detailed conclusions for Chapter 3 and Chapter 4 can be found in the respective chapters, and are summarized in the following sections.

5.2.1 Conclusions on Identifying Expansive Shotcrete Mixtures Consisting of CSA, OPC, and CS

1) Expansive mixtures and strength-enhanced mixtures can be created by combining calcium sulfoaluminate cement (CSA), ordinary Portland cement (OPC), and calcum sulfate (CS) in the binder. The expansive mixtures (mixtures showing expansion on the 28th day without cracking) in general have 40% or more CS content in the binder. These can be used as shrinkage-compensating

shotcrete mixtures to reduce cracking. In contrast, strength-enhanced mixtures (mixtures having higher unconfined compressive strength, UCS, when compared to the 100% OPC mixture) are created when CS content is 20% or less, except one mixture which has 40%CSA+20%OPC+40%CS in the binder. This strength enhanced mixture with 40% CS is also expansive, and it was selected for fiber reinforcements in Chapter 4 to further improve mixture performances.

2) It was observed that using CSA or CS instead of OPC in the shotcrete mixtures would decrease the oven-dry density, enhance the water absorption, and increase the volume of permeable pore space. Because the water absorption and the volume of permeable pore space reflect the permeability, when CSA or CS is used instead of OPC the permeability increases, which indirectly decreases the durability. In other words, CSA-OPC-CS mixtures are less durable than OPC mixture.
3) Water contact seems to enable cracking. From the experiments conducted in Chapter 3, two mixtures cracked when cured in water; however, when these mixtures were cured in moisture room, no visible cracks developed. It is thus suggested that reducing the water contact would decrease the probability of cracking for the CSA-OPC-CS mixtures.

5.2.2 Conclusions on Evaluating the Effects of Fibers on Expansive CSA-OPC-CS Shotcrete Mixture

1) The additions of fibers to expansive CSA-OPC-CS shotcrete mixture increases durability, unconfined compressive strength (UCS), and splitting tensile strength (STS). It is shown in Chapter 4 that water absorption and volume of permeable pore space decreased after fibers additions, suggesting a decrease in permeability and thus an increase in durability. The improvements in UCS and STS stemmed from fibers bridging and mitigating cracks in the mixture, which provide extra supports. However, because self-stresses are introduced into the mixture when expansion is restrained, the STS is improved more than the UCS; the restrained expansion induced extra compressive stresses into the mixture, which indirectly mitigated UCS improvement from fiber reinforcements and further increased STS.

2) The additions of fibers to expansive CSA-OPC-CS shotcrete mixture also restrain expansion. It is observed from Chapter 4 that the restraining effect increases as fiber size decreases. This phenomenon may be explained by smaller fiber size allowing more contact area at the same fiber volume fraction, which improved bonding and increased restraining effect. Therefore, fiber with smaller diameter and length should be used when better restraining effect is required.

These results showed that expansive shotcrete mixtures can be created by combining CSA, OPC, and CS in the binder to mitigate cracking. In addition, adding fibers to the expansive CSA-OPC-CS mixture would improve UCS, STS, and durability. The expansion is also restrained and controlled by fiber reinforcements. It is thus suggested that fibers be added to the expansive CSA-OPC-CS shotcrete mixtures. The identified fiber-reinforced expansive CSA-OPC-CS mixtures show potential for crack-mitigation, and should be studied further to reduce costs and times spend on repairing cracked shotcrete.

5.3 Research Contributions

The contributions of this thesis are as follows:

1) This thesis initiated studies on CSA-OPC-CS mixtures by systemically adjusting the binder composition. Expansive mixtures that can mitigate shrinkage-cracking and strength-enhanced mixtures are identified, providing alternative choices to currently available products.
2) The relationships between the ratios of CSA, OPC, and CS in the binder and the mixture performances such as UCS and expansion are established, making it easier to design CSA-OPC-CS mixtures to achieve desired properties and avoid unwanted performances.
3) The effects of fibers on expansive CSA-OPC-CS mixture are evaluated, providing information for fiber addition design. As fibers additions to the mixture increase UCS, STS, durability, while restraining expansion, fiber addition has been established as a method to improve shotcrete performances. As different fiber has different influences on the mixtures, fiber can be selected based on the desired effects.

4) Potential crack-mitigating fiber-reinforced expansive shotcrete mixtures are identified, which after further investigation may replace current applied mixture to reduce cost and time spent on crack repair.

5.4 Recommendations for Future Research

Although potential crack-resistant shotcrete mixtures have been identified in this thesis, there are more investigations that can be performed to advance the development of such mixtures. The following steps are suggested to improve the understanding of crack resistant fiber-reinforced expansive CSA-OPC-CS shotcrete mixture:

1) It is recommended to test CSA-OPC-CS mixtures at binder proportions other than the combinations studied in this thesis. Relationship between expansion and CSA-OPC-CS ratios can be better established with smaller binder material ratio change increments (e.g., 10% and 5%), and optimized performance may be achieved.
2) Besides changing the CSA-OPC-CS ratios, it is also recommended that the limestone aggregates used in this thesis be replaced with other types of aggregates, so the effects of aggregate-binder interactions can be evaluated. It is also possible that other types of aggregates would increase mixture performances if they have high UCS and low alkalinity.
3) To verify that the expansion of the CSA-OPC-CS mixture is generated from ettringite formation, it is suggested X-ray Powdered Diffraction test (XRD) be conducted throughout the test periods (up until the 28^{th} day). The relationship

between ettringite formation and expansion rate would provide possible evidence for ettringite-induced expansion.

4) Different fiber volume fractions should also be tested (e.g., 0.5% and 1.5%). Since that high fiber volume fractions would disrupt the matrix and reduce concrete performances, it is possible that at other fiber volume fractions the effects of fibers would be different than the ones observed in this thesis. Therefore, optimum fiber volume fraction should be established so that fiber additions would not diminish mixture performance.

5) In addition, other types of fibers should be added to expansive CSA-OPC-CS mixtures so that the individual effects of each fiber can be identified. Other fibers (i.e., recycled fiber and natural fiber) may provide similar improvement as the fibers tested (e.g., nylon fiber, glass fiber, and steel fiber) and required investigation for comparison.

6) The adhesive strength of the shotcrete mixtures was not tested in this thesis. However, shotcrete applied at underground mines may fail due to poor adhesion (shotcrete fails to bond properly with the receiving surface), leading to flexural failures and displaced materials. Therefore, adhesive strength of shotcrete mixtures should be identified to further determine the shotcrete's ability as ground support.

7) The influences of actual shotcreting (pneumatic projection) on the developed mixtures should also be studied. Shotcreting would cause self-compaction and rebound, which affect mixture properties. The compaction improves concrete strength and durability, while rebound compromises these performances.

Therefore, the shotcrete mixtures developed in this thesis would have different characteristics after pneumatic projections. To ensure that the mixtures developed in this thesis can act as shotcrete at mine sites, pneumatic projections should be conducted with the resulting influences on mixture performances recorded.

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