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Concrete: an enabler of large-scale block and sublevel cave mining projects globally

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Abstract

Concrete, applied by a range of different methods and forms has been used in large-scale block and sublevel cave operations for decades. However, over the last 20 years, concrete has seen an exponential growth in usage for a wide variety of applications. Thanks to its local availability, its good cost performance compared to other construction and underground support technologies, and the flexibility of production, transport and application, concrete has become the go to material when it comes to efficient design and execution of critical key components of mass-mine structures. This paper gives an overview about such critical infrastructure components such as shafts, raises, ore and waste passes and yielding shotcrete liners for primary and permanent underground support.

As the design, production, transport and placement of the concrete are the most important factors for the successful completion of a specific project, various concrete systems used today in different underground mines are discussed. Such systems include the batching of large concrete volumes in wet batch plants above- or underground, the supply of pre-bagged concrete to the point of use, the operation of concrete slick lines to deliver concrete underground and the application of sprayed concrete in various forms for a range of applications.

Examples and lessons learned from large caving projects such as Kiruna in Sweden, Grasberg in Indonesia, Oyu Tolgoi in Mongolia and Chuquicamata in Chile have been compiled and critically reviewed. With view towards the expected service life, the durability of concrete is discussed. The paper also discusses the sustainability aspect when using concrete as a construction material and the potential impact of new, concrete related technologies on the lifecycle assessment of such materials. Such technologies include clinker free cements and technologies to reduce the overall amount of cement and steel in concrete.

Keywords: *shotcrete, concrete, block caving, underground support, sustainability, sprayed concrete, ore passes, admixtures, fibres*

1 Introduction

In today's mass caving projects, which have emerged globally, rapid mine development, mass ore handling underground and efficient haulage of ore and waste are critical. Concrete and shotcrete have acted as enablers for such critical mass mining components. Thanks to the ready availability of cement and aggregates and the powerful impact of modern admixtures on the fresh and final state of concrete as well as the addition of supplementary materials such as fibres, concrete has made rapid advancements in all large-scale, modern, block and sublevel cave projects globally. Concrete can be cast, poured, levelled, sprayed, formed and nowadays also printed. It can be placed under water, over head or injected. The working time of fresh concrete can be greatly extended to accommodate large transportation distances. At the same time, a concrete mix can be greatly accelerated to reduce curing and down time. In the most extreme case, concrete can be accelerated to a point where it sets almost instantly on the wall rock when sprayed and this is what we widely refer to as shotcrete.

With the emergence of large caving projects, the necessity and ability to efficiently install extensive underground infrastructure before ore can be mined became evident. Mining companies were suddenly exposed to a large pre-production capital which had to be minimised, meaning shortening the time to first ore for a given caving operation. In-cycle applied wet shotcrete was a game changer for rapid mine development, especially when larger spans were involved. Compared to bolts and mesh and other types of active and passive support systems, it became possible to reduce the bolt density and the overall amounts of bolts and mesh consumed and to maintain a workable tunnel perimeter with a rigid shotcrete support liner, even under highly stressed conditions.

Today, shotcrete is combined with all forms of other support systems such as mesh, screens, lacing and straps to accommodate the geotechnical situation at a given place. Fibre-reinforced shotcrete itself has also proven to be a good indicator of how the stress is acting on a given mine opening as cracking concrete is an indicator of active loads being diverted onto the shotcrete liner.

New developments in machine technology that evolved alongside advanced admixture technologies paved the way to spray up to 25 m^3 of concrete per hour using modern, peristatic piston pumps and semi-automated, telescoping spray arms.

Modern concrete accelerating admixtures, so called shotcrete accelerators, provide the early strength needed to reduce the re-entry time after the shotcrete had been placed and bolts can be placed through the sprayed shotcrete liner.

To ensure the quality and volume of the required concrete and shotcrete during the infrastructure development and undercutting phase of a cave operation, companies increasingly started to establish concrete production facilities close to the project portal (Kiruna, El Teniente, Chuquicamata) or even established dedicated concrete batch plants underground, close to the point of use (Grasberg). Some mines such as Oyu Tolgoi or Mt Isa went for a hybrid solution and supply the concrete through a vertical or semi-vertical slick line to an underground re-batching point. Whatever the set-up, the assurance of a consistent concrete quality to maintain the required volumes at the point of use is critical.

While sprayed concrete has established itself as a fundamental part of the underground support in many mines, other mass applications for concrete are entering the industry. Mass pouring of concrete and other cementitious systems for shaft rehabilitation projects are discussed in this paper.

However, there is a draw back when using concrete in large volumes. Global cement production accounts for 7–8% of global CO_2 emissions (Guo et al. 2021). This large CO_2 footprint is mainly related to the energy intensive nature of cement production, namely burning clinker out of limestone and clay. Depending on the type of cement or cement blend, a ton of cement is loaded with a carbon footprint of around 700–1,000 kg per ton cement produced (Mahasenan et al. 2002). This impacts the CO_2 emissions of a mine site significantly, particularly the supply related emissions, widely referred to as Scope 3 emissions. Despite advances in admixture technologies, which greatly reduced cement requirements in modern concrete and shotcrete mix designs, while maintaining desired fresh concrete properties and specified strengths at both the early stage and the final stage, there is an urgency to look for alternative binder systems to reduce the environmental footprint.

2 Methodology

This paper starts with an overview of different sprayed concrete systems that form the state of the art in modern mines. Shotcrete used as an in-cycle component will always have a primary support function for the freshly mined excavation perimeter and hence the energy absorption of this shotcrete is important. Data from different mine sites were collected and show the energy absorption of different fibres, fibre combinations and fibre-reinforced shotcrete with mesh.

The second part of the paper deals with mass applications of cementitious systems in mines. Lessons learned from the LKAB Kiruna mine in Sweden are described, where such mass concrete is used for rehabilitating ore and waste passes. Within the same scope, alternative binder systems are discussed and results, in terms of the compressive strengths, shown. The limitations of such systems are discussed. Expanding on this, the use of such alternative systems for shotcrete, push the boundaries to the current limit. Shotcrete is the most extreme form of concrete applications and using such alternative binders are creating several challenges that eventually will be overcome by new admixture technologies and application systems.

3 Data

The standards that have been followed for the data contained in this paper are listed in Table 1. These standards describe in detail, how a concrete needs to be tested to assess the fresh state properties after it has been produced. The standards advice, how early strength development of the shotcrete as well as the young and final strength should be measured and how the flexural strength or energy absorption of the sprayed concrete can be evaluated. Data of sprayed concrete applications have been exclusively gathered from mine sites that use the spray equipment and application personnel of the mine. Testing equipment was also mostly utilised from the respective mines.

Table 1 Standards

Fresh state concrete properties	EN 12350–2, EN12350–5, EN12350–8
Shotcrete early strength	EN 14487–2, ASTM C1140/C1140M-11
Young and final concrete strength	EN 14488–1, EN 14488–2, EN 12390–3
Shotcrete energy absorption (flexural strength)	EN 15588, ASTM C1550–12

4 Shotcrete systems and applications in caving projects

With the advent of mass concrete production and the possibility to spray wet concrete in a semi-automated way, sprayed concrete has found its way to mass mining projects globally over the past 20 years (Erismann et al. 2018). When looking back in history of how shotcrete evolved, it’s important to understand the application procedures that differ greatly from a pre-bagged dry shotcrete mix to a wet concrete mix produced in a ready-mix facility and transported in wet form to the point of use. These two main applications coexist until today. The general view that dry, pre-bagged mixes would soon be replaced by modern wet shotcrete applications has not become reality. Today, dry-applied, pre-bagged mixes play an ongoing, critical role, especially in North America.

However, by far the largest concrete volumes in modern cave operations are applied in wet form. This means, concrete is batched at an onsite, ready-mix plant where cement, aggregates, water and admixtures are blended together in a certain proportion to produce a concrete mix of the required specification and desired fresh state properties. Such wet mixes are typically used for:

- In-cycle shotcrete applications.
- Shotcrete for rehabilitation purposes.
- Cast concrete for drawpoint fortifications.
- Cast panels in drawpoint areas and critical haulage locations.
- Concrete for chutes, loading pockets, grizzly stations and transfer points.

For areas that cannot be accessed with concrete agitator trucks, mixes can be pre-bagged into bulk bags and transported to the point of use where this mix can be blended with water, agitated, and cast or sprayed at the point of use. Wet mixes are most common applied using piston pumping equipment and mechanically handled hose and nozzle. Due to the concrete output volumes and associated pressure, manual application is often not possible. These equipment components are usually combined into a complete, mobile shotcrete spraying rig. Dry mixes on the other hand are usually handled in pre-bagged form. They find their use often in niche applications such as the lining of critical ore/waste handling components or as specific ground support applications where access for larger equipment is limited or handling and transport distances make the transport of wet mixes impractical.

Such applications include:

- Lining or ore/waste passes.
- Lining and refurbishment of ore silos.
- Shaft sinking.
- Specific applications using specially engineered mixes to counter seismicity or to provide additional early strength or abrasion resistance.

Volumes applied using the dry spray process are usually significantly lower compared with the wet process and equipment is smaller and easier to handle, as shown in Figures 1 and 2. Small, modular, dry spraying equipment usually consists of an air or electricity powered rotary pump and a hand-held hose with nozzle and water injector. These two application methods, wet and dry, allow caving projects to cover most underground construction challenges. An overview about the different shotcrete set ups is shown in Figures 1 and 2.

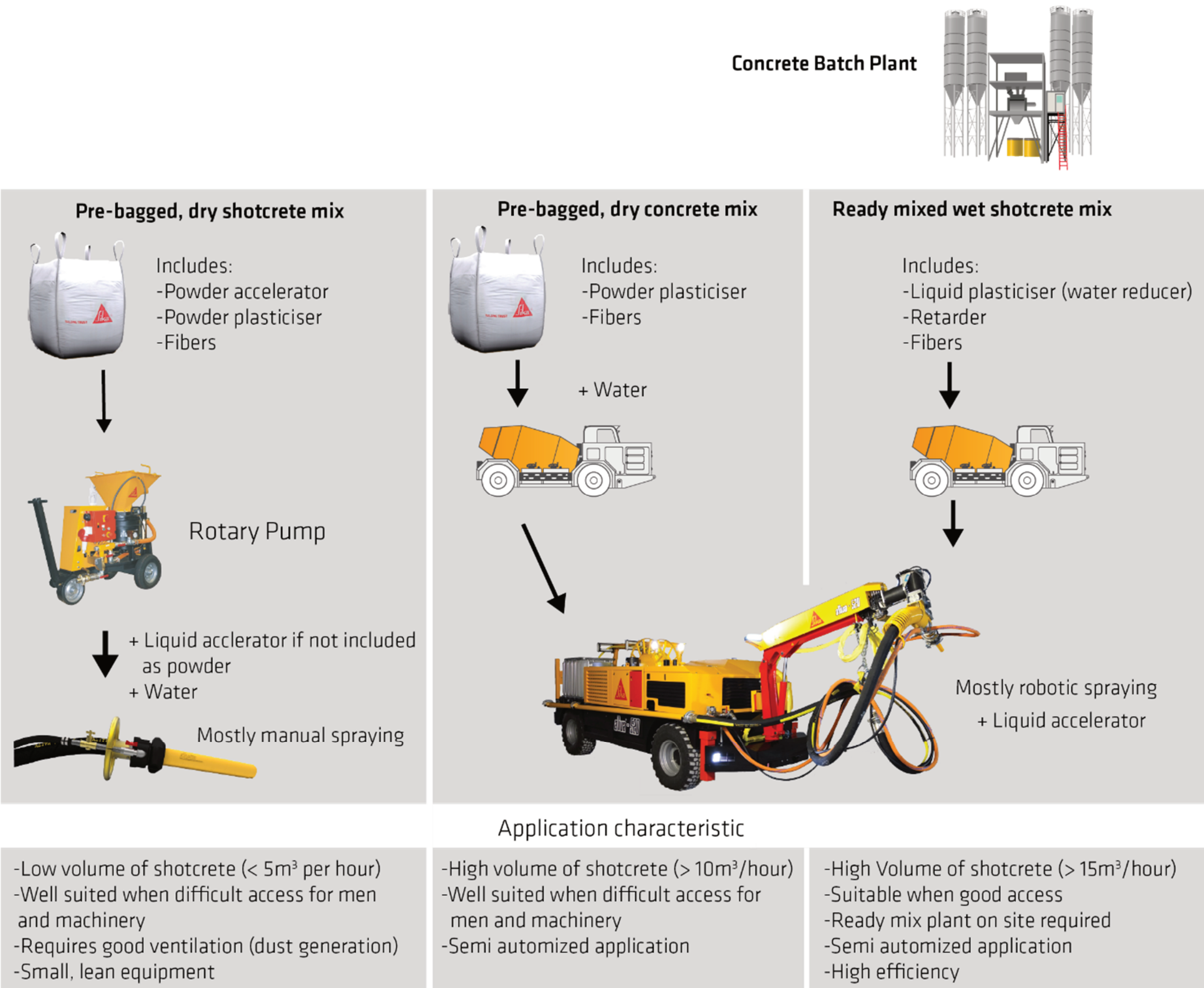

Figure 1 **Different shotcrete systems ranging from dry mixes applied with a rotary pump and dry-sprayed at the left side to pre-bagged and transported to the point of use where the mix is agitated with water and then wet-sprayed (centre image) to ready mix concrete which is wet-sprayed using piston pumping equipment (right hand side)**

Figure 2 Dry shotcrete unit on the left-hand side showing a rotary pump where a dry mix is fed from a big bag into the pump hopper. Centre image shows the blending of a pre-bagged mix with water. The right image shows a modern, state of the art wet shotcrete rig which includes a piston pump and a semi-automated spray arm. A liquid accelerator needs to be dosed into the concrete stream. Concrete is supplied by an agitator truck (not in the picture)

4.1 New advancements in energy absorption of shotcrete

Once mines reach deeper depths and infrastructure components such as drifts and drawpoints are closely aligned, energy absorption and the behaviour of the ground support under dynamic (non-static) loads becomes critical. For shotcrete to take on lithostatic loads, the shotcrete, which is a brittle material, needs to be reinforced with a yielding component. Fibres, added directly into the concrete mix, have proven to be a powerful way to increase the energy absorption or the shotcrete’s yielding capabilities. The energy absorption of a fibre-reinforced shotcrete liner increases linearly with the placed shotcrete thickness (Erismann & Hansson 2019) and recent trials at various mine sites have shown that a combination of polypropylene macro fibres in combination with steel fibres results in additional yielding. Such trials have been performed at the LKAB Kiruna mine and are ongoing. Macro polypropylene and macro steel fibres were added to the concrete and ASTM 1550–12 round panels were sprayed and subsequently tested. Sika Fibre LHO-65/35 NB macro steel fibres as well as the Sika Fibre Force 60 polypropylene macro fibres were used. Furthermore, a mesh was embedded into the ASTM panel and subsequently sprayed with the shotcrete mix containing specified amounts of fibres and a concrete without any fibres in order to compare the energy absorption.

As shown in Table 2, the concrete mix used for all trials had a cement content of 490 kg per m^3. The same dosage of concrete super plasticiser, also widely referred to as the high range water reducer (HRWR), was used as well as a retarder to account for the transportation distance to the trial area. Furthermore, an air entrainer was added to improve the workability and spray-ability of the concrete. Two aggregate fractions were mixed in a ratio of 4:1 and the concrete batched at the LKAB Kiruna batch plant.

Table 2 Shotcrete mix design

Concrete mix design	kg/m³
Water to binder ratio (W/C)	0.48
Cement: CEM II A-V 52.5N	490
High range water reducer (plasticiser)	1.7
Concrete retarder	1.2
Air entrainer	0.3
Aggregates	
(0–4 mm) crushed granite	80%
(4–8 mm) crushed granite	20%

Five different mixes were tested during this trial, as shown in Table 3, with three ASTM C1550–12 round panels tested for each mix. Mix A contained 40 kg of steel fibres as currently in use for the large shotcrete volumes at the mine site. Mix B contained a dosage of 6 kg polypropylene macro fibres. Mix C contained both, 40 kg of steel macro fibres and 6 kg of polypropylene macro fibres. Mix D was a plane shotcrete without fibres but the ASTM round panel contained a 7 mm strong 80 mm sized welded mesh that was mounted 50 mm from the bottom of the panel. Mix E contained 40 kg of steel macro fibres which was sprayed on welded mesh reinforced panel and mix F was a mix containing 6 kg of polypropylene macro fibres sprayed on welded mesh reinforced panel.

Table 3 Different mixes used during the spray trials

Reinforcement material	A	B	C	D	E	F
SikaFibre LHO-65/35 NB	40 kg/m³	–	40 kg/m³	–	40 kg/m³	–
SikaFibre Force-60	–	6 kg/m³	6 kg/m³			6 kg/m³
Welded wire mesh	–	–	–	7Ø80*	7Ø80*	7Ø80*

* Orientation of mesh 50 mm from top of ASTM C1550 round panel mould

During the spray process, the shotcrete accelerator was added at the nozzle (Figure 3 left hand side) and dosed into the concrete stream while spraying to accelerate the shotcrete mix. The following day, the ASTM panels were demoulded and stored for 28 days at constant temperatures underground and covered with plastic foil. After this curing period, the panels were tested using the LKAB testing facility ac cording to the ASTM C1550–12 energy absorption test for shotcrete as shown in Figure 3 right hand side.

Figure 3 Shotcrete operator spraying ASTM C1550–12 round panel (left) and energy absorption testing the demoulded panel after 28 days using ASTM C1550–12 testing equipment (right)

4.2 Results

The results of the shotcrete trials are shown in Figure 4. Testing ASTM round panels includes the central loading of the panel as show in Figure 3, right hand side. Once the deflection of the panel reaches 40 mm, the test is completed. 6 kg of good quality polypropylene fibres can replace 40 kg of macro steel fibres. A sprayed in mesh (D) reaches significantly higher energy absorptions in the order of 900 Joules. A combination of polypropylene macro fibres with steel fibres (C), reaches similar energy absorptions compared with a fibre-reinforced shotcrete in combination of a sprayed in mesh, regardless of the fibre type.

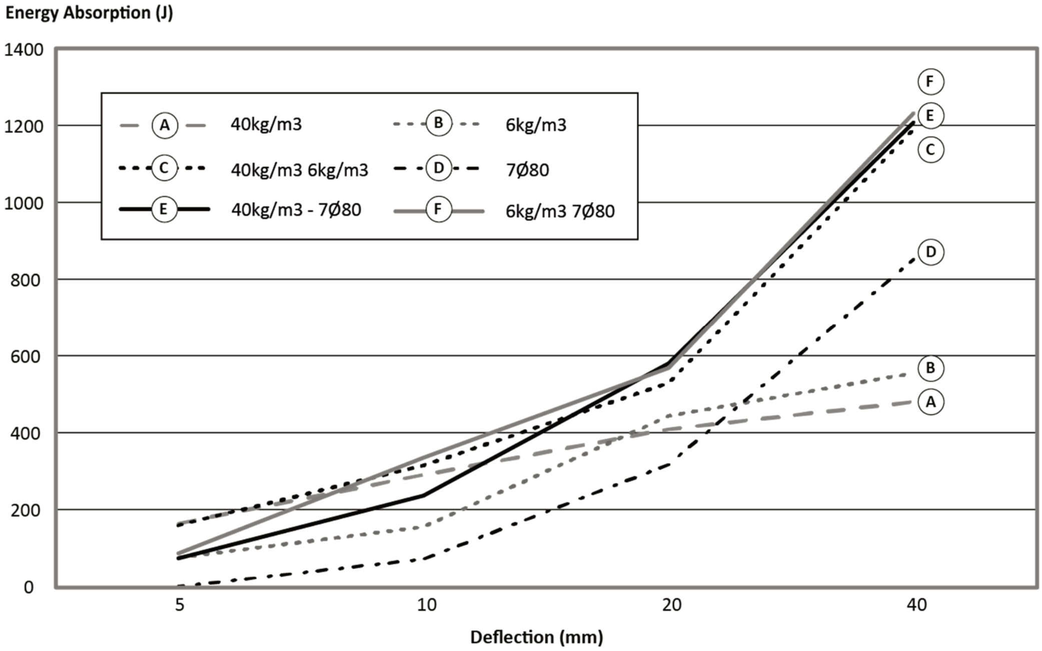

Figure 4 ASTM C1550–12 energy absorption results displaying the round panel deflection at the X-axis and the absorbed energy in Joules on the Y-axis

5 Mass concrete applications using alternative binder systems

Mass concrete applications in large, block and sublevel cave developments are numerous. At the Freeport Grasberg mine, extensive concrete volumes are cast for the rail haulage level and drawpoints are heavily reinforced with cast concrete. Haulage slabs along the production level are poured in place. At Oyu Tolgoi in Mongolia, 100 MPa haulage slabs and special panels along the production level are pre-cast, transported and installed at the site. Similar systems are used at Chuquicamata. At LKAB Kiruna, mass concrete is applied to rehabilitate ore and waste passes in the mine. For areas where placing shotcrete is not feasible or the structure to rehabilitate is damaged beyond the point where shotcreting is no longer possible or dangerous, mines have endeavoured into different directions to solve these issues.

The LKAB Kiruna mine rehabilitates parts of the ore/waste pass system using a backfill and raise method. Damaged ore passes are refilled with high strength, 80 MPa concrete. Once cured, the ore pass is re-raised, using raiseboring equipment as shown in Figure 5. Due to the large amounts of cement used for this procedure to fill the total volume of 15,000–20,000 m^3 per ore pass, alternatives were investigated to reduce the cement content of this set-up. As part of the mine's circular economy, the use of waste smelter slag was proposed and evaluated as part of a completely new binder system. Using ground granulated blast furnace slag (GGBS) for concrete is not new. In Europe, cement blends using 10–35% GGBS for concrete are common. The EN 197–1 Norm states that a CEM III can contain up to 95% slag. In North America, binders containing up to 90% GGBS are used for paste backfill operations throughout Canada (Peyronnarda & Benzaazouaa 2012; Belem et al. 2010; Xiao et al. 2021).

The GGBS material for the LKAB application originates from the steel making process using LKAB iron ore. The slag is ground by a third party and routed back to the mine site for concrete production. To evaluate large proportions of GGBS for the ore pass rehabilitation, three mixes were initially tested. A gradual increase of the GGBS content was applied and compared to the reference mix used in previous ore pass rehabilitation projects where a CEM II A-LL 42.5R was used as binder as shown in Table 4. To push the limit further, a fourth mix was established to evaluate a 'zero clinker binder system', which means, a binder system, not containing any clinker material.

To achieve sufficient hydration products and strength-gain, an additional waste component from the iron ore processing was chosen in combination with a hydration enhancing admixture especially developed for this purpose. Laboratory trials confirmed, that 50% of the clinker could be replaced by an equal amount of waste slag material from the mill. Further clinker reduction however would ultimately result in strength losses at the final curing stage, keeping everything else equal. Figure 5 shows a schematic of the process of the ore-waste pass rehabilitation. The ore pass is emptied of ore. The ore pass is then sealed from the bottom by casting a concrete plug. The ore pass is subsequently filled with concrete through drilled boreholes from the upper level. A raise drill is used to raise a new ore pass into the cured concrete.

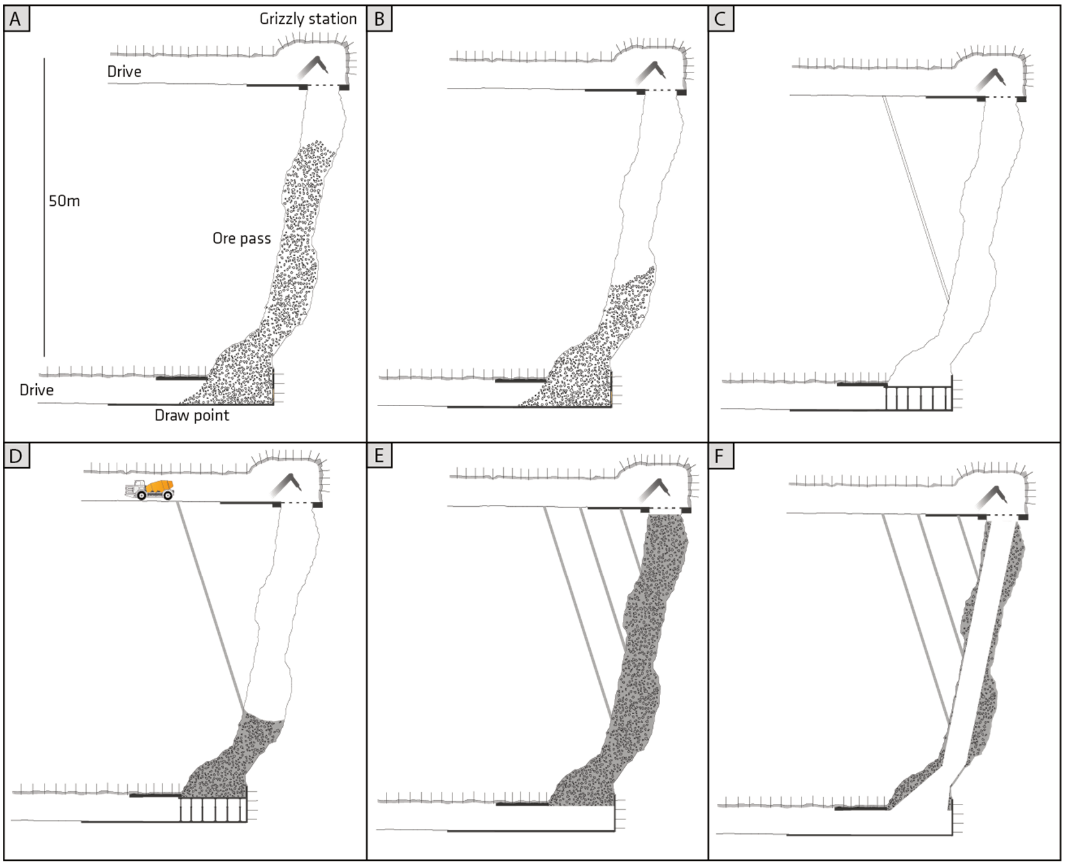

Figure 5 Schematic illustration of the ore/waste-pass rehabilitation at LKAB Kiruna. Pass is emptied of ore (A/B). Ore pass is closed off (C) and concrete is filled into the ore pass (D). Curing of the fill (E). Raising a new ore pass through the cured backfill (F)

Table 4 Backfill mix design for the ore/waste pass rehabilitation

Mix design	Reference	50% GGBS	75% GGBS	90% GGBS	80% GGBS/ 20% waste
Batch size (m^3)	4	4	4	4	4
Material (kg/m^3)					
Water to Cement ratio (W/C)	0.42	0.8	1.43	3.44	n/a
Water to Cement eqv-ratio	0.42	0.5	0.51	0.56	0.38
Water	185	192	172	172	191
Cement (CEM II A-LL 42.5R)	480	240	120	50	0
GGBS	0	240	360	430	320
Additional waste material from process					80
Total Binder	480	480	480	480	400
GGBS by weight of total binder	0%	50%	75%	90%	100%
High range water reducer*	0.65%	0.5%	0.38%	0.35%	0.93%
Special accelerator	0%	0%	0%	0%	2%
Retarder: Sika Retarder (% bwoc**)	0.5%	0.25%	0.2%	0.2%	0%
Aggregates					
(0.4 mm) crushed granite/gneiss	64%	64%	64%	64%	64%
(8–16 mm) crushed granite/gneiss	36%	36%	36%	36%	36%

* by weight of binder; ** by weight of cement

5.1 Results

Results are summarised in Table 5. All mixes fulfilled the workability requirements and the requirement to maintain the slump over a specified time. With the reduction of clinker, the water to cement ratio goes up. As the reduced amount of clinker is compensated with GGBS, the water to binder ratio remains constant, using a GGBS activity index of one. This is justified, as the only concrete requirement is the final 28 day uniaxial compressive strength (UCS). It is possible to reduce 50% of the CEM II with the GGBS product from the smelter and to maintain the 28 days strength compared to the reference mix with the CEM II cement. Lower 28 days results were achieved with higher GGBS proportions as insufficient hydration for the 80 MPa strength requirement is achieved. The 'zero clinker' system containing 80% GGBS and 20% waste material showed very promising results and additional testing has been conducted to eventually create a system that fulfills the strength requirements. Such a system has now been selected for future ore pass rehabilitation projects at LKAB Kiruna.

Table 5 Strength results for the different ore pass backfill mixes

Mix design	Reference	50% GGBS	75% GGBS	90% GGBS	80% GGBS/ 20% waste
GGBS by weight of total binder	0%	50%	75%	90%	100%
UCS (after days)					
1	22.8	-		-	4.5
7	63.4	51.5	36.2	21.3	39.9
14	68.3	64.6	50.1	29.4	-
28	74.2	75.7	57.2	31.4	58.6
56	79.7	88.8	66.2	36.1	68.0

6 Shotcrete applications using alternative binder systems

The last aim was to evaluate the suitability of an alternative concrete mix for shotcrete. Again, different mixes were designed, containing different proportions of GGBS material and this was compared to a standard shotcrete mix containing 490 kg of CEM II. The different mixes are shown in Table 6 where the lowest proportion of GGBS is 28% and then highest 75%. To accelerate the system adequately and make it viable for in-cycle, primary support, an additional accelerator was developed and dosed into the concrete stream at the nozzle together with the existing shotcrete accelerator. The purpose of this additional accelerator is to activate the large proportion of pozzolanic material, the slag, in addition to the hydration products derived from the clinker. To dose this admixture, a special injector was used (Sika Cyclone). A second accelerator dosing pump was needed as shown in Figure 5, middle. To achieve the specified workability of the fresh concrete in terms of its slump value, a smaller plasticiser dosage was required for the GGBS mixes. 40 kg of steel fibres per cubic metre of concrete were added to all mixes. Workability requirements were achieved for all mixes.

Figure 6 Flow and workability of the alternative binder-based shotcrete reinforced with 40 kg steel fibres (left hand side). Second dosing pump with additional accelerator in IBC behind, mounted on a truck (central image). Spraying process of the shotcrete (right hand side)

Table 6 Shotcrete mix designs based on alternative binder system

Mix design	Reference	28% GGBS	28% GGBS	50% GGBS	75% GGBS
Batch size (m^3)	4	4	4	4	4
CEM II A-V 52,5N	490	353	353	245	125
GGBS	0	137	137	245	365
High range water reducer (% bwob)	0.4	0.4	0.4	0.3	0.3
Retarder (% bwob)	0.25	0.17	0.17	0.16	0.08
Air entrainer (% bwob)	0.08	0.08	0.08	0.08	0.08
Macro steel fibres (kg/m^3)	40	40	40	40	40
Water to cement ratio (W/C)*	0.47	0.94	0.94	0.94	1.84
Water to cement eqv-ratio **	0.47	0.47	0.47	0.47	0.47
Aggregate					
(0–4 mm) (crushed granite)	88%	88%	88%	88%	88%
(4–8 mm) (crushed granite)	12%	12%	12%	12%	12%
Slump/Flow table spread (mm)	200 @ 3H	190 @ 3H	190 @ 3H	180 @ 3H	220 @ 3H
Nozzle	Sika Cyclone	Sika Cyclone	Sika Cyclone	Sika Cyclone	Sika Cyclone
Accelerator 1	n/a	10%	6%	6%	6%
Accelerator Sigunit L2721 AF	7%	7%	7%	7%	7%

* Water to binder ratio; ** Water to effective binder ratio (including the GGBS material with an activation factor of 1)

6.1 Results

According to EN 14487–1, different strength limits need to be achieved depending on the type of ground support. For above head application in underground construction for example, an early shotcrete strength of J2, as illustrated in Figure 7, has to be achieved. Also, a class J2 sprayed concrete is required in applications where thick layers have to be achieved within short time. This type of sprayed concrete achieves a rapid load build-up and can be applied overhead to build-up a reasonable shotcrete lining, suitable for excavation stabilisation. This kind of shotcrete is part of the usual working cycle in drill & blast development. The LKAB Kiruna operations has among the most stringent early strength requirements for shotcrete. 4 MPa have to be reached after 4 hours which is well within the J2 requirement and above the J3 requirement after 4 hours. This requirement from LKAB is currently achieved using a CEM II cement and an accelerator dosage of around 7% as shown in Figure 7. By replacing cement with GGBS material, lower early strengths are achieved but the results, using a two-component activation system, look promising. Especially for dosages of 28% GGBS and 50% GGBS the early strength development looks good, well within J2 but not reaching the 4 MPa after 4 hours requirement as shown in Figure 7. Even at a 75% GGBS dosage, the early strengths are well within J2.

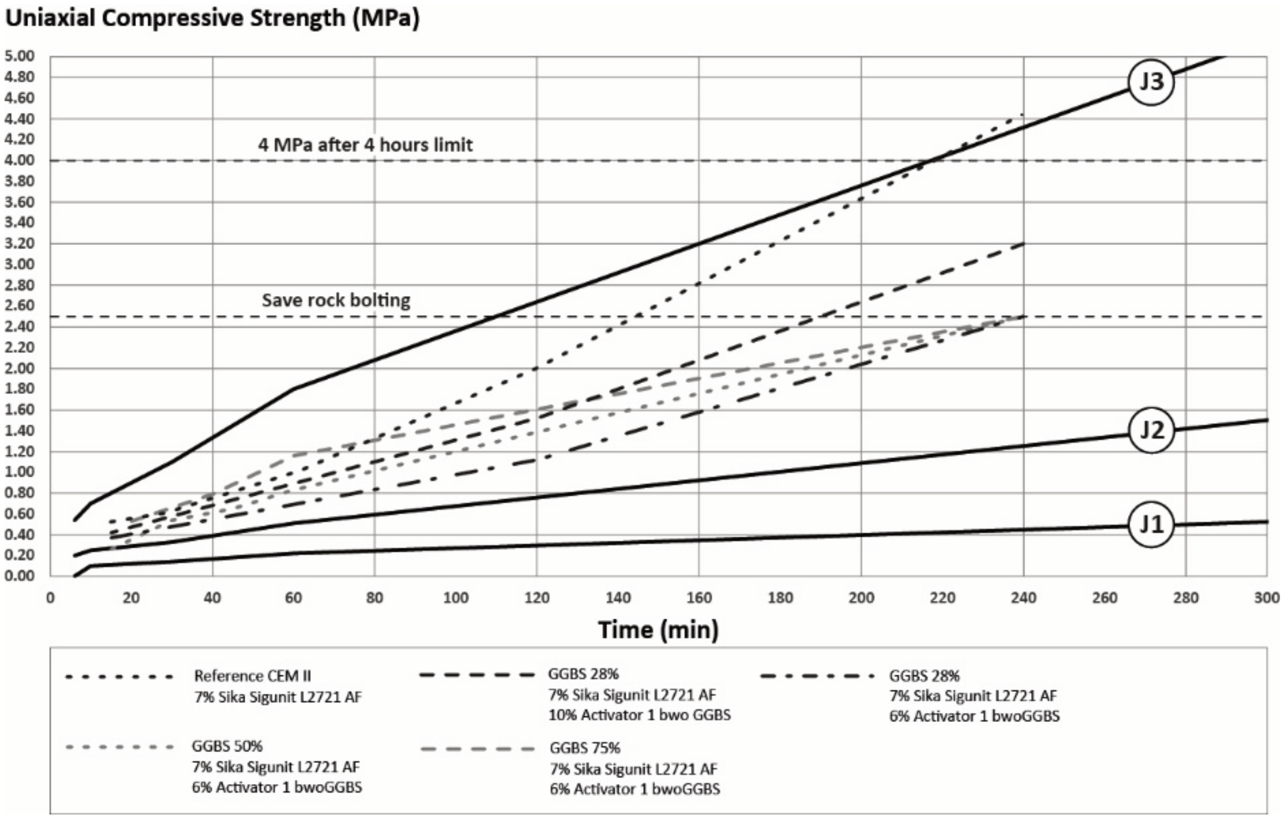

Figure 7 Uniaxial compressive strengths (Y-axis) reached after a certain curing time (X-axis). Horizontal lines indicate the strength requirements for bolting and general re-entry

7 Discussion

The results confirmed findings from previous studies (Erismann & Hansson 2019), that a dosage of 40 kg high quality steel fibres per m^3 of shotcrete can be replaced with 6 kg of good quality polypropylene macro fibres. This study also showed that a combination of polypropylene macro fibres and steel fibres can yield very high energy absorptions that can be compared to a welded mesh in combination with a fibre-reinforced shotcrete. From a cost performance perspective this is a very interesting finding as it shows the potential of reducing extensive mesh installations in mines to achieve a certain energy absorption. Such a combination of either two different fibre types or a sprayed in mesh in combination with fibre-reinforced shotcrete yields in roughly twice the energy absorption compared to a purely fibre-reinforced shotcrete. Combining such systems shows the versatile use of shotcrete in highly stressed underground openings. Depending on the yielding requirements of the system, the thickness of the shotcrete liner, the fibre dosage and combination of fibres and the placement of a mesh either within the concrete or on the outside can be chosen with great flexibility and relatively low additional effort. Despite drawbacks in terms of the limited deformation capability of fibre-reinforced shotcrete and the high rigidity, shotcrete continues to be the best support method for seismic prone areas.

When it comes to mass applications of concrete, alternative binder systems have proven to be an interesting option for applications such as ore pass rehabilitation and potentially even shotcrete. However, new developments in accelerator technologies need to be developed to compete with the early strengths, a conventional binder system provides today. Lessons learned from clinker reduced or clinker free binder systems, as planned for mass concrete applications at LKAB, will guide future shotcrete developments.

In terms of sustainability and durability, GGBS, sourced as part of the mine's circular economy, is reducing the environmental footprint of concrete intensive operations significantly. In the case of LKAB, roughly 160,000 m^3 of concrete are produced every year including shotcrete and concrete. Of this, around 80,000 m^3 are used annually for shaft rehabilitations. Replacing 50% of the CEM II with GGBS for the ore pass rehabilitation efforts, will reduce annual CO_2 emissions of LKAB Kiruna by 13,000 tons (LKAB 2021). Moving to clinker free systems and applying the same technology also for shotcrete would reduce annual CO_2 emissions significantly further. Industry estimates for CO_2 charges per ton of clinker cements such as CEM II as used by LKAB are in the range of 700–800 kg/ton (Leese & Casey 2019). Lifecycle assessments for GGBS show CO_2 charges per ton of GGBS in the range of 20–50 kg per ton (World Cement 2009). This illustrates the excellent potential to reduce mine site related CO_2 emissions when it comes to concrete intensive operations such as block and sublevel cave operations. In terms of durability, reducing the clinker-based cements and replacing them with GGBS is increasing the density of the concrete matrix due to the lower hydration heat generated during the curing phase. A denser matrix generally results in a higher abrasion resistance which is important for applications such as ore passes. Furthermore, in presence of sulphides, which is the case in many metalliferous mines, acid and sulphate attack of the concrete will be reduced significantly and the lifespan of concrete structures prolonged.

8 Conclusion

Data published in this paper confirmed the opportunity of phasing out steel fibres and replacing them by a much lower dosage of polypropylene macro fibres in standard shotcrete mixes. For high energy absorption requirements, a mix between macro polypropylene fibres and steel fibres is an interesting option. Such high energy requirements are common in large, mass caving operations where stress interference between closely aligned infrastructure as well as changing abutment stresses represent a challenge for rapid mine development and the lifespan of critical, ore handling infrastructure. Such fibre combinations open the possibility to strongly reduce mesh and bolt installations and to speed up mine cycle times further.

Mines are predestined to come up with alternative binder systems. Metal mines with metal smelting facilities close by can have access to interesting smelter slag waste products that can partially be used as latent hydraulic binders. Other waste products from the ore refining process can be blended into a system to provide further advantages in terms of the hydraulic activation of alternative binder systems. As these systems generally generate less heat due to the slower hydration, they are well suited for mass applications such as shaft linings, ore ore/waste pass rehabilitation projects as well as general concrete casting applications. When it comes to shotcrete, the slower early strength development has been a problem. Testing of different blending and activation options are currently underway with very interesting results, leading the way for a potential clinker free shotcrete, fulfilling the circular economy efforts of mines and producing cementitious systems with a minimal carbon footprint. Such systems are of particular interest where access to smelter slag is given such as the Mt Isa complex in Australia, the Sudbury mines in Canada, the Chuquicamata mine in Chile, the LKAB mines in Sweden and others.

Aknowledgement

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