Experimental Studies on the Stability of Reinforced Cemented Paste Backfill

by

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DECLARATION FOR THESIS CONTAINING PUBLISHED WORK AND/OR WORK PREPARED FOR PUBLICATION

In accordance with regulations of the University of Western Australia, this thesis is organised as a series of papers. This thesis contains published work and/or work prepared for publication, which has been co-authored. The bibliographical details of the work and where it appears in the thesis are outlined below.

Paper 1
This paper is presented as Chapter 2, first-authored by the candidate, co-authored by Professor Guowei Ma and Professor Andy Fourie, and published as


The estimated percentage contribution of the candidate is 70%.

The candidate has planned and performed this experimental programme, and has drafted the paper for publication. Professor Guowei Ma and Professor Andy Fourie have checked the experimental results and reviewed the original draft.

Paper 2
This paper is presented in Chapter 3, first-authored by the candidate, co-authored by Mr. Zhijian Li, Professor Andy Fourie and Professor Guowei Ma, and submitted as


The estimated percentage contribution of the candidate is 60%.

The candidate has developed this experimental program to identify the ideal type of polypropylene fibre used for improving the stability of CPB filled mine stopes. Mr. Zhijian Li has assisted the conduct of laboratory tests. The interpretation of results and the paper
drafting have been completed by the candidate in collaboration with Professor Andy Fourie and Professor Guowei Ma.

**Paper 3**

This paper is presented in Chapter 4, first-authored by the candidate, co-authored by Mr. Zhijian Li, Professor Andy Fourie and Professor Guowei Ma, and submitted as


The estimated percentage contribution of the candidate is 50%.

The candidate has planned this experimental programme. Mr. Zhijian Li has carried out the laboratory tests and reported the testing results. The final draft has been completed by the candidate and corrected by Professor Guowei Ma and Professor Andy Fourie.

**Paper 4**

This paper is presented in Chapter 5, first-authored by the candidate, co-authored by Professor Andy Fourie and Professor Guowei Ma, and submitted as


The estimated percentage contribution of the candidate is 70%.

Under the supervision of Professor Guowei Ma and Professor Andy Fourie, the candidate has planned and conducted this experimental programme, and also has processed the testing data and drafted the paper. All the work has been reviewed and corrected by Professor Guowei Ma and Professor Andy Fourie.

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Abstract

Cemented paste backfill (CPB) is increasingly important in underground mines over the past few decades. However, until now, limited research has been accomplished in reinforcing CPB and studying its behaviour from yield to complete failure. This thesis presents experimental investigations on the mechanical behaviour of fibre-reinforced CPB. Mine tailings from a nickel mine in Western Australian and a copper mine in China were adopted for the specimen preparation. Different types of polypropylene fibres with diverse length, thickness and structure were used in the study. Initially, a series of unconfined compressive strength (UCS) tests were carried out on both unreinforced and fibre-reinforced specimens (Chapter 2 and Chapter 3). The effects of fibre reinforcement on the UCS, failure mode, average residual strength and energy absorption capacity were compared and discussed. The stress-strain curves showed that the inclusion of fibres increased both strength and ductility, but significantly reduced the post peak strength loss of CPB. The failure mode of fibre-reinforced specimens exhibited ductile behaviour with few dislodged fragments and retaining integrity. Sliced images acquired from X-ray computed tomography (CT-scan) explained the ductile behaviour as the restraint to crack propagation and extension by the mobilised fibre tensile strength (Chapter 2). The ideal types of polypropylene fibres for the reinforcement of CPB were identified from the testing results (Chapter 3). Subsequently, triaxial shear tests were performed at the confining pressure of 100, 200, 300, 400 kPa to explore the effects of cement and fibre contents on the shear strengths of CPB (Chapter 4). The results demonstrated that the increase of cement content enhanced the shear strength while the inclusion of fibres
increased the deformability index of CPB, and the impact of fibres was more significant to the CPB with lower cement content. In Chapter 5, the stability of CPB models with vertically exposed faces was investigated by a series of centrifuge tests. The partial or whole body of CPB models were reinforced with a specific type of polypropylene fibres. The modelling data showed that the prototype height of fibre-reinforced CPB was much higher than that of unreinforced CPB depending on the variety of reinforcing rates. The conclusion (Chapter 6) suggested that both strength and ductility ought to be considered in CPB design to optimise the economy and safety of mining with backfill. The application of fibre reinforcement would potentially improve the self-supporting capacity of the fill mass using less cement, and reduce backfill dilution when excavating to adjacent stopes.
I would like to express my deep and sincere gratitude to my supervisors, Professor Guowei Ma and Professor Andy Fourie, who supported and guided me persistently during my PhD. Professor Ma has always been there for the regular meeting every week to discuss the recent progress of my research and to give inspired feedback. Especially, great thanks to Professor Ma for generously financial support in attending international conferences and conducting laboratory experiments. Professor Fourie has always given me excellent suggestions about testing results and made significant contributions to all my published work. There is no exaggeration to say that what I have learnt from them will benefit me greatly in the rest of my life.

Many thanks must go to all my colleagues in the School of Civil, Environmental and Mining Engineering, especially to Xiaofan Lou, Feifei Tong, Yang Wang, Xiaojun Li, Jinglong Gao, Diego Gomez, Colm O’Beirne, Simon Leckie and Feng Ren for their understanding and encouragement.

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Chapter 1

Introduction

1.1 Background

During the underground mining process, numerous voids (stopes) are usually generated due to the ore extraction. These multiple opening stopes are typically 30 to 80 m high and 20 m x 20 m in plane dimension, which often induce ground surface subsidence (Guo et al., 2011; Kashnikov et al., 2012) or mine collapse (Dreger et al., 2008) unless backfill is used to support the previously excavated stopes. Besides, massive ore pillars that are left for supporting mining regions would definitely cause enormous loss of mineral resources. After mineral processing, waste tailings are commonly stored on surface as a seemingly straightforward and cheap method of waste disposal and management. However, it turns out not only wasting available land but also causing environmental and health issues (Bentel, 2011; Kossoff et al., 2014). For these reasons, the tailings-based mine backfill is adopted as an effective mining and waste disposal method by transporting a large amount of tailings back into the underground mined stopes. The fill mass is usually used as either temporary or permanent pillars, which providing additional structural support for continuous excavations and minimising the loss of minerals.

Hydraulic backfill is one of the most commonly used methods in mining industry, which contains classified tailings and large amount of water. Before placement of backfill, the structural barricades are built at the base of stopes and the drainage systems are placed on
the barricades to remove the excess water for collection and re-use, as well as minimising risks to underground workers. In many cases, to achieve 100% ore extraction, the filled stope usually exposes one or two faces during the mining of adjacent stopes (Helinski et al., 2007; Festugato et al., 2013). Thus, cement is usually used as an important component for the filled mass to obtain self-supporting ability and to maintain sufficient strength to ensure the stability of working areas (Sivakugan et al., 2006). The drawbacks of using hydraulic backfill include the large number of barricade failure incidents (Grice, 1998; Torlach, 2000) as well as the difficulties of managing large volumes of water. Therefore, there has been a gradual trend to increased utilisation of cemented paste backfill (CPB) over the past decades (Fall and Samb, 2007; Helinski et al., 2011), especially in Australia and Canada (Potvin et al., 2005).

CPB was first developed in the early 1980s at Bad Grund Mine, Germany (Dave, 2001). The typical CPB is comprised of full stream tailings, with water and a small amount of cement. It generally contains 70% to 85% solids by weight of total solids, and it characterises high-density and non-segregating when flowing through the pipeline comparing with conventional hydraulic fill (Klein and Simon, 2006). The general dosage of cement in CPB is 1% to 10% by dry mass of tailings, which represents around 15% costs of the mining operation (Belem and Benzaazoua, 2004). Obviously, the filled stope is weak with the small proportion of cement and normally has falling CPB fragments when excavating adjacent stopes owing to the brittleness of filling materials. Increasing cement usage can improve the strength of backfill, but it also increases the cost of materials and transportation for filling massive volumes of stopes (Fall et al., 2008). Desire has rarely been ambitious for tougher and more ductile CPB ever. Mitchell and Stone (1987) first investigated the effect of reinforcement on cemented backfill for reducing cement usage while still achieving a certain safety factor. Their study showed that the application of
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Introduction  

Shotcrete wire fibre and anchored fibre has reached the goal for reinforcement but not been practical and economical in late 1980s.

At present, fibre reinforcement has been widely applied in civil and geotechnical engineering. New types of fibres, such as polypropylene fibres have been developed for fibre-reinforced concrete, soils, clays and gravels. Many laboratory tests reported that the inclusion of fibres helps rectify the weakness of ordinary concrete by mobilising tensile strength along the failure planes (Ramesh et al., 2003), and provided a crack-arresting ability and enhanced the strength (compressive strength, flexural strength, tensile strength and impact strength), toughness and ductility (Balaguru and Shah, 1992; Mansur et al., 1997). In particular, polypropylene fibres have advantages of resistance to corrosion and easier dispersion within a concrete mix than steel fibres (Machine et al., 2008). Similar results from studies of fibre-reinforced sand and fibre-reinforced cemented soil have been also reported. The inclusion of randomly mixed fibres significantly increased the ultimate strength and stiffness of sands and soils, and increased the shear strength without specimens exhibiting distinct failure planes (Maher and Gray, 1990; Consoli et al., 2007; 2011; Rattley et al., 2008).

However, it is uncertain that fibres would have guaranteed effects of reinforcement on CPB since CPB has different properties from concrete and cemented sand, in terms of having finer particles and wider particle size distributions, much lower cement content and various chemical components from the tailings and process water. Therefore, this study has adopted multiple experimental methods including unconfined compression strength (UCS), X-ray computed tomography (CT-scan), triaxial and centrifuge tests. Figure 1-1 shows CPB method and cemented paste example. Figure 1-2 gives the test equipment used in the present study to investigate the mechanical behaviour of fibre-reinforced CPB.
1.2 Research objectives

This study was undertaken with the aims of:

- Investigating the effect of fibre reinforcement and aging effect on the compressive behaviour and crack formation mechanism of CPB.

- Evaluating the influence of fibre properties on the compressive behaviour of CPB and identifying the optimised candidate of polypropylene fibres for CPB reinforcement.

- Proposing a new concept of ductile backfill and verifying this concept by conducting unconfined, confined compression and centrifuge tests of reinforced CPB specimens. And identifying the optimised formula of fibre-reinforced CPB.

- Discussing the feasibility of ductile backfill in practical application.

1.3 Outline

This thesis comprises six chapters. The five chapters following this introductory chapter are arranged as follows:

Chapter 2 explores the effects of polypropylene fibres on the compressive behaviour of CPB through a series of UCS tests and CT-scans. The unconfined compressive response and ductility, curing time effect and failure pattern of unreinforced and fibre-reinforced CPB are compared and discussed.

Chapter 3 continues to study the effect of fibre reinforcement on the compressive behaviour of CPB reinforced with different fibres, and to identify the optimised fibre types for the application of reinforcement on CPB.
Chapter 4 conducts the triaxial tests to investigate the influence of different cement and fibre contents on the triaxial compression strength of CPB. The discussion of peak and residual strength, average energy absorption capacity and ductility are included. The optimised formula of fibre-reinforced CPB is concluded in this chapter.

Chapter 5 performs the centrifuge model study of fibre-reinforced CPB. Eight centrifuge models are designed with different reinforcing rates and the testing results are compared with those obtained from UCS test. The vertical displacement, failure modes and failure mass ratio are presented and discussed.

Chapter 6 summarises the main findings of this research, along with suggestions for future studies.

1.4 References


Chapter 1


Chapter 1


Figure 1-1. Mine fill: (a) Backfilled stope; (b) Cemented paste
Figure 1-2. Laboratory test instruments: (a) UCS test; (b) X-ray computed tomography; (c) Triaxial compressive test; (d) Centrifuge test
Chapter 2

Compressive Behaviour of Fibre-Reinforced Cemented Paste Backfill

By: Xiawei Yi, Guowei Ma and Andy Fourie

Abstract: Reinforcement of cemented paste backfill (CPB) with polypropylene fibres was investigated as a way of improving the stability of backfilled underground mine stopes. A series of unconfined compressive strength (UCS) tests were carried out on both non-reinforced and fibre-reinforced cemented tailings. Sandy silt tailings from a nickel mine in Western Australia were used in the study. Ordinary Portland cement at concentrations of 3% to 5% by weight of tailings and 0 to 0.5% Adfil-Ignis polypropylene fibres by weight of total solids were used for specimen preparation. The stress-strain curves from the UCS tests showed the inclusion of fibres increased the UCS and significantly reduced the post-peak strength loss. Accordingly, the fibre-reinforced specimens were found to be much more ductile than unreinforced specimens, which is highly desirable in many backfill applications. Sliced images acquired from X-ray computed tomography (CT-scan) demonstrated that the observed ductile behaviour of reinforced specimens could explain by the restraint to crack growth provided by the mobilised fibre tensile strength. At large strains, fibre-reinforced specimens had virtually zero dislodged fragments and retained their integrity as shown in both experimental photos and CT sliced images. This was different from unreinforced specimens, which developed large, wide cracks that resulted in fracturing of the tested specimens. The potential for improving the self-supporting capacity...
Chapter 2

Compressive behaviour of fibre-reinforced cemented paste backfill of the fill mass using fibre reinforcing but less cement is discussed and potential advantages, such as reduced ore dilution when excavating adjacent stopes discussed.

**Keywords:** Geosynthetics; Reinforced cemented paste backfill; Unconfined compressive strength; Polypropylene fibres; X-ray tomography.

2.1 Introduction

Mill tailings are the main waste stream from mineral processing. Rather than storing this waste material on surface, where it presents environmental and safety risks, there is increasing interest in using mill tailings for backfilling of underground voids, thus providing additional structural support to future excavations and minimising the loss of ore due to dilution. Unfortunately, mill tailings often contain fine particles that can impede drainage rates, leading to the initial preference in the mining industry for use of coarser hydraulic backfill. Paste backfill was first developed in the early 1980s at Bad Grund Mine, Germany (Dave, 2001; Yilmaz et al., 2004). Cemented paste backfill (CPB) is generally comprised of full stream tailings, with water and a small amount of cement (of the order of 5% by dry mass). The mass concentration of CPB ranges from 75% to 85% solids by weight of total solids and it does not segregate when flowing to stopes. Considering the advantages of CPB, such as reduced risk of barricade failure and stable flow through delivery pipes, paste backfill has been increasingly accepted as a preferred mine fill method.

During the mining process, the fill mass is usually used as either temporary or permanent pillars to support the mined regions or as self-supporting structures to prevent the exposure of unstable excavated stopes (Yumlu, 2001). Throughout the period of mining adjacent stopes, the mine backfill should maintain sufficient strength to ensure the stability of the working area (Sivakugan et al., 2006). However, at least twelve barricade failures were reported between 2003 and 2006, many of them being due to filling rates that were
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Compressive behaviour of fibre-reinforced cemented paste backfill

too fast (Helinski et al., 2011). Obviously a filled stope with a small proportion of binder is weak and failure may be induced by impact stresses from the country rock (Aubertin et al., 2003), as it is common to have falling backfill fragments when excavating adjacent stopes, owing to the brittleness of filling materials. This would increase the ore dilution, where previously-placed backfilled material is entrained with the ore extracted from the new stope and loss of mineral products occurs (Dirige and De Souza, 2008).

Fibre-reinforced concrete (FRC) is increasingly popular in civil engineering, being used to increase the tensile and flexural strength of structures in the last few decades. In ordinary concrete, the internal micro-cracks contribute to the failure of structures and associated poor ductility. Inclusion of fibres helps rectify the weakness of materials by mobilizing tensile strength along the failure planes (Ramesh et al., 2003). Many laboratory tests reported that randomly mixed fibres such as metal, glass, synthetic and carbon, in plain concrete provided a crack-arresting ability and enhanced the strength, toughness, ductility and post-cracking resistance (Balaguru and Shah, 1992; Chen and Carson, 1971; Fanella and Naaman, 1985; Mansur et al., 1997).

In addition, studies on fibre-reinforced sand and fibre-reinforced cemented soil have also been reported. Maher and Gray (1990) carried out triaxial compression tests to observe the behaviour of sands reinforced with randomly distributed fibres. The inclusion of fibres significantly increased the ultimate strength and stiffness of the sands tested. Similar results from triaxial compression tests of geosynthetic-reinforced sand were reported by Latha and Murthy (2007). Consoli et al. (2003, 2007b) conducted plate load tests and ring shear tests on polypropylene fibre-reinforced sandy soil, and at large strains, the stress-strain behaviour had distinct differences from that of non-reinforced soil. Other investigators (e.g. Consoli et al., 2007a, 2009, 2010b, 2011a; Tang et al., 2007; Dalla Rosa et al., 2008; Rattley et al., 2008) presented the mechanical behaviour of cemented soils reinforced with
different fibres. All these studies indicated that randomly mixed fibres within the soil mass provided an increase of shear strength without specimens exhibiting distinct failure planes.

In mining engineering, Mitchell and Stone (1987) first proposed the method of fibre reinforcement for the design of mine backfills in order to reduce the overall cement usage. Their laboratory investigation compared the stabilities of layered fills and bulk fills reinforced with metal shotcrete fibres and anchored fibres. For the same safety factor, the fibre-reinforced tailings demonstrated a remarkable reduction in cement usage, providing potentially significant cost savings for backfilling operations. As a solution for tailings disposal, Zou and Sahito (2004) studied the use of fibre-reinforced tailings for shotcrete to support underground openings and strengthen pillars. The flexural strength was found to be increased by 59% with polymer fibres and by 25% with the same mass of steel fibres. Based on previous research of fibre reinforcement, Festugato et al. (2013) conceived the potential strength improvement of fibre-reinforced CPB and studied the shear response of fibre-reinforced CPB under cyclic simple shear tests. The fibre inclusions were found to provide resisting forces and increase the load-carrying capability of the CPB. However, CPB has different properties from concrete and cemented sand, in terms of having finer particles and wider particle size distributions, much lower cement content and various chemical components from the tailings and process water that may affect strength. The mechanical behaviour of fibre-reinforced CPB has rarely been studied before (Festugato et al., 2013). Therefore, the purpose of the laboratory tests in this paper is to primarily explore the effects of polypropylene fibres on the compressive strength of CPB through a series of unconfined compression tests. The X-ray tomography technique was used to examine the internal deformation behaviour of non-reinforced and fibre-reinforced CPB and explain the observed stress-strain response.
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Compressive behaviour of fibre-reinforced cemented paste backfill

2.2 Experimental program

2.2.1 Materials

The tailings adopted in this study were from a nickel mine located 42 kilometres south of Kambalda, Western Australia. The particle size distribution of the tailings is shown in Figure 2-1. It is classified as sandy silt with a specific gravity of 2.81 and a liquid limit of 26%. The chemical composition of the material is listed in Table 2-1.

Monofilament polypropylene fibres termed Adfil-Ignis (Figure 2-2) were used to reinforce the CPB. The selection of Adfil-Ignis fibres was mainly based on the experience from previous research (e.g. Festugato et al., 2013) as well as considerations of economy and availability. The Adfil-Ignis fibres were 6 mm long and 18 micrometres in diameter, with a tensile strength of 600 MPa and specific gravity of 0.91. The fibre supplier reported the Adfil-Ignis product has excellent acid and alkali resistance capabilities and has a non-absorbent character. Furthermore, the mining process requires exposure of cemented backfilled stopes as soon as possible after placement of the backfill, to expedite ore extraction. As shown later in the paper, even after 28 days there was no indication of a decrease in strength. Thus although the question of fibre durability in the presence of mine process water is an important one, it was not considered a major factor in the present study. If fibre-reinforced CPB were to be used in an application where long-term strengths were a consideration, or other fibres were to be used, additional studies of fibre durability would certainly be warranted. The effects of fibre content on reinforced cemented soils have been studied previously and the results showed a fibre percentage between 0.25% and 0.75% (by dry mass) resulted in a significant increase in compressive strength (Consoli et al., 2011b, 2012; Zaimoglu and Yetimoglu, 2012). The fibre contents chosen in this study were 0.3% and 0.5% by mass of the sum of dry tailings and cement.
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The binder used was ordinary Portland cement. The most common cement dosage ranges between 1% and 10% in Australian sites (Potvin et al., 2005). Both non-reinforced and reinforced specimens with 3% and 5% cement content by dry mass of tailings were tested to compare the contributions of cement and fibres to the compressive strength and ductility of reinforced CPB.

The water from the mine site was utilised in the laboratory to prepare testing specimens (details of the process water quality are provided in Table 2-2). The salt content of the process water was much higher than that of domestic tap water. Some laboratory studies have demonstrated the influence of salt on the backfill strengths during the curing process (Wang and Villaescusa, 2000; Li et al., 2003). Nevertheless, it was essential to reproduce the site conditions as accurately as possible, hence the use of process water. Specimens were prepared at a solid content (by total mass) of 75%, which is representative of the value used at the site in question.

2.2.2 Testing procedures

All materials for the specimen preparation were weighed by electronic scale with an accuracy of 0.01 g. Tailings, cement and water with different proportions were mixed in laboratory blenders for about 10 minutes. Fibres were added after the beginning of mixing to avoid the floating of fibres (Consoli et al., 2010a). All mixtures had similar slump values of around 218 mm. Disposable plastic moulds 50 mm in diameter and 100 mm high were used to cast the specimens. The prepared specimens were sealed and cured in a constant humidity chamber at 23 ± 2 °C and a relative humidity of 80% for 7 days, 14 days and 28 days. After curing, the weight, diameter and height of specimens were measured with accuracies of 0.01 g and 0.1 mm and then specimens were transferred to the equipment to start the unconfined compression test.
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The testing conditions used in this study were based on the accumulated experience of unconfined compression tests for concrete and cemented soils (Lim and Nawy, 2005; Hsie et al., 2008; Nili and Afroughsabet, 2012; Consoli et al., 2007a; Park, 2008). Equipment with a maximum capacity of 12 kN was used for carrying out the UCS tests. After curing, the cylindrical specimen was placed between two plastic plates in the loading frame and the loading platen engaged. Specimens were loaded under constant displacement conditions, using a displacement rate of 0.1 mm/min. Readings were recorded every two seconds. Axial loading was ceased when the specimen developed an obvious shearing plane and peak strength had been mobilised. Tests were carried out in triplicate, and were required to meet the criteria that with a maximum 10% error from the mean strength. Reported results are the average of the three replicates. The testing programme comprised of 12 groups of unconfined compression tests on 36 specimens with different curing times and different proportions of cement and fibres.

The original invention of X-ray computed tomography occurred in the field of medical science. Raynaud et al. (1989) investigated the inner structure of rocks using a medical CT, and the sliced images clearly revealed the internal pores, fractures and cracks. The internal structure of concrete and soils were also studied by using X-ray CT (Buyukozturk, 1998; Grevers et al., 1989) and a loading device was assembled to research the mechanical behaviour of rocks (Cnudde et al., 2006).

The tests in this study adopted an industrial CT real-time imaging system, with high resolution. It was designed by American Bio-imaging Research Inc. and China University of Mining and Technology Beijing. The X-ray source, detector and image analysis system constitute the main components of the instrument. The cylinder specimen with height of 50 mm and diameter of 25 mm was placed between the X-ray source and the detector. X-rays penetrated a certain section of the specimen which was rotated regularly until finishing
the entire specimen scan. The intensity of X-rays were captured and measured by the detector after passing through the specimen and the information was transferred to the computer system for analysing and rebuilding sliced images. It took around 50 seconds to complete each scan and generate a 16-bit gray image with $1024 \times 1024 \times 1440$ pixel views. The scanning resolution of the sliced image was approximately $10 \, \mu m$. Peng et al. (2011) found that reducing the size of the rock specimen helped increase the resolution of the scanned image. The CT number of each material cell was transformed to a pixel value using purpose developed software. The darker parts of each image represented a zone of lower density. Thus planes of failure can be distinguished from intact material, with the latter being lighter in colour.

2.3 Results and discussion

2.3.1 Unconfined compressive response and ductility

Figures 2-3 to 2-5 show the axial stress-strain behaviour of unreinforced and fibre-reinforced CPB specimens. All results showed that fibre reinforcement increased the peak compressive strength of CPB and transformed the brittle behaviour to more ductile behaviour. The unconfined compression strength (UCS) of specimens prepared with 5\% cement rose faster than 3\%-cement specimens during the elastic stage, while all curves of reinforced specimens reached a higher peak strength than non-reinforced specimens. Cement produced the initial stiff load response; after only about 1\% to 2\% strain, the cemented component of strength was fully mobilized and the response to loading increasingly transferred to the frictional component of strength. A useful discussion of the relative contribution of cemented (cohesive) and frictional strength is provided by Wang and Leung (2008) and is consistent with the above discussion. After mobilisation of the cement strength component, the unreinforced specimens exhibit very brittle behaviour, whereas reinforced specimens were much more ductile. Curves of 0.5\%-fibre-reinforced specimens did not show a peak strength, unlike the typical shape of non-reinforced
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Compressive behaviour of fibre-reinforced cemented paste backfill specimens (at least up to the maximum strain achieved, which was about 25%) and achieved significantly higher peak strengths. All tests on reinforced specimens exhibited strain-hardening behaviour with increasing strength as the strain increased. An exception was the 28 day specimens’ response, where, after large axial strains of between 12% and 20%, a slight decrease in load carrying capacity became evident. The phenomenon of enhanced ductility is attributed to the supplementary contribution of the tensile strength of fibres at higher strain values. As a comparison, the strength development of non-reinforced specimens was due to the cement hydration, which produced a bonding effect. With small cement usage, the bonds between particles were easier to break and the peak strength of non-reinforced curves approached 305 kPa as the highest record in Figure 2-5. The dramatic post peak drop in unconfined compression strength clearly showed the brittle behaviour of non-reinforced specimens, for which the failure strain was less than 7%, i.e. nearly three times less than that of 0.5%-fibre-reinforced specimens in Figure 2-5. Likewise, observed reductions in the UCS and strain values at peak strength of the 0.3% fibre-reinforced specimens were related to the decreased fibre content. Although the peak strength was lower than that of 0.5% fibre-reinforced specimens, there was still about 5% increase of failure strain compared with that of non-reinforced specimens and the peak strength was higher. On the other hand, the decrease in cement content to 3% resulted in a reduction in UCS of less than 30%, and retained the ductile post-peak response. This confirmed that both cement and fibre contribute to the development of UCS but the fibre content dominates the post peak behaviour. It is also worth noting that reinforced specimens with only 3% cement performed better than unreinforced 5% cement specimens, in terms of both peak strength and post-peak ductility. Thus if the costs of fibre reinforcing are economically viable, there are clear benefits in replacing some cement with fibres.
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Unreinforced specimens showed distinct splitting after the peak strength reached. However, fibre reinforcement enabled these split blocks to continue to act in union, providing further resistance to compressive load, even after first yield occurred. This allowed the development of additional deformation without further strength loss. In other words, the fibre addition resulted in a significant increase in the ductility of CPBs due to the mobilisation of resisting forces by fibres crossing developing failure planes. The potential benefits in a backfilling application are that significant movements of an exposed backfilled stope would be clearly apparent well before ultimate strengths were mobilized. Contrast this with the unreinforced backfill, where little or no warning of impending failure would occur due to the brittle behaviour of this material.

2.3.2 Effect of the curing period

Figure 2-6 shows the stress-strain relationship of non-reinforced specimens after 7, 14 and 28 days curing time. The peak strength increases from 130 kPa at 7 days to 310 kPa for the 28-day cured specimens. On the other hand, the strain values at peak strength drop from 7% to 4.2% as curing occurs, i.e. specimens become more brittle with curing. The strength generated by cement bonding is limited, with the amount of cement used being relatively small (compared with concrete). Increasing brittleness with time is particularly undesirable in the underground backfilling application, where vertical exposures, sometimes up to 80m high, occur during mining of subsequent stopes, with these exposures occurring 14 days or more after the CPB was initially poured.

Fibre inclusion enhances particle-particle (and particle-fibre) interaction, with the fibres interlocking with the cemented structure as the tensile strength of fibres is mobilised. However, the fibre-reinforced specimens are also affected by curing time, as shown in Figure 2-7. The early age fibre-reinforced specimens show excellent strength mobilization, with a monotonic stress increase until reaching high strain levels. Although the strength is
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Compressive behaviour of fibre-reinforced cemented paste backfill

Conspicuously improved, the reinforcement performance is less evident for the 28-day cured specimens with a slight drop after the peak strength of 550 kPa at a strain value of 19%. The specimens have once again shown more brittleness with time, although to a much lesser extent than shown by the unreinforced specimens.

The resistance to load of an unreinforced specimen has two components, the cohesive strength (provided by cement bonding) and the frictional component. As discussed by Wang and Leung (2008), these strengths are mobilized at different strains during loading, with cohesive bonds being broken before sufficient displacements occur to mobilise frictional strength. For reinforced specimens the interactions are even more complex, with the contributions from the reinforcing only being mobilised once relative movement between particles becomes large enough to for fractures within the cemented specimen begin to develop. The relative contribution of these components is evident from Figure 2-7. The cemented bonds provide the initial resistance, with the frictional and fibre contributions being mobilized as the axial stress increases.

2.3.3 Pattern of failure

Figure 2-8 shows the different failure patterns of cured specimens. Differences between the unreinforced and reinforced specimens are clearly evident. Unreinforced specimens fail with the development of only one or two major cracks, so shear stresses can be assumed to concentrate along these cracks. The relatively low strains at failure are also evident by comparing the samples in Figure 2-8 (a) with those in b-d. The reinforced specimens show more of a ‘barreling’ failure mode and clearly undergo much more displacement (and thus strain) than the unreinforced specimens. Also, rather than just one or two major cracks, a multitude of smaller and finer cracks are evident for the reinforced specimens, confirming that the reinforcing effect is probably best mobilised when a crack develops and localised strain occurs. The fibres tend to bridge these cracks, mobilising tensile fibre strength,
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which prevents the crack propagating, thus preventing premature failure. In 7-day old reinforced specimens the width of propagating cracks is about 0.5 to 1 mm and the length is shorter than 20 mm generally. At this early age, cement hydration is still occurring at a high rate and the water content is at its highest level, which results in more ductile failure modes even for the non-reinforced specimen. In comparison, 14-day and 28-day cured specimens present more brittle response, showing clear splits and formation of blocks, particularly with the unreinforced specimens. In the reinforced specimens, the fibres are interlocked with individual blocks, providing internal tensile strength to prevent blocks from segregating and thus delaying the failure of specimens.

Figures 2-9 and 2-10 contrast the scanned slices of failed specimens cured for different periods. After 28 days, there is much more cracking apparent in both unreinforced and reinforced specimens. The unreinforced specimen cured for 7 days has one obvious, major crack propagating from the top to the bottom of the specimen, whereas the 28-day unreinforced specimen generates circumferential cracks and these cracks extend radially from cores to rings. The reinforced specimens restricted the development of cracks by the bridging effects of fibres, and the failures happen via development of irregular crevices at the edge of specimens cured for 28 days. There is almost no cracking evident in the reinforced, 7 day old specimen. In summary, the curing process increases the compressive strength as well as the brittleness of materials. It leads to sudden failure of unreinforced specimens when the load exceeds the peak strength. The potential benefits of fibre inclusion are therefore the development of a much more ductile fill mass, reducing the potential for unexpected falls of blocks of CPB when adjacent mining occurs. Rather, once the shear stress in the reinforced CPB approaches the available shear strength, large displacements are likely to occur (due to the vastly increased ductility), providing ample warning of an impending block collapse. In addition, much more displacement is necessary
to mobilise the ultimate strength, potentially allowing enough time for subsequent stope filling before a face collapse occurs.

2.4 Conclusions

The beneficial effect of adding polypropylene fibres to cemented paste backfill was investigated in this paper. A series of uniaxial compression tests were conducted and X-ray computed tomography was used to explore the internal failure mechanism of non-reinforced and fibre-reinforced CPB specimens. From the results of the tests, the following conclusions can be drawn.

The fibre inclusions substantially enhanced the UCS and the ductility of CPB specimens. Specimens prepared with 5% cement and 0.5% fibre had a strength increase of 70% to 90% compared to unreinforced specimens with 5% cement. The axial strain at failure was about three times larger for the reinforced specimens and the ductility was vastly improved, with little or no post-peak loss of strength. Conversely, unreinforced cemented specimens displayed distinctly brittle behaviour.

Increased cement content improved the compressive strength of reinforced CPB specimens but had no influence on the increase of strain values at peak strength. Inspection of failed specimens using X-ray computed tomography clearly demonstrated the beneficial contribution of fibres; the propagation of cracks was arrested by the development of fibre tensile forces across the developing crack. In contrast, failed specimens of unreinforced CPB generally showed one or two major cracks that ran virtually the entire length of the specimens and were much wider than the cracks developed in the reinforced specimens. Fibre-reinforced specimens maintained their integrity throughout the application of load in the UCS tests, contrary to the unreinforced cemented specimens that exhibited significant spalling during testing. This points to the potentially beneficial effect of these small
polypropylene fibres in improving the ductility of CPB in situ, potentially preventing the fall of blocks and the dilution of ore. As with any major change to mining methods, implementation of a fibre-reinforced cemented paste backfill technology is unlikely to happen overnight. Nevertheless, the results presented in this paper provide a potentially inexpensive technique for reducing a major safety and financial risk when using the cut-and-fill and open stoping methods of underground mining.

Future studies will investigate the effects of reinforcement with different fibres, test the durability of fibres in CPB and explore the tensile behaviour of fibre-reinforced CPB.

2.5 References


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Table 2-1. Chemical composition of the tailing

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<th>Chemical composition</th>
<th>Amount: %</th>
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Table 2-2. Quality of process water

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<th>Na</th>
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<td>K</td>
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</tr>
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</table>


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Figure 2-1. Particle distribution

Figure 2-2. Adfil-Ignis polypropylene fibres (6mm long and 18μm in diameter)
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Figure 2-3. Stress-strain curves for 7-day cured specimens

Figure 2-4. Stress-strain curves for 14-day cured specimens
Figure 2.5. Stress-strain curves for 28-day cured specimens

Figure 2.6. Stress-strain curves for 5% cement non-reinforced specimens
Figure 2.7. Stress-strain curves for 5% cement 0.5% fibre-reinforced specimens
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(a) 7 day  14 day  28 day

(b) 7 day  14 day  28 day
Figure 2-8. Failure specimens cured for 7, 14 and 28 days: (a) 5% cement non-reinforced; (b) 5% cement 0.5% fibre-reinforced; (c) 3% cement 0.5% fibre-reinforced; (d) 5% cement 0.3% fibre-reinforced
Figure 2.9. CT sliced images of failed 7-day cured specimens from bottom to top (i.e., from 0 to 100%): (a) specimens with tailings+5% cement; (b) specimens with tailings+5% cement+0.5% fibre
Figure 2-10. CT sliced images of failed 28-day cured specimens scanned from bottom to top (i.e., from 0 to 100%): (a) specimens with tailings+5% cement; (b) specimens with tailings+5% cement+0.5% fibre
Chapter 3

Experimental study of cemented paste backfill reinforced with different fibres

By: Xiawei Yi, Zhijian Li, Andy Fourie and Guowei Ma

Abstract: Unconfined compressive strength (UCS) tests on unreinforced and fibre-reinforced cemented paste backfill (CPB) specimens have been carried out to identify the ideal type that can be used for improving the stability of CPB filled mine stopes, and to quantify improvements to the ductile of backfill that are possible using fibre reinforcing. Three types of polypropylene fibres with different length, thickness and structure were adopted as reinforcing materials in specimen preparation. The effects of fibre reinforcement on the UCS, failure mode, average residual strength and energy absorption capacity were compared and discussed. The results indicate one or two excellent candidates for the reinforcement of CPB, and illustrate potentially important benefits provided by the improved ductility of some reinforced specimens. The discussion suggests that both strength and ductility ought to be considered in CPB design to optimise the economics of mining with backfill.

Keywords: Reinforced CPB; Ductile backfill; UCS tests; Polypropylene fibres

3.1 Introduction

As underground mining operations proceed, numerous voids (stopes) are generated due to the extraction of ore bodies. The stope sizes are typically 30 to 80 m high and around 20 m \( \times \) 20 m in plane dimension, although much larger and indeed much smaller stopes are also
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mined. The large volumes of voids often induce ground surface subsidence (Jung and Biswas 2002; Guo et al., 2011; Kashnikov et al., 2012) or mine collapse (Szwedzicki 2001; Dreger et al., 2008) unless backfill is used to support the previously excavated stopes, while massive ore pillars that are left for the purpose of supporting mining regions represent an enormous loss of mineral resources. Therefore, it is essential to stabilise these stopes in order to optimise mining strategies and increase recovery of ore bodies. Commonly, waste tailings are placed on surface after mineral processing, as a seemingly easier and cheaper method of tailings disposal and management. However, this approach often results in not only occupying hundreds of hectares of land but causing environmental and health issues (Bentel, 2011).

For these reasons, tailings-based mine backfill has been adopted for many underground mining operations. It is a process of transporting the waste mill tailings back into the mined stopes. Cement is usually used as a critical component of backfill materials in order to not only obtain the self-supporting ability when some vertical faces of the filled mass are exposed due to subsequent extraction, but also to reach the minimum uniaxial compressive strength of 100 kPa to reduce the risk of liquefaction during the early age of paste backfill hydration (Clough et al., 1989). Backfill is transported as a slurry, at a solids content that is as high as possible in order to develop high strengths, but not so high that smooth flow of backfill through the delivery pipe becomes difficult, or even impossible. Before placement of backfill, structural barricades are built at the base of stopes to retain the backfill until it develops sufficient strength to be self-supporting. Hydraulic backfill is one of the most commonly used methods in mining industry, which contains classified mill tailings and large amounts of water, which requires the drainage system to be placed on the barricade to remove the excess water for collection and re-use, as well as minimising risks to underground workers. The disadvantages of using hydraulic backfill include the large number of barricade failure incidents (Grice, 1998; Torlach, 2000) as well as the difficulties
of managing large volumes of water. There has therefore been a gradual move to increased utilisation of cemented paste backfill (CPB) over the past decade (Fall et al., 2007; Fall and Samb, 2009; Helinski et al., 2010, 2011). CPB is considered to offer more advantages than traditional hydraulic backfill in terms of consuming less cement to reach the target strength, generating lower pressures upon barricades at the early age of backfill hydration and developing a more efficient delivery system with its laminar flow behaviour (Potvin et al., 2005). Typical CPB is comprised of dewatered tailings, water and binders (e.g. cement, fly ash, slag or gypsum). Up to 75% to 85% solids (tailings and binders) by weight of total mixture are included, while the binder addition rates are usually only between 1% and 10% by dry mass. The tailings for producing paste backfill should contain at least 15% fine particles (<75µm) finer than 20 µm to maintain laminar flow in transportation pipelines and to maximise final strength once hydration is complete. Cement is commonly used as the binder agent owing to its wide availability in many countries and consistent quality. Increasing cement usage can improve the strength of backfill (Mitchell et al., 1982; Fall et al., 2007), but it also increases the cost of materials and transportation for filling massive volumes of stopes. This fact motivated the rapid advancement of studies during recent decades aiming to improve the quality of cemented mine backfill without increasing expenditure where possible. Fourie et al., (2006) and Helinski et al., (2007) evaluated the decrease in positive pore pressure during CPB consolidation and hydration. A predictive model was developed by Fall et al., (2008) to observe the performance of cemented tailings backfill with different proportions of mix components. Fahey et al., (2009) and Helinski et al., (2010) studied the influence of arching on stress distribution in filled stopes through numerical modelling.

Mitchell and Stone (1987) first investigated the effect of reinforcement on cemented backfill for reducing cement usage while still achieving a certain safety factor. Their study showed that a low-cement backfill reinforced with strongly cemented layers could achieve
the same required fill strength as the normal cemented bulk fill, but also concluded that the shotcrete wire fibre and anchored fibre would not be practical and economical as reinforcement at the time (in late 1980s). New types of fibre were expected by the writers to be developed in the future.

At the present time, fibre reinforcement has been widely applied in civil engineering and geotechnical engineering, such as fibre-reinforced concrete, soils, clays and gravels. Many studies revealed that fibre inclusion improved strength (compressive strength, flexural strength, tensile strength and impact strength) and ductility of specimens with a better crack-arresting capability. Fibres can help rectify the tensile weakness of concrete by distributing loads at internal micro-cracks, thus indirectly enhancing confinement under compressive loads (Ramesh et al., 2003). In particular, polypropylene fibres have become increasingly popular for reinforced concrete due to the materials’ resistance to corrosion and easier dispersion within a concrete mix than steel fibres (Machine et al., 2008). The shear strength of fibre-reinforced soil is also enhanced by the mobilised tensile stress of fibres (Li and Zornberg, 2013). Zornberg (2002) proposed a discrete framework to define the equivalent shear strength of a fibre-reinforced specimen that is invariably higher than the unreinforced one. However, CPB has its own unique character in that cement contents are substantially lower than concrete and contains finer particles than concrete (which usually contains stone, as well as sand). The mechanical behaviour of fibre-reinforced CPB is a relatively unexplored topic. Festugato et al., (2013) studied the cyclic response of fibre-reinforced CPB through direct simple shear tests, although the effect of fibre properties (e.g., length, thickness, and tensile strength) on the mechanical behaviour of specimens was not further explored. In view of this observation, the current research focusses on the interaction between the cemented matrix and various polypropylene fibres, as well as identifying the best choice for reinforcing CPB.
Chapter 3 Experimental study of cemented paste backfill reinforced with different fibres

3.2 Experimental procedure

The properties of tailings and various polypropylene fibres were identified for testing and evaluation of the effects of reinforcement on CPB. A series of unconfined compressive strength (UCS) tests were carried out to measure the strength and ductility of samples at early and later ages (7 days and 28 days).

3.2.1 Sample preparation

The CPB samples consist mainly of mine tailings, Portland cement and water provided by a copper mine in Tibet. Mine tailings were tested by Mastersizer particle size analyser and X-ray Fluorescence (XRF) analyser. The particle size distribution and chemical composition of the tailings are shown in Figure 3-1 and Table 3-1, respectively. Approximately 39% of particles are smaller than 20 microns and the specific gravity of tailings is 2.88. General Portland cement was used as the binder, accounting for 5% by dry mass of tailings. It was mixed with 0.5% fibres by weight of the sum of tailings and cement and 20% process water by total mass of the CPB sample. The quality of process water is shown in Table 3-2. Three types of polypropylene fibres (Figure 3-2, Table 3-3) were adopted for the purpose of improving compressive strength and ductility of CPB. Tailings, cement and water were first mixed for 3 minutes before adding a particular fibre, ensuring the fibres were evenly distributed in the mixture. The mixture was then poured into plastic moulds and placed in a constant humidity chamber at a temperature of 23 °C and a relative humidity of 80% for 7 or 28 days prior to testing. Samples were stripped from the moulds and the ends trimmed to produce specimens of 50 mm × 100 mm (diameter and height). Both ends were flatted to ensure a perpendicular loading process.

3.2.2 Techniques

A loading instrument with the SPAX-2000 system of GCTS company was utilised for the whole UCS testing programme. The loading rate was 0.2 mm/min and data was recorded every 5 seconds. Twelve groups of samples, categorised by different fibres and different
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Experimental study of cemented paste backfill reinforced with different fibres  
curing periods, were tested in triplicate. Test results were required to meet the criteria that  
with a maximum 10% error from the mean value.

3.3 Results  
The results presented in this section include the stress-strain behaviour, failure modes,  
residual strengths and energy absorption capacities of unreinforced and various reinforced  
CPB specimens. The effect of curing time is also taken into account.

3.3.1 UCS  
Figures 3-3 and 3-4 show the typical stress-strain plots of unreinforced and fibre-reinforced  
CPBs cured for 7 and 28 days, respectively. The UCS of triplicate specimens was used to  
obtain the mean strength value for each set of variables tested. All curves shown in Figures  
3-3 and 3-4 have three obvious stages, which are an initial linear increase in axial stress with  
increasing strain, a marked or slight drop in axial stress, and finally a fluctuation in axial  
stress that is observable for all specimens tested. The peak strengths of the 28-day old  
specimens were always greater than corresponding 7-day old specimens, as expected, but  
the increase in peak strength varied between 13% and 121%, depending on the reinforcing  
used. All fibre-reinforced specimens exhibited better strain-hardening performance post- 
peak than did unreinforced specimens.

For 7-day tests, Unreinforced (U) curve has higher peak strength but more significant  
strength loss than the three fibre-reinforced CPB materials. However, all the fibre- 
reinforced specimens display ductile post-peak behaviour.

Econo (E) specimens always have highest strengths, but more importantly they exhibit no  
sign of strain softening, even after as much as 18% axial strain in the 28-day old tests.  
These samples reached axial stress values of up to 1450 kPa (7-day) and 2500 kPa (28-day),  
whereas Forta (F) curves levelled off at around 600 kPa with 7-day specimens and 850 kPa
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with 28-day specimens. Adfil (A) specimens also maintained their strengths at values between E and F before losing some strength at the strain value of approximately 11%. There is a clear benefit of improved ductility for all three fibre-reinforced specimens; none of the U specimens exhibited post-peak ductility. The improved ductility of reinforced specimens was achieved irrespective of fibre length or diameter, although it would be expected there would be an optimum choice in terms of cost, performance and ease of use.

A comparison of peak strengths and associated strain values is shown in Figure 3-5. The peak compression strengths of all four types of specimens increase with curing time, although curing age has a limited impact on the strain values at peak strengths. Figure 3-5 also shows that A and F reinforced specimens have almost the same strain value at peak strengths as the U specimen, whereas the value of specimen E is much higher than the others. Reasons for differences in behaviour of the various reinforced specimens are explored later.

3.3.2  Failure modes

Photographs of different failure patterns of specimens are shown in Figure 3-6. U specimen behaves in a brittle fashion, with only one or two major cracks in the vertical direction along with relatively small deformations after failure. The structure of the U specimen is severely damaged due to massive spalling, especially for the 28-day old specimen. Specimen A has an obvious shear failure plane with largely vertical compression and lateral expansion, but the blocks either side of the failure plane remained relatively intact. F and E specimens exhibit detached flakes on the surface and significant bulging failure modes, but no obvious discrete failure plane. The cores of F and E remain relatively undamaged. In general, failures were observed to initiate at the upper ends of specimens and develop downwards by crack propagation. Fibre-reinforced specimens (A, F and E) always deformed more, along with the development of many more, but smaller, cracks compared with U specimen.
3.3.3 Residual strength

The average residual strengths of the four specimens are plotted in Figure 3-7. Two bar charts represent strengths of 7-day and 28-day cured specimens, and they have similar relative values indicating the consistent relationship among four different types of specimens. The strength of U is rising from 316 kPa (7-day) to 424 kPa (28-day), which are nearly half the values of F specimens around 600 kPa in both charts. A and E have higher residual strengths than the other two specimens, especially the strengths of E specimens which reached 1062 kPa for 7-day old specimens and 2240 kPa for 28-day old specimens. It is clear that fibre reinforcement has enhanced the value from between two to seven times that of U specimens.

3.3.4 Energy absorption

The effect of reinforcement can be also reflected by comparison of energy absorption capacities as shown in Figure 8. The fracture energy is calculated by integrating the area under the stress-strain curve before the first evident decline, while the post peak energy is obtained from the integration of the rest of the area below the curve (i.e. the post-peak behaviour).

For 7-day cured specimens, the fracture energy of each specimen is similar but the contribution of post peak energy to total energy differs greatly. For example, the post peak energy of A (100 KJ/m$^3$) is roughly 8 times as high as U (12.5 KJ/m$^3$). Specimen F (82 KJ/m$^3$) is 6 times higher and E (97 KJ/m$^3$) is 7 times higher. For 28-day cured specimens, all fracture and post-peak energy improve except the fracture value of U. Specimen E now has the highest value of both fracture and post peak energy absorption capacities with 64 and 303 KJ/m$^3$, respectively, which is followed by A and F. The differences between the 7-day and 28-day old reinforced specimens are stark. At 7 days, all three are similar, but after 28 days specimen E clearly outperforms the other two.
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3.4 Discussion

3.4.1 Comprehensive performance of fibres

All test results indicate that the bonding mechanism and bonding quality of specimens are influenced by the traits of fibres and curing time of specimens. Polypropylene fibres contribute to the reinforcement in different testing stages, and some specimens show more brittle behaviour at older curing age.

Fibre reinforcement compensates for the loss of particle-particle bonds by mobilising tensile fibre strength, which prevents crack propagation. Figures 3-3 and 3-4 show that the curves of fibre-reinforced specimens do not fall substantially but retain their load carrying capacity during stage two and three of the tests. It can be drawn in the new stress-strain model (Figure 3-10) for the general fibre-reinforced specimens showing that there would be always stable fluctuations of the residual strength in stage three. The ends of fibres are bonded in the CPB matrix until pulled out by crack expansion. Figure 3-9 demonstrates that the failure of reinforced specimens is governed by fibre pullout instead of tensile breakage as the tensile strengths of fibres shown in Table 3-3 are much higher than the tensile strength of the CPB matrix. The mobilised tensile strength is derived from both the friction between fibres and the CPB matrix, and the mobilised tensile strength of fibres. This observation is consistent with the fluctuating strengths during stage three of the stress-strain curves, which suggest that the pullout process is one in which the pullout resistance of individual fibres is mobilised and exceeded.

Although both cement and fibres contribute to the peak compressive strengths of CPBs (Yi et al., 2015), the particle-particle bonds generated by cement hydration tend to dominate the strength development to reach the peak values. Figure 3-3 shows that the peak strength of specimen U is higher than those of fibre-reinforced specimens, indicating that the inclusion of fibres may initially interfere with the development of particle-particle
contacts. When the curing time increases, the improved contact bonds between particles and fibres result in higher peak strengths than U specimens, as shown in Figure 3-4. Fibre reinforcement sometimes maintains the post peak strength at this higher value (shown in Figure 3-7), producing very ductile post-peak behaviour, especially for specimen E.

Figure 3-6 confirms that fibre-reinforced specimens do not fail along discrete failure planes and undergo substantial deformation during tests. The contribution of reinforcement summarised in Figure 3-8 shows that the majority of energy absorption occurs post-peak, with fibres preventing the propagation of cracks, rather producing a specimen with many, smaller cracks.

Despite the improved strength and ductility observed above, there are distinct differences in the performance of the three reinforced specimens. To explore likely reasons for this, Table 3-3 includes the aspect ratio (length/diameter) of the three different fibres. The aspect ratio for specimen E is the highest, which is consistent with this specimen having the highest peak strength and best post-peak performance. Similarly, specimen F has the lowest aspect ratio and performs worse than the other two reinforced specimens in terms of both peak strength and ductility (for 28-day old specimens). It is also interesting to consider how the numbers of individual fibres (per unit volume) affect the reinforcing effects of fibres. Considering all fibres were added to the CPB in equal masses, the relative number of fibres per unit volume was calculated, the results being values of 1:20:5340 for specimens F:E:A respectively. This means that in a given volume of CPB there are about 5340 fibres of type A for every type F fibre. These relative numbers of fibres do not correlate with the observed behaviour of reinforced specimens, e.g. although specimen A has many more fibres per unit volume, it exhibits inferior post-peak behaviour to specimen E. Thus although there are many type A fibres in a given volume of CPB, their length may
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be precluding them from contributing to post-peak strength in the same way that fewer, but longer, type E fibres do.

3.4.2 Quantification of the effect of fibre shape
Fibre reinforcement has been shown to increase and maintain the shear resistance of specimens, which can be expressed as a function of the equivalent shear strength, $S_{eq}$ when failure is governed by the pullout of fibres, as follows (Li and Zornberg, 2013):

$$S_{eq} = c_{eq} + (\tan \phi)_{eq} \cdot \sigma_n$$ 3-1

$$c_{eq} = (1 + \alpha \cdot \mu \cdot \gamma \cdot c_c) \cdot c$$ 3-2

$$(\tan \phi)_{eq} = (1 + \alpha \cdot \mu \cdot \gamma \cdot c_{\phi}) \cdot \tan \phi$$ 3-3

where $c$ and $\tan \phi$ are the shear strength parameters of the unreinforced CPB; $\sigma_n$ is the stress on the fibres; $\alpha$ is an empirical coefficient related to the orientation of fibres; $\mu$ is defined as the ratio of fibre length over individual diameter; $\gamma$ is the ratio of volume of fibres over total volume of the specimen; The interaction coefficients, $c_c$ and $c_{\phi}$ relate to the interface shear strength between fibres and CPB matrix.

Eq. 3-1 explains that longer and thinner fibres will have the larger value of $\mu$. For specimens cast with the same type of tailings and cement content, the values of parameter $c$ and $\phi$ ought to be similar, whereas $\sigma_n$ is affected by curing age, since the stress on fibres should increase as the strength of the CPB matrix develops with age. Table 3-3 shows that E has the highest value of $\mu$, which leads to the highest peak compression strength with E reinforced specimens in Figure 3-3 and 3-4. The ratio $\gamma$ of all fibres is the same as the same mass and density. Figure 3-6 shows that A and E reinforced specimens result in more stable and integral conditions after failure compared with F reinforced specimens. Longer structural fibres such as E extend the process of pullout, thus increasing the axial strain at peak strength. Furthermore, the energy absorption capability is excellent for specimens.
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reinforced with fibre E at both early and late ages. The net structure of fibre E assists in improving the interconnection of monofilaments so that multi-directional tensile forces are mobilised.

3.5 Conclusions

This paper has extended the study of fibre-reinforced CPB to investigate the performance of CPB specimens reinforced with three different types of fibres. The primary objective is to find the ideal reinforcing inclusions for CPB and to explore the micromechanics of both unreinforced and reinforced specimens using a series of unconfined compressive strength tests. According to the test results, the following conclusions can be drawn.

Fibre reinforcement was mainly mobilised during the post-peak strength stage when resistance to pullout from the CPB matrix was mobilised. However, fibres were also functional to provide tensile strength at the very beginning of tests when wrapping pressure (the external pressure on the surface of a single fibre) of the CPB matrix was heavy enough. Several factors of fibres would affect the performance of reinforcement, such as the length, diameter and amount of monofilament. Longer and thinner fibres improved both the equivalent shear strength and the axial strain at peak strength, and specimens with larger amount of fibres had better performance of reinforcement.

At the early curing age, fibres would prevent partial development of particle-particle bonds instead of contributing to post-cracking resistance due to the weak wrapping pressure from the CPB matrix. After the particle-particle bonds being fully developed through cement hydration, the maximum tension of fibres would be mobilised resulting in the significant improvement of compressive strength and energy absorption capability.
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For the current cut-and-fill and open stoping methods, both strength and durability of CPBs should be considered in the assessment of stope stability when mining the adjacent ore. The massive addition of cement content would not boost the ductility of CPB but only strength before failure. In some extreme conditions, like rock burst, squeezing ground, blast or seismic event, it is more important for CPBs to maintain the stability and integrity after damage until the end of recent cycle. The new concept of ductile backfill is most likely to cut the cost of cement consumption, meanwhile to improve the overall stability of CPBs.

The future work will be focused on studies of the tensile behaviour and in-situ performance of reinforced CPB with laboratory modelling tests.

3.6 References


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### Table 3-1. Chemical composition of mine tailings

<table>
<thead>
<tr>
<th>Compound</th>
<th>Content (%)</th>
<th>Compound</th>
<th>Content (%)</th>
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</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>42.73</td>
<td>Na$_2$O</td>
<td>0.57</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>8.27</td>
<td>K$_2$O</td>
<td>1.17</td>
</tr>
<tr>
<td>TFe</td>
<td>4.69</td>
<td>TiO$_2$</td>
<td>0.27</td>
</tr>
<tr>
<td>FeO</td>
<td>0.70</td>
<td>P$_2$O$_5$</td>
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</tr>
<tr>
<td>MgO</td>
<td>4.75</td>
<td>MnO</td>
<td>0.41</td>
</tr>
<tr>
<td>CaO</td>
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<td>S</td>
<td>0.16</td>
</tr>
<tr>
<td>H$_2$O$^-$</td>
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### Table 3-2. Quality of process water

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<th>g/L</th>
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</tr>
<tr>
<td>Na</td>
<td>1.02</td>
</tr>
<tr>
<td>Cr</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Co</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>pH</td>
<td>10.60</td>
</tr>
</tbody>
</table>

### Table 3-3. Physical properties of fibres

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Form</th>
<th>Length (mm)</th>
<th>Diameter (µm)</th>
<th>Aspect ratio</th>
<th>Tensile strength (MPa)</th>
<th>Acid/Alkali resistance</th>
<th>Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adfil-Ignis</td>
<td>Polypropylene</td>
<td>Monofilament</td>
<td>6</td>
<td>18</td>
<td>333</td>
<td>600</td>
<td>Excellent</td>
<td>Nil</td>
</tr>
<tr>
<td>Forta-Ferro</td>
<td>Co-polymer</td>
<td>fibrillated</td>
<td>54</td>
<td>350</td>
<td>154</td>
<td>620-758</td>
<td>Excellent</td>
<td>Nil</td>
</tr>
<tr>
<td>Econo-Net</td>
<td>Homopolymer</td>
<td>Collated</td>
<td>51</td>
<td>74</td>
<td>689</td>
<td>600</td>
<td>Excellent</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>polypropylene</td>
<td>fibrillated</td>
<td>network</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Figure 3-1. Particle size distribution of mine tailings

Figure 3-2. Multiple fibres
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Experimental study of cemented paste backfill reinforced with different fibres

Figure 3-3. Stress-strain curves for 7-day cured specimens

Figure 3-4. Stress-strain curves for 28-day cured specimens
Figure 3-5. Peak compression strength and strain at peak strength
Figure 3-6. Failure specimens cured for 7 and 28 days
Figure 3-7. The average residual strength of 7-day and 28-day cured specimens
Figure 3-8. Energy absorption capacities: (a) 7-day cured specimens; (b) 28-day cured specimens
Figure 3-9. Pullout behaviour of fibres
Figure 3-10. Typical stress-strain model of fibre-reinforced CPB
Chapter 3  Experimental study of cemented paste backfill reinforced with different fibres
Chapter 4  
Triaxial compressive behaviour of fibre-reinforced cemented paste backfill  

By: Xiawei Yi, Zhijian Li, Andy Fourie, and Guowei Ma

Abstract: Fibre-reinforced cemented paste backfill (CPB) was investigated to improve the stability of filled stopes. A series of triaxial compressive tests were conducted to explore the effects of cement and polypropylene fibres contents on the triaxial compressive strengths of CPB. Samples were prepared with 5.0% to 12.5% cement contents by weight of dry tailings and 0-0.7% Monofilament polypropylene (PP) fibres by weight of dry solids. Triaxial tests were performed at the confining pressure of 100, 200, 300, 400 kPa, respectively. The results indicated that the increase of cement content enhanced the shear strength, but weakened the ductility of CPB. While, the inclusion of polypropylene fibres increased the peak and residual shear strength of CPB as well as the deformability index, and changed the CPB behaviour to be more ductile. The impact of fibres was more significant for the CPB with lower cement content. The optimum fibre content was determined around 0.5% for achieving the maximum strength of CPB. The average energy absorption capacity of CPB increased 92-150% with 0.5% fibres content, and also the peak friction angle and cohesion intercept had evident variations with fibre reinforcement.

Keywords: Polypropylene fibres; Triaxial test; Cement paste backfill; Matching performance.
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4.1 Introduction

The disposal of mine tailings on surface is not only expensive, but generates serious geotechnical and environmental hazards (Sharma and Al-Busaidi, 2001; Ritcey, 2005; Johnson and Younger, 2006; Kossoff et al., 2014). Mine backfill is well known as an effective mining method in some circumstances with the added benefit of reducing the volume of surface storage, by delivering a large amount of tailings back into the underground mined voids, which providing ground support for continuous excavations and increasing mineral products. Cement paste backfill (CPB) is an engineered mixture of mine tailings typically (75-85% solids by weight), water, and hydraulic binder (2-9% by dry total paste weight) (Ercikdi et al., 2014). CPB has been used since the early 1980s and is used in underground mining in Canada and Australia for reducing the risk of barricade failure, full stream tailings disposal, no segregation in the pipeline, and alleviating the environmental impact of potentially hazardous mine tailings (Ercikdi et al., 2009).

In many cases, to maximise ore extraction, filled stopes may be exposed on one or two faces that can reach up to 80 m high during the mining of adjacent stopes (Helinski et al., 2007; Festugato et al., 2013). Therefore, the fill mass should be self-supporting and be able to resist the imposed stress from the country rock, even dynamic impacts, such as development blasts and seismic events. Failure of backfilled stopes has been reported from time to time (Festugato et al., 2013) incurring economic losses and injury or death of miners in underground mines (Helinski et al., 2007). In order to maintain the stability of filled stopes, large amounts of binders (which may account for up to 75% of the cost of backfill) are usually added to the tailings stream in the paste plant. However, the cemented fill-mass exhibits a brittle behaviour after curing, with spalls or falling CPB fragments when excavating adjacent stopes, causing significant ore dilution and unexpected risks.
Short and randomly distributed fibres have been incorporated into chemically stabilised soft soil to improve strength, ductility and energy absorption capacity. These improvements result from the contribution to the delay of crack initiation, especially crack propagation of the fibres (Cai et al., 2006; Estabragh et al., 2012; Fatahi et al., 2012; Anggraini et al., 2015; Cristelo et al., 2015; Correia et al., 2015). Tang et al. (2007) studied the behaviour of cemented clayey soil with and without the reinforcement of polypropylene fibre and concluded that the inclusion of fibres increased the compressive strength, shear strength, and axial strain at failure. In addition, it changed the brittle behaviour of cemented soil to a more ductile one. Olgun (2013) indicated that the addition of fibres to cement-fly ash stabilized clay soil increased the compressive and especially the tensile strength.

Many researchers have also reported the use of fibres in sand, whether or not they were stabilized with cement (Consoli et al., 2010, 2013; Ahmad et al., 2010; Silva Dos Santos et al., 2010; Park, 2011). Consoli et al. (2009) reported that the fibre reinforcement increased the peak strength and the ultimate strength of cemented sand for a given cement content, but decreased the stiffness. Hamidi and Hooresfand (2013) conducted conventional triaxial compression tests on cemented sand reinforced with fibres. They found that the addition of fibres increased both peak and residual shear strength of samples, and the fibre reinforcement was more effective for samples with 70% relative density, or greater. All these studies indicated that fibre-reinforced cemented soil or sand had a larger shear strength and improved ductility compared with unreinforced specimens, and could potentially change the failure patterns of samples. Tailings (the main component of CPB) usually have finer particles and a wider particle size distribution than natural sands, and the apparent cohesion and compressibility are lower than those of soft soils. Furthermore, tailings contain a variety of chemical components due to the complex composition of the ore from which they are derived. Normally, CPB needs to have lower solids content than
Triaxial compressive behaviour of fibre-reinforced cemented paste backfill cemented soil and sand such as those used for foundation improvements, due to the requirement of being easily pumpable. Previous studies of the mechanical behaviour of fibre-reinforced CPB are limited (Festugato et al., 2013; Yi et al., 2015). Festugato et al. (2013) conducted cyclic simple shear tests on fibre-reinforced CPB, and briefly stated that the inclusion of fibres increased the shear stress values of CPB with successive load cycles. Yi et al. (2015) investigated the unconfined compressive behaviour of fibre-reinforced CPB, and pointed out that the fibre reinforcement improved the compressive strength and significantly reduced the post peak strength loss. They also reported that fibre-reinforced CPB samples still retained their integrity after failure, which is distinct from unreinforced samples. However, very little work has been done on the triaxial shear behaviour of fibre-reinforced CPB (in-situ, CPB is under a three-dimensional stress state). Moreover, previous studies did not present the performance of fibre-reinforced CPB with different combinations of fibre and cement contents in detail.

This study aims to quantitatively investigate the triaxial shear behaviour of fibre-reinforced CPB by altering the percentages of PP fibre and cement contents to explore the effect on the stress-strain behaviour, peak and residual shear strength, deformability index, and energy absorption capacity of CPB.

4.2 Experimental program

4.2.1 Materials

In this study, the full stream of tailings from a copper mine located in Dongchuan City, China was utilised. The physical and chemical characteristics of tailings were tested and shown in Figure 4-1 ($d_{10}=12.49 \, \mu m$, $d_{50}=78.85 \, \mu m$, $d_{90}=216.04 \, \mu m$, $C_u=8.00$, $C_c=1.62$) and Table 4-1. The tailings have 23% fine particles (<20 \, \mu m) and they are classified as medium-size tailings with a relatively high potential of water retention to transport the paste (Landriault, 2001). The specific gravity ($G_s$) of tailings is 3.01. The chemical composition of
Chapter 4  Triaxial compressive behaviour of fibre-reinforced cemented paste backfill tailings was analyzed using X-ray fluorescence (XRF) with a detection limit of 0.02 wt.% (Table 4-1), which indicated a low percentage of sulphide content in the tailings.

Ordinary Portland cement (type II) was chosen as the binder agent, which was appropriate for the tailings that contain little sulphide. Tap water with a PH value of 7.4 was used in this study.

PP fibres are the common geosynthetic material used to reinforce concrete and soil (Maher and Ho, 1994; Hamidi and Hooresfand, 2013; Yilmaz, 2015). PP fibres are economical, non-corrosive, hydrophobic and resistant to alkalis and chemicals. More importantly, it is possible to mix the bundles of monofilament fibres with the cement and tailings evenly by observation. The PP fibres are 23 μm in diameter and 19 mm in length. They have a relative density of 0.91, tensile resistance of 350 MPa, elastic modulus of 3 GPa, and linear strain at failure of 80%. Figure 4-2 shows the nature of the PP fibres.

4.2.2 Sample preparation and testing procedures

The contents of tailings, cement and fibres for sample preparation were calculated using the following equations,

\[ \rho_c = \frac{w_c}{w} \quad 4-1 \]

\[ \rho_f = \frac{w_f}{w + w_c} \quad 4-2 \]

where \( w_f, w_c \) and \( w \) were the dry weights of fibres, cement and tailings, respectively. The different cement contents (5.0%, 7.5%, 10.0% and 12.5%) were selected based on in-situ experience of CPB worldwide (Ercikdi et al., 2014; Festugato et al., 2013; Yi et al., 2015; Fall et al., 2009, 2010). The selected fibre contents (0%, 0.3%, 0.5% and 0.7%) were consistent with previous studies on fibre-reinforced cemented soil and sand (Silva Dos Santos et al., 2010; Consoli et al., 2009a, 2010; Olgun, 2013).
This testing program included a total of 16 groups of CPB samples (each group has four replicate samples). All materials were weighed with accuracies of 0.01 g before mixture. The tailings, cement and water were mixed for 5 minutes before the PP-fibres were gradually added to the blender. The blender was then run for another 10 minutes until the mixture was visually smooth and without lumps (Correia et al., 2015). The water content was 25% by total weight of the mixture; this value was chosen based on site practice. The slump value was approximately 216 mm for all specimens according to the ASTM C143 standard. The CPB mixtures with different fibre and cement contents were poured into cylindrical plastic moulds having a diameter of 50 mm and height of 100 mm. After 24 hours, the samples were removed from the moulds and cured in a humidity chamber at 23±2 °C and relative humidity of 80% for 27 days, then were taken into water for another day. After curing, the diameter and height of samples were measured with accuracies of 0.01 mm, then samples were transferred to the equipment to start triaxial compression tests.

A series of triaxial tests were carried out on cured CPB specimens at confining pressures of 100, 200, 300 and 400 kPa. Pressure transducers monitored the confining pressure, while a load cell with capacity of 20 kN measured the vertical load with a resolution of 0.01 kN. The axial displacement was monitored by a linearly variable differential transformer (LVDT) with a resolution smaller than 10 μm. The samples were first brought to the required confinement pressure and then the axial compressive loading was applied at a strain rate of 0.2%/min. After reaching the peak strength, compression continued until at least 3% axial strain considering no much higher values were actually achieved after that. An electronic data acquisition system recorded the reading of deviatoric stress, axial relative displacement and confining pressure every two seconds.
4.3 Results and discussion

4.3.1 Stress-strain response

Figure 4-3 shows the deviator stress-strain curves of unreinforced and fibre-reinforced CPBs. The $\sigma'_1$, $\sigma'_3$, $\varepsilon$ in Figure 4-3 were the major effective principal stress, minor effective principal stress, and the axial strain. The peak shear strength, stiffness and brittleness of all samples were enhanced by the increase of cement content, as shown by Figure 4-3 (a) with 5.0% to (d) with 12.5% (for the results with $\rho_i = 0\%$). The peak strengths of unreinforced and 0.5% fibre-reinforced samples increased from 831 kPa and 1404 kPa to 2002 kPa and 2308 kPa, respectively, and the strain values at peak strength decreased from 12% and 17% to 4% and 7% respectively. Higher cement contents (10% and 12.5%) reduced the difference in strain values at peak strength of unreinforced and fibre-reinforced samples, which is attributable to the increased cohesive strength of the CPB matrix by cement hydration. All curves show that the initial stiffness of CPB was slightly reduced by adding fibres. Apparently, the introduction of fibres impeded partial cementing bonds and produced more pores and micro cracks in CPB matrix. However, fibre reinforcement had a distinct influence on the strength after an axial strain of about 2%, especially for CPBs with 5% and 7.5% cement content. It provided the major contribution to strength at later testing stages when cementing bonds were damaged. This is because the bond strength (cemented bonds) is mobilised at small strains, before the contribution to strength offered by the fibres can be mobilized. The fibres need to undergo more extension before their contribution to load resistance becomes mobilized. The effect is that the benefits derived from fibre addition is less than in samples with a lower cement content. That explains the more ductile behaviour of fibre-reinforced curves in Figures (a) and (b).

Figure 4-4 shows the variation of the average peak and residual shear strength (obtained from the average post-peak deviator stress) of CPB samples, for the range of confining pressures tested. As suggested by Consoli et al. (1999), the shear strengths were considered
Triaxial compressive behaviour of fibre-reinforced cemented paste backfill to vary approximately linearly with confining pressures. It clearly illustrates that the average peak shear strength of CPB increased linearly along with the increase of cement content except the CPB with 0.7% fibres. The improvement of residual strength reduced with higher cement content, owing to the enhanced brittleness of these specimens. The results in Figure 4-4 indicate that an optimum addition rate of fibres is about 0.5%. For all values of cement content, addition of 0.3% fibres increases the peak and residual strengths; addition of 0.5% fibres results in a further increase. However, no further benefit is derived by adding additional fibres (see the result for 0.7%). At fibre addition rates of 0.7% there are probably too many fibres, which begin to interfere with the development of cemented bonds, as well as clumping of fibres beginning to occur. Figure 4-5 shows an SEM photograph of a specimen with 0.7% fibres and 10% cement content. The proximity of fibres to one another is clearly evident, with attendant interference of development of cement-aggregate bonding. As cost will always be a consideration when considering alternative binders or materials (such as fibres), keeping the required volume to a minimum is crucially important. The results summarised in Figure 4-4 clearly indicate that around 0.5% fibres appears to be a good target value.

4.3.2 Deformability characteristics

The deformability index proposed by Park et al. (2011) was used to describe the ductility of fibre-reinforced CPB specimens. The deformability index was defined as

\[ D = \frac{\Delta_{\text{fiber}}}{\Delta_{\text{no fiber}}} \]

Where \( \Delta_{\text{fiber}} \) was the average axial strain at failure of fibre-reinforced CPB, \( \Delta_{\text{no fiber}} \) was the average axial strain at failure of unreinforced CPB. The index \( D \) against fibre content is illustrated in Figure 4-6. Figure 4-6 shows that for a particular cement content, the inclusion of fibres resulted in an improvement of the specimen ductility. Furthermore, the higher fibre content produced a higher deformability index, except a slight decrease of \( D \).
value of the sample with 10.0% cement and 0.7% fibres. The most effective improvement of ductility by inclusion of fibres occurred when the cement content was around 7.5% (the value of $D$ increased from 1.7 to 2.2 as the fibre content increased from 0.3% to 0.7%). This is probably because at lower cement contents (e.g. 5%) the unreinforced specimens were themselves ductile, whereas at cement contents higher than 7.5% even the reinforced specimens mobilized peak strength (which is primarily due to cemented bonds) at low strains. In both these situations, the $\Delta_{\text{fibre}}$ was closer to $\Delta_{\text{no fibre}}$ and accordingly the deformability index was smaller.

From the above, it is suggested that there is an optimum value for both cement and fibre content to achieve desired strength and ductility of CPB materials. However, the optimum composition of fibre-reinforced CPB ought to be based on the specific mining requirements in terms of the mining method, the stope size and the cycle time, etc.

4.3.3 *Energy absorption capacity*

Energy absorption capacity indicates the amount of energy required to induce deformation in fibre-reinforced material (Hamidi et al., 2013). The average peak absorbed energy was calculated from the area under stress-strain curves before failure. It can be seen from Figure 4-7 that the average peak absorbed energy of unreinforced CPBs increased slightly from 75 to 90 KJ/m$^3$ with an increase of cement content from 5.0% to 10.0%, but decreased to 80 KJ/m$^3$ when cement content was 12.5%. It can also be observed that the addition of fibres significantly increased the average peak absorbed energy for the whole range of fibre content tested. For instance, the average peak absorbed energy increased by between 92% and 150% in CPB when 0.5% fibres were added, as shown in Figure 4-7. The elongation of fibres and development of friction between fibres and particles under stress resulted in a greater capacity to absorb energy before failure.
4.3.4 Failure envelopes and shear strength parameters

The failure envelopes for both unreinforced and fibre-reinforced CPBs are presented in Figure 4-8. The $\sigma_1$, $\sigma_2$, $\sigma_3$ in Figure 4-8 were the major principal stress, medium principal stress, minor principal stress. It can be seen that the fibre-reinforced envelopes were always above the unreinforced ones, especially for CPBs with 5% and 7.5% cement. It should be also noted that the strength benefits of fibre reinforcement at higher confining pressures for the samples with 5.0% cement were more pronounced than with 7.5% cement. The results in Figure 4-8 also emphasise the earlier point that addition of fibres beyond 0.5% appears to have relatively little additional benefit, if any at all.

The peak shear strength parameters friction cohesion $c'$ and angle $\varphi'$ for unreinforced and fiber-reinforced CPBs are obtained by following formula and shown in Table 2.

\[
q = \frac{\sigma_1' - \sigma_3'}{2} \quad \text{4-4}
\]
\[
p = \frac{\sigma_1' + \sigma_3'}{2} \quad \text{4-5}
\]
\[
q = k_f p + a \quad \text{4-6}
\]
\[
\varphi' = \arcsin(k_f) \quad \text{4-7}
\]
\[
c' = \frac{a}{\cos \varphi'} \quad \text{4-8}
\]

Where $k_f$ and $a$ were the slope and intercept of p-q curve, respectively. The peak shear strength parameters for unreinforced and fibre-reinforced CPBs are shown in Table 4-2. The data shows that the friction cohesion $c'$ and angle $\varphi'$ of unreinforced CPB increased from 31.0° and 108.3 kPa to 39.3° and 316.4 kPa with an increase of cement content from 5.0% to 12.5%, as the cementing bonds were enhanced among tailings particles. Table 4-2 also confirms that the peak cohesion of CPB increased with the increase of fibre content owing to the large contribution of tensile strength of fibres. Reinforced CPB containing
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0.5% fibres exhibited a change from 31.0 - 3.9.3° to 30.3 - 41.7° in peak friction angle and 108.3 - 316.4 kPa to 235.4 - 465.2 kPa in apparent cohesion compared to unreinforced CPB (cement content from 5% to 12.5%).

The failure mode of samples changed with the fibre content and the confining pressure, so the shear strength parameters $c'$ and $\varphi'$ in Table 4-2 were not actual cohesion and friction angle as inclusion of material with significant fibre content does not usually follow a Mohr-Coulomb strength interpretation. However, the results are still useful as an indication of potential strength improvements achievable through the use of fibre reinforcing.

4.3.5  

Mode of failure

Typical failure patterns of unreinforced and fibre-reinforced samples are shown in Figure 4-9. Brittle failure was observed in (a) and (b) which had a high cement content (12.5%). They show well-defined failure planes extended from the top of samples to the bottom. The cracks became less obvious when reducing the cement content as shown in (c) and (d), due to increased ductility. The fibres bridged developing cracks within the CPB matrix and prevented expansion of the cracks, especially for samples with lower cement content, as shown in (d). The samples experienced changes in failure modes from localized shear to barreling when adding fibres or/and increasing confinements as shown in (c) and (d). Under this latter condition, the samples maintained integrity during the whole testing process, which would potentially reduce the ore dilution in situ when mining the adjacent stope.

4.4 Conclusions

The following conclusions can be drawn from the results of triaxial compression tests on fibre-reinforced and unreinforced cemented paste backfill:
An increase of cement content in CPB significantly increased the peak and residual shear strength, initial stiffness and brittleness. However, the addition of polypropylene fibres increased the peak and residual shear strength, deformability index, and changed the load response of CPB to a noticeably ductile behaviour. For achieving maximum strength, the optimum fibre content for reinforced CPB should be around 0.5% by weight of total solids (for the particular tailings used). The reinforcement of PP fibres was more effective when used with lower cement contents (below 7.5%) in terms of the strength and ductility enhancement.

The increase of cement content resulted in a slight increase in the average energy absorption capacity of unreinforced CPB, whereas the value of 0.5% fibre-reinforced CPB increased by between 92% and 150%.

The peak cohesion intercept of CPB also increased with the increase of the fibre and cement contents. The peak friction angle of unreinforced CPB increased from 31° (with 5% cement content) to 39.3° (with 10.0% cement content). CPB reinforced with 0.5% fibres exhibited a change from 31.0 - 39.3° to 30.3 - 41.7° (cement content from 5% to 12.5%) in peak friction angle and 108.3 - 316.4 kPa to 235.4 - 465.2 kPa in cohesion intercept compared to non-reinforced CPB.

Especially for the cut-and-fill and open stoping mining methods, fibre-reinforced CPB may be a viable option because the enhanced ductility provided by fibres reduced the loss of post peak strength and maintained the strength value until reaching a much higher strain, even with lower cement content, than unreinforced CPB. Under extreme conditions such as rock bursts and seismic events, the reinforced CPB would remain more stable and intact until the adjacent excavation was completed. The application of this technique has the potential to reduce the amount of cement used, as well as reduce risks of stope failure.
4.5 References


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Table 4-1. Chemical composition of mine tailings

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<thead>
<tr>
<th>Chemical composition</th>
<th>Amount: %</th>
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<th>Amount: %</th>
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Table 4-2. Peak shear strength parameters for non-reinforced and fiber-reinforced CPB samples

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<th>Cement content (%)</th>
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<th>Fiber-reinforced</th>
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<td></td>
<td></td>
<td>0.3% fiber</td>
</tr>
<tr>
<td>c’</td>
<td>p’</td>
<td>c’</td>
</tr>
<tr>
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<td>108.3</td>
<td>110.6</td>
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<tr>
<td>10.0</td>
<td>215.4</td>
<td>221.2</td>
</tr>
<tr>
<td>12.5</td>
<td>316.4</td>
<td>345.9</td>
</tr>
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</table>
Figure 4-1. Particle size distribution of mine tailings used in tests

Figure 4-2. Photograph showing the discrete short PP-fiber used in tests
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Triaxial compressive behaviour of fibre-reinforced cemented paste backfill

0.0% fiber
0.3% fiber
0.5% fiber
0.7% fiber

(a)
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(b)
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(c)
Figure 4-3. Deviator stress-axial strain response of CPB: (a) 5% cement, (b) 7.5% cement, (c) 10% cement, (d) 12.5% cement
Figure 4-4. Variation of average peak and residual shear strength of CPB
Figure 4-5. SEM image of 10% cement-0.7% fiber-reinforced CPB specimen before loading
Figure 4-6. Deformability index increase due to inclusion inclusion of fibers
Figure 4-7. Variation of energy absorption capacity with fiber content
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(a)

(b)
Figure 4-8. Failure envelopes for CPB with different cement and fiber contents: (a) 5.0% cement, (b) 7.5% cement, (c) 10.0% cement, (d) 12.5% cement
Figure 4-9. Failure modes of tested specimens (left is for 100 kPa confining pressure and right is for 400 kPa in each photograph): (a) 12.5% cement, (b) 12.5% cement + 0.5% fiber, (c) 5.0% cement, (d) 5.0% cement + 0.5% fiber
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Chapter 5

Centrifuge model studies on the stability of fibre-reinforced cemented paste backfill

By: Xiawei Yi, Andy Fourie and Guowei Ma

Abstract: Cemented paste backfill (CPB) is used extensively in Australia for providing ground support during underground mining operations. This paper considered the use of polypropylene fibres to reinforce the partial or whole body of CPB models in laboratory centrifuge tests. Specimens were cast as non-reinforced (tailings, cement and water), quarter-height, half-height and full height fibre-reinforced CPB model stopes. The stability of CPB models with vertically exposed faces was investigated by a series of centrifuge tests. The modelling data showed that the prototype height of fibre reinforced CPB stopes could be much higher than that of unreinforced stopes depending on the extent of reinforcing. The vertical displacement and failure mass ratio of CPB models were also compared and discussed. The distinct failure modes showed that fibre reinforcement was effective in preventing the CPB failing into the strong box. Furthermore, virtually no fragments were spalled from the exposed faces of reinforced sections of the stopes. It indicated that the application of fibre reinforcement would potentially reduce ore dilution and recovery costs since the risks of failure could be lowered and prototype stope sizes be enlarged.

Keywords: Geosynthetics; Cemented paste backfill; Fibre reinforcement; Centrifuge
5.1 Introduction

The application of cemented paste backfill (CPB) has become increasingly common in Australia and Canada over the past decades (Potvin et al., 2005, Fourie et al., 2015). It is a practical operation for many cut-and-fill underground mines, especially those that have high stopes (Fourie et al., 2007). Typical CPB is the mixture of mine tailings, Portland cement and water, which is comprised of 70% to 85% solids by total mass. It is characterised by high-density and is non-segregating when flowing through delivery pipelines, especially compared with conventional hydraulic fill (Klein and Simon, 2006). The general dosage of cement in CPB is 1%-10% by dry mass of tailings, which represents around 15% costs of the mining operation (Belem and Benzaazoua, 2004). Therefore, the CPB design should achieve an economical operation as well as ensuring stability and safety.

Different factors that may affect the performance of CPB have been considered in previous studies, such as the properties of CPB components (Li et al., 2003; Fall and Benzaazoua, 2005; Fall et al., 2008; Ereikdi et al., 2010, 2012), curing conditions (Fall and Samb, 2009; Huang et al., 2011; Yilmaz et al., 2014; Walske et al., 2015) and in-situ circumstances in terms of arching effects (Belem and Benzaazoua, 2004; Fahey et al., 2009; Thompson et al., 2012) and self-weight consolidation (Yilmaz et al., 2009, 2014b; Fahey et al., 2011). The majority of research efforts are concentrated on the strength development, especially the unconfined compression strength (UCS) of CPB that is widely accepted as the most important parameter for backfill design. CPB stopes will usually serve as a working floor, a replacement roof or a self-supporting wall during a specific mining cycle. The durability and deformation behaviour need to be considered since CPB structures should remain stable and allow deformation in a ductile fashion instead of undergoing sudden failure.
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Mitchell and Stone (1987) compared several kinds of reinforcement in cemented fill using drop-box model testing, and their results showed that fibre reinforcement was a promising technique to improve the stability of cemented backfill and potentially reduce cement usage. Based on this evaluation, Festugato et al. (2013) and Yi et al. (2015) have demonstrated that the addition of polypropylene fibres enhanced not only the shear strength but the ductility of the CPB. However, fibre reinforced CPB has until now not been adopted in the mining industry, and performance under realistic field conditions is untested. Due to the high cost of field-scale tests, the centrifuge modelling technique provides an appropriate alternative technique for evaluating the effectiveness of fibre-reinforcing at the prototype scale. Mitchell (1986, 1989) designed centrifuge model tests for comparing the predicted prototype heights of backfilled stopes obtained from centrifuge tests and from UCS tests, and for investigating the effects of hanging wall-foot wall dip angles and closure stress on the stability of cemented backfill. His tests were found to accurately represent full-scale stopes with exposed faces, and credible testing results were achieved.

The purpose of this paper is to explore the contribution of fibre reinforcement to the potential increase of prototype heights of CPB stopes by conducting centrifuge tests on eight models using four different reinforcement configurations. These results are also compared with predicted stable stope heights obtained from UCS tests. The design of the models was based on the evaluation of previous studies on reinforced CPB and centrifuge tests. The failure behaviour and failure mass ratio are presented and discussed.

5.2 Experimental program

5.2.1 Materials

The tailings used in the models were from a copper mine in Southern China. Figure 5-1 shows the particle-size distribution curve and Table 1 shows the chemical composition of
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Centrifuge model studies on the stability of fibre-reinforced cemented paste backfill the tailings. Ordinary Portland cement was chosen as the binder. Monofilament polypropylene fibres were used for reinforcement (Figure 5-2), which were 19 mm in length and 18 micron in diameter. The fibre has an ultimate tensile strength of 600 MPa and a specific gravity of 0.91. Distilled water was used to mix the tailings, cement and fibres.

5.2.2 Testing models 

Eight centrifuge model stopes in four different reinforcement configurations (i.e. two replicates of each configuration) were cast in wooden moulds 100 mm by 100 mm by 500 mm high, and transferred to the strongbox in the moulds after being cured for 28 days. The lateral plates of the moulds were vertical and were relatively smooth, which could thus not simulate the roughness of stope walls in-situ. However, it did make comparison of the relative performance of different reinforcement configurations easier. Separately, 3 specimens were cast into cylindrical plastic moulds 50 mm in diameter and 100 mm high for UCS tests on unreinforced and reinforced specimens in order to facilitate comparison of the predicted prototype heights with centrifuge results.

All models contained 2.5% cement content by dry mass of tailings. Models 1 and 2 were unreinforced, while models 3 and 4 were reinforced over the full stope height with 0.5% fibres by mass of the total solids. Previous studies have shown that the compressive strength of reinforced cemented soils could be significantly increased when the fibre content was between 0.25% and 0.75% of total solids (Consoli et al., 2011, 2012; Zaimoglu and Yetimoglu, 2012). Models 5 and 6 followed the same formula of fibre reinforcement but were only reinforced from the bottom up to ¼ model height, and models 7 and 8 were reinforced over only the bottom half of the stope height (Figure 5-3).
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The CPB mixture was prepared at a solids content of 78% and a slump value of 209 mm, which were representative of values used at the site. The unreinforced and fibre reinforced CPB mixture were produced at the same time, and poured in sequence, depending on the reinforcement configuration, into the individual stope moulds. The prepared models and specimens then were sealed and cured for 28 days before starting centrifuge tests and UCS tests.

5.2.3  Testing equipment

In this study, the tests were carried out using the geotechnical beam centrifuge at Tsinghua University. The equipment has a nominal radius of 2 m and a capacity of 50 g-tonne, with a maximum acceleration of 250 g. Four CPB models were placed in a row inside a rectangular strongbox made of aluminium alloy with internal dimensions of 450 mm in length and width, 600 mm in height. Laser displacement sensors were installed above models, and cameras were fixed facing towards the exposed faces of models (Figure 5-4). The vertical displacement and the lateral deformation of models were observed and recorded by laser displacement sensors and micro cameras. A SPAX-2000 true triaxial test system with a maximum capacity of 25kN at Beijing University of Technology was used for the UCS tests.

5.2.4  Testing procedures

After 28 days of curing, the front plate of each mould was removed and four models were placed into the strongbox for a single flight. The front face of each model was spray painted in red and marked with a number for the purpose of recognising the failure and the model type. The marked faces can be seen through the Plexiglas wall of the strongbox in Figure 4. Models were measured and weighed before and after testing for the calculation of failure mass ratio. Models 1, 2, 5, 6 were tested in the first flight and models 3, 4, 7, 8 tested in the second test. Models were conditioned at an acceleration of 5g for 5 minutes and were then brought to failure by incrementing the centrifuge speed by 2.5g/minute
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increment with 1 minute interval between every 5g increment. The vertical subsidence of models was measured by laser displacement sensors and the whole testing process was monitored by video cameras.

For UCS tests, the cylindrical specimens (also cured for 28 days) were compressed using a displacement rate of 0.1mm/min. The final results were obtained from the average value of triplicate tests.

5.3 Results and discussion

5.3.1 Vertical displacement

Figure 5-5 shows the continuously monitored vertical displacements (average values of repeated measurements) of models along with the testing time in the centrifuge. The displacements stopped when the models failed or testing ceased. The unreinforced curve had two apparent boosts of displacement, occurring at 540 seconds from 2.32 mm to 3.27 mm and at 1212 seconds from 6.51 mm to 8.51 mm. Failure of unreinforced model happened soon afterwards at 1215 seconds with total vertical displacement of 8.53 mm (equivalent to 0.39 m at full scale). The quarter-height reinforced stope had a longer and smoother trace than the unreinforced curve, although one slightly sharp increase from 13.96 mm to 18.22 mm occurred before immediate failure. The half and full height reinforced stopes had fairly smooth traces and reached final vertical displacements of 27.91 mm and 28.02 mm respectively (the full-scale displacement of a full reinforced model was 4.09 m, without reaching failure). It was clear that the vertical deformation of reinforced stopes was more ductile than that of unreinforced stopes, and with higher reinforcing rates (half or full height reinforced), the ductility was more significant. Without fibre reinforcement, a rapid and substantial increase of vertical displacement of the stope occurs when cemented particle bonds are broken within a substantial mass of the backfill, enabling large movements to occur. However, the inclusion of fibres compensates for the
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breaking of bonds and bridges the micro-cracks that form when bonds break, much like the CT-scan observations on UCS samples discussed by Yi et al., (2015). With fibre reinforcement, the magnitude of vertical displacement with time reduced (the unreinforced curve was always above reinforced curves) but the stiffness was vastly improved. From visual observations, it was clear that reinforced zones contributed more to the reduction of vertical displacements of models than unreinforced parts.

5.3.2 Failure mass ratio

Figure 5-6 illustrates the percentages of failure mass by total mass of stopes. Unreinforced models (1 and 2) lost 75.0% and 70.7% of the backfill mass after failure, whereas full height reinforced models (3 and 4) had less than 1% failure mass. Models 5 and 6 with quarter-height reinforcement had more than 60% failure mass. When the reinforced zone increased to ½ stope height, model 7 only lost 12.4% of total mass whereas model 8 lost 59.6% of total mass, under the same conditions, which revealed the instability of models with unreinforced parts.

The results demonstrated that with the higher reinforcing rate, the failure mass ratio of models decreased sharply. However, the part-reinforced models were not always stable, showing sudden failures and substantial losses in mass. Any failure of a CPB stope, unreinforced, part-reinforced or fully reinforced would generate unacceptable ore dilution and severe safety issues. Although full height reinforcement appears to have the potential to eliminate significant failure, the choice of reinforcement content should be considered according to cost considerations and ease of achieving thorough and uniform mixing of reinforcement fibre within the backfill.

5.3.3 Failure modes

Figure 5-7 shows failure patterns of models with different reinforcement configurations. Nearly all the reinforced zones remained intact (some reinforced areas were damaged by
blocks fallen from above) after failure, whereas unreinforced zones exhibited brittle failure. The two unreinforced models failed at similarly low equivalent heights. The first evidence of yield was fragments falling off the exposed vertical surface. Then a steep failure plane (about 60° above the horizontal) developed near the toe and extended to meet the back wall of the model. The resulting blocky mass dislodged immediately after this failure plane developed and the block dislodged with such speed that it was thoroughly smashed on impact with the centrifuge strongbox floor. Every part-reinforced stope showed similar failure behaviour as the unreinforced stope, although the failure plane always initiated from the interface between reinforced and unreinforced zones. The fully-reinforced stopes could not be brought to failure even with accelerations exceeding 150g, and they exhibited high relative integrity without dislodged fragments being evident. Instead, only slight cracks appeared near the foot of the two fully reinforced stopes.

The fibre reinforcement demonstrated a remarkable advantage in improving the self-supporting capability of stopes. Failures always developed only in unreinforced zones, while reinforced zones showed ductile yield with formation of surface ridges due to the vertical compression and associated lateral restraint. Thus even though the walls were prepared with a relatively smooth finish, friction would have been generated between the walls and the CPB as a result of the lateral expansion of CPB during spin-up. The results proved again that increasing the reinforcement percentage could benefit a large volume of the CPB in terms of improvement of stope stability and reduction of ore dilution.

5.3.4 Prototype heights
The equivalent prototype heights shown in Figure 5-8 indicated the potentially achievable heights of exposed faces of unreinforced and fibre reinforced CPB stopes. Unreinforced stopes 1 and 2 failed first at 20.2m and 26.6m. Full height reinforced stopes 3 and 4 remained stable at an acceleration of 150 g that was equivalent to about 73.0 m. One
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Quarter-reinforced models 5 and 6 failed at the same speed of 197 r/min, which is equivalent to 42.2 m prototype height. Half-height reinforced models 7 and 8 exhibited different heights of 68.9 and 41.7 m, even though they were tested under the same testing conditions.

The equivalent prototype heights of fibre reinforced stopes were nearly twice, to more than three times as large as unreinforced stopes. This indicates the potential to increase the exposure heights of CPB stopes in underground mines using cut-and-fill, benching or open stoping mining methods, thus decreasing stope fill cycle times, which would provide productivity improvements and cost reductions. There is also the potential to reduce cement content if reinforcing is used, thus potentially balancing the cost of the reinforcing. However, it should be noted that the combined application of unreinforced and fibre reinforced CPB still has many uncertainties in stability evaluation and recipe design, etc. More centrifuge tests on part-reinforced CPB models are planned in order to explore the optimisation of this application.

5.3.5  Centrifuge versus UCS

Mitchell solution (1982) is commonly used for backfill design in calculating the required strength of backfilled stopes with exposed faces (Figure 5-9). The expression of required unconfined compressive strength is as

\[
UCS = \frac{\gamma H}{1 + H/L} F_s
\]

where \( \gamma \) is unit weight of backfill (= 21 kN/m\(^3\)), \( H \) is fill height, \( L \) is width of exposed face, \( F_s \) is factor of safety. The predicted prototype heights based on UCS and centrifuge tests using this equation are compared in Table 5-2. The average UCS values of unreinforced and fibre-reinforced CPBs were 197.1kPa and 246.5 kPa respectively, and UCS based estimated safe prototype heights were 17.7 m and 28.4 m, respectively. The results showed that prototype heights from centrifuge tests were larger than those from...
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UCS tests. It would be conservative for backfill design to use the UCS data, particularly for the reinforced stopes. The failure height (obtained in the centrifuge) divided by the predicted height based on the UCS value may be considered a form of safety factor, $F_s$. For the unreinforced stopes, $F_s = 1.32$, whereas for the fully reinforced stopes, $F_s > 2.57$ (remembering that these stopes did not fail). Moreover, the practical failure heights of fibre reinforced CPB stopes are not likely to be predicted by the conventional Mitchell solution as both strength and ductility have an impact on achievable prototype heights, a factor that is not accounted for by Mitchell’s solution. Improved ductility allows the peak strength to be mobilized over the entire failure surface within a fill mass, whereas in a brittle (e.g. unreinforced) material the sharp loss in post-peak strength results in progressive failure whereby the strength mobilized at failure is less than the peak strength.

5.4 Conclusions

A series of model tests were successfully carried out in the 50 g-tonne centrifuge equipment at Tsinghua University to explore the performance of fibre-reinforced CPB stopes in underground mines. The failure stope heights in the centrifuge were compared with conventional predictions based on UCS test data. The following conclusions can be drawn from this work.

Fibre reinforced CPB stopes behaved in a more ductile fashion than unreinforced stopes, exhibiting significantly larger displacements towards the exposed face of the model stope prior to failure (if failure indeed occurred) than unreinforced stopes, with the pattern of outward displacement also being smoother than for unreinforced stopes. The ductility of part-reinforced models was more significant when higher reinforcement percentages were used.
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The failure mass ratio of stopes became much lower when increasing the reinforcement percentage, especially for fully reinforced stopes, when the ratios were close to zero. Reduced ore dilution and increased production rates could potentially be achieved by using fibre-reinforced CPB, especially when filled stopes are exposed by adjacent excavations.

Not all fibre-reinforced zones of model stopes failed under the maximum applied centrifugal acceleration, whereas unreinforced zones showed brittle failure behaviour, with sudden falls of material, which occurred with such velocity that the dislodged blocks were severely fragmented upon contact with the centrifuge floor. In partly reinforced stopes, the failure plane always developed from the interface between reinforced and unreinforced areas.

The predicted prototype heights of models were increased by at least 100% with full fibre reinforcing. It indicates the possibility of shortening stope fill cycle times by increasing the exposure height of CPB stopes.

The backfill design method based on UCS test data was conservative compared with centrifuge results, providing a reasonable factor of safety. However, Mitchell’s solution proved inappropriate for the design of fibre-reinforced CPB stopes, severely underestimating the failure height of these stopes. Future work will focus on developing a new method of stability evaluation for reinforced CPB stopes and for exploring the potential applications of fibre reinforcement in underground mining.

5.5 References


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Huang, S., Xia, K., Qiao, L., 2011. Dynamic tests of cemented paste backfill: effects of strain rate, curing time, and cement content on compressive strength. J. Mater. Sci. 46 (15), 5165-5170.


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Table 5-1. Chemical composition of the tailing

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<th>Amount: %</th>
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<th>Amount: %</th>
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Table 5-2. Summary of test data

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<tr>
<th>Model type</th>
<th>Average UCS (kPa)</th>
<th>UCS based prototype height (m)</th>
<th>Centrifuge based prototype height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced CPB</td>
<td>197.1</td>
<td>17.7</td>
<td>23.4</td>
</tr>
<tr>
<td>Full-reinforced CPB</td>
<td>246.5</td>
<td>28.4</td>
<td>73.0</td>
</tr>
</tbody>
</table>
Chapter 5

Centrifuge model studies on the stability of fibre-reinforced cemented paste backfill

Figure 5-1. Particle-size distribution

Figure 5-2. Monofilament polypropylene fibres
Figure 5-3. Testing models

Figure 5-4. Strongbox with models
Figure 5-5. Vertical displacement versus time
Figure 5-6. Failure mass ratios of models 1-8
Figure 5-7. Failure patterns of models 1-8
Figure 5-8. Equivalent prototype heights of models 1-8
Figure 5-9. Backfilled stope with the exposed face
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6.1 Main findings

This thesis has presented experimental studies on the mechanical behaviour of fibre-reinforced cemented paste backfill. Unconfined compression tests, X-ray computed tomography, triaxial compression tests and centrifuge model tests were successfully carried out to accomplish the research objects. The major contributions and outcomes made in this research are summarised below.

The inclusion of polypropylene fibres substantially enhanced the peak and residual shear strength and deformability of CPB, and changed the load response of CPB to a noticeably ductile behaviour. Fibre-reinforced CPB exhibited a significant yield instead of failure, with little or no post-peak loss of strength throughout compressive tests, and always maintained its integrity without evident spalling and fallen fragments.

Inspection of failed fibre-reinforced CPB using X-ray computed tomography demonstrated that the propagation of cracks was arrested by the development of fibre tension across the developing crack. Fibre reinforcement was mainly mobilised during the post-peak strength stage when resistance to pullout from the CPB matrix was mobilised. At the early curing age, fibres contributed less to post-cracking resistance due to the weak wrapping pressure from the CPB matrix, while after the particle-to-particle bonds being fully developed
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through cement hydration, the maximum tension of fibres would be mobilised resulting in
the significant improvement of compressive strength and energy absorption capability.

Several factors of fibres would influence the performance of reinforcement, in terms of the
length, diameter and quantity. Longer and thinner fibres were identified as the optimised
for the particular tailings used to improve both the equivalent shear strength and the axial
strain at the peak strength. Generally, for achieving maximum strength, the optimum fibre
content for reinforced CPB should be around 0.5% by weight of total solids.

An increase of cement content in CPB significantly increased the peak and residual shear
strength, initial stiffness and brittleness, but had little influence on the increase of strain
values at peak strength and the increase of energy absorption capacity.

The centrifuge model study certified that fibre-reinforced CPB behaved more ductile with
smoother and larger increase of displacement along the increment of gravity acceleration.
Failure mass ratio was reduced and predicted prototype height was increased, as long as the
increase of fibre-reinforcing rate.

The potentially beneficial effect of these polypropylene fibres in improving the stability of
CPB in-situ is to prevent the fall of blocks and the dilution of ore. Especially for the
current cut-and-fill method, both strength and durability of CPB should be considered in
the assessment of stope stability when mining the adjacent ore. Massive addition of cement
content would not improve the ductility of CPB but only benefit the strength before
failure. When under the extreme conditions, such as rock burst, squeezing ground, blast or
seismic event, it is more important for CPB to maintain the stability and integrity after
damage until the end of recent cycle. Meanwhile, the increased exposure height of CPB is
likely to shorten the stope fill cycle time for economic and efficient purpose.
Overall, the results presented in this research provide a potentially inexpensive technique for reducing a major safety and financial risk of underground mining.

6.2 Recommendations for future work

Experimental investigations of mechanical behaviour of fibre-reinforced cemented paste backfill have been carried out in this research. Further investigations needed to refine the research results reported in this thesis are outlined below:

Tensile strength is also critical in the assessment of CPB stability for some particular mining methods. The commonly used splitting tensile strength test is not appropriate for the study of CPB since its properties are different from concrete and soils. A more precisely experimental plan can be developed to investigate the tensile behaviour of unreinforced and fibre-reinforced CPB.

The specimen preparation of fibre-reinforced CPB was conducted in the laboratory by mixing tailings, cement, water and fibres in the blender and curing the specimens in the humidity chamber. However, the planting of backfilling materials in-situ is more complicated. The mix, pumpability and in-situ curing conditions of fibre-reinforced CPB need to be considered and simulated for further laboratory tests.

Centrifuge tests were carried out on four CPB models with different reinforcing rates. Although the effect of fibre reinforcement was remarkable, more testing models with different cement and fibre content can be developed in centrifuge for a comprehensive investigation.
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Numerical simulation can be adopted to study the deformation and failure of unreinforced and fibre-reinforced CPBs under loading conditions. However, a newly numerical model should be developed to simulate the interaction between fibres and CPB matrix.