Temperature dependence of interface shear behavior of cemented paste backfill-rock

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ABSTRACT
A thorough understanding of the mechanical behavior of the interface between cemented paste backfill (CPB) and rock under different curing temperatures is critical for the safe and economical design of CPB structures. However, to date, only limited studies on the mechanical response of CPB-rock interface have been conducted, and none of them has considered the effects of temperature on the shear behavior and properties of CPB-rock interface. In this paper, the authors present experimental results of the change of shear behavior and strength of CPB-rock interface with curing temperature (20°C, and 35°C) and time. The obtained results show that the temperature can either positively or negatively affect the shear strength of the CPB-rock interface depending on the curing time. The high curing temperature (35°C) increases the shear strength of the early age interface samples, as a result of accelerated cement hydration. But for samples cured for 28 days, the sample cured at a temperature of 35°C experiences lower shear strength than that cured at 20°C. The findings in this paper contribute to a better assessment of the stability of CPB structures, and are also important for barricade design.

RÉSUMÉ
Une compréhension approfondie du comportement mécanique de l'interface entre le remblai en pâte cimentée (RPC) et la roche soumis à différentes températures est essentielle pour la conception sûre et économique des structures de remblai en pâte cimentée. Toutefois, à ce jour, seules des études limitées sur la réponse mécanique de l'interface RPC-roche ont été menées, et aucune d'entre elles n'a pris en compte les effets de la temperature de durcissement sur le comportement au cisaillement et les propriétés de l'interface CPB-roche. Dans cet article, les auteurs présentent les résultats expérimentaux du changement de la résistance au cisaillement de l'interface CPB-roche avec la température de durcissement (20°C, et 35°C) et le temps. Les résultats obtenus montrent que la température peut affecter positivement ou négativement la résistance au cisaillement de l'interface CPB-roche en fonction du temps de durcissement. La température élevée (35°C) augmente la résistance au cisaillement des échantillons de l'interface d'âge précoce, en raison de l'hydratation accélérée du ciment. Mais pour les échantillons durcis pendant 28 jours, l'échantillon durci à une température de 35°C présente une résistance au cisaillement inférieure à celle des échantillons durcis à 20°C. Les résultats de cet article contribuent à une meilleure évaluation de la stabilité des structures des RPC et sont également importants pour la conception des barricades.

1 INTRODUCTION

Cemented paste backfill (CPB), which was firstly introduced in the Bad Grund Mine (Germany) in the late 1970s, has become increasing popular in underground mining operations during the last three decades (Brackebusch 1994; Hassani and Archibal 1998). CPB is a cementitious material produced by mixing thickened tailings (with a solid percentage of 70%-85%), binder (3%-7%, often) and water in paste backfill plant commonly located on the surface of the mine. Thereafter, the obtained CPB mixture is transported to underground through pipes by pumping or gravity to fill the voids created by ore extraction. The underground management of tailings can not only reduce the cost of constructing tailings storage facilities (TSFs, e.g., embankments and dams), but also solve or limit the environmental issues caused by surface disposal of tailings (e.g., acid mine drainage (AMD), water and land pollution, potential threats of dam failure) (Buckby et al. 2003). Moreover, the CPB structure can also maintain the stability of underground mining space which is critical for the safety of the mine workers. Besides, with the support of the CPB structure, the recovery ratio can also be significantly increased.

The mechanical strength of the CPB is one of the main design criteria for CPB structures. Therefore, to ensure the stability of the CPB structure, many studies have been performed to investigate the uniaxial compressive strength (UCS) (Kesimal et al. 2005; Yilmaz et al. 2009; Fall et al. 2010). However, given that the bonded interface between dissimilar materials is always a weak link in terms of the mechanical stability (Dong et al., 2017), the shear strength of the interface between CPB and surrounding rock is another key factor. Moreover, the shear behavior of the CPB-rock interface is closely associated to the arching effect, which is a result of shear stress distribution and CPB consolidation. The occurrence of arching effect can significantly reduce the vertical stress in backing body, which is obviously lower than the in-situ stress due to self-weight (Marston 1930; Pirapakaran and Sivakugan 2007; Cui and Fall 2017). This means a better understanding of the shear performance of CPB-rock interface can help to decrease the strength required to ensure the stability of the CPB structure, therefore reducing the amount of cement consumed. The cost cement can represents up to the 75% of the cost of CPB (Gani 1997; Benzaazoua and Fall, 2004).

With geographically widespread applications around the world (Australia, Canada, China, South Africa, etc.) and at various mine depths, the CPB structure is inevitably exposed to different thermal environmental conditions. Hence, studying the shear properties of CPB-rock interface at different temperature is critical for a safer and cost-effective design of CPB structure. However, despite the fact that many studies have been conducted on the effects of temperature on the strength of cementitious material (Schneider 1988; Kim et al. 1998), the influence of temperature on the shear behavior of CPB-rock interface still remained unknown. Therefore, the main objective of this study is to experimentally study and present the evolution of shear strength and properties of CPB-rock interface with curing time.

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

2.1.1 Tailings

Synthetic (silica tailings (ST)) and polymetallic natural tailings (NT) were used in this study. The grain size distribution cures of the NT and ST are similar, as shown in Figure 1. Besides, the shear performance and strength of CPB-rock interface produced with NT are also similar to that produced with ST (Fang and Fall, 2019). All the samples used and presented in this paper are made of ST.

ST is essentially made of quartz (contain 99.8% S_iO_2), a dominant mineral found in Canadian hard rock mines. Using ST helps to reduce the uncertainties in the results that can be caused by the use of natural tailings. Indeed, NT can contain various reactive minerals which can oxidize during the storage of the tailings and/or the preparation of the CPB samples as well as interact with the cement hydration process, and thus affect the accuracy and interpretation of the results.

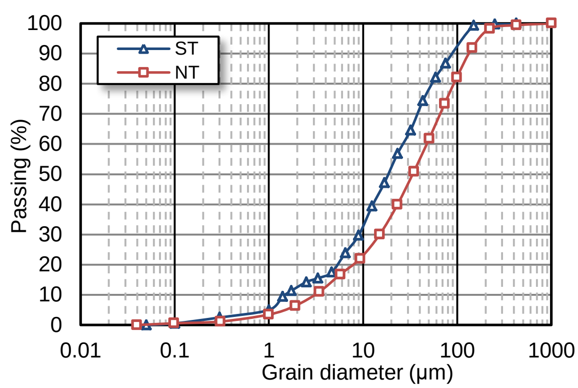


Figure 1. Grain size distribution of silica tailings (ST) and natural tailings (NT)

2.1.2 Binder

Many materials can be used as a binder (e.g., slag, fly ash, cement). In this study, Portland cement type I (PCI, which is the most common type of cement used in CPB operations), with a weight proportion of 4.5% is used to produce the CPB part of the sample.

2.1.3 Mixing water

Distilled water was used to mix the binder and tailings (with a water-to-cement ratio (w/c) of 7.35).

2.1.4 Rock samples

The rock part of the interface sample is granite, and the average UCS of the granite is about 160 MPa. After been cut into small pieces with dimensions of 60×60×10 mm, the surface of the granite was then polished to be smooth. According to the joint roughness coefficient (JRC) of typical roughness profiles proposed by Tse and Cruden (Tse and Cruden 1979), the surface roughness of the granite surface was determined as zero. This process can eliminate the influence of the roughness of rock on the shear behaviour of the CPB-rock interface.

2.2 Sample preparation and testing apparatus

2.2.1 Sample preparation and test plans

CPB was prepared by mixing the required amounts of tailings, PCI and water in a food mixer, and then stirred for about seven minutes until a homogeneous paste was obtained. After placing the granite into a plastic container with dimensions of 60×60×30 mm, the prepared CPB was poured on top of the granite. Thereafter, the plastic container underwent manual vibration to remove air bubbles that formed on the CPB-rock interface. The container was then covered with a plastic film to prevent water from evaporating. Lastly, the samples were cured in a temperature-controlled chamber with two different temperatures of 20°C and 35°C for 1, 3, 7 and 28 days. Examples of interface samples (cured for 1 day) at different temperatures are shown in Figure 2.

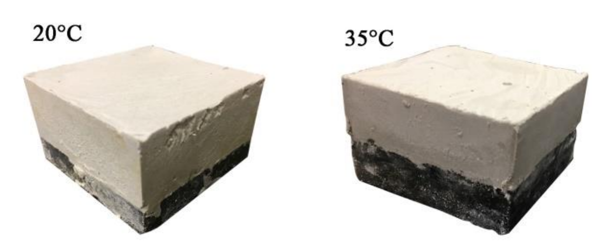


Figure 2. CPB-rock samples cured for 1 day

All of the samples were subjected to direct shear test after being cured for 1, 3, 7 and 28 days. To determine the shear strength envelope of the CPB-rock interface, three constant normal stresses (50 kPa, 100 kPa and 150 kPa) were applied on the samples during testing. Besides, each test iwas repeated at least three times to ensure the repeatability of the results. The experimental details are provided in Table 1.

Table 1. Experimental plan

Binder content (%)	w/c ratio	Curing time	Normal stress/kPa	Curing temperature/ °C
4.5	7.35	1 day	50	20, 35
4.5	7.35	1 day	100	20, 35
4.5	7.35	1 day	150	20, 35
4.5	7.35	3 days	50	20, 35
4.5	7.35	3 days	100	20, 35
4.5	7.35	3 days	150	20, 35
4.5	7.35	7 days	50	20, 35
4.5	7.35	7 days	100	20, 35
4.5	7.35	7 days	150	20, 35
4.5	7.35	28 days	50	20, 35
4.5	7.35	28 days	100	20, 35
4.5	7.35	28 days	150	20, 35

2.2.2 Testing apparatus

A direct shear device was employed to conduct the direct shear test according to ASTM D3080-04. The configuration of direct shear device is shown in Figure 3. As can be clearly seen from the figure, two linear variable differential transformers (LVDTs) are adopted to measure the horizontal and normal displacement, while a load cell is used for load measurement. To ensure the experimental data collected by computer software (Labview) are relevant to the CPB-rock interface, several steel balls are set between the upper and lower shear boxes. When shearing, a certain normal stress is applied on top of the sample, and during the test, the lower shear box is driven by a motor at a speed of 0.5 mm/min, while the upper shear box is maintained stationary.

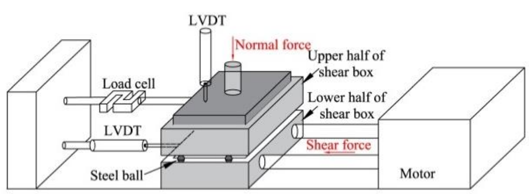


Figure 3. Configuration of the direct shear device

2.3 Microstructural analyses and monitoring program

2.3.1 Microstructure analysis

The microstructure of the samples was mainly investigated by adopting two techniques, namely thermal analyses (including thermogravimetry (TG) analysis and differential thermogravimetric (DTG) analysis) and mercury intrusion porosimetry (MIP).

The TG and DTG analyses were performed on cement paste (w/c = 1) of CPB (priorly dried at 45°C) by using a Q5000IR thermogravimetric analyzer, which allows the temperature to rise up to 1,000°C at a rate of 10°C per minute. The weight loss and thermal decomposition rate of the samples are recorded with the increase in temperature. By monitoring the amount of cement hydration products, the effects of temperature on degree of cement hydration can be assessed.

The MIP test was performed on dried CPB samples (dried at a temperature of 45°C for 4 days) with Micromeritics AutoPore Ⅴ mercury porosimeter. With the intrusion pressure increase to 60,000 psi, the minimum pore size with 3 nm can be detected. The pore size distribution and porosity of CPB cured at different temperatures can be obtained from the MIP results.

2.3.2 Suction and volumetric water content monitoring

The evolution of matrix suction in CPB was monitored by using a dielectric water potential sensor, MPS-6, which has the capacity to measure the matrix suction range from -9 kPa to -100,000 kPa. Besides, it can also record temperature changes from -40°C to 60°C. The changes in the matrix suction are indicative of the progression of self-desiccation, while the changes in temperature reflect the degree of the cement hydration. Similarly, another sensor 5TE was placed at the interface to monitor the evolution of volumetric water content (VWC) with time. The specific measurement range and accuracy of 5TE sensor is given in Fang and Fall (2018). The monitoring results of VWC provide information on the amount of water drainage and consumed capillary water through cement hydration. Meanwhile, the 5TE sensor can record the changes in temperature in the CPB as well. The data collected by sensors MPS-6 and 5TE are both recorded by using the EM50 data logger.

2.3.3 Electrical conductivity monitoring

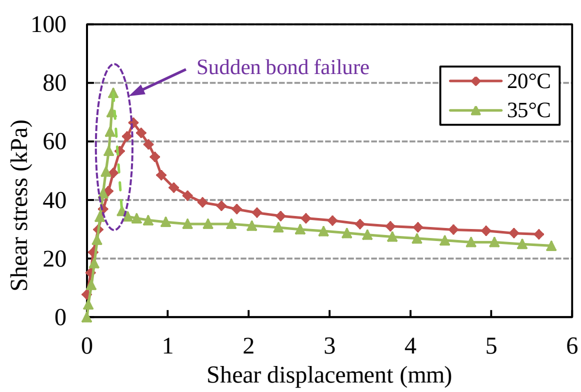
The 5TE sensor can record the evolution of electrical conductivity (EC) in CPB with time. The 5TE sensor has an EC measurement range from 0 dS/m to 23 dS/m, with an accuracy of ±10% from 0 to 7 dS/m. The EC result is closely related to the rate of ion movement, from which, the rate and degree of cement hydration can be easily assessed.

3 RESULTS AND DISCUSSION

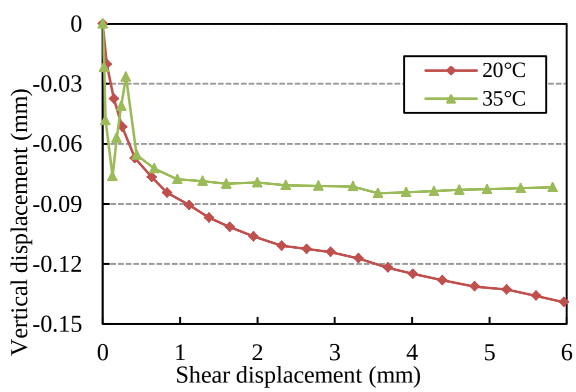
3.1 Effects of curing temperature on shear behaviour of CPB-rock interface

Figure 4 shows typical shear behaviour of the CPB-rock interface cured at two temperatures (20°C and 35°C) for 3 days (with a normal stress of 50 kPa). It can be observed from the figure that the temperature has a significant effect on the shear behaviour.

The shear displacement-shear stress curve presented in Figure 4(a) shows that regardless of the curing temperature, the shear stress curves depict similar trends, with an increase up to the shear strength, and then followed by a decrease to residual shear stress. However, for sample cured at 35°C, it experiences a sudden bond failure of the cohesive surface which was also observed on cemented shotcrete-rock joints (Saiang et al. 2005; Tian et al. 2015). In contrast, the sample cured at a temperature of 20°C shows a gradual softening behaviour. Besides, the shear stiffness of the samples cured at 35°C is found to be higher than that cured at 20°C. Moreover, it can also be seen that the highest curing temperature generally corresponds to the higher shear strength. The increased shear strength with temperature is mainly attributed to the combined effects of two factors: (i) temperature induced increase in the rate of cement hydration; and (ii) temperature induced increase in self-desiccation, which will be discussed in more detail below.



(a) Shear displacement-shear stress curve



(b) Shear displacement-normal displacement curve

Figure 4. Effect of curing temperature on the shear behavior of CPB-rock interface (cured for 3 days; normal stress=50 kPa)

The corresponding normal displacement-shear displacement curves of CPB-rock interface in Figure 4(b) show that regardless of the curing temperature, the interface of all CPB-rock samples shows obvious contraction at the beginning of the direct shear test. However, with increasing shear displacement up to the displacement that corresponds to that of the peak shear stress, the sample cured at higher temperature (35°C) shows dilating behaviour, while the sample cured at a lower temperature (20°C) continues to contract. For subsequent shear deformation beyond the deformation that corresponds to the shear strength, all of the samples show in general, contraction at the interface.

3.1.1 Temperature induced increase in rate of cement hydration

It is well know that higher curing temperature is beneficial to the increase in rate of cement hydration (Fall et al. 2010). The increased rate of cement hydration then leads to the formation of larger amounts of cement hydration products, such as ettringite, gypsum as well as calcium silicate hydrate (C-S-H) (Taylor 1964; Lothenbach et al. 2007). C-S-H is regarded as the major binding phase in hardened cement (Gani 1997; Fall and Pokharel 2013). As a result, the larger volume of C-S-H results in a stronger binding force between the CPB and rock as the curing temperature is increased, thereby increasing the shear strength of the interface. Besides, the larger amounts of cement hydration products will also form stronger interlocking structure at the interface, which contributes to the occurrence of shear dilation.

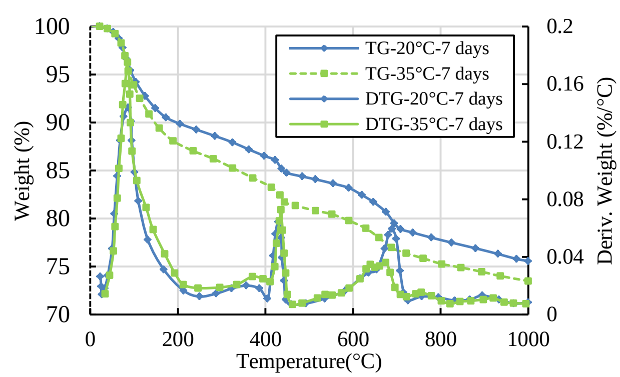


Figure 5. Plotted TG and DTG of cement paste of CPB-rock samples cured at 20°C and 35°C (cured for seven days)

The increasing amount of cement hydration products with temperature is confirmed by the results of thermal analysis on cement paste, as shown in Figure

5. It is well known that the peak or weight loss situated between 30°C-200°C is due to the dehydration of hydration products, such as ettringite, gypsum and C-S-H, while the weight loss at 400°C-450°C and 600°C-750°C is attributed to the decomposition of CH and calcite, respectively (Nonnet et al. 1999; Sha et al. 1999; Pane and Hansen 2005). A comparison of the TG and DTG of the cement paste cured at 20°C and 35°C indicates the weight loss due to the dehydration of cement hydration products of samples cured at 35°C is greater than the sample cured at 20°C. This means more cement hydration products are generated in samples cured at a temperature of 35°C. Besides, the higher shear stiffness of samples cured at 35°C (in comparison to samples cured at 20°C) is due to the temperature-induced increase in rate of cement hydration. This argument is supported by the results of EC test, which is shown in Figure 6. For samples cured at 35°C, it requires less time before the EC reaches the maximum value, which indicates the acceleration of the cement hydration process at higher temperatures. Indeed, the EC values peak after curing for 4.8 hours and 1.25 hours at a curing temperature of 20°C and 35°C, respectively.

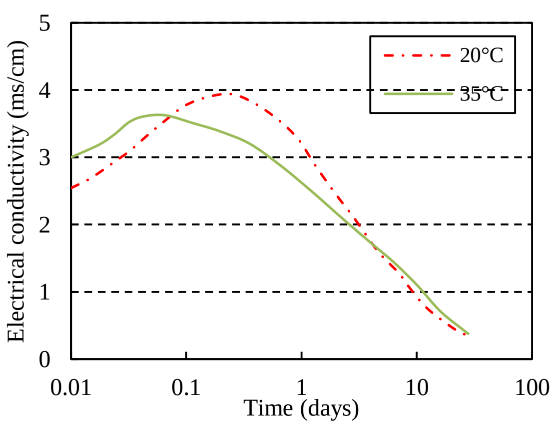


Figure 6. Changes in electrical conductivity of the samples cured at different temperatures

3.1.2 Temperature-induced increase of self-desiccation

The process of cement hydration consumes water, which decreases the pore water pressure and moisture content in CPB. This phenomenon, called self-desiccation, is significantly influenced by curing temperature (Wang et al. 2016). Given the effects of temperature on cement hydration, the self-desiccation can also be enhanced by the temperature. Consequently, the temperature induced self-desiccation then results in higher suction or capillary pressure at the interface. The increased suction contributes to the increase in shear strength. These arguments can be demonstrated by the evolution of VWC and suction in CPB, as shown in Figure 7. It can be clearly seen that the time-dependent changes in the matric suction and VWC of CPB vary with curing temperature. Higher curing temperatures lead to lower VWC values but higher matrix suction values. These are particularly obvious for early ages samples. In other words, a higher curing temperature results in more intense self-desiccation. For example, the measured VWC and recorded suction values for the 7 day samples is 0.41 and 0.39, and 250 and 284 kPa at curing temperatures of 20°C and 35°C, respectively.

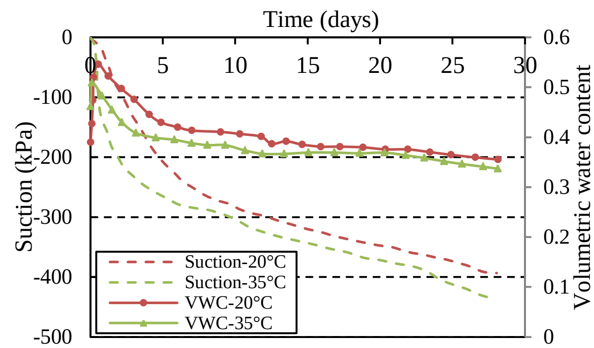


Figure 7. Effect of curing temperature on changes in volumetric water content and suction in CPB

3.2 Effect of curing temperature and curing time on shear strength and properties of CPB-rock interface

3.2.1 Combined effect of curing temperature and curing time on the shear strength evolution of CPB-rock interface

Figure 8 shows the effects of curing temperature and time on the shear strength of the CPB-rock interface. It can be seen from the figure that the shear strength at the CPB-rock interface increases with curing time, regardless of the curing temperature. The increase in the shear strength with curing time is attributed to the increased cement hydration. This argument is supported by the results of thermal analysis on samples cured for 7 days and 28 days shown in Figure 9, in which the weight losses at temperatures of 30°C-200°C and 400°C-450°C for the 28 day samples are higher than those that are only cured for 7 days. This means that more ettringite, C-S-H and CH are generated in the former. The C-S-H can increase the binding force between particles, while the precipitation of more hydration products (e.g. ettringite, CH) results in the refinement of the pore structure within the CPB, and thus increase the shear strength of the CPB-rock interface as explained previously.

Moreover, in addition to the curing time, the shear strength of the CPB-rock interface is also significantly affected by the curing temperature as presented in Figure 8. In general, higher curing temperature leads to higher shear strength at the interface (except for samples cured at 35°C for 28 days; this will be discussed later). The higher shear strength of the interface observed for samples cured at higher temperatures is due to the temperature-induced acceleration of cement hydration and self-desiccation. This has been already demonstrated and discussed previously. In addition to the temperature-induced self-desiccation, the refinement of the pore structure of CPB due to the precipitation of more hydration products also contribute to the increase in shear strength. This argument is supported by the results of MIP test on CPB cured at temperature of 20°C and 35°C for 7 days, which is shown in Figure 10. In comparison the CPB sample cured at 20°C, the sample cured at 35°C has a finer pore structure. The finer pore structure is indicative of the precipitation of more hydration products in the capillary pores of CPB as the higher temperature significantly reduces the coarseness of the pore structure, thereby increasing the contact area between the CPB and the rock surface, which in turn increases the shear strength of the CPB-rock interface.

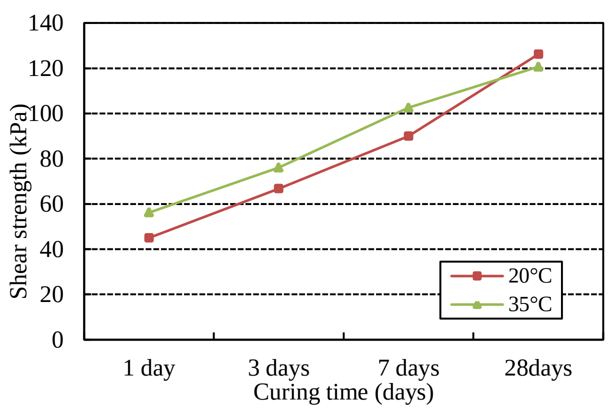


Figure 8. Development of shear strength of CPB-rock interface (normal stress: 50 kPa)

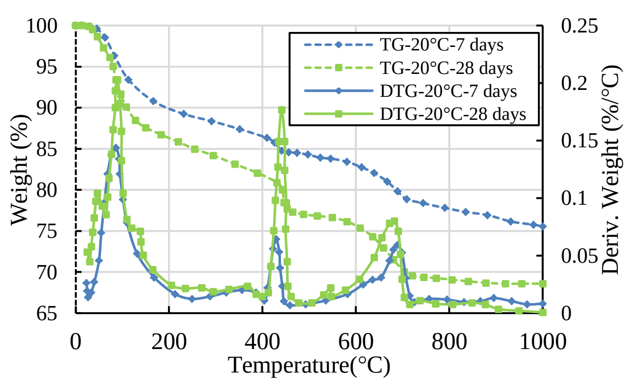


Figure 9. TG/DTG analyses on cement paste of CPB-rock samples cured for 7 and 28 days (20°C)

However, the lower shear strength of the interface of the CPB-rock sample cured at 35°C for 28 days (in comparison to that cured at 20°C) is because of the crossover effect, which mainly takes place in cementitious materials cured at high temperatures at the advanced ages (Kjellsen et al. 1991; Escalante-Garcia and Sharp 2001). The occurrence of the crossover effect is commonly a result of: (i) formation of microcracks. The increased temperature accelerates the cement hydration and as a result, large amounts of cement hydration products are generated. This then leads to the physical damage inside the CPB, thereby decreasing the increasing rate in shear strength; (ii) non-uniform distribution of cement hydration products. The cement hydration products are characterized by low solubility and diffusivity, and because of this, they cannot diffuse to a significant distance. Meanwhile, the dense hydration products can also serve as diffusion barriers, which further prevent the hydration products from migrating. Thus, a higher curing temperature results in a coarse pore structure at the advanced ages.

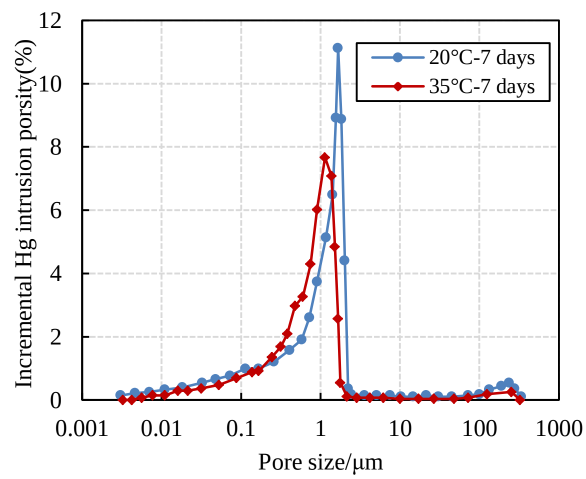


Figure 9. MIP pore size distribution of CPB

3.2.2 Combined effects of curing temperature and curing time on evolution of adhesion and friction angle of CPB-rock interface

Figure 10 shows the evolution of the adhesion and friction angle of the CPB-rock interface cured at temperatures of 20°C and 35°C with time.

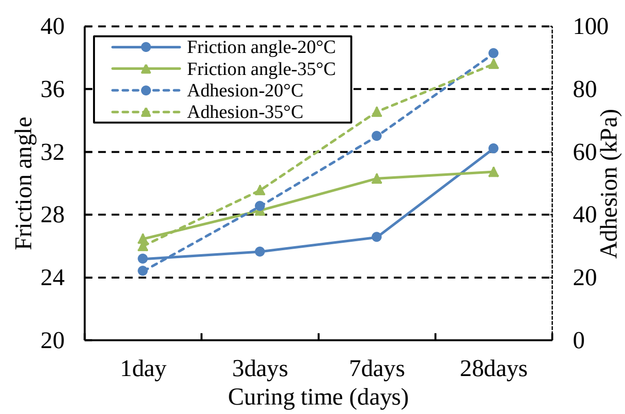


Figure 10. Evolution of adhesion and friction angle of CPB-rock interface

It can be seen that the time-dependent change of the friction angle and adhesion of the interface is significantly affected by the curing temperature. For example, the friction angle of the interface of the samples cured at 20°C and 35°C increases from 25.2° and 26.5° on the first day of curing to 32.2° and 30.7° on the twenty-eighth day of curing, respectively. In contrast, the adhesion of the corresponding interface rises from 22 kPa and 30 KPa on the first day to 91.3 kPa and 88 kPa on the twenty-eighth day of curing sharply. The higher values of friction angle and adhesion of interface samples with time are attributed to the increased degree of cement hydration with time and temperature.

4 CONCLUSION

This experimental study presents the combined effects of curing temperature and time on the shear performance of CPB-rock interface. The main results are summarized below:

Higher curing temperature can speed up the cement hydration and self-desiccation. Therefore, the shear strength and shear properties of the CPB-rock interface are significantly increased with curing temperature and time. However, the compressibility of the CPB is reduced with curing temperature and time.

The interface samples cured at temperature of 35°C for a long time (28 days in this study) has less adhesion and smaller friction angle in comparison to samples cured at 20°C. These decreased increasing rates in friction angle and adhesion are due to the crossover effects.

The results shown in this study is beneficial to the understanding of the effects of temperature on the shear behaviour of CPB-rock interface. This is critical for the design and assessment of CPB structures.

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