PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

DEVELOPMENT OF AN IMPROVED MIXTURE PROPOSAL OF SHOTCRETE FOR USE IN UNDERGROUND MINING

CAMILA FERNANDA ORTIZ GARCIA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisors:
ALVARO VIDELA
MAURICIO LOPEZ

Santiago, Chile (January 2020)

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Grateful to my family

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ABSTRACT

Tunnel fortification is commonly achieved by using shotcrete. However, there is a risk of shotcrete detachment from the surface of the rock causing accidents and ultimately the loss of human lives. In order to reduce the risk of workers´ exposition to the shotcrete detachment, three different properties of shotcrete were studied and improved: density, residual load and bonding by using lightweight aggregates (LWAs), fibers, and nano silica, respectively. Several prismatic, cubic and cylindric specimens were produced and tested. Properties like residual load, compressive strength, splitting tensile strength, density, early strength and rheology were measured and analyzed. Results indicate that: 6 kg/m^3 of polypropylene fibers improve the residual load by 2.93 MPa; 70% replacement of the natural sand by lightweight expanded glass aggregates (LEGA) allows to reach a density of 1,600 kg/m^3 with compressive strengths at 28 days above 17 MPa, which permit to classify those mixtures as lightweight structural concrete.

Keywords: shotcrete, lightweight concrete (LWC), polypropylene fiber (PF), residual load, bonding, nano silica.

RESUMEN

La fortificación del túnel se realiza comúnmente mediante el uso de hormigón proyectado. Sin embargo, existe el riesgo de desprendimiento de hormigón de la superficie de la roca que causa accidentes y, en última instancia, la pérdida de vidas humanas. Con el fin de reducir el riesgo de exposición de los trabajadores al desprendimiento de hormigón proyectado, se estudiaron y mejoraron tres propiedades diferentes: densidad, resistencia residual y unión mediante agregado liviano, fibras y nano sílice, respectivamente. Se produjeron y testearon varias probetas prismáticas, cúbicas y cilíndricas. Se midieron y analizaron propiedades como la carga residual, la resistencia a la compresión, la resistencia a la rotura por tracción, la densidad, la resistencia temprana y la reología. Los resultados indican que: 6 kg/m^3 de fibras de polipropileno mejoran la carga residual en 2,93 MPa; el reemplazo del 70% de la arena natural por agregados de vidrio expandido livianos (LEGA) permite alcanzar una densidad de 1,600 kg/m^3 con resistencias a la compresión a 28 días por encima de 17 MPa, lo que permite clasificar esas mezclas como un hormigón estructural liviano.

Palabras clave: hormigón proyectado, hormigón liviano (LWC), fibra de polipropileno (PF), carga residual, adherencia, nano sílice.

1. INTRODUCTION

The term “shotcrete” has been adopted in Chile in accordance to the American Concrete Institute (ACI), which defines it as mortar or concrete transported through a hose and pneumatically projected at high speed onto a surface (ICH, 2016). The main use of shotcrete is in underground works as a temporary fortification by lining the substrate.

In the case of the study -Chilean Teniente mine- the construction method used to fortify tunnels consists of the application of a two-layer reinforced shotcrete cover: first a layer of 50 mm of shotcrete is applied directly to the rock surface, then a steel mesh is installed using bolts and finally a second layer of 10 mm of shotcrete is applied. However, seismicity and mining operations make some pieces of concrete to detach and fallout. At the mine they call the phenomenon "shotcrete rain". The size of these pieces is such that can cause deaths.

Two alternatives to reduce the risk of exposition of the workers to slab fallouts are explored: reduction of detachment energy and improvement of concrete attachment.

The detachment energy of a slab fallout depends on the potential energy of the slab, that is: mass *gravity acceleration* height. The only parameter that can be managed by concrete technology is the mass of the slab, which can be achieved by decreasing the density of the concrete. Approximately 70% of the concrete by volume corresponds to aggregates, so the density of concrete can be reduced by decreasing the density of aggregates. Nowadays, lightweight aggregate concrete is being widely used in construction industry due to its unique advantages, including lower density, higher specific strength, superior thermal insulation and better durability (Li et al., 2017). Despite this, the use of LWC in shotcrete has not been completely studied.

Literature review shows that different LWAs can produce lightweight structural concrete, which implies having densities between 1,440 and 1,840 kg/m^3 and compressive strengths higher than 17 MPa (ASTM C330, 2014). These LWAs could be natural or manufactured.

Some natural aggregates that have been studied and have shown promising mechanical behavior are pumice (Lynda Amel et al., 2017), wood shavings (Corinaldesi et al., 2016) and oil palm shells (Traore et al., 2018). Manufactured aggregates have been widely studied, such as expanded clays (Nepomuceno et al., 2018; Pla et al., 2018; Remesar et al., 2017), expanded perlites (Jedidi et al., 2015; Topçu & Işikdağ, 2008; Zhao et al., 2018) and expanded glass (Chung et al., 2018; Yu et al., 2016). One advantage of manufacture over natural LWAs is that the materials have more stable properties such as size, shape, porosity, intrinsic strength and composition, which gives more reliability for concrete mixtures design.

The shotcrete attachment depends on the adherence to the previous layer or substrate and the capacity to prevent slab fallout even after adherence fails. The use of nano silica is considered for the improvement of the adherence and the use of fibers for the improvement of the toughness and the prevention of slab fallout.

Nano silica has been studied to replace the use of silica fume due to all the benefits that it represents on health and concrete behavior. Nano silica is an additive generated in laboratory, which makes it a fully stable product in terms of the variations in its purity. Nano silica provides superior performance or, in the worst-case equivalent to that, of silica fume (Jimenez, 2017).

Regarding to fibers, polypropylene fibers are gaining popularity in mining industry because they are less prone to corrosion and produce less wear on the machines (Massone & Nazar, 2018). For that reason, in this study the polypropylene fibers are preferred instead of steel fibers.

1.1 LWAs to reduce concrete density

The normal density of concrete is usually between 2,200 and 2,400 kg/m^3 (ICH, 2016). However, a LWC has an *in situ* density of the order of 1,440–1,840 kg/m^3. For structural applications the concrete strength must be greater than 17 MPa (ASTM C330, 2014). To reach these densities and strengths several authors have investigated the use of LWAs (LWAs) to replace the coarse and/or fine aggregate of the mixture. There are many LWAs to be used in concrete, but only a few studies have reported structural strengths. Some of them are exposed bellow.

1.1.1 Pumice

Pumice, as other natural lightweight aggregate, presents difficulties due to the great variability of its properties since, according to its type of formation, the porosity varies notably from one source to another. Due to this the use in concrete has not been fruitful (Mauricio Lopez, 2018).

However, there are concrete structures that have been built with pumice stones or expanded shales, decreasing density by 25-30%. In an experimental study conducted by Lynda Amel et al. (2017), three mixtures were made with different normal weight sand contents and an 491 kg/m^3 of pumice stone (900 kg/m^3 density). The results show that the mixture that reaches the highest resistances is between 17 and 22 MPa and has 1,850 kg/m^3 density.

1.1.2 Wood shavings

Some authors have studied the effect of different wood shavings on concrete. Coatanlem et al. (2006) made concrete mixtures with densities lower than 803 kg/m^3, but the highest compressive strength reached only 10.2 MPa. Similarly, M. Li et al. (2017) obtained densities lower than 765 kg/m^{3}and compressive strengths reached only 5.3 MPa. Both cases cannot be considered as structural lightweight concrete. In another study Corinaldesi et al. (2016) made 18 LWC mixtures with three levels of sand replacement by wood shavings (from 0 to 10 mm). Only one of those mixtures can be considered as structural LWC because it had 1,800 kg/m^3 density and reached 25 MPa.

1.1.3 Oil palm shells (OPS)

Many authors have OPC in LWC without reaching structural strengths (REF). However, the effect of the incorporation of treated OPS in the concrete was studied in detail by Traore et al. (2018). They examined the influence of five shells treatments on the physical and mechanical properties of concrete: treatment with lime, sodium silicate, polyvinyl alcohol, heat treatment and OPS saturation. The treatment with lime in OPS showed a good improvement in the mechanical properties of concrete compared to the untreated OPS, but saturation treatment yielded best results with 1,822 kg/m^3 density and a compressive strength of 20.5 MPa at day 28.

1.1.4 Expanded clay aggregates (ECA)

ECA has been widely used to produce LWC and there are many authors that have obtained adequate behavior on concrete mixtures. An example is Nepomuceno et al. (2018) which used ECA and the addition of limestone powder and reached oven dry densities of 1,750 kg/m^3 and compressive strengths over 35 MPa. Also, Pla et al. (2018) made an experimental research with different percentages of ECA and limestone aggregates, combination that allows mixture LWC1 to reach 1,700 kg/m^3 density and a compressive strength of 35.8 MPa. In both cases mixtures can be considered as lightweight structural concretes.

1.1.5 Expanded perlites aggregates (EPA)

Liu et al. (2014) conducted a study where normal weight sand was replaced by EP in different percentages (between 0 and 100%) in a concrete mixture. They carried out tests on cast concrete and shotcrete and concluded that the effects of EPA in compressive strength and oven dry densities were similar in both cases (see Figure 1). Also, they obtained densities ranging between 750 and 2,200 kg/m^3 according to the replacement level and compressive strengths ranging between 5 and 48 MPa. In addition, the authors found that at higher EPA contents there is an increase in the rebound of shotcrete from 11 to 29%, a phenomenon that is explained by the lower density of the mixture.

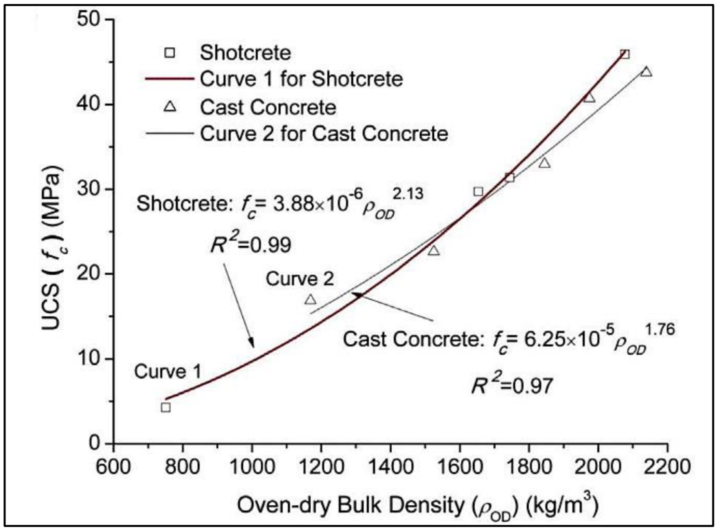

Figure 1: Variations of UCS with oven-dry bulk density for concrete and shotcrete (Liu et al., 2014)

Jedidi et al. (2015) made concrete with different EPA contents varying between 0 and 80%, with a 0.7 w/c. They reached concrete densities between 560 and 1,510 kg/m^3, however, only one of the mixtures. The one with the highest density could be considered as structural LWC since it reached a compressive strength of 18.5 MPa.

Topçu & Işikdağ (2008) also investigated concrete using EPA. In their experiments, they reached a minimum density of 1,800 kg/m^3 and compressive strengths between 20 and 30 MPa.

1.1.6 Expanded glass aggregates (EGA)

EGA is a relatively new artificial lightweight aggregate made by glass waste. Chung et al. (2018) made concrete mixtures using LWAs and EGA was one of them. They obtained densities varying from 1,100 to 1,300 kg/m^3 and compressive strengths varying from 16 to 23 MPa. Although it cannot be strictly considered as structural LWC because of the densities below 1,440 kg/m^3, it can certainly meet the requirement by using lower EGA contents. The same happened with experiments carried on by Yu et al. (2016), who obtained mean densities of 750 kg/m^3 and compressive strengths between 12 and 15 MPa.

In another study, Rumsys et al. (2018) carried on experiments in concrete with EGA replacement of natural sand from 0 to 100% along with additions of silica fume or ground quartz sand and superplasticizer. They obtained mixtures in which, even with a 100% of EGA, density was 1,468 kg/m^3 and compressive strength was 39.5 MPa, demonstrating that it is possible to obtain LWC with EGA.

In accordance to all studies presented, it can be concluded that the manufactured LWAs (expanded clays, perlites and glass) show better mechanical behavior than natural LWAs. It is due the lower variability in properties shown by the manufactured LWAs.

1.2 Use of silica fume and nano silica to improve adherence and mechanical behavior

In order to improve the adherence of the two layers of shotcrete that are used in Teniente mine the use of nano silica instead of silica fume is studied. As explained by the Chilean Guide to Shotcrete (ICH, 2016), the surface to be projected must be clean and free of residues in order to maximize the development of adhesion. It has been observed that the hydro wash preparation promotes greater adhesion capacity (Clements et al., 2004) while, in some applications, the use of an adhesion promoting agent can also improve this ability.

Micro silica (or silica fume) is a form of amorphous silica. It is a finely divided material that can be added to the shotcrete to improve or achieve certain properties in a fresh and/or hardened state (ICH, 2016). The benefits of using silica fume in the shotcrete include: greater durability including reduced permeability due to the smaller particle size, which is significantly smaller than a cement particle; rebound reduction; improved adhesion to substrates; improvement in pumping capacity, reducing wear on the pump and nozzle; and improvement in the cohesion of the mixture allowing the projection of shotcrete of thicker layers.

A typical dose of silica fume in the shotcrete generally ranges from 5% to 10% by weight with respect to cement. Bubshait & Tahir (1997) studied the behavior of the interface between concrete and reinforcement of steel bars by incorporating silica fume at a rate of 10% by weight of the cement in the mixture. They achieved resistance improvement from KN 21.7 to KN 27.8 in a pull-out test.

Nano silica: it is defined by the ICH (2016) as a form of amorphous and synthetic silica, of nanometric size, which has a high specific surface. When added to the concrete it generates a notable increase in the cohesion of the mixture, reducing the risk of segregation and/or exudation in its fresh state and also allowing to improve the pumping capacity, significantly reducing the bounce and increasing the projected layer thickness *per* pass. The guide recommends use between 0.5% and 1.5% by weight with respect to cement.

Li et al. (2004) investigated and compared different percentages of silica fume and nano-silica by cement weight and showed that adding 10% nano-silica increased the compressive strength of concrete by 26% while adding the same amount of silica fume improved compression by 18%.

Amin & Abu El-Hassan (2015) investigated the effects of the use of various types of nanomaterials on the mechanical properties of high strength concrete. The results obtained (see Figure 2) indicate that adding 3% of nano-silica would be an optimal dosage for improving the mechanical properties of the concrete, since it increases the compressive strength by 21% and the flexural strength by 23%.

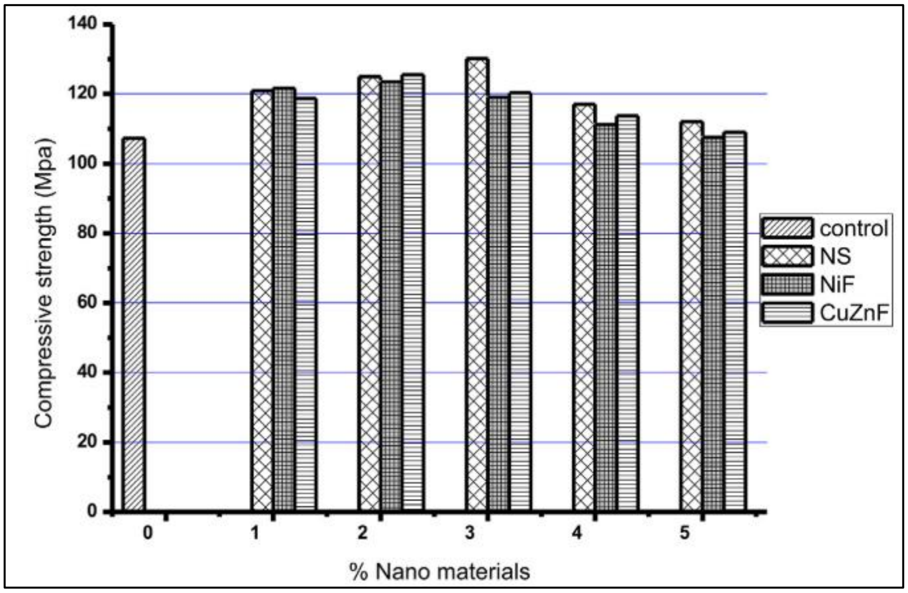

Figure 2. Relationship between the compressive strength of concrete containing granite after 28 days and added nano materials with different ratios (Amin & Abu El-Hassan, 2015)

1.3 Use of fibers to prevent slab fallout

In tunnel fortification the use of steel meshes has been complemented and/or replaced by the incorporation of fibers in the concrete. The ASTM C1116/C1116M-10a (2015) standard defines fibers as an "elongated and slender filament in the form of a bundle, mesh or strand of natural or manufactured material that can be distributed through fresh concrete". The same standard classifies fibers for concrete and use in shotcrete according to the type of material: Type I: steel fibers (stainless, alloy or carbon); Type II: glass fibers (may suffer alkali attack, unless they are specially produced as resistant to them): and Type III: synthetic fibers (virgin homopolymer polypropylene; other materials must have a history of durability).

Fiber reinforced shotcrete (FRS) can also follow the irregular profile on the rock, which provides more efficiency than mesh reinforcement. The vibration of the mesh during shotcreting that can lead to a loss of bonding with the substrate is also avoided by using FRS instead of mesh reinforcement. Logistics can also be simplified with FRS compared to mesh reinforcement due to improvement in project application, safety and productivity (ICH, 2016). On the other hand, synthetic fibers are generally used only to control cracking by plastic shrinkage, but they are also useful for rebound reduction. In addition, they contribute to the release of vapor, reduce the water pressure buildup and therefore reduce the shedding of shotcrete when subjected to fire loads.

Brandt (2008) studied the use of fibers and showed that samples with fibers had a more ductile failure mode and post-failure structural performance. This is attributed to the fiber's ability to distribute tensions and slow down the crack propagation process. The most common used fibers in shotcrete are 30 or 40 mm in length and 0.50 mm in diameter.

Regarding the performance of each type of fiber, Yin et al. (2015) explains that steel fibers can greatly improve both tensile and flexural strength of concrete due to their ability to absorb energy and control cracks. However, corrosion of steel fibers can be harmful and lead to rapid deterioration of concrete structures. Fiberglass fibers have an excellent strengthening effect but poor alkali resistance. On the other hand, natural fibers, such as sisal, coconut, sugarcane bagasse, wood, palm and vegetable fibers are less expensive and easier to get but have low durability. By last, synthetic fibers can be made of acrylic, polyolefin, aramid and carbon. They can prevent cracks by plastic shrinkage in fresh concrete and improve the behavior of concrete after cracking.

Due to the presence of water in mining tunnels and the use of shotcrete in permanent fortification, synthetic fibers are usually preferred. Furthermore, according to studies of Yin et al. (2015) fibers of polypropylene are the most commonly used. It is expected for these fibers to improve the post cracking behavior, leading to increase the residual load of concrete.

This study aims to investigate the effect of lightweight aggregate in reducing the detachment energy, nano-silica in increasing the strength and adherence and fibers in increasing toughness and fallout prevention.

The study focused at laboratory level and considered in-cast specimens as opposed to shotcrete. Testing included slump, density, compressive strength, residual load and adherence. Proposed mixtures shall reach more than 22.5 MPa at day 28 as requirement of the Teniente mine.

2. THESIS PROPOSAL

2.1 Investigation opportunity

A bibliographic review of research papers that have addressed the issue of lightweight concrete -including the use of LWAs (Liu et al., 2014; Pla et al., 2018)- is carried out in the first instance. In the case of adhesion, the review considers investigations on the use of nano silica (Choi et al., 2016; Abdulaziz et al., 1997) and use of polymeric and steel fibers (Brandt, 2008; Cengiz & Turanli, 2004; Yin et al., 2015; Li et al., 2017).

The mixture of a real project will be used as a reference and modifications based on the foregoing in knowledge shall be prepared. The objective is to assess the effect of three parameters: i) LWAs, such as EGA; ii) adhesion additives that include nano silica; and iii) polypropylene fibers. Mixtures will consider the single and combined effect of these three parameters. Then a statically analysis should allow to understand the implication of each one of them separately and together.

The test program design will consider tests such as: slump measure (ASTM C143), rheology, early resistance gain with penetrometer needle (EN 14488-2, 2007), interlayer adhesion test, fiber reinforced concrete flex-tensile test (EN 14651, 2007) and compression resistance test after 28 days (ASTM C39, 2015).

Finally, for the case in question the slab fallout risk model will be defined based on a methodology that incorporates the eventual reduction of the slab weight, the eventual improvement in adhesion and/or the benefit associated with safety.

2.2 Hypothesis

The aim of this work is to reduce the risk of shotcrete detachment in the mining tunnels, which can be reduced in short term by improving the concrete mixture that is projected over the reinforcement mesh. This improvement is expected to be achieved through a decrease in density and therefore decrease in the detachment energy and, in addition, through an improvement in adhesion and residual load to prevent slabs from falling.

The hypothesis is that “the use of lightweight aggregate, nano silica and fibers will reduce the risk of shotcrete detachment not only by their single effects but also by their interactions”.

2.3 Objectives

2.3.1 General objective

Develop shotcrete proposal for mining use that allows reducing the risk exposure of workers due to shotcrete detachments.

2.3.2 Specific objectives

1) Carry out an exhaustive bibliographic review to know the state of the art of the shotcrete, its properties and the factors that determine bonding, residual load, density and mechanical properties.
2) Based on what has been found, design a set of improved concrete mixtures and compare them experimentally with the one currently used in a real project.
3) Create an index that allows quantifying the risk reduction achieved with the proposed mixtures.
4) Make a statically analysis to determine the relative influence of each change in the mixture behavior.

3. A LIGHTWEIGHT FIBER-BASED APPROACH TO REDUCE THE RISK OF CONCRETE DETACHMENT IN SHOTCRETE FORTIFIED TUNNELS

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Abstract

Concrete detachments in shotcrete fortified tunnels are a hazard to workers and users that can be reduced by changing density, residual load and bond strength. A factorial experimental design was carried out to assess the influence of lightweight aggregates (LWAs), polypropylene fibers (PF) and nano silica (NS) in the mixture performance. Results indicate that 6 kg/m^3 of PF increase residual loads up to 2.93 MPa, 70% of LWA reduced density below 1,600 kg/m^3 with structural compressive strength above 22.5 MPa. The safest mixtures had fibers to withhold the unbonded shotcrete piece and LWA to reduce the detachment and impact energy involved.

Keywords: shotcrete, lightweight concrete (LWC), polypropylene fiber (PF), residual load, adherence, bonding, nano silica, safety.

Highlights

- A lightweight fiber-based structural shotcrete was made with fibers and expanded glass aggregate (EGA).
- 70% of EGA reduced density by 30% and yielded compressive strength above 22.5 MPa.

- 6 kg/m^3 of polypropylene fibers increased in the residual load up to 2.9 MPa; the effect was linear.
- The proposed safety index was greatly increased with 6 kg/m^3 of fibers and 70% of expanded glass LWA.

3.1 Introduction

In the case of study -El Teniente mine in Chile- the construction method used to fortify tunnels consists on the application of a first layer of 50 mm of projected concrete (shotcrete). Then mesh and bolts are installed and the second layer of 10 mm of shotcrete is projected. However, the seismicity induced naturally and by operations causes shotcrete to debond from the substrate producing a concrete detachment. At the mine they referred to this phenomenon as "shotcrete rain". The size of the concrete detachments can cause deaths.

Two approaches to reduce the risk of exposition of the workers to concrete detachments are possible (Ashworth & Ashworth, 1991; Meng & Jin-yang, 2013). The first one aims to reduce the energy involved in the detachment to reduce the unbounding and the second one aims to avoid the fall once debonding has occurred. Additionally, the bond between the shotcrete layers must be improved as an intermediate strategy by using, for example, surface treatments, adhesion bridges and fibers (Carrillo et al., 2017) and by improving the bond strength of the concrete mixture.

The detachment energy of a shotcrete layer depends on potential energy of the concrete piece, which is calculated by multiplying the mass and height of the concrete piece with the gravity acceleration. The only parameter in the equation that can be engineered is the mass of the concrete piece by using lightweight concrete (LWC) (Meng & Jin-yang, 2013). Since approximately 70% of the concrete by mass corresponds to aggregates, the most efficient way to make structural LWC is by using lightweight aggregates (LWAs) (Short, A., & Kinniburgh, 1963). Nowadays, LWC is being widely used in construction industry due to its unique advantages, including lower density, higher specific strength, superior thermal insulation and better durability (ACI 213, 2014; M. Li et al., 2017). In spite of this, the use of lightweight shotcrete has not been studied deeply (Cheng, Liu, & Chen, 2017; Shukla, Brown, & Ruggiero, 2007).

Literature review shows that different LWAs are enabled to produce structural LWC, which implies reaching densities below 1,840 kg/m^3 and compressive strength above 17 MPa (ASTM C330, 2014). These aggregates could be natural or manufactured. Some natural aggregates that have been studied and have a promising mechanical behavior are pumice (Lynda Amel et al., 2017; Videla & Lopez, 2000; Videla & Lopez, 1999), wood shavings (Corinaldesi et al., 2016) and oil palm shells (Traore et al., 2018). Manufactured aggregates have been widely studied, such as expanded clays (Nepomuceno et al., 2018; Pla et al., 2018; Remesar et al., 2017), expanded perlites (Jedidi et al., 2015; Topçu & Işikdağ, 2008; Zhao et al., 2018) and expanded glass (Arriagada, Navarrete, & Lopez, 2019; Chung et al., 2018; Yu et al., 2016). All these manufactured LWA have the advantage of having controlled properties as size, shape and composition, which gives more confidence to concrete mixtures design (ACI 213, 2014).

In order to improve the bonding and the bearing capacity after debonding from the shotcrete layer, the uses of nano silica and fibers have been studied. Regarding to bonding, the nano silica has been studied to improve bonding and replace the use of silica fume due to all the benefits that it represents in terms of health and concrete performance. Nano silica is an additive generated in laboratory, which makes it a fully stable product in terms of the variations in its purity. Nano silica provides superior performance or, in the worst-case scenario, equivalent to silica fume’s (Jimenez, 2017). Regarding to fibers, polypropylene fibers are gaining popularity in mining industry because they are less prone to corrosion and they produce less wear on the machines (Massone & Nazar, 2018). For that reason, in this study the polypropylene fibers are preferred instead of steel fibers.

The use of lightweight fiber reinforced shotcrete possesses as a promising alternative to reduce the risk of concrete detachment and therefore increase the safety in shotcrete fortified tunnels. However, there are only few studies exploring the influence of LWA and fibers on the performance of shotcrete. This study aims to systematically assess the effect of the use of LWA, nano silica, fibers and their interactions through different laboratory tests with traditional in cast specimens.

3.2 Experimental program

3.2.1 Raw materials

This study used Type IP Portland Pozzolanic Cement -according to ASTM C595 (ASTM C595, 2018), whose specific gravity and fineness are 3.0 and 5,000 cm^2/g, respectively. The silica fume used had a specific gravity and fineness of 2.2 and 200,000 cm^2/g. The colloidal nano silica used was composed by 50% of solids that is dissolved in water. Chemical compositions of cement, silica fume and nano silica are shown in Table 1.

Table 1: Chemical composition of cementitious materials

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
Cement	26.3	5.92	3.26	55.68	1.22	2.99	0.41	0.98	2.61
Silica fume	95.04	0.31	0.23	-	0.14	-	0.05	0.26	3.79
Nano silica	99.60	-	0.03	0.04	-	0.09	-	-	-

Properties of the aggregates are listed in Table 2. The coarse aggregate was a crushed rock with a maximum aggregate size of 10 mm and specific gravity of 2.70. The fine aggregate was river sand with specific gravity of 2.67. The expanded glass aggregates (EGA) classified as lightweight aggregate according to EN 13055-1 (CEN, 2003) had specific gravity of 0.475.

Table 2: Physical properties of aggregates

Aggregate	Origin	Size range (mm)	Oven-dry density (kg/m3)	SSD density (kg/m3)	Absorption (%)
Coarse NWA	Crushed	0 to 10	2,670	2,697	1.0
Fine NWA	Natural sand from river	0 to 5	2,630	2,669	1.5
Expanded glass aggregate (LWA)	Rotatory kiln produced in Germany	0 to 8	381	475	24.7
Polypropylene fibers	Produced by melt spinning process	48/0.72	900	N.A.	0.0

Polypropylene fibers were crimpled, 48-mm in length and 0.72 mm in diameter, with a specific gravity of 0.9. They had a tensile strength of 640 MPa and a Young's Modulus is 12 GPa. To attain the required workability and improve mixture behavior a plasticizer and high range water reducer (HRWR), as well as a setting accelerator were introduced in all concrete mixtures as a weight percentage of the total cementitious materials.

3.2.2 Mixture proportions

According to the project in which this study is based, the proposed mixtures designs must have a compressive strength above 22.5 MPa at day 28. The control mixture is the one being used in the actual project, it has 425 kg/m3 of cement and 29.8 kg/m3 of silica fume, at a water-to-cementitious material ratio of 0.42 with 1,629 kg/m3 of conventional normal weight aggregates. A triethanolamine-based plasticizer was considered in all mixtures and a proper dosage of polycarboxylate-based superplasticizer was used to achieve a slump between 20 and 22 cm that is required on site. An aluminum sulfate-based set accelerator was considered in a fixed dosage of 8% respect to cement weight to improve the initial strength development.

The experimental program aims to assess the effect of using three factors: nano silica to improve the bonding between layers (reducing debonding); fibers to reduce detachment of concrete once debonded from the previous layer; and LWA to reduce the detachment energy and impact energy if concrete falls. The two levels and three factors formed a 2^3 factorial experimental design is shown in Table 3.

Table 3: Levels and factors of the experimental program

Name	Description	-1	0	1
F1	Nano silica replacement level of cement	0.50%	1.75%	3%
F2	LWA to total coarse aggregate ratio	0	35%	70%
F3	Fiber relative volume *per* cubic meter	2.50%	4.25%	6%

A replacement of 0.5 or 3.0% of nano silica (NS) by mass of the cement was made. The limits are according to other studies (Amin & Abu El-Hassan, 2015; H. Li et al., 2004), in which a 3% dosage of nano silica replacing cement presents the best behavior in compressive strength and flexural load. Also, in order to reach lower densities, EGA were added in replacement of the volume to total coarse aggregate in two percentages: 0 or 70% by volume. Fibers were added in two levels: 2.5 or 6.0 kg/m^3, according to the producer recommendations. Besides the eight mixtures of the 2^3 factorial experimental program, two additional mixtures were studied, one as the control mixture without nano silica, LWA or fibers and the other one as the central mixture with intermediate levels for each factor.

The experimental mixtures in this study are named as follows: M with correlative number followed by: i) XX NS or XX SF, which indicate the presence of either nano silica or silica fume in the concrete, respectively, and XX, which indicates the dosage by weight in terms of cement replacement; ii) Y LWA, where Y indicates the dosage of LWA; and iii) ZF, which indicates the dosage of fibers in kg/m^3. Mixture proportions and names are provided in Table 4.

Table 4: Mixture proportions of the studied concretes

Mixture	Cement (kg/m3)	Silica fume (kg/m^3)	Water (kg/m^3)	Water reducer (kg/m^3)	Super plasticizer (kg/m^3)	Coarse NWA (kg/m^3)	Fine NWA (kg/m^3)	Nano silica (kg/m^3)	LWA (kg/m^3)	Fibers (kg/m^3)
M0-7SF-0LWA-0F	425	29.8	191	2.55	4.25	1,303	326	0	0	0
M1-0.5NS-0LWA-2.5F	452.5	0	191	3.62	8.15	1,303	326	4.55	0	2.5
M2-0.5NS-0LWA-6F	452.5	0	191	2.72	8.15	1,303	326	4.55	0	6
M3-0.5NS-70LWA-2.5F	452.5	0	191	2.72	4.53	390	326	4.55	129	2.5
M4-0.5NS-70LWA-6F	452.5	0	191	2.72	6.79	390	326	4.55	129	6
M5-3NS-0LWA-2.5F	441.2	0	191	3.53	9.71	1,303	326	27.3	0	2.5
M6-3NS-0LWA-6F	441.2	0	191	3.53	5.52	1,303	326	27.3	0	6
M7-3NS-70LWA-2.5F	441.2	0	191	2.65	4.41	390	326	27.3	129	2.5
M8-3NS-70LWA-6F	441.2	0	191	3.53	6.62	390	326	27.3	129	6
M9-1.75NS-35LWA-4.25F	446.8	0	189	2.65	11.03	847	326	15.925	64	4.25

3.2.3 Experimental methods

The mixtures were produced in a 200-liter vertical axis mixer. The LWA were submerged in water (with 70% of the total mixture water content) for 72 hours, according to ASTM C330 (ASTM C330, 2014) . The procedure started with the addition of cement, sand and EGA into the mixer and dry-mixed for 30 seconds. Then, the fibers were progressively fed into mixer by hand and mixed for 60 seconds. After that, admixture, NS (if it corresponds) and water were added and mixed for 180 seconds. Then, partial tests were conducted on the fresh concrete to study the rheological behavior of mixtures using an ICAR rheometer, and to determine the slump according to ASTM C143 (ASTM C143, 2015). If the slump was not between 20 and 22 cm, the quantify of superplasticizer was increased until the required workability was reached.

The early strength of mixtures was measured using a needle penetrometer according to EN 14488-2 (EN 14488-2, 2007). The equipment used was Mecmesin (see Figure 3), which is provided with a needle of 3 mm of diameter and 15 mm of length. The conversion of the penetrometer reading to compressive strength resistance was made according the Equation 1, considering that the nominal maximum size of aggregate of all mixtures was 4.75 mm.

$$Compresive\ strength\ (MPa) = \frac{Penetrometer\ reading\ (N) - 37}{526} \quad (1)$$

Figure 3: Measure of early strength with a penetrometer.

Density of concrete mixtures was measured according to ASTM C567 (2004). Specimens were placed in the oven at 110 ± 5 °C for 24 hours to obtain the oven dry density and then equilibrium density was calculated.

Finally, the fresh concrete was cast into the molds and consolidated on a vibration table and stored in a curing room with 20°C temperature and relative humidity (HR) of 95% until demolding after 24 hours. After that, the specimens were submerged in water at 20°C until the age of testing at day 7 or day 28. Nine 300x150mm cylinders for compressive strength testing according to ASTM C39 (2015), three 150-mm cubes for interlayer bonding strength and three 150x150x530mm beams for residual strength were prepared for each mixture.

The interlayer bond strength was measured by the splitting tensile strength method according to ASTM C496 (2011) by using a cube instead a cylinder (Geissert et al., 1999;

Qian & Xu, 2018) to evaluate the bond strength between the two layers. The general process consisted of casting the two layers, allow them to bond, and then split them apart and measure the bond strength. Specifically, the casting process is represented in Figure 4 and consisted of casting two layers in the cubic mold, 40 minutes apart. The first layer was consolidated on a vibration table, and the second with an immersion vibrator without penetrating the first layer. This created a horizontal bond plane at the middle of the specimen. After demolding and 28 days of curing, the two-layer 150 mm-cubic specimens were tested by placing them in the compression testing machine with the bond plane vertically. Load was applied at the rate of 8,01 KN/min. The splitting tensile strength was calculated using Equation 2.

$$f_{bs} = \frac{2P}{\pi A} \tag{2}$$

where f_{bs} is the interfacial bond strength (MPa), P is the maximum load (N), and A is the area of the bond plane (mm^2).

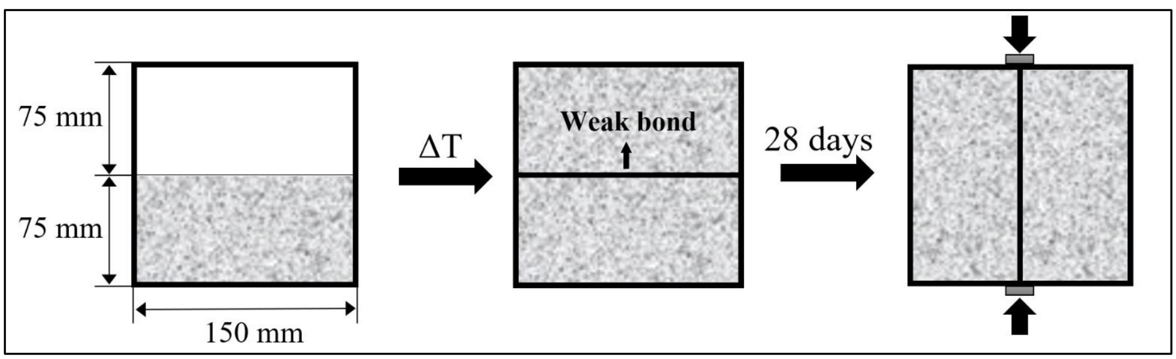

Figure 4: Schematic diagram from splitting tensile strength measure

The residual strength and the analysis of load-CMOD (crack mouth opening displacement) curves were performed according to EN 14651(EN 14651, 2007), allowing to obtain four residual strengths (fr1, fr2, fr3 and fr4) at different CMODs of sizes: 0.5, 1.5, 2.5 and 3.5 mm, respectively (see Figure 5).

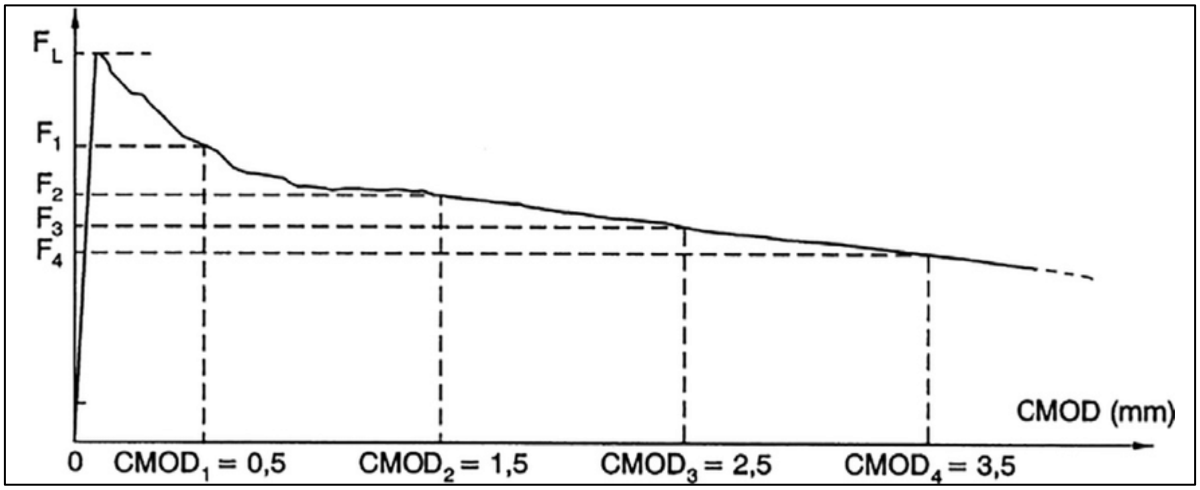

Figure 5: Load v/s crack mouth opening according to EN 14651

3.3 Results and discussion

3.3.1 Rheology

The rheological properties of different concrete mixtures were studied using an ICAR rheometer. Studies have shown that the rheology behavior of concrete can be described by Bingham model (Chen et al., 2019; Choi, Yun, & Yeon, 2017; Feys & Khayat, 2013). A Bingham fluid presents a relation of torque (T) with rotation speed (N) such as T = g + h N, where g (Nm) is the flow resistance, and h (Nm*s) the torque viscosity. These have a comparable physical meaning to the yield stress and plastic viscosity, respectively (Chen et al., 2019; Yun, Choi, & Yeon, 2015).

Two shotcreting performance indicators are used by others authors: shootability, defined as the ability of a material to adhere to or to build up on the receiving surface, and pumpability, that is the ability of concrete to be delivered through a hose or pipe system under pressure. Well established relationships agree that increased yield stress improves shootability and a decreased plastic viscosity improves pumpability of mixtures (Choi et al., 2017; Feys & Khayat, 2013; Yurdakul et al., 2015).

From the measurements (see Table 5), it can be observed that a 70% by volume of LWA replacing NWA decreased flow resistance (or yield value), while a 3% of NS produced an increase. Mixtures with NWA, 3% of NS and fibers (M1, M2) would have a similar or better shootability than that of M0 while Mixtures M5 and M6 with a yield values three times greater than M0 could present shootability difficulties that need to be further investigated. Fibers by itself do not seem to affect yield value significantly as seen when comparing M1 with M2, M3 with M4, M5 with and M5 and M7 with M8. Mixtures M3 and M4 with low NS content and 70% of LWA had a yield value lower than that of M0 and therefore a lower shootability. Mixtures M7 and M8 with 3% of NS and 70% of LWA had similar yield values than M0 and a similar expected shootability.

On the other hand, viscosity value does not present clear tendency when incrementing NS or LWA, which suggests that those factors do not affect pumpability. Nevertheless, the increase in fiber content increased the viscosity value in most of the cases with the only exceptions of M5 and M6. Therefore, fibers as expected (Cheng et al., 2017) would decrease pumpability.

In general terms, a proper shootability and pumpability of the mixtures with NS, fibers and LWA can be attained considering the opposing effect that they can have. For instance, yield and viscosity values of M8 are similar to those of the control M0 mixture.

Table 5: Rheology properties of mixtures

Mixture	Yield Value	Viscosity Value
	Nm	Nm*s
M0-7SF-0LWA-0F	1.5	4.1
M1-0.5NS-0LWA-2.5F	1.7	1.7
M2-0.5NS-0LWA-6F	2.1	8.8
M3-0.5NS-70LWA-2.5F	0.9	2.6
M4-0.5NS-70LWA-6F	0.9	4.3
M5-3NS-0LWA-2.5F	4.6	5.0
M6-3NS-0LWA-6F	4.4	2.2
M7-3NS-70LWA-2.5F	1.4	2.8
M8-3NS-70LWA-6F	1.1	4.2
M9-1.75NS-35LWA-4.25F	2.2	10.6

3.3.2 Early strength

Early strength -using the needle penetrometer- was measured every 15 minutes since the water was added to the mixture for one hour. Then, the measurements were taken every 30 minutes for three additional hours (see Figure 6). It has been suggested (Mohajerani et al., 2015) that a minimum of 0.5 MPa is required to prevent loose rocks or fractured blocks punching through the fresh shotcrete. Other studies (Amin & Abu El-Hassan, 2015; Yurdakul et al., 2015) show that the use of NS improves the early strength of concrete mixtures due to its ability stimulate cement hydration and its pozzolanic activity which is higher than that of silica fume (Mena et al., 2020).

Mixtures with NWA and NS instead of SF gain strength faster than M0 with the only exception being M5. Mixtures with LWA exhibited a slower gain of strength than M0 which might have been caused by the fact that the needle hit a porous LWA instead of paste or NWA.

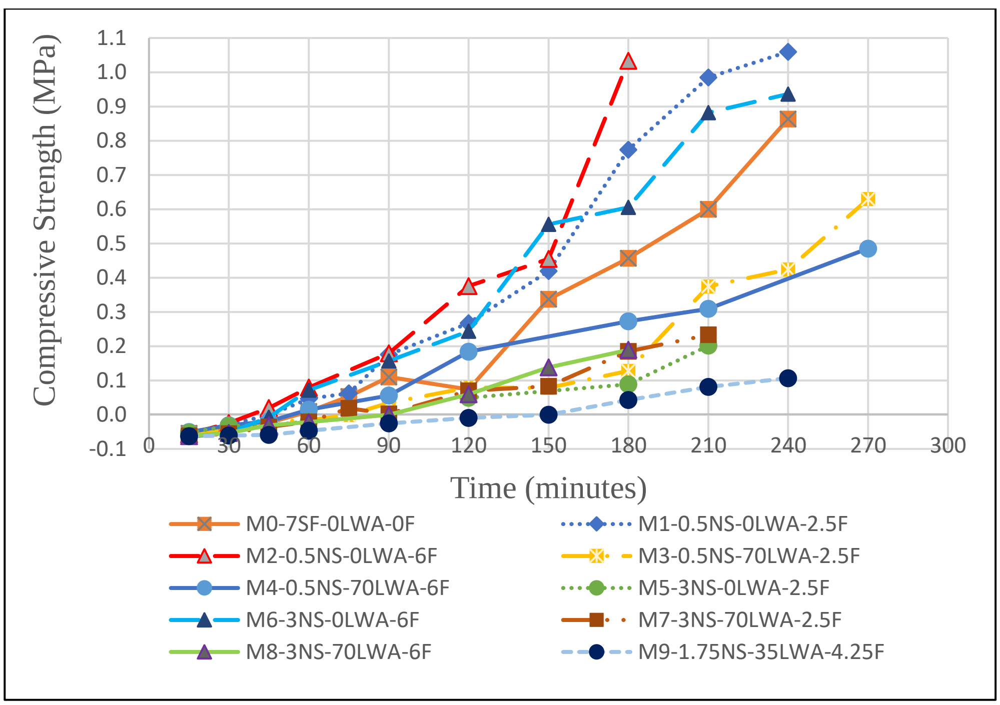

Figure 6: Early strength of concrete mixtures.

Most mixtures reached 0.5 MPa after 270 minutes or less, with the exception of M5 with NWA, and M7 and M9 with LWA.

3.3.3 Compressive strength

The results show that the addition of fibers increased the compressive strength of mixtures while the replacement of NWA by LWA decreased the compressive strength (see Figure 7). In fact, the mixtures with 70% of LWA (M3, M4, M7 and M8) had the lowest compressive strength, reaching an average of 25.5 MPa at day 28, which represents only 37% of the compressive strength of M0. This was expected since the lower intrinsic strength of EGA with respect to NWA, induces the mechanical failure at lower stresses (Carlos Videla & Lopez, 1999). Despite this reduction in compressive strength, all mixtures had a 28-day compressive strength above 22.5 MPa which is the specified strength required in El Teniente mine.

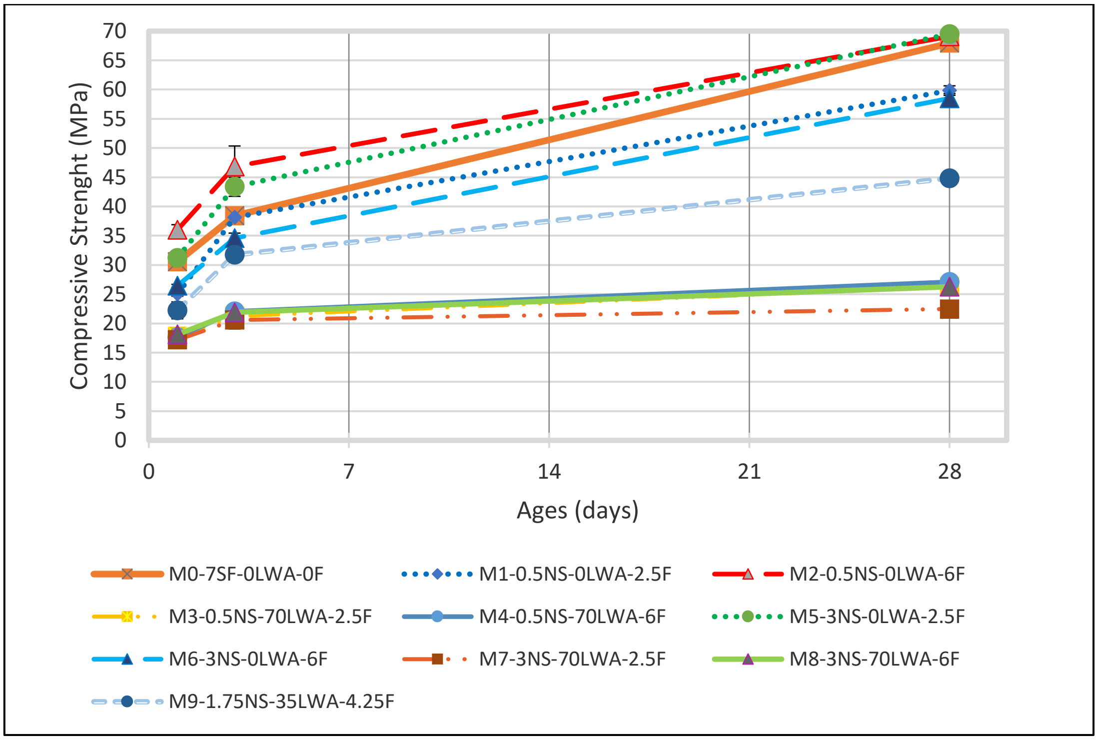

Figure 7: Compressive strength of mixtures at different ages

At early ages, only M2 and M5 had higher compressive strength than M0. Those mixtures do not have LWA, but fibers and NS.

The increase in the NS content increases de compressive strength at all ages as seen when comparing mixtures M1 and M5 that have the same composition except for the NS content and previously reported in the literature (Amin & Abu El-Hassan, 2015; H. Li et al., 2004). The opposite is observed when comparing mixtures M2 and M6. On the other hand, mixtures M3-M7 and M4-M8, that have a 70% of LWA, do not show a statically significant effect of NS in the compressive strength.

A multiple linear regression analysis that relates 28-day compressive strength with the three main factor (NS, LWA and fibers) shows that the volume of LWA is the only statically significant variable in the model LWA. A 10% replacement of NWA by LWA, produces a 3.9-MPa reduction in the compressive strength. Conversely, the model indicates that the addition of fibers generated a slight increase of compressive strength. The LWA variable explain 96% of the variability of the 28-day compressive strength.

3.3.4 Residual load

Similar to compressive strength, the NS and the fiber content do not have a statistically significant effect when comparing the control mixture (M0) with M1, M2 M5 and M6 that have increasing amounts of NS and fibers and show similar first crack loads (FL) (see Table 6). Conversely, the replacement of NWA by LWA decreased the FL values by 46% on average.

Table 6: Residual loads at CMOD of 0.5, 1.5, 2.5 and 3.5 mm

		Residual load			
Mixture	**FL(MPa)**	**fr1 (MPa)**	**fr2 (MPa)**	**fr3 (MPa)**	**fr4 (MPa)**
M0-7SF-0LWA-0F	18.5				
M1-0.5NS-0LWA-2.5F	15.2	2.9	0.9	1.0	1.0
M2-0.5NS-0LWA-6F	19.4	6.5	2.6	2.9	2.9
M3-0.5NS-70LWA-2.5F	10.4	3.5	1.1	1.1	1.2
M4-0.5NS-70LWA-6F	10.9	2.0	2.6	2.9	2.9
M5-3NS-0LWA-2.5F	18.1	6.1	1.1	1.2	1.2
M6-3NS-0LWA-6F	14.8	2.1	2.4	2.6	2.6
M7-3NS-70LWA-2.5F	9.5	3.2	1.1	1.2	1.2
M8-3NS-70LWA-6F	9.6	2.4	2.1	2.3	2.3
M9-1.75NS-35LWA-4.25F	15.6	5.3	1.2	1.4	1.4

The results of post-peak behavior show that regardless of the NS or LWA addition, all fiber-reinforced mixtures had a post-hardening behavior as expected (see Table 6). Since all mixtures achieved a maximum residual load for CMOD between 2.5 and 3.5mm, the fr4 (the fourth residual load at CMOD of 3.5mm) was chosen to make all comparisons and analyses. The higher the fiber content, the higher the fr4 values which demonstrates that fibers improve significantly the flexural load the toughness (see Figure 8). In fact, the average value for fr4 was 1.1 MPa and 2.7 MPa when 2.5 kg/m^3 and 6 kg/m^3 of fibers were added, respectively. This means that a 138% increase for fr4 was obtained when the fiber dosage increased by 140%. This suggests a fairly linear correlation between fiber content and residual load which is consistent with previous results (Koenig et al., 2019).

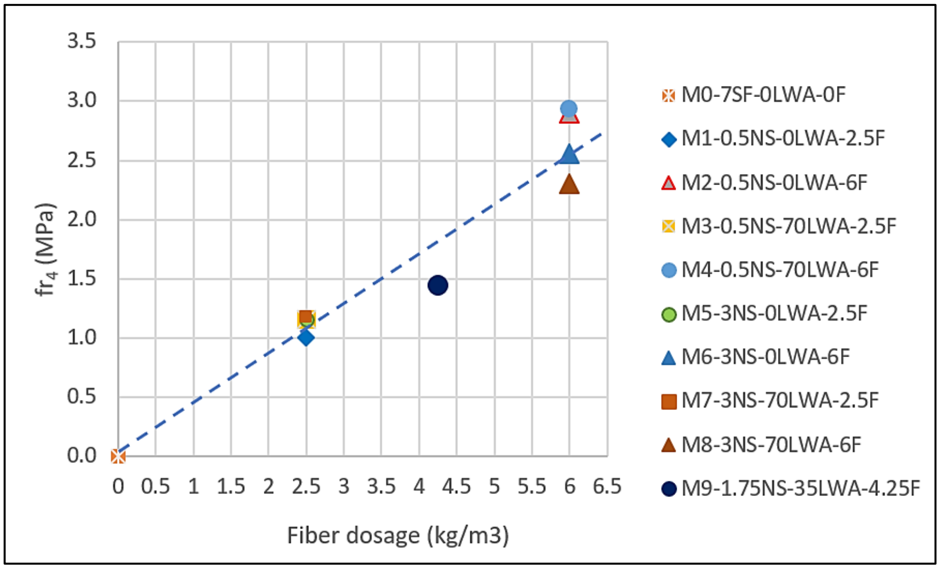

Figure 8: Residual load at CMOD of 3.5mm for different fiber dosages

The addition of NS does not show an important effect on fr4. In fact, M1, M2, M3 and M4 with a content of 0.5% of NS have residual loads between 1 and 2.9 MPa, with an average of 2 MPa, while M5, M6, M7 and M9 with a content of 3% of NS have residual loads between 1.2 and 2.6 MPa, with an average of 1.8 MPa. The replacement of NWA by LWA does not show a relevant effect on fr4 either. In fact, M3, M4, M7 and M8 show very similar fr4 values than their counterparts with 100% NWA with residual loads between 1.16 and 2.93 MPa.

A multiple linear regression model in which fr4 is estimated based on NS, LWA and fibers support the same conclusion, that is that the only statically significant parameter was the content of fibers, with a P-value of 0.0001 and explaining the 89.8% of the variability of fr4.

3.3.5 Density

The density of the mixtures was reduced by the presence of LWA and fibers (see Table 7), since both constituents have a density below 1.0 as shown (see Table 2). Mixtures with 70% replacement of NWA by LWA show approximately a 30% reduction on their density compared with their NWA counterparts. However, the addition of LWA also produced a reduction in strength. Since the purpose of this investigation is to study mixtures reduction in density while keeping a compressive strength above 22.5 MPa, the strength-to-density ratio index is proposed to evaluate mixtures (see Figure 9).

Table 7: Density and mechanical properties of the studied concretes

Mixture	ρ_{eq} (kg/m^3)	ρ_{OD} (kg/m^3)	fc 1 day (MPa)	fc 3 days (MPa)	fc 28 days (MPa)
M0-7MS-0LWA-0F	2,289	2,239	30.5	38.4	67.9
M1-0.5NS-0LWA-2.5F	2,269	2,219	25.0	38.1	59.8
M2-0.5NS-0LWA-6F	2,340	2,290	36.0	46.8	69.1
M3-0.5NS-70LWA-2.5F	1,625	1,575	17.8	21.2	26.3
M4-0.5NS-70LWA-6F	1,631	1,581	17.6	22.0	27.1
M5-3NS-0LWA-2.5F	2,273	2,223	31.2	43.4	69.5
M6-3NS-0LWA-6F	2,236	2,186	26.4	34.6	58.5
M7-3NS-70LWA-2.5F	1,577	1,527	17.2	20.6	22.5
M8-3NS-70LWA-6F	1,601	1,551	18.1	21.9	26.3
M9-1.75NS-35LWA-4.25F	2,042	1,992	22.2	31.8	44.8

The strength-to-density ratio of all mixtures reached values between 0.011 and 0.020 MPa*m^3/kg at 1 and 3 days of age with no relevant differences among them (see Figure 7). However, mixtures with LWA showed an important decrease in the ratio at 28 days. This can be explained with the phenomenon of strength ceiling. According to ACI 213R-14 (ACI 213, 2014), the strength ceiling is the upper limit in compressive and tensile strength above which paste strength is no longer the controlling factor in concrete strength. Therefore, the LWAs becomes the strength control factor that impose a new strength limit to the mixtures for M3, M4, M7 and M8. Different LWAs will impose different strength ceilings as measured previously (Arriagada et al., 2019; Moreno et al., 2014).

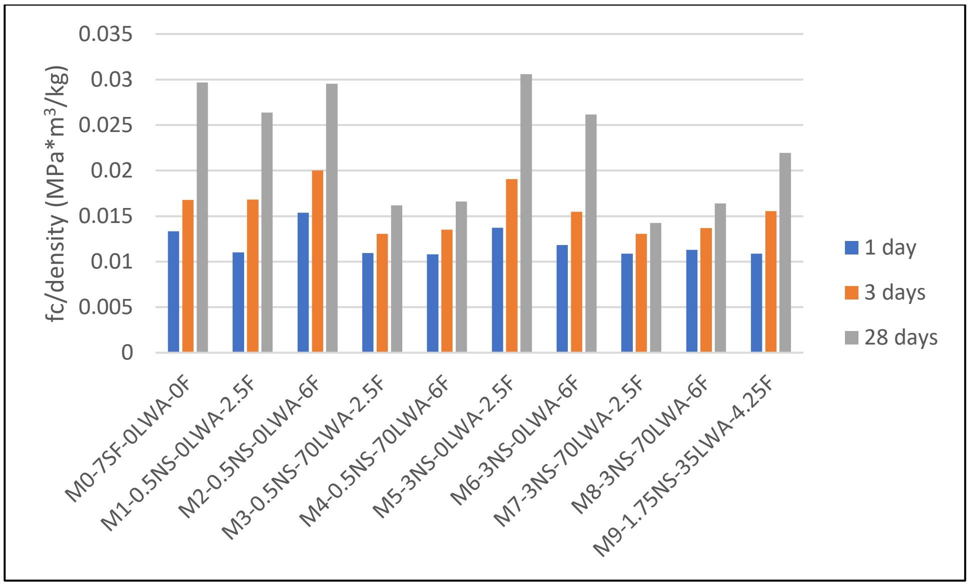

Figure 9. Strength-to-density ratio at different ages of mixtures

According to ASTM C330 (ASTM C330, 2014), a concrete produced with a combination of normal weight and lightweight aggregates shall conform requirements of a minimum compressive strength of 17 MPa and a maximum density of 1,680 kg/m^3 to be considered as a structural lightweight concrete. All four mixtures with 70% replacement of NWA by LWA met the ASTM requirement, but that with 35% of LWA did not meet the requirement. Therefore, more than 35% replacement of NWA by volume of LWA is needed to obtain structural LWA as similarly concluded by another studies (Cheng et al., 2017; Meng & Jin-yang, 2013; Rumsys et al., 2018).

3.3.6 Bond strength

The results show that there is no clear effect of NS on the interlayer bond strength as no significant differences were observed in the splitting tensile strength between M1-M5, M2-M6, M3-M7 and M4-M8 (see Figure 10). Furthermore, the variability of the results, expressed as the coefficient of variation in Figure 10, ranged from 7 to 25%, which are higher than those reported by other authors (Geissert et al., 1999; Rashid et al., 2015). These could be explained based on the variation in the time elapsed between placement of the layers of the specimen, which ranged from 30 and 40 minutes. The relatively high cementitious material contents, set accelerator, and therefore, the rapid setting of the mixtures (see Figure 6) could have induced a cold joint between the layers with lower bond strength.

There was not clear effect of the fiber content on the splitting tensile strength between layers as observed when comparing M1-M2, M3-M4, M5-M6 and M7-M8. This was expected since there were not fibers across the interface between layers.

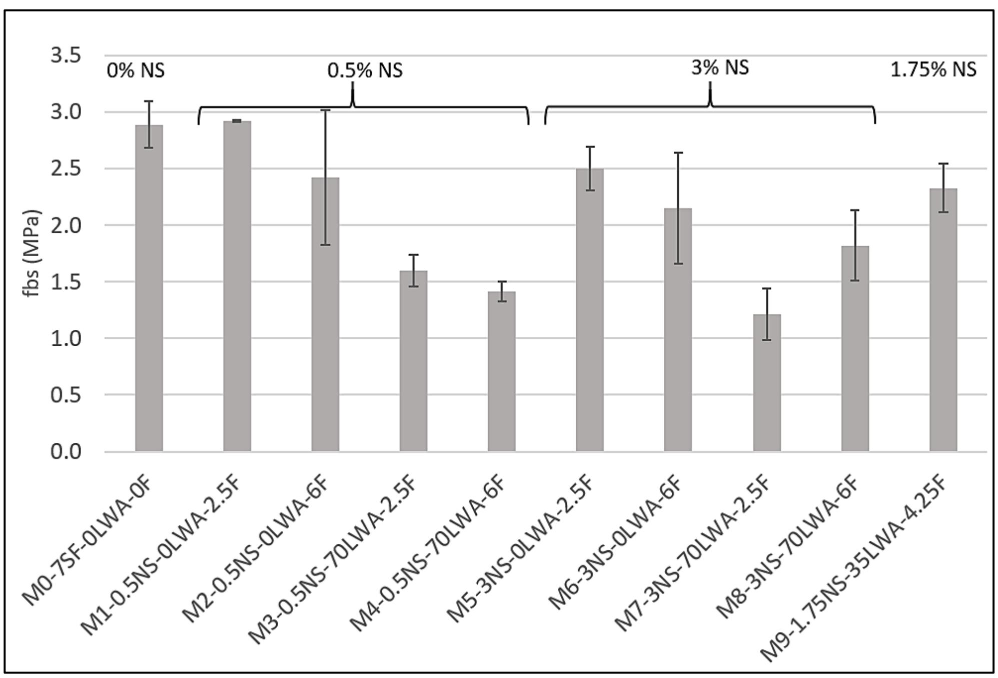

Figure 10: Interlayer bond strength of mixtures

A multiple linear regression analysis that relates bond strength with the three main factor (NS, LWA and fibers) concluded that only the combined effect between NS and fibers is statically significant, explaining the 73.7% of the variability in bond strength. This could be explained by the pozzolanic capacity of the NS and its capacity to stimulate the cement reaction improving the fiber bonding into the matrix (Amin & Abu El-Hassan, 2015; Fallah & Nematzadeh, 2017; Mena et al., 2020).

3.4 Concrete detachment safety index and operational safety

In order to evaluate the influence of each factor of mixtures design on the risk of occurring a concrete detachment, the combined effect of the density and fr4 is analyzed. The density represents the detachment energy and the impact energy if a concrete piece falls and fr4 the capacity of the mixture to withhold the debonded piece of concrete. The bonding strength was excluded since bond strength was not importantly affected by NS.

Therefore, a concrete detachment safety index (I_s) is defined as present in Equation 3 and Table 8, fr_4 is the residual load at CMOD of 3.5 mm in MPa and ρ is the equilibrium density of shotcrete in kg/m^3. The higher the index, the less likelihood of a concrete detachment to fall, i.e. the safer the shotcrete application.

$$I_s = \frac{fr_4}{\rho} \qquad (3)$$

Table 8: Concrete detachment safety of the studied concretes

Mixture	fr4 (MPa)	ρ_{OD} (kg/m^3)	I_s (MPa/(kg/m^3))
M0-7MS-0LWA-0F		2,289	0.0E+00
M1-0.5NS-0LWA-2.5F	1.0	2,269	4.4E-04
M2-0.5NS-0LWA-6F	2.9	2,340	1.2E-03
M3-0.5NS-70LWA-2.5F	1.2	1,625	7.1E-04
M4-0.5NS-70LWA-6F	2.9	1,631	1.8E-03
M5-3NS-0LWA-2.5F	1.2	2,273	5.1E-04
M6-3NS-0LWA-6F	2.6	2,236	1.1E-03
M7-3NS-70LWA-2.5F	1.2	1,577	7.5E-04
M8-3NS-70LWA-6F	2.3	1,601	1.4E-03
M9-1.75NS-35LWA-4.25F	1.4	2,042	7.1E-04

The safety index increased from 0.0 x 10^{-3} MPa/(kg/m^3) for M0 without fibers and NWA to 1.8 x 10^{-3} MPa/(kg/m^3) for M4 with 0.5% of NS, 6 kg/m^3 of fibers and 70% of LWA. The second-best index was obtained by M8 with 3.0% of NS, 6 kg/m^3 of fibers and 70% of LWA. Therefore, as expected, the fibers and LWA became the most important variables in increasing the safety index. The increase in NS did not produce an increase in the safety factor.

This index is analyzed using a multiple linear regression (MLR). MLR models assume that a linear relationship exists between each independent variable (factors), and their interactions expresses by the product between factors. The factors in this study that are: NS volume replacement of cement, LWA to total coarse aggregate ratio and F as fiber relative content, and a dependent variable (Index of safety). The first proposed model is represented in Equation 4 and their coefficients in Table 9.

$$I_s = \beta_0 + \beta_1 * NS + \beta_2 * LWA + \beta_3 * F + \beta_4 * NS * LWA + \beta_5 * NS * F + \beta_6 * LWA * F \quad (4)$$

Table 9: First MLR model coefficients and statistics for concrete detachment index

	Coefficients	Standard error	P-value
β_0	-3.0E-04	3.9E-04	0.5277
β_1	1.3E-04	1.6E-04	0.5094
β_2	3.3E-06	6.2E-06	0.6436
β_3	2.6E-04	8.3E-05	0.0878
β_4	-8.5E-07	1.7E-06	0.6595
β_5	-3.2E-05	3.3E-05	0.4378
β_6	7.1E-07	1.2E-06	0.6102
R^2	94.98		

The first proposed model explained the 95% of the variability of the index. However, none of the variables are statically significant, since their P-values are higher than 0.05 (see Table 10). A progressive elimination of the variables with P-values higher than 0.05 was made, until all remaining variables were statistically significant. Therefore, a refined model is proposed where only content of fibers and the combined effect of LWA*F remain as represented in Equation 5 and their coefficients in Table 10:

$$I_s = \gamma_0 + \gamma_1 * F + \gamma_2 * LWA * F \quad (5)$$

Table 10: Second MLR model coefficients and statistics for index of behavior

	Coefficients	Standardized coefficients	Standard error	P-value
γ_0	-5.2E-06	-2.123	1.5E-04	0.9733
γ_1	1.9E-04	0.417	3.5E-05	0.0015
γ_2	1.1E-06	0.002	3.5E-07	0.0222
R^2	90.8			

The refined proposed model explained the 90.1% of the variability of the index and the two variables, F and LWA*F, are statically significant having their P-values below 0.05 (see Table 10). The effect of F in the safety index is much greater than that of LWA*F as seen than comparing the standardized coefficients of each of them.

The concrete detachment index could help to adequately manage the risk associated to concrete detachment since it allows to quantify the likelihood of debonding and fallout of a shotcrete piece (shotcrete rain). The index not only quantifies the risk but equation 5 helps to improve it by including fibers and LWA into the mixture design.

The combined use of fibers and NS improves the toughness of the concrete and allows to absorb more energy after fracture and prevent the shotcrete fallout. The safety of workers increases since the concrete detachment can be detected by visual inspection and therefore gives time to the mining operators to remove loosened pieces of shotcrete. Additionally, the reduction of the density of shotcrete reduces the detachment energy associated and therefore increases the workers safety.

In the current conditions, if a 10-kg shotcrete piece is unbound from the tunnel it will fall immediately since the control mixture cannot retain it in place because of the lack of fibers. Conversely, all the mixtures proposed in the study showed a better behavior, especially mixtures M2 and M4, which have residual loads over 2.9 MPa. Additionally, mixture M4 have a density 30% lower than that of the of the control mixture. Therefore, the shotcrete piece will not weigh 10 kg but only 7.1 kg, making it less probable to debond. Moreover, even if the shotcrete piece debonds and falls there would be only a 70% of the energy of impact, causing less damages.

3.5 Conclusions

This laboratory study investigated the effect on the main physical and mechanical properties of concrete mixtures containing NS, fibers and LWA at different levels to assess their impact on improving bond strength, residual load, and density. The bond strength represents the ability of a concrete mixture to remain bonded to the previous layer or substrate; the residual load represents the capacity of the mixture to withhold the debonded shotcrete piece in place without falling; and the lower density represents the reduction in the potential detachment energy and energy of impact if a shotcrete piece falls.

Concrete mixtures exhibited compressive strength at 28 days ranging from 22.5 MPa to 69.5 MPa, residual load at CMOD= 3.5 mm from 1 MPa to 2.9 MPa, densities from 1,577 kg/m^3 to 2,340 kg/m^3 and bond strengths at 28 days from 1.4 MPa to 2.9 MPa. The impacts of each of the constituent on the concrete properties was evaluated. The main conclusions are listed as follows:

- The fresh concrete properties can be properly managed to project the concrete in tunnel reinforcement. Mixtures with nano silica, polypropylene fibers and expanded glass LWA can maintain the shootability and pumpability of the control mixture.
- Most mixtures with nano silica, polypropylene fibers and expanded glass LWA reached 0.5 MPa required to prevent early failures of shotcrete at 270 minutes or less.
- The use of 70% replacement by volume of NWA by expanded glass LWA produced a 30% reduction in density compared with the control mixture. These LWC shotcrete can be used in structural applications (> 17 MPa) and meet the specifications of El Teniente mine (> 22.5 MPa).
- The use of polypropylene fibers produced an important increase in the energy absorption capacity compared to the control mixture. In fact, the increase in the residual load was nearly linear with the fiber content.
- The use of nano silica did not have a significant effect in the interlayer bond strength as expected. The methodology for measuring bond strength presents important variability that need to be reduced in the future by perfecting the test method.
- LWC shotcrete presented a strength-to-density ratio similar to their normal weight counterparts at early ages, when the compressive strength is mainly governed by the cement paste. Nevertheless, at later ages LWC shotcrete presented a strength-to-

density ratio of approximately 50% of that of their normal weight counterparts meaning that is the expanded glass LWA the one controlling the compressive strength.

- According to the multiple linear regression models the decrease in density was explained in a 98% by the expanded glass LWA; the increase in residual load (fr4) was explained in an 89.8% by the polypropylene fibers; and the increase in the interlayer bond strength was explained in a 73.7% by the product between nano silica and fibers content.
- A safety index of was proposed to assess the risk of concrete detachment for a particular shotcrete mixture. The index is the residual strength-to-density ratio and varied from 0.0 x 10^{-3} to 1.8 x 10^{-3} MPa/(kg/m^3). The two highest indexes were obtained by the shotcrete mixtures with nano silica, 6 kg/m^3 of fibers and 70% of expanded glass LWA. In fact, the fibers and the product of the fibers by the expanded glass LWA explains 90.8% of the variability of the index.
- Overall, the shotcrete mixtures with fibers and expanded glass LWA meet with all the structural requirements for the El Teniente mine and are potentially safer to use than the current mixture design. The results need to be validated in the field environment projecting the concrete and measuring the performance in real conditions.

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3 THESIS CONCLUSIONS

4.1 Hypothesis and objective assessment

The presented study validates the proposed hypothesis because of the interaction of the new components of the mixtures. The simultaneous presence of LWAs and fibers showed a decrease of the risk of shotcrete detachment due to the improve of residual load and the diminish of concrete density. The proposed index of security achieves values 44.8% higher when fibers and a 70% of LWAs are used instead of only NWA.

The specific objectives of conducting an exhaustive bibliographic review, designing a set of improved concrete mixtures and performing a static analysis to determine the effects of each new component were achieved. Eight improved mixtures were made varying quantities of LWAs, nano silica and fibers, according what literatures said. And an MLR was made.

The general objective was assessed since this study presented shotcrete proposal for mining use that allows to reduce the risk exposure of workers due to shotcrete detachments.

4.2 Future work recommendation

This study allowed to know that a concrete mixture with lightweight aggregate, nano silica and fibers can be used as a tunnel lining to improve its behavior in case that concrete slabs form. Future works must be carried out in order to perform experimental work to real scale, with “roboshot” (machine that projects concrete) and, according international standards, to shotcrete. For instance, to measure toughness panels according to EN 14488-5 (square panels of 100 x 600 x 600 mm) or ASTM C1550 (rounded panels with diameter of 800 mm x 75 mm of thickness) must be made.

Further research is needed to obtain better early resistances in these mixtures in order to improve construction rhythm. The dosages of additives and combined effect between them need to be clarified.

On the other hand, the use of LWAs would add a new stage on concrete plants, because of the need to be submerged in water at least 24 hours (time that depends on absorption capacity of every type of aggregate) prior to be mixed with the other ingredients. So, logistic work is needed to implement it.

Different method to measure adherence is needed. The one used in this research presented uncertain results, making the influence of nano silica unable to be studied. If the new method founds good results about the influence of nano silica, it should be considered on the security index.

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