Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

# Effects of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate cement, ordinary Portland cement, and calcium sulfate

H. Yu, L. Wu, W.V. Liu*, Y. Pourrahimian

*School of Mining and Petroleum Engineering, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta T6G 2R3, Canada*

ARTICLE INFO

*Article history:*
Received 21 August 2017
Received in revised form
23 November 2017
Accepted 14 December 2017
Available online xxx

*Keywords:*
Shotcrete
Restrained expansion
Fibers
Calcium sulfoaluminate cement (CSA)
Ordinary Portland cement (OPC)
Calcium sulfate (CS)

ABSTRACT

The mining industry often uses shotcrete for ground stabilization. However, cracking within shotcrete is commonly observed, 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) to reduce shrinkage. Furthermore, fibers can be added to the mixture to restrain expansion and impede cracking. The objective of this paper is to study the effects of nylon fiber, glass fiber, and steel fiber on an expansive shotcrete mixture that can better resist cracking. 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 fiber-added expansive mixtures were determined at different time periods (i.e. the strengths on the 28th day, and the volume changes on the 1st, 7th, 14th, 21st, and 28th days). The results show that addition of fibers can improve 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 restrained up to 50% by glass fiber, up to 43% by nylon fiber, and up to 28% by steel fiber. The results show that the STS was improved by 57% with glass fiber addition, 43% with steel fiber addition, and 38% with nylon fiber addition. The UCS was also increased by 31% after steel fiber addition, 26% after nylon fiber addition, and 16% after glass fiber addition. These results suggest that fiber additions to the expansive shotcrete mixtures can improve durability and strengths while controlling expansion.

## 1. Introduction

Shotcrete or sprayed concrete, a cement-based mixture projected pneumatically in high velocities (ACI CT_13, 2013), is often used by the mining industry (ACI 506.5R-09, 2009; ASS, 2010; Martin et al., 2011). The flexibility of shotcrete makes it an effective alternative to conventional concrete in rock support, tunnel lining, and concrete repair. For example, the pneumatic projection allows shotcrete to be applied quickly on the uneven substrate surfaces, acting as excavation stabilization and arch lining in mines (Höfler and Schlumpf, 2006). In another instance, shotcrete had been found to provide capable ground supports in underground mines, preserving beams and maintaining confinement of the surrounding rock (Morissette et al., 2017). Such results have led the mining industry to use over 700,000 m$^3$ of shotcrete per year in North America and Australia (Rispin and Brooks, 2001; Stefan, 2009).

Although shotcrete is widely and frequently used, cracking in shotcrete construction is a common issue, resulting in structural failures, falling rocks, increasing maintenance costs, and delaying production schedule (Drover and Villaescusa, 2015; Poisel et al., 2016; Lewis et al., 2017). Ground movement and shrinkage of shotcrete are the two primary 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 stresses exerted by substrate and causes cracking. The commonly used ordinary Portland cement (OPC) shotcrete mixture can shrink up to 9% due to the drying and formation of smaller hydration products (Lagerblad et al., 2010), leading to further cracking. That is, the shrinkage generates small cracks in shotcrete, where high stresses are concentrated on the cracks tips (Irwin, 1957). Due to this, these

---

* Corresponding author.

*E-mail addresses:* hau1@ualberta.ca (H. Yu), linping@ualberta.ca (L. Wu), victor.liu@ualberta.ca (W.V. Liu), yashar.pourrahimian@ualberta.ca (Y. Pourrahimian).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.12.001

1674-7755

Please cite this article in press as: Yu H, et al., Effects of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate cement, ordinary Portland cement, and calcium sulfate, Journal of Rock Mechanics and Geotechnical Engineering (2018), https://doi.org/10.1016/j.jrmge.2017.12.001

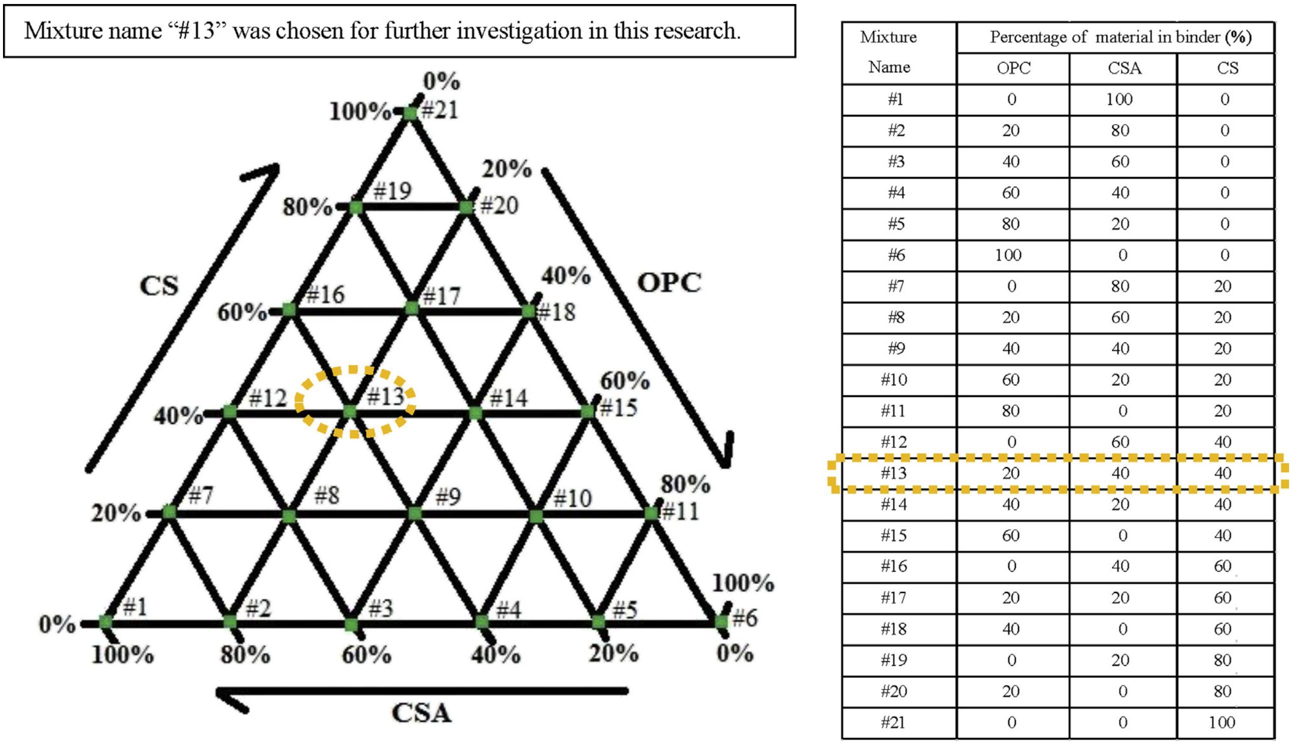
small cracks are easily affected by ground movement, developing larger cracks (Campbell, 1999). Therefore, much effort must be spent on repairing and reducing shotcrete cracks. For example, many complaints about extensive cracking in shotcrete were reported for a large traffic tunnel in Sweden, which 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.

To reduce cracking, shrinkage-compensating shotcrete mixtures are used at underground mines (Storrie, 2001; King Shotcrete, 2014a). For example, shrinkage-compensating shotcrete was used to construct an ore pass bin at a nickel and copper mine in Canada (King Shotcrete, 2014a). Expansive cement is usually added to the shotcrete mixture for shrinkage compensation, and there are currently many commercial expansive cement products (e.g. CTS Type-K cement, DENKA CSA#20, and Komponent®) available (ASS, 2010; Huang and Ma, 2011). The expansive cement is categorized into type K, type M, type S, and type G based on their constituents (ACI 223R-10, 2010). Type K expansive cement mainly consists 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 cement, premixed shrinkage-reduced shotcrete mixtures are also available for application in various mine locations such as ore passes and rock chutes (King Shotcrete, 2014b).

Despite the fact that there are many expansive cement or shotcrete mixture products on the market, the compositions and ingredients of these commercial products are usually confidential information or trade secrets. This limits the development and optimization of shrinkage-compensating shotcrete mixtures. To address this problem, expansive mixtures with known compositions and different ingredients should be studied. The authors had previously combined commonly used binder components such as CSA (calcium sulfoaluminate cement), 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 study are shown in Fig. 1, and the binders of the 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 study.

In addition to the shrinkage-compensation, restraint (e.g. rebar, and fibers) could be introduced into the expansive mixtures to generate self-compressive stresses in mixture and self-tensile stresses in restraint (Scholer et al., 1978; ACI 223R-10, 2010). 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 (Valentine, 2000; Jabbari and Vallens, 2014). 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 in the shotcrete area. In particular, the effects of fibers as a restraint on expansive shotcrete mixtures are still unknown. This is important because fibers are usually added to the mixture under the guide of the Barton's Q-system chart (Vandewalle, 1998; NGI, 2015), 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. (2015) suggested that nylon fiber can improve the rheological performances such as yield stress and plastic viscosity. Bryne et al. (2014) identified that glass fiber added to shotcrete mixture could reduce shrinkage cracking. Zhu (2013) added steel


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

| Mixture Name | Percentage of 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 |

**Fig. 1.** CSA-OPC-CS mixtures previously tested (Yu et al., 2017).

Please cite this article in press as: Yu H, et al., Effects of fibers on expansive shotcrete mixtures consisting of calcium sulfoaluminate cement, ordinary Portland cement, and calcium sulfate, Journal of Rock Mechanics and Geotechnical Engineering (2018), https://doi.org/10.1016/j.jrmge.2017.12.001