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The Use of Slag in Accelerated Shotcrete for Rock Support: A Pilot Study on the Influence on the Early Compressive Strength



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ABSTRACT
Today, the world is facing an enormous challenge where the emissions of greenhouse gases must be reduced significantly to stop the increasing mean temperature. For the construction industry, this challenge means that structures must be designed more carefully, and materials must be used and produced more efficiently. Concrete is one of the most widely used materials, and cement production alone contributes to around 8 % of the world's total CO_2 emissions. This paper presents a pilot study in which part of the cement clinker content in accelerated shotcrete is replaced with ground granulated blast furnace slag (GGBS). Shotcrete is widely used as part of the rock support for tunnels in hard rock and has a large cement content. Thus, the environmental impact must be reduced significantly to meet future demands. However, introducing GGBS will slow down strength development, which is a crucial part of shotcrete. Thus, this paper aims to investigate the early strength development, i.e., after one and seven days. The results show that an average compressive strength of 18 MPa can be reached after 24 hours when 35 % of the cement clinker content is replaced with GGBS. Finally, some important topics for further studies are pointed out.

Key words: shotcrete, blast furnace slag, compressive strength, laboratory test, rock support.

1. INTRODUCTION

World leaders have, together with the United Nations (UN), set up Agenda 2030 with 17 Sustainable Development Goals (SDGs) for creating a better world [1]. The SDGs are ambitious commitments that connect all aspects of sustainability: environmental, economic and social. Besides reducing the effect of climate change, the aim is also to end poverty and inequality. Reducing the emissions of greenhouse gases (GHG), particularly the CO_2 emissions, is one of the most relevant topics to solve the climate crisis. According to Huang et al. [2], the construction sector within the European Union (EU) was responsible for 579 million tons (approximately 18 %) of GHG emissions in 2009. In this context, cement production in the EU during 2006 constituted approximately 268 million tons, or around 11 % of the world's production [3]. Moreover, Miller et al. [4] report that 3800 million tons of cement were produced worldwide during 2012. This is equivalent to 3200 million tons of CO_2, which is around 8 % of the annual worldwide CO2 emissions. In Sweden, the expected annual production of concrete in 2022 was 6 million tons [5]. As a rough estimation, the shotcrete constitutes around 5 % of the total volume of concrete in Sweden [6-7]. Thus, it is clear that the extensive use of concrete and today's production technology largely contribute to the emissions of CO_2. To reduce this, innovative solutions for the design and construction to minimize the use of concrete and a more carefully designed concrete mix must be used to reduce the increasing global temperature and limit global warming below 2°C to coop with the Paris Agreement [8]. Researchers have recently focused on reducing the concrete environmental impact to achieve this. Two important methods to reduce the climate impact of the cement industry exist: Carbon Capture and Storage (CCS) and reducing the content of cement clinker with low CO_2 supplementary materials. According to Scrivener et al. [9], CCS is a very costly technique that consumes much energy today. Lower-cost alternatives are therefore desirable, especially to reduce GHG emissions in developing countries. Thus, a more cost-effective way of reducing GHG emissions is by reducing the clinker content in the cement, which is commonly achieved by replacing cement clinker with fly ash or slag. However, with the target of reaching zero emissions from then concrete production, a combination of the two methods is beneficial.

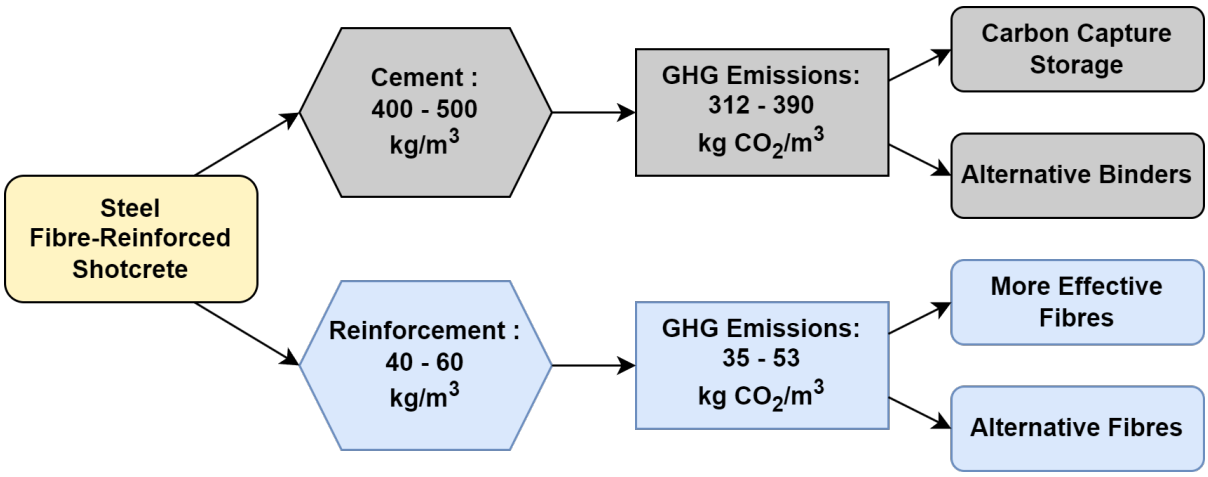


Figure 1 – Main contribution to emissions of GHG from steel fibre-reinforced shotcrete and methods to reduce the environmental impact.

Rock support for tunnels in hard rock is an application in which large amounts of cement are consumed. Here, shotcrete (sprayed concrete) is used, and the mix traditionally contains between 400 and 500 kg/m^3 of cement [10-13]. This could be compared to ordinary concrete, where the cement content normally is between 260 and 360 kg/m^3 [14]. Thus, shotcrete has a significantly larger environmental impact compared to ordinary concrete. Reducing the GHG emissions from shotcrete is, therefore, an important task. Shotcrete is commonly reinforced with fibres to increase the material's ductility. Today, fibres made of steel, polypropylene, basalt and glass are available on the market, but steel and polypropylene fibres are most commonly used. The type of fibres depends on the design philosophy and varies between countries, as summarized by [15]. However, the volume fraction of fibres is often between 0.5 and 1.0 %, which results in a dosage between 4.5 to 9.0 kg/m^3 and 40 to 80 kg/m^3 for polypropylene and steel fibres, respectively. Here, it can be noted that the new version of Eurocode 2 introduces an annex focusing on the design of steel fibre-reinforced concrete. The main aspects of this upcoming document is summarised in [16] and may lead to a more harmonised design in the future.

Brodd and Östlund [17] investigated different ways, i.e., alternative binder materials and test methods, to reduce the environmental impact of fibre-reinforced shotcrete (FRS) used as tunnel support. Figure 1 shows an overview of the main contributions to GHG emissions from a traditionally used steel fibre-reinforced shotcrete mix. Here, the CO_2 emissions have been calculated based on the mean value from different manufacturers of steel fibres and CEM I based on Environmental Product Declarations (EPD) [17]. The figure shows that concrete, represented by cement production, is the largest contributor to GHG emissions. The figure also shows the main alternatives to reduce the environmental impact.

The scientific community has focused on ways of reducing the use of cement clinker in concrete, e.g. Andersson et al. [18], Favier et al. [19] and Gencel et al. [20]. Using Ground Granulated Blast Furnace Slag (GGBS) is one way to achieve this, which has been studied to a great extent, e.g. [20-22]. However, few studies have been made on the effect of additional materials in shotcrete. For shotcrete, fast strength development and good adhesive properties are vital parameters [23]. Tunnels in hard rock are typically excavated through drill and blast. Therefore, fast strength development is crucial both to ensure the safety of the workers and to give the shotcrete sufficient strength to withstand the pressure wave from the explosion of the next excavation round, e.g.

Ansell [24] and Ahmed and Ansell [25]. Therefore, this paper aims to investigate how accelerated shotcrete's strength development is affected when GGBS replaces part of the Portland cement clinker content. In particular, the paper focuses on the development of early strength after 24 hours since this is an important parameter to consider during tunnel construction. First, a background to shotcrete and its use in tunnels is presented. Then, the design of a small experimental pilot study is presented, followed by the results and the discussion. The work presented in this paper is based on the Master Thesis presented by Brodd and Östlund [17].

2. SHOTCRETE AS ROCK SUPPORT

This section presents the use of shotcrete as rock support and the possibilities of using alternative cementitious materials in shotcrete.

2.1 Support mechanisms

When excavated in an arch shape, tunnels in hard rock are commonly able to support their own weight. However, depending on the orientation of rock joints, the presence of water and the in-situ horizontal forces, individual blocks may become loose and fall out. This could have catastrophic consequences, and rock support is usually installed. Commonly, fibre-reinforced shotcrete and rock bolts are used in combination. Here, rock bolts are used to secure larger blocks, while shotcrete is used to secure blocks that fit between the bolts [27], as illustrated in Figure 2. The structural capacity of the lining is governed by the residual flexural capacity of the shotcrete or the bond strength between shotcrete and rock. The failure mode depends to a great extent on the bond strength but also on the structural interaction between shotcrete and rock bolts and the horizontal confinement, as shown in [26].

Shotcrete is sprayed directly on the rock surface using high pneumatic pressure. At the nozzle, set accelerators are added to the shotcrete mix. The accelerators react rapidly with the cement and water in the shotcrete mix to build a stiff ettringite structure. This, in combination with the impact created through the spraying process, makes the shotcrete stick to the surface, and no mould is required. The time between excavation and applying shotcrete depends on the stability of the rock mass, i.e., the assessed risk of a block falling down. Commonly, it is recommended to avoid working under an unsupported tunnel area, or special considerations regarding the safety of the workers should be taken [11-12]. Thus, shotcrete is commonly installed early after the excavation to provide a safe working environment. National or project-specific rules commonly exist that

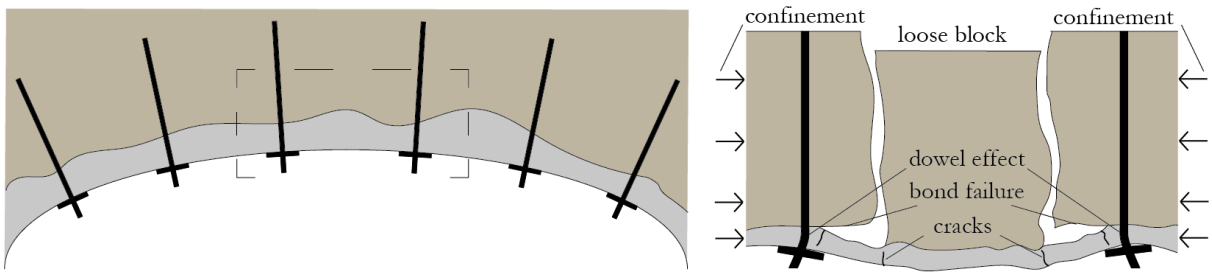


Figure 2 – Support mechanism for a bolt-anchored shotcrete lining subjected to the loading of a loose block. From Sjölander et al. [26].

specify when it is safe to work under freshly sprayed concrete and when the next round of blasting could be performed. These rules are linked to the compressive strength of the shotcrete. According to EN 14487-1 [28], the compressive strength of young shotcrete is divided into classes J1-J3. The minimum strength after 24 h to be classified as J1, J2, and J3 is 2, 4 and 15 MPa, respectively. In Sweden, most contracts are formulated based on a series of reference work that stipulates requirements on material and execution during the construction process (AMA). Based on [29], a compressive strength of 6 MPa should be reached before the subsequent excavation. Thus, early development of strength is necessary to not slow down the excavation process.

2.2 Binder material of shotcrete

As mentioned, cement production contributes largely to the global CO_2-emissions. Andersson et al. [18] estimates that approximately 60 % of the CO_2 emissions of cement clinker originate from the calcination process, which is the process in which calcium carbonate $CaCO_3$ is heated to high temperatures. In this process, calcium oxide CaO and carbon dioxide CO_2 are released according to the reaction below [30]:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \quad (1)$$

While being the only method resulting in zero emissions, CCS is an expensive method, and using supplementary cementitious materials (SCM) is often more feasible. Today, fly ash, silica fume, or ground granulated blast furnace slag (GGBS) are used in different proportions to reduce GHG emissions. For the design of structures in Europe, the maximum allowed SCM content is regulated in the different parts of EN 197. The properties of the concrete related to each exposure class are defined in EN 206 [31], and each country could then apply national parameters. This leads to the fact that the maximum replacement rate of cement clinker with various SCM varies between countries. Fly ash is a by-product generated from burning pulverised coal [42]. However, its availability in Europe will likely decrease over the coming years since many countries plan to shut down their coal-fired power plants due to climate actions. Silica fume could also be used to replace part of the cement clinker content. However, according to EN 197-1 [33], a maximum replacement of 10 % is allowed today. Thus, other supplementary materials such as GGBS, natural calcined pozzolans and limestone have today a greater potential in lowering the emission of GHG since the maximum allowed replacement rate is much higher compared to silica fume. At the same time, Wally et al. [34] discuss the concepts of performance-based design instead of the traditionally prescriptive concept, in which limit values of, e.g. minimum cement clinker content and water-cement ratio are given. A performance-based design focus instead of achieving the correct properties of the concrete. This is implemented in EN 206-1 [42], which describes the principles of *Equivalent Concrete Performance Concept* (ECPC) and the principles of *Equivalent Performance of Combinations Concepts* (EPCC). These principles allow changes in the mix requirements, i.e., cement clinker content and maximum water-cement ratio, if the concrete performs similarly. However, if the rate of SCM is higher compared to the standards [31-32],

extensive and expensive testing must be performed to show that similar performance is achieved with the new mix. Usually, this responsibility is put on the contractor, who typically lacks the incitement to reduce GHG emissions. Thus, the concepts of EPCP and EPCC must be introduced in the contract between owners and contractors before they will be used fully.

This paper will focus on GGBS, a by-product from crude iron production used in CEM II-III types of cement [36]. The maximum GGBS content in CEM II and III is between 35 and 81 %. Since GGBS is a by-product, it lowers the need for natural resources and the environmental impact of concrete production. Based on Environmental Product Declarations (EPD), the CO_2 emissions from cradle-to-gate for CEM I vary between 726 to 873 kg CO_2 equivalent per 1000 kg of cement [36-39], while the CO_2 emissions for slag vary between 20 to 42 kg CO_2 equivalent [40-41]. GGBS shows latent hydraulic properties in concrete, i.e., it activates in the alkali environment created during the cement-water reaction. Thus, strength development is slower in a mix containing GGBS compared to a mix with pure Portland cement (CEM I) [36, 42]. However, the strength after 28 days is normally not affected, and apart from this, GGBS often improves the rheology of the concrete mix due to its fine particle size. Polder et al. [43] report on the positive experience from nearly two decades of using concrete mixes in which up to 80 % of the cement clinker was replaced with GGBS.

2.3 Properties of shotcrete with GGBS

The addition of ground granulated blast furnace slag (GGBS) in shotcrete affects the material in different ways. Even though this paper focuses on the early development of strength, it is important to understand how other material properties are affected. Two essential properties of shotcrete are rapid strength development and its ability to bond to the rock surface. The slower development of strength for shotcrete with GGBS has already been discussed. The adhesive properties and the shotcrete's ability to bond and stick to the rock surface are partly governed by using set accelerators. These have been developed to activate the cement. Thus, an extensive replacement of cement clinker could change the efficiency of the accelerators. Ishida et al. [44] used a powder accelerator based on calcium aluminate to compare the strength and adhesive development of a traditional shotcrete mix to a shotcrete mix containing 36 % Blast furnace slag and 20 % fly ash. The tests indicate that both mixes were suitable for use and that an overhead thickness of 200 mm could likely be sprayed. Thus, a shotcrete with high rate of SCM is sprayable, but a different type of accelerator may be required.

Tunnels and rock support are commonly designed for a technical lifetime of 120 years. The shotcrete's ability to withstand chemical attacks is essential to achieve this. Introducing GGBS in the concrete mix will alter its resistance to various deterioration mechanisms [45]. Gesoglu et al. [46] showed that introducing GGBS decreased concrete's chloride ion and water permeability. Thus, improving the durability of the mix. Carbonation is a common long-term process that occurs in the concrete and is initiated by the intrusion of CO_2 in the cement matrix. This is usually a slow process but could lead to shrinkage, cracking and an increased porosity of the concrete [47]. Moreover, the pH of the concrete decreases with the introduction of GGBS, which perhaps could effect the alkaline environment that protects the steel from corrosion. Borges et al. [47] showed that the carbonation rate increases with an increased replacement of cement clinker with GGBS. Perhaps, synthetic and basalt fibres are more suitable for shotcrete with large amounts of GGBS.

A common problem in tunnels is cracking related to restrained shrinkage, which is presented by e.g. Sjölander and Ansell [48], Malmgren et al. [49], and Lagerblad et al. [50]. Based on a review by [45], the magnitude of shrinkage depends on the ratio between cement clinker and GGBS. Darquennes et al. [51] compared the total shrinkage for a reference mix with only Portland cement to mixes where 50 and 75 % of the cement clinker was replaced with GGBS. The results showed that the total amount of shrinkage was smaller for the mix with 50 % replacement, while the total amount of shrinkage was the same for the reference mix and the mix with 75 % replacement. Similar results were obtained by El-Chabib and Syed [52], in which the magnitude of shrinkage was similar when the rate of cement clinker replacement was 70 %.

3. EXPERIMENTAL CAMPAIGN

As mentioned, rapid development of the shotcrete strength is essential to keep up the tunnel's construction process. Therefore, this experimental campaign aimed to study the development of the compressive strength of shotcrete with GGBS after one and seven days of curing. The test contained three different mixes, presented in Table 1, and the strength development was evaluated according to the standard EN-12390-3 [53], i.e., test on cast cubes. Three samples were tested for each mix and curing time, which makes it a total of 18 samples (sb1-sb18). A reference mix with only CEM-I cement was compared with two mixes, in which 15 and 35 % of the CEM-I content was replaced with GGBS. Here, 35 % is the maximum allowed replacement rate of cement for exposure class XF2-XF4 [54], i.e., concrete subjected to freeze-thaw cycles, a typical exposure class for Swedish tunnels. A superplasticizer was added to achieve a workable concrete, and differences between the mixes as given in Table 1. The effective binder-to-water ratio was calculated according to Eq. 2 and kept equal to 0.4.

$$w/b = \frac{W}{C+k\times B} \tag{2}$$

Table 1 – Shotcrete mixes for experimental tests.

	Test 1 0% slag		Test 2 15% slag		Test 3 35% slag	
Material	Quantity	Unit	Quantity	Unit	Quantity	Unit
Cement	500	kg/m^3	425	kg/m^3	325	kg/m^3
Slag	0	kg/m^3	75	kg/m^3	175	kg/m^3
Water	200	kg/m^3	188	kg/m^3	172	kg/m^3
w/b	0.4	-	0.4	-	0.4	-
Aggregate 0-8 mm	1630	kg/m^3	1630	kg/m^3	1630	kg/m^3
Accelerator[1]	30	kg/m^3	30	kg/m^3	30	kg/m^3
Superplasticizer[2]	14.8-18.5	kg/m^3	9.6	kg/m^3	10.7	kg/m^3

[1]Mapequick AF 70
[2]MasterGlenium 5118

Here, W is the water mass, C and B are the masses of cement and addition material, respectively. Finally, k is the effect factor of the GGBS, and varies between producers. Here, Slagg Bremen produced by Thomas Concrete [41] was used with k=0.6.



Figure 3 – Overview of the experimental campaign. Storing of ingredients overnight (top-left), mixing of ingredients (top-right), placement of concrete in formwork (bottom-left) and curing in water (bottom-right).

All materials should be kept at a low temperature to slow down the reaction between the accelerator and the cement. Therefore, all dry ingredients were stored in plastic containers outside overnight where the average temperature was around 0 ºC, see Figure 3. Initially, a small hand mixer was used to mix concrete for two samples (sb1 and sb10). However, this method was inefficient and a high amount of superplasticizer was required to mix the concrete. This resulted in visible separation that may affect the test results. Thus, the remaining samples were mixed using a rotating mixer, see top-right in Figure 3. The accelerator was added at the end of the mixing process. After that, the concrete was poured into 150 mm cubic steel moulds. The cubes were stored in the laboratory for approximately 24 hours in which the temperature was around 20ºC. After that, the moulds were removed, and three cubes from each test series were tested. The remaining nine cubes were stored in water with an approximate temperature of 10ºC for six more days before testing. All tests are considered to be performed on wet samples.

4. RESULTS AND DISCUSSION

The results from compressive strength testing after one and seven days of curing are presented in Tables 2 and 3, respectively. As a reminder, the first sample in each table, i.e., sb1 and sb10, were mixed by hand while a rotating mixer mixed all other samples. The test series after one day was performed approximately 26 hours after casting. The results in Table 2 indicate that replacing 15 % of the cement content with GGBS has no or low effect on the strength. However, the mix with 35 % of GGBS showed a reduction of around 30 % in strength. However, the mix still meets the demand for the J3-class, i.e., the highest early strength according to EN 14487-1 [28]. Moreover, all the mixes meet the requirements of a 6 MPa strength, commonly required before the next round is blasted in Swedish tunnels. For the test performed after seven days, no significant differences can be seen between the mean values of the different mixes. Nevertheless, it should be noted that the results from the hand-mixed sample (sb10) are more than 20 % lower (45 MPa compared to 57 and 58 MPa, respectively) compared to the machine-mixed samples. Thus, removing the results from the hand-mixed samples would create a clearer trend in which the samples with only cement show the highest strength after one and seven days of curing. Still, all mixes achieve a high strength.

Table 2 – Test results for samples after one day of curing.

Sample	Slag	Mass	Ultimate load	Density	$f_{c,cube}$	Average	Std
nr	%	g	kN	kg/m^3	MPa	MPa	MPa
sb1	0	7272	531	2330	23.6		
sb2	0	8000	576	2370	25.6	25.6	1.7
sb3	0	7935	624	2350	27.7		
sb4	15	7900	602	2340	26.8		
sb5	15	7905	589	2340	26.2	25.7	1.1
sb6	15	7885	543	2340	24.1		
sb7	35	7888	401	2340	17.8		
sb8	35	7921	410	2350	18.2	18.2	0.3
sb9	35	7953	416	2360	18.5		

Table 3 – Test results for samples after seven days of curing.

Sample	Slag	Mass	Ultimate load	Density	$f_{c,cube}$	Average	Std
nr	%	g	kN	kg/m^3	MPa	MPa	MPa
sb1	0	7934	1004	2350	44.6		
sb2	0	8111	1275	2400	56.7	53.0	6.0
sb3	0	8047	1298	2380	57.7		
sb4	15	8004	1155	2370	51.4		
sb5	15	8005	1194	2370	53.1	52.2	0.7
sb6	15	8039	1174	2380	52.2		
sb7	35	7963	1124	2360	50.0		
sb8	35	7901	1094	2340	48.6	49.1	0.6
sb9	35	7988	1097	2370	48.8		

From an environmental perspective, the introduction of GGBS in the shotcrete mix has a significant impact on the CO_2-emissions. Below, the calculated kg CO_2 equivalent for the three mixes tested are shown:

- **Mix-1 0 % Slag:** 437 kg CO_2-equ.
- **Mix-2 15 % Slag:** 373 kg CO_2-equ.
- **Mix-3 35 % Slag:** 289 kg CO_2-equ.

Thus, a reduction of GHG-emissions with 34 % could be achieved by replacing 35 % of the cement clinker content with GGBS. This is a significant reduction in CO_2-emissions but will not be enough to reach the goal of the Paris Agreement, which aims for a 50 % reduction of the GHG emissions. To reach this, either a higher rate of supplementary cementitious materials (SCM) must be used, or other solutions to reduce GHG emissions must be used in combination with SCM.

5. CONCLUSIONS AND FURTHER RESEARCH

The results in this paper have highlighted the potentiality of using GGBS as a partial replacement to the cement clinker in accelerated shotcrete. The results indicate that a sufficiently high early strength of the shotcrete is reached, and the introduction of GGBS significantly reduces the environmental impact. However, when part of the cement clinker is replaced with GGBS, the chemical composition of the mix changes, and several aspects must be further studied.

When GGBS is introduced, the alkaline environment in the shotcrete is reduced. The alkalinity is the governing protective mechanism against steel fibre corrosion, and further research should focus on whether steel fibres are suitable to use in shotcrete with a high amount of GGBS or if alternative fibres should be used. Failure of a shotcrete lining is normally initiated by bond failure between shotcrete and rock and is thereafter governed by the ductility of the fibre-reinforced shotcrete. For fibre-reinforced shotcrete, the governing energy consumption mechanism post-cracking is the deformation and pull-out of the fibres from the shotcrete matrix. While the deformation of the fibres depends on the material's stiffness and geometry, the pull-out of individual fibres depends on the bond strength between the fibres and the shotcrete matrix. Further studies should, therefore, focus on whether the introduction of GGBS will affect the bond strength between shotcrete and rock as well as shotcrete and fibres. Lastly, today's set accelerators have been developed to activate the cement clinker. With a large amount of GGBS replacement, the efficiency of the accelerator may change. This could lead to the shotcrete not sticking to the surface, or a thinner layer must be sprayed. Thus, further testing of shotcrete with GGBS should include sprayed samples to investigate the efficiency of the accelerators.

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