Influence of rock crystal structure on bond strength at the rock-shotcrete interface

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ABSTRACT: The bond strength at the aggregate-cement paste interface is affected by the microstructure of the interfacial transition zone (ITZ). However, the influence of substrate crystal structure on the rock-shotcrete interface behaviour has received limited attention. This study investigates the impact of substrate crystal structure on the bonding strength of the rock-shotcrete interface. Gabbros and basalts used in this study have similar mineral compositions but have different grain sizes due to different cooling rates. Applying plain shotcrete to substrate samples to study the interface behaviours. Direct pull-off tests are conducted to investigate the bond strength at the interface after 28-day curing. The failed surfaces are examined using scanning electron microscopy imaging technique to further analyse the failure interface. The results indicate that hydration products can cover and embed into the rock surface. Basalt with fine-grained texture achieves denser ITZ than coarse-grained gabbro and results in stronger bond between rock and shotcrete.

Keywords: Basalt, Gabbro, Rock-shotcrete interface, Bond strength, Crystal structure.

1 INTRODUCTION

Achieving strong bonding at the rock-shotcrete interface is a crucial prerequisite for the effective performance of shotcrete in its supporting functions. The bond strength of shotcrete is commonly defined as the capacity to adhere to a given surface, generally composed of rock or concrete (Bryne et al., 2014). Bonding failure consists of adhesion loss and cohesion loss. The former term refers to the separation of two materials, such as rock and cement mortar, along their interface at the contact area. The cohesion loss means the disappearance of the cohesive forces between particles within a single material, such as cement mortar (Luo et al., 2017). The predominant cause of shotcrete failure is the loss of adhesion between the shotcrete and the substrate (Chang & Stille, 1995). Barrett and McCreath (1995) provided an explanation of shotcrete failure modes and found that the performance of shotcrete is highly dependent on the bond between shotcrete and rock.

Adhesion mechanisms can be broadly categorised into three types: mechanical interaction, thermodynamic mechanisms, and chemical bonding (Beushausen & Alexander, 2008). Numerous factors influence the bonding strength of a rock-shotcrete interface, including rock mineral composition (Hahn & Holmgren, 1979), surface roughness (Saiang et al., 2005), interface treatments (Malmgren et al., 2005), and shotcrete mixture (Galan et al., 2019) as well as the spraying method (Vandewalle, 1991). The aforementioned factors can impact the mechanical interaction and chemical bonding at the rock-shotcrete interface.

The interfacial transition zone (ITZ) was first introduced to describe the boundary between the cement matrix and aggregate in concrete, and the microstructure of this zone substantially influences the properties of concrete (Muslim, 2020). The interface between concrete/shotcrete and a rock surface is also characterised by the presence of ITZ. The ITZ is a thin layer that forms between an aggregate and cement paste matrix. It is composed of a double layer consisting of calcium hydroxide crystals ($Ca(OH)_2$) and the hydrated calcium silicate (C-S-H) gel (Vargas et al., 2017). The ITZ is widely recognised as the weakest layer due to its high porosity, inadequate densification, and enrichment of calcium hydroxide (CH) (Bryne, 2014; Shen et al., 2019; Yue et al., 2022). Many studies have indicated the influence of the substrate on ITZ at the rock-shotcrete interface. For instance, Tasong et al. (1999) and Lothenbach et al. (2008) pointed out that when the $CaCO_3$ in limestone comes into contact with cement, the released gas leads to a high porosity at ITZ, which is considered the main factor for the weak bond achieved at an early age. At the latter age, the chemical reaction between limestone and cement paste produces carboaluminates that increase bond strength.

Numerous studies have been devoted to examining the influence of surface roughness and interface cleanliness on the bonding behaviours at the rock-shotcrete interface. However, few studies have focused on the influence of substrate crystal structure on bond strength at the rock-shotcrete interface. We use two rock substrates, basalt and gabbro, with similar mineral compositions, verified through X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis. Shotcrete is applied to the polished rock surfaces, and bond strength testing is carried out after a 28-day curing period. To investigate the underlying mechanisms, scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) techniques are utilised to examine the damaged interfaces, assess the microstructure, and analyse the chemical elemental composition of the ITZ in both rock types.

2 METHODOLOGY

2.1 Materials

Basalt and gabbro are common types of igneous rocks formed from molten magma or lava, but they have some distinct differences in composition and physical characteristics. Basalt is classified as a fine-grained, extrusive igneous rock primarily composed of plagioclase feldspar, pyroxene, and, on occasion, olivine. It is usually black or dark grey in colour and has a smooth texture. Basalt forms when lava cools and solidifies on the Earth's surface, often forming extensive lava flows. Gabbro is a coarse-grained, intrusive igneous rock that is, similar to gabbro, composed mainly of plagioclase feldspar, pyroxene, and occasionally olivine. It is usually dark-coloured and has a rough, uneven texture. Gabbro forms deep beneath the Earth's surface, and its slow cooling allows large crystals to form.

The basalt used in this study exhibits a bulk density of 2.98 g/cm^3 and a compressive strength of 231.3 MPa, while the gabbro has a bulk density of 2.93 g/cm^3 and a compressive strength of 179.0 MPa. Small rock samples are extracted from the basalt and gabbro specimens and then crushed for XRD and XRF analysis to determine their mineral and elemental compositions, respectively.

A cementitious-based shotcrete was used in this study. The water and shotcrete material are mixed at a mass ratio of 0.14, after 28-day curing period, the unconfined compressive and flexural strength reach 62.7 MPa and 3.8 MPa, respectively.

2.2 Experimental procedure

The tested surfaces of the basalt and gabbro specimens are ground and polished using an air sander to achieve a smooth finish to minimize the impact of surface roughness. Subsequently, according to ASTM C1583/C1583M, a coring apparatus equipped with a drill bit measuring 50 mm in diameter was employed to drill circular cuts perpendicular to the polished rock surfaces to a depth of 10 mm, with 100 mm between the centre of each core. The rock surfaces are thoroughly cleaned of any dust or debris with water and an air gun before applying the shotcrete. Afterwards, a 60 mm thick layer of expanded polyethylene (EPE) foam is positioned around the core as a mould. The EPE foam has uniform closed cells and is advantageous for its flexibility, lightweight, and consistent moisture retention properties. The water and shotcrete material are mixed at a mass ratio of 0.14, and the resulting mixture is poured into the EPE foam. To ensure homogeneity, an air-driven bar is utilised to vibrate the shotcrete within the mould. Once the shotcrete is relatively set, typically by the second day, the EPE foam is cut to remove the mould. After a 28-day curing, direct pull-off tests are carried out on the samples to assess the bond strength at the interface. Round steel dollies with 50 mm diatmeter are attached on the top of shotcrete before conducting bond strength tests. One end of the loading cell is connected to the pull actuator while the signal generated by the applied pull force is transmitted to a terminal device located at the other end. The variations in bond strength are recorded for both rocks.

The failure surfaces are then analysed using SEM-EDS imaging (Hitachi TM4000Plus) to further examine the interface and determine the cause of failure.

3 RESULTS AND DISCUSSION

Based on XRD analysis of substrate samples, the mineralogical composition of basalt predominantly comprises labradorite, clinopyroxene, olivine, and K-feldspar, with minor amounts of amphibole and quartz. XRD analysis finds that the gabbro specimens contain significant amounts of labradorite, clinopyroxene, and K-feldspar, as well as small amounts of amphibole and quartz. The basalt specimen differs from the gabbro as it also contains some amount of olivine. The elemental composition determined by XRF are listed in Table 1. Overall, they have similar mineral compositions. However, Figure 1 shows that basalt contains a finer grain texture and a less distinct crystal structure than gabbro due to the difference in their cooling rates.

Table 1. Elemental compositions of basalt and gabbro (element oxide wt.%).

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3	L.O.I	Total
Basalt	2.97	10.26	12.46	45.77	2.08	9.52	2.06	12.12	0.95	98.19
Gabbro	2.52	5.03	16.92	51.91	2.39	9.21	1.13	9.54	0.07	98.72

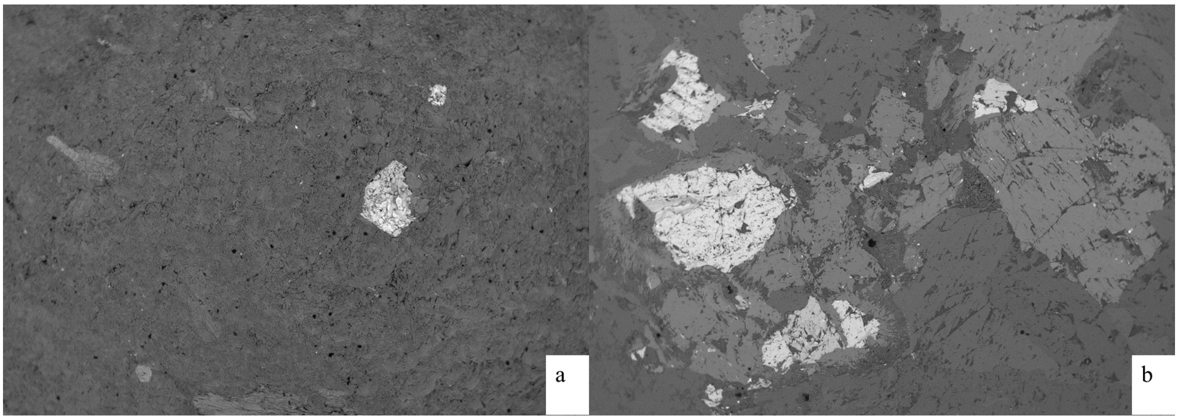

Figure 1. SEM micrograph of (a) basalt, and (b) gabbro rock surfaces (mag. x30).

The smooth surface of the rocks results in low bond strength at the interface, which remains low even after 28-day of curing. Many samples are damaged during the direct pull-off test due to disturbance during placement. Fifteen sets of valid experimental data are obtained for basalt samples, and thirty sets of valid experimental data for gabbro samples. The bond strengths at the smooth rock-shotcrete interfaces of basalt and gabbro are 27 kPa and 16 kPa, respectively. The maximum bond strength at the interface is found to be 86 kPa for the basalt specimen, while for the gabbro specimen, the maximum was only 51 kPa. Basalt and gabbro have a similar mineral composition, however, variations in the crystal structure may lead to differences in bond strength at the rock-shotcrete interfaces.

Basalt and gabbro failed interface samples are collected for further analysis using SEM-EDS imaging. Two types of bond behaviour are identified based on the SEM micrographs: hydration products covering the rock surface (Figure 2(a)) and hydration products embedding into the rock surface (Figure 2(b)). Even though the rock surfaces are ground and polished, micro undulations and fractures are still present in the mineral structure. The hydration products embed and interlock with fractures, meaning that they are able to form a bond between the shotcrete and rock surfaces. It can be seen in Figure 2 that the interface of basalt shows significant adhesion of cement hydration products that cover the rock surface, whereas the failure interface of gabbro-shotcrete exhibits fewer hydration particles. This difference in the amount of hydration products on the interface may be due to the difference in grain size between basalt and gabbro. Elsharief et al. (2003) indicated that increasing the size of the aggregate results in a higher porosity at ITZ. The increased porosity can decrease the bond strength between the aggregate and the surrounding cement paste. Similar to the aggregate-cement paste interface, fine-grained minerals may increase the surface area, leading to a denser ITZ between the rock-shotcrete interface with lower porosity, resulting in a stronger and more durable bond between the two materials.

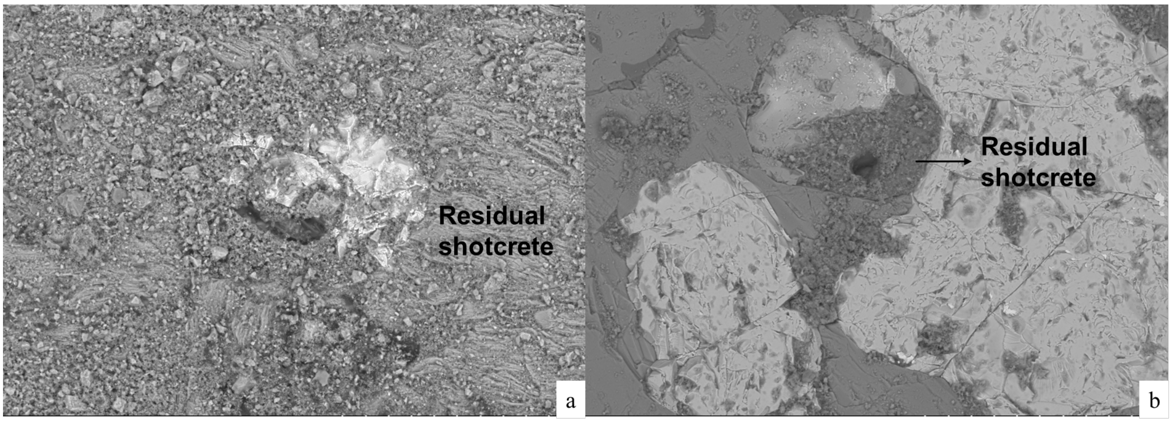

Figure 2. SEM micrograph of (a) basalt-shotcrete and (b) gabbro-shotcrete bond failure interfaces (mag. x250).

4 CONCLUSION

This study finds that the bond strength at the interface between basalt and shotcrete is more than twice that of gabbro and shotcrete, with values of 27 kPa and 16 kPa, respectively. Analysis using SEM-EDS for the failure interfaces indicates that the basalt-shotcrete interface exhibits a substantial amount of cement hydration products that essentially cover the rock surface. In contrast, the failure interface of the gabbro-shotcrete displays a relatively low amount of cement hydration particles. The results suggest that the fine particles in the basalt substrate provide a larger surface area per unit volume, resulting in a denser interfacial transition zone and a stronger bond between the rock and shotcrete. The outcomes of this study provide valuable information for the effective use of shotcrete in the construction and mining industries. Further investigations are recommended to explore the factors that influence the interfacial transition zone, such as the substrate mineral lattice structure and elemental composition. These studies may provide a deeper understanding of the mechanisms that govern the bond strength between rock and shotcrete and help optimise shotcrete applications in the mining and construction industries.

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REFERENCES

Barrett, S., & McCreath, D. 1995. Shortcrete support design in blocky ground: Towards a deterministic approach. *Tunnelling and Underground Space Technology, 10*(1), 79-89.

Beushausen, H., & Alexander, M. G. 2008. Bond strength development between concretes of different ages. *Magazine of Concrete Research, 60*(1), 65-74.

Bryne, L. E. 2014. *Time dependent material properties of shotcrete for hard rock tunnelling* KTH, Royal Institute of Technology]. Sweden.

Bryne, L. E., Ansell, A., & Holmgren, J. (2014, 2014-03-01). Laboratory testing of early age bond strength of shotcrete on hard rock. *Tunnelling and Underground Space Technology, 41*, 113-119. https://doi.org/10.1016/j.tust.2013.12.002

Chang, Y., & Stille, H. 1995. Shotcrete as a tunnel lining-A laboratory study. 8th ISRM Congress,

Elsharief, A., Cohen, M. D., & Olek, J. 2003. Influence of aggregate size, water cement ratio and age on the microstructure of the interfacial transition zone. *Cement and Concrete Research, 33*(11), 1837-1849. https://doi.org/10.1016/s0008-8846(03)00205-9

Galan, I., Baldermann, A., Kusterle, W., Dietzel, M., & Mittermayr, F. 2019. Durability of shotcrete for underground support– Review and update. *Construction and Building Materials, 202*, 465-493. https://doi.org/10.1016/j.conbuildmat.2018.12.151

Hahn, T., & Holmgren, J. 1979. Adhesion of shotcrete to various types of rock surfaces. 4th ISRM Congress.

Lothenbach, B., Le Saout, G., Gallucci, E., & Scrivener, K. 2008. Influence of limestone on the hydration of Portland cements. *Cement and Concrete Research, 38*(6), 848-860.

Luo, L., Li, X., Tao, M., & Dong, L. 2017. Mechanical behavior of rock-shotcrete interface under static and dynamic tensile loads. *Tunnelling and Underground Space Technology, 65*, 215-224.

Malmgren, L., Nordlund, E., & Rolund, S. 2005. Adhesion strength and shrinkage of shotcrete. *Tunnelling and Underground Space Technology, 20*(1), 33-48.

Muslim, F. 2020. A Review on The Microstructure of Interfaces in Reinforced Concrete and Its Effect on The Bond Strength. *CSID Journal of Infrastructure Development, 3*(1). https://doi.org/10.32783/csid-jid.v3i1.105

Saiang, D., Malmgren, L., & Nordlund, E. 2005. Laboratory Tests on Shotcrete-Rock Joints in Direct Shear, Tension and Compression. *Rock Mechanics and Rock Engineering, 38*(4), 275-297. https://doi.org/10.1007/s00603-005-0055-6

Shen, Y., Wang, Y., Yang, Y., Sun, Q., Luo, T., & Zhang, H. 2019. Influence of surface roughness and hydrophilicity on bonding strength of concrete-rock interface. *Construction and Building Materials, 213*, 156-166. https://doi.org/10.1016/j.conbuildmat.2019.04.078

Tasong, W. A., Lynsdale, C. J., & Cripps, J. C. 1999. Aggregate-cement paste interface Part I. Influence of aggregate geochemistry. *Cement and Concrete Research 29, 29*(10), 1453-1465.

Vandewalle, M. (1991). *Dramix-tunnelling the world:[with 7 reference projects]*. Bekaert.

Vargas, P., Restrepo-Baena, O., & Tobón, J. I. 2017. Microstructural analysis of interfacial transition zone (ITZ) and its impact on the compressive strength of lightweight concretes. *Construction and Building Materials, 137*, 381-389.

Yue, J., Sheng, J., Wang, H., Hu, Y., Zhang, K., Luo, Y., Zhou, Q., & Zhan, M. 2022. Investigation on Pore Structure and Permeability of Concrete–Rock Interfacial Transition Zones Based on Fractal Theory. *Fractal and Fractional, 6*(6). https://doi.org/10.3390/fractalfract6060329