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Zhenjun Shan

Ting Ren

Douglas Pateman

Guanzheng Wu

Jan Nemcik

See next page for additional authors

Authors

Zhenjun Shan, Ting Ren, Douglas Pateman, Guanzheng Wu, Jan Nemcik, Hongchao Zhao, and Xiaohan Yang

EXPERIMENTAL STUDY ON THE UNIAXIAL COMPRESSIVE BEHAVIOUR OF A FIBRE REINFORCED POLYMER STANDING SUPPORT

Zhenjun Shan[1], Ting Ren[2]*, Douglas Pateman[3], Guanzheng Wu[4], Jan Nemcik[5], Hongchao Zhao[6] and Xiaohan Yang[7]

ABSTRACT: Laboratory tests were conducted to investigate the behaviour of an innovative fibre reinforced polymer (FRP) standing support subject to uniaxial compression. The FRP standing support consisted of two major components: 1) the internal cylindrical concrete column made of coal rejects and a cementitious grout, and 2) the external FRP jacket. A total of ten specimens with different water-to-cementitious grout (w/c) ratios and various layers of FRP confinement were prepared and tested. As expected, an increased w/c ratio adversely affected the compressive strength of the internal cylindrical column. The compressive strength of the column decreased from 15.9 MPa to 13.4 MPa when the w/c ratio increased from 1 to 1.2. Test results also indicated that the columns became much stronger and more deformable when confined with an FRP jacket. In contrast to the unconfined control specimens, the columns confined with two layers of FRP experienced an increase of approximately 150% in maximum compressive strength at approximately 500% higher axial deformation. A further growth in strength and deformability was also observed when the columns were confined with four layers of FRP. The maximum strength and deformability achieved were up to 49.6 MPa and 7.2% respectively.

INTRODUCTION

Conventional standing supports, such as pumpable cribs and the can supports, have been widely used for roof support in underground mines for a long time. However, they both have some intrinsic disadvantages. Application of pumpable cribs is not labour intensive but they generally have low deformability before peak load and afterwards demonstrate load-shedding behaviour (Barczak 2005). It is well established that high deformable standing support is desirable for strata control in longwall tailgates where high roof to floor convergence prevails. While the can-support is highly deformable (Barczak and Tadolini 2008), its handling limitations and disruption to ventilation become important concerns when it needs to be scaled up to achieve a higher load capacity (Tarrant 2005). Also, the can support might be a potential cause of gas explosions when cut by the shearer (Yu et al. 2019).

Due to the high strength-to-weight ratio and superior corrosion resistance, FRP jackets have been widely used in the civil industry to confine concrete columns (Lam and Teng 2003). It has been proven that FRP is able to significantly enhance both the strength and ductility of the concrete columns (Ozbakkaloglu and Lim 2013). As such, an innovative standing support concept using mine waste infill confined with FRP was proposed at the University of Wollongong and has been under development for 5 years. The novel FRP standing support consists of two major components: the external FRP jacket which generates confining resistance to the dilated infill column under compression, and the infill column made of cementitious grout mixed with mine waste such as coal rejects. Many studies have been conducted to investigate the influence of FRP type and thickness and infill material composition on the performance of the novel standing support (Zhao et al. 2021a; Zhao et al. 2021b; Ren et al. 2022a). The

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[1] *Research fellow, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia. Email: zshan@uow.edu.au.*

[2] *Professor, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia. Email: tren@uow.edu.au.*

* *Corresponding author*

[3] *Marketing and Business Development Lead, Minova Australia. Email: douglas.pateman@minovaglobal.com.*

[4] *PhD candidate, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia. Email: jnemcik@uow.edu.au.*

[5] *Honorary fellow, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia. Email: jnemcik@uow.edu.au.*

[6] *Associate professor, School of Geology and Mining Engineering, Xinjiang University, Urumqi, Xinjiang 830000, China. Email: zhaohongchao@xju.edu.cn.*

[7] *Research fellow, School of Civil Engineering, University of Queensland, Brisbane, QLD 4072, Australia. Email: xiaohan.yang@uq.edu.au.*

strength of a potential infill material made of mine waste with various mixtures has also been evaluated (Ren et al. 2022b). This study is an extension to the previous research with the objective to assess the behaviour of a FRP standing support with the infill column made of crushed coal rejects when subject to uniaxial compression. Success of the new standing supports is envisaged to not only help maintain the stability of the strata but also bring environmental and economic benefits.

EXPERIMENTAL PROGRAMME

To investigate performance of the FRP standing supports subjected to uniaxial compression, 10 columns with and without FRP confinement were prepared. As mentioned above, the infill column was made of coal rejects and one type of cementitious grout (FB200 grout provided by Minova). Among the 10 columns, four of them had a water to cementitious grout ratio of 1 and the other six columns had a ratio of 1.2. To evaluate the influence of FRP thickness on its confinement performance this study used no FRP as a control group and two and four FRP layers. For easy reference, each specimen was given a name in this study (**Table 1**). The specimen’s name starts with the letter ‘R’ and a number, which indicates the w/c ratio of the infill column followed by the letter ‘F’ and a number which identifies the number of FRP layers. Note that the letter ‘F’ and the specimen number are omitted if the column is unconfined with FRP shell. The specimen name ends up with dash ‘-‘ and a number, indicating the particular specimen in that group.

Table 1: Specimen descriptions and key test results

Specimen name	Confinement	w/c ratio	f'_{cc} (f'_{co}), MPa	f'_{cc}/f'_{co}	ε_{cc} (ε_{co}), %	$\varepsilon_{cc}/\varepsilon_{co}$	*E (E_1, E_2), GPa*
R1-1	N/A	1	16.3	-	0.63	-	2.6
R1-2	N/A	1	15.5	-	0.71	-	2.2
R1F2-1	2 layers of FRP	1	37.5	2.4	3.93	5.9	2.6, 0.27
R1F4-1	4 layers of FRP	1	49.6	3.1	4.91	7.3	2.3, 0.44
R1.2-1	N/A	1.2	13.1	-	0.75	-	1.8
R1.2-2	N/A	1.2	13.7	-	0.72	-	1.9
R1.2F2-1	2 layers of FRP	1.2	32.6	2.4	5.07	6.9	1.6, 0.23
R1.2F2-2	2 layers of FRP	1.2	33.6	2.5	4.32	5.8	1.7, 0.27
R1.2F4-1	4 layers of FRP	1.2	46.3	3.5	7.93	10.7	1.7, 0.30
R1.2F4-2	4 layers of FRP	1.2	42.9	3.2	6.37	8.6	1.7, 0.31

Figure 1 shows the preparation process of the specimens. Coal rejects were collected from a local coal mine and placed in an oven at 105°C for 24 hours to minimise the effect of various moisture levels on the specimen performance. Dry coal rejects were crushed to a nominal maximum size of 10 mm (**Figure 1a**). FB200 grout was mixed with water, then evenly mixed with prepared coal rejects using an electrical drill (**Figure 1b**). The mixture was then poured into a plastic mould and cured for 24 hours before removing (**Figure 1c**). The cylindrical columns, 150 mm in diameter and 450 mm in height, were further cured in a humidity room for more than 180 days (**Figure 1d**) prior to being wrapped with glass FRP (**Figure 1e**). Note that a 150 mm overlapping zone was applied to all FRP confined columns. The columns were capped with high strength plaster at both ends (**Figure 1f**) before testing to ensure even loading distribution.

Figure 2 illustrates the test set-up. The tests were conducted using a 500 tonne compression machine. A consistent loading rate of 0.6 mm/min was applied to all specimens. Two linear variable differential transformers (LVDT) were placed at diagonal positions to measure the axial displacement of the specimens, with the load recorded by the data loger. For the plain columns, the test was terminated immediately after visible cracking was observed. When testing the FRP confined columns, the test was stopped when an FRP rupture was observerved.

Figure 1: Preparation of specimens

Figure 2: Test set-up

RESULTS AND DISCUSSIONS

Failure modes

The typical failure modes of the specimens are shown in **Figure 3**. As expected, the plain column experienced brittle failure with a single shear plane observed when the column failed (**Figure 3a**). While testing the FRP confined columns, the polymer resin began to yield when the white horizontal straps appeared as shown in **Figure 3b**. The confining pressure in the FRP jacket kept increasing in response to the continuous axial load increase until sudden rupture of the FRP jacket occurred, indicating a total sample failure.

Axial stress-axial strain curves

Figure 4 illustrates the axial stress vs axial strain curves of the specimens. Note that the thickness of the FRP jacket was included as part of the cross-sectional area when calculating the axial stresses from the axial load. The axial strain was the average of the two LVDT measurements divided by the original overall height of the specimen. The stress-strain curves of the plain column samples were approximately linear prior to brittle failure. The columns with a lower w/c ratio were slightly stiffer than the columns with higher w/c ratios. The average Young's moduli of the two types of plain columns were 2.4 GPa and 1.9

GPa respectively (**Table 1**). On the other hand, the FRP columns featured generally a bilinear ascending relationship before reaching the peak stress, which was attributed to the confinement provided by the FRP shell. The elastic loading of FRP samples reached a much higher axial stress (more than double of the unconfined sample strength) prior to yielding of the infill due to the confinement provided by FRP. After the infill failure, the FRP sample strength kept rising due to the continuous confinement provided by the FRP jacket. The loading slope for the first ascending stage of the FRP confined specimens was similar to that of their unconfined counterparts, indicating that the FRP confinement was passive before the infill failure. It is worth noting that the slope of the second ascending stage was smaller than that of the first stage because the failed infill column dilated quicker in the second stage (Ozbakkaloglu et al. 2013). Also, slight fluctuations were observed during the second stage of some FRP confined specimens, likely occurring due to cracking of the capping plaster and yielding of the FRP or behaviour in the inner column.

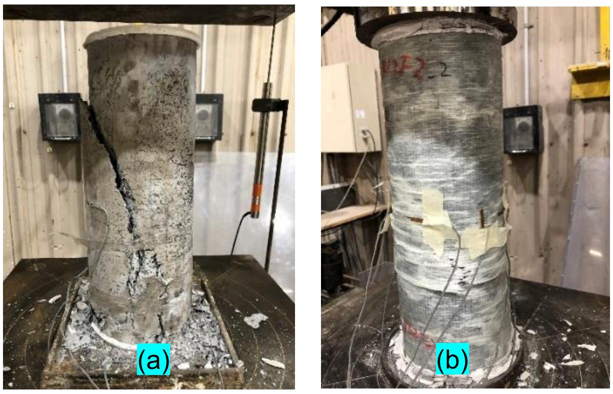

Figure 3: Failure modes of plain and FRP confined columns

To quantitatively compare the stiffness of the FRP confined columns in the two ascending stages, the average Young's moduli of the specimens were referred to as *E₁* and *E₂* respectively and were calculated using the following equations:

$$E_1 = \frac{f_y'}{\varepsilon_y} \tag{1}$$

$$E_2 = \frac{f_{cc}' - f_y'}{\varepsilon_{cc} - \varepsilon_y} \tag{2}$$

Where, f_y' is the stress at yield which marks the beginning of significant change in the slope of the stress-strain curve; ε_y is the axial strain at yield; f_{cc}' is the maximum stress achieved and ε_{cc} is the corresponding axial strain. While E_1 of columns with confinement of two FRP layers and a w/c ratio of 1.2 (R1.2F2) was 1.7 GPa, E_2 was substantially reduced to 0.25 GPa (average value) as shown in **Table 1**. The same trend was also observed for the columns confined with four layers of FRP. Test results also demonstrated that the thickness of the FRP shell was able to enhance the stiffness of the columns in the second ascending stage. While E_2 of R1.2F2 was 0.25 GPa, it slightly increased to 0.31 GPa when four layers of FRP were applied. This was because a thicker FRP shell was able to generate a greater resistance force than the thinner FRP jacket under the same hoop strain condition.

Figure 5 illustrates the influence of infill material strength on the performance of the FRP confined columns. It can be seen that stronger infill resulted in greater stiffness in the first ascending stage. E_1 of the specimens with a w/c ratio of 1 was larger than that of the specimens with a w/c ratio of 1.2, regardless of the number of FRP layers applied. With respect to the stiffness in the second ascending stage, the difference in E_2 was negligible for the two groups of specimens with two layers of FRP confinement. The difference became larger when the specimens were confined with four layers of FRP. E_2 of R1F4 was 0.44 GPa while E_2 of R1.2F4 was 0.31 GPa. This was likely due to the greater w/c ratio weakening the infill column in the second ascending stage.

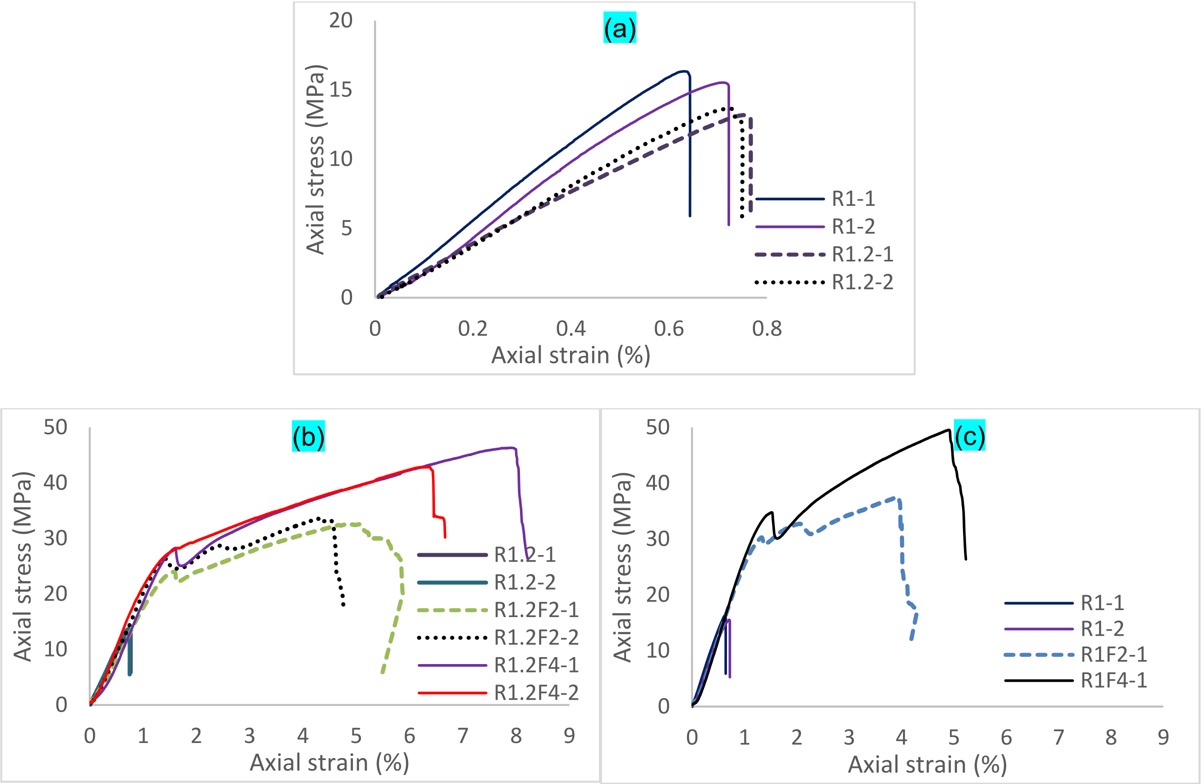

Figure 4: Axial stress-axial strain curves of the specimens: a) plain columns showing variation in w/c ratios; b) Columns with w/c ratio of 1.2; c) Columns with w/c ratio of 1

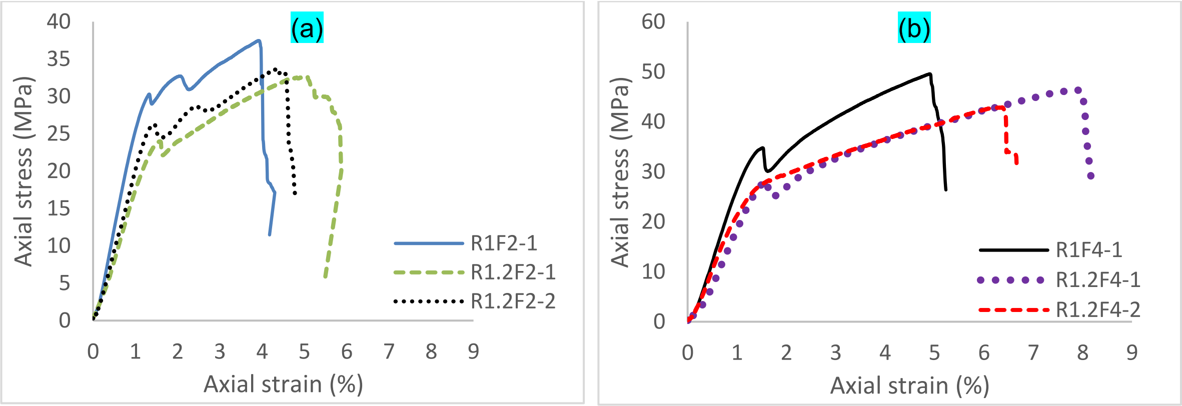

Figure 5: Effect of infill column strength on the behaviour of the specimens: a) specimens with two layers of FRP, b) specimens with four layers of FRP

Strength and deformability

The strength and deformability of the studied specimens are shown in **Figure 6** and **Table 1**. It can be seen that a decrease in the w/c ratio resulted in a stronger infill column. When the w/c ratio reduced from 1.2 to 1, the uniaxial compressive strength (UCS) of the unconfined infill column (f'_{co}) increased by 19% from 13.4 MPa to 15.9 MPa. As expected, the UCS of the FRP confined column (f'_{cc}) was significantly higher as a result of the FRP confinement. In general, the thicker the FRP layer, the stronger the FRP column. The thicker FRP layer is able to provide greater confining pressure which can be calculated using the following equation (Vincent and Ozbakkaloglu 2013):

$$f_{l,a} = \frac{2tE_{frp}\varepsilon_{h,rup}}{D} \tag{3}$$

Where $f_{l,a}$ is the actual confining pressure of the FRP, *t* is the thickness of the FRP jacket, E_{frp} is the elastic modulus of the FRP, $\varepsilon_{h,rup}$ is the hoop rupture strain of the FRP and D is the diameter of the infill column. As shown in **Figure 6a**, the UCS of the plain column with a w/c ratio of 1.2 increased approximately 1.5 times when confined with two layers of FRP. The increase in UCS was further improved on average 2.3 times when four layers of FRP were applied. A similar trend was also found for the group of specimens with a w/c ratio of 1, where the strength enhancement ratios (f'_{cc}/f'_{co}) were 2.4 and 3.1 for 2 layers and 4 layers of FRP respectively (**Figure 7a**).

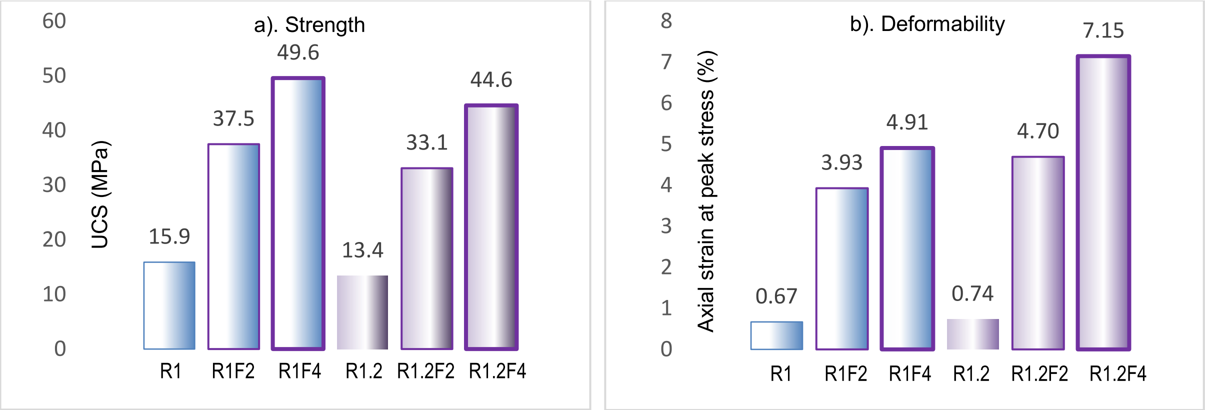

Figure 6: Strength and deformability of the specimens

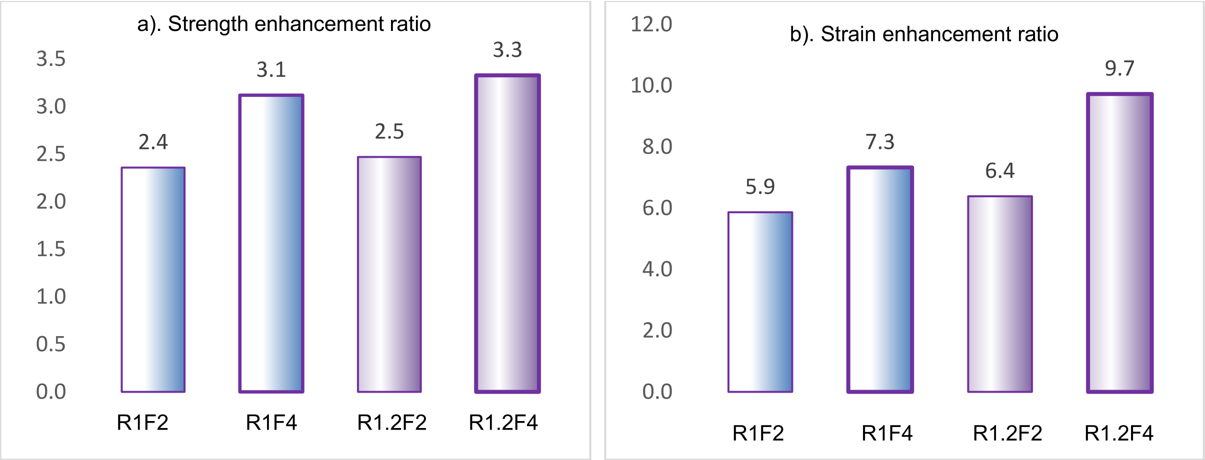

Figure 7: Strength enhancement ratios (a) and strain enhancement ratios (b) of the specimens

The scale effect needs to be considered to estimate the required thickness of the FRP for *insitu* use. The equation (3) above indicates that the FRP thickness is approximately proportional to the diameter of the column to provide comparable confinement for any column diameter.

In addition to the strength of the FRP standing support, deformability is another important factor that determines the suitability of the innovative standing support. These supports with high deformability are desirable for roof support in longwall tailgates where large roof to floor convergence prevails. **Figure 6b** illustrates the axial strain of the specimens at peak stress. It is clear that a slight reduction in axial strain was experienced in the unconfined infill columns when the w/c ratio decreased from 1.2 to 1, dropping from 0.74% to 0.67%. The FRP shell was able to not only enhance the strength of the columns but also significantly improve their deformability. The axial strain at peak stress increased to 4.7% when the columns with a w/c ratio of 1.2 were confined with two layers of FRP shell. A further increase to 7.15% was achieved when the columns were confined with four layers of FRP shell. Both groups of specimens demonstrated that the strain enhancement ratio ($\varepsilon_{cc}/\varepsilon_{co}$) increased with greater number of FRP layers as shown in **Figure 7b**.

CONCLUSIONS

This study investigates the behaviour of an innovative glass fibre reinforced polymer (FRP) standing support using laboratory testing. The experiments compared the plain unconfined coal rejects-grout columns against the FRP confined column samples with two water-to-cementitious grout ratios of 1 and 1.2. The confined samples with two and four 1.25mm thick FRP layers were 2.4 to 3.3 times stronger than the unconfined samples. In the elastic stage of loading, the FRP column strength increased by more than twice when compared with unconfined samples. Other benefits are the significant increase in ductility ranging from six to ten times the measured deformation of the plain columns at failure.

The scale effect needs to be considered to estimate the required thickness of the FRP for *insitu* use. The equation (3) above indicates that the FRP thickness is approximately proportional to the diameter of the column to provide comparable confinement for any column diameter.

Two water-to-grout (w/c) ratios of 1 and 1.2 were assessed. With higher w/c ratios, all samples exhibited lower strength but higher deformability with lower Young's moduli.

These tests clearly demonstrate the significant benefits of the FRP confinement. One of the major advantages of FRP columns is that the ductility increases with the strength of the samples. In contrast to the unconfined columns made of stronger materials the columns usually exhibit a brittle behaviour with limited deformability. This is undesirable in coal mines where large convergences are unavoidable with premature failure of brittle supports.

Further research on testing larger scale columns would be desirable prior to the field applications.

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REFERENCES

Barczak T (2005). An overview of standing roof support practices and developments in the United States. In: Proceedings of the Third South African Rock Engineering Symposium: South African Institute of Mining and Metallurgy, Johannesburg, Republic of South Africa, October, pp 301–334.

Barczak TM and Tadolini SC (2008). Pumpable roof supports: an evolution in longwall roof support technology. Trans Soc Min Met Explor 324:19–31.

Lam L and Teng JG (2003). Design-oriented stress–strain model for FRP-confined concrete, Constr. Build. Mater. 17 (6-7) (2003) 471–489.

Ozbakkaloglu T and Lim JC (2013). Axial compressive behavior of FRP-confined concrete: Experimental test database and a new design-oriented model. Composites: Part B; 55: 607-634.

Ozbakkaloglu T, Lim JC and Vincent T (2013). FRP-confined concrete in circular sections: Review and assessment of stress–strain models. Eng Struct; 49:1068–88.

Ren T, Zhao HC, Remennikov A, Shan Z (2022a). Fibre-reinforced polymer confined-coal rejects concrete: Compressive behaviour. Compos Struct 2022;299:116063.

Ren T., Shan Z., Yang X., Zhao H. & Nemcik J. (2022b). Using coal rejects and tailings as infills for standing supports in underground gateroads, Proceedings of the 2022 Resource Operators Conference (pp. 224-231), Australia: University of Wollongong.

Tarrant G (2005). Loading Mechanics of the 'Can' and Implications for Improved Strength and Stiffness Properties, Proceedings of the 2005 Coal Operators' Conference (pp. 63-72), Brisbane, QLD, Australia.

Vincent T and Ozbakkaloglu T (2013). Influence of concrete strength and confinement method on axial compressive behavior of FRP confined high- and ultra high-strength concrete. Composites: Part B; 50: 413-428.

Yu T, Zhao H, Ren T and Remennikov A (2019). Novel hybrid FRP tubular columns with large deformation capacity: Concept and behaviour. Compos Struct; 212:500–12.

Zhao H, Ren T and Remennikov A (2021a). A hybrid tubular standing support for underground mines: Compressive behaviour. International Journal of Mining Science and Technology; 31(2):215-224.

Zhao H, Ren T and Remennikov A (2021b). Behaviour of FRP-confined coal rejects based backfill material under compression. Construction and Building Materials; 268:121171.