E-ISSN 2541-2116
ISSN 2443-2083

Jurnal Geomine

Jurnal Geomine, Volume 9, Nomor 1: April 2021, Hal. 73 - 87

Analysis of Reinforcement System (Rock Bolt and Shotcrete) Effect on The Pillars Strength in Underground Mining Using Physical Models Testing in Laboratory

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ABSTRACT

The effects of reinforcement system on pillars were tested in laboratory, using three types of pillars with different strengths. The tests were performed using the UCS machine, to test pillar without reinforcement, pillar with rock bolt reinforcement, pillar with shotcrete reinforcement and pillar with the combination of both rock bolt and shotcrete reinforcement. Uniaxial compressive strength (UCS) testing aims to determine the effects of the reinforcement system on pillar strength. The results of this study indicate that the reinforcement system on high strength pillars causes a strength increase of 14.93% on pillar with rock bolt reinforcement, 21.45% on pillar with shotcrete reinforcement and 34.67% on pillar with combination of rock bolt and shotcrete reinforcement. On medium strength pillars, reinforcement installation shows a strength increase of 16.27% on pillar with reinforced rock bolt, 19.83% on pillar with reinforced shotcrete and 44.40% on pillar with combination of rock bolt and shotcrete reinforcement. Likewise, on low strength pillars, reinforcement installation causes a strength increase of 13.13% on pillar with reinforced rock bolt, 36.21% on pillar with reinforced shotcrete and 53.85% on pillar with combination of rock bolt and shotcrete reinforcement. The results of laboratory testing and numerical modeling indicate that the increase in strength occurs because the horizontal displacement on the surface of the pillar wall is detained by shotcrete and faceplate on rock bolt, so that the pillar seems to have confining pressure throughout the pillar wall surface, which is called as equivalent confining pressure.

Keywords: Pillar; Reinforcement; Confining Pressure; Modeling.

SARI

Pengaruh sistem perkuatan terhadap pilar diuji di laboratorium, menggunakan tiga jenis pilar dengan kekuatan berbeda. Pengujian dilakukan dengan menggunakan mesin UCS, untuk pengujian pilar tanpa perkuatan, pilar dengan perkuatan rock bolt, pilar dengan perkuatan shotcrete dan pilar dengan kombinasi perkuatan rock bolt dan perkuatan shotcrete.

How to Cite: Dzakir, L.O., Rai, M.A., Widodo, N.P., 2021. Analysis of Reinforcement System (Rock Bolt and Shotcrete) Effect on The Pillars Strength in Underground Mining Using Physical Models Testing in Laboratory. Jurnal Geomine, 9(1): 73-87.

Published By:
Fakultas Teknologi Industri
Universitas Muslim Indonesia
Address:
Jl. Urip Sumoharjo Km. 05
Makassar, Sulawesi Selatan
Email:
geomine@umi.ac.id

Article History:
Submite 03 Oktober 2020
Received in from 10 Oktober 2021
Accepted 05 April 2021

E-ISSN 2541-2116
ISSN 2443-2083

Pengujian kuat tekan uniaksial (UCS) bertujuan untuk mengetahui pengaruh sistem perkuatan terhadap kekuatan pilar. Hasil penelitian ini menunjukkan bahwa sistem perkuatan pada pilar kekuatan tinggi menyebabkan peningkatan kekuatan 14,93% pada pilar dengan tulangan baut batu, 21,45% pada pilar dengan tulangan shotcrete dan 34,67% pada pilar dengan kombinasi tulangan rock bolt dan shotcrete. Pada pilar kekuatan sedang, pemasangan tulangan menunjukkan peningkatan kekuatan sebesar 16,27% pada pilar dengan perkuatan rock bolt, 19,83% pada pilar dengan perkuatan shotcrete dan 44,40% pada pilar dengan kombinasi perkuatan rock bolt dan perkuatan shotcrete. Demikian pula pada pilar dengan kekuatan rendah, pemasangan perkuatan menyebabkan peningkatan kekuatan sebesar 13,13% pada pilar dengan perkuatan rock bolt, 36,21% pada pilar dengan perkuatan shotcrete dan 53,85% pada pilar dengan kombinasi perkuatan rock bolt dan perkuatan shotcrete. Hasil pengujian laboratorium dan pemodelan numerik menunjukkan bahwa peningkatan kekuatan terjadi karena perpindahan horizontal pada permukaan dinding pilar tertahan oleh shotcrete dan faceplate pada rock bolt, sehingga pilar tersebut seolah-olah mengalami confining pressure di seluruh permukaan dinding pilar, yang disebut dengan confining pressure ekivalen.

Kata kunci: Pillar; Perkuatan; Confining Pressure; Pemodelan.

INTRODUCTION

Pillars are an integral load bearing member in underground mines and play an important role in upholding the functional integrity of the mine openings (Sinha and Walton, 2021). Rock pillars are commonly used in underground mines to maintain stability of excavations (Wang and Cai, 2021). Using the rock itself as the support element, rather than introducing artificial, and hence more expensive, materials is an elegant engineering solution to rock engineering projects (Hudson and Harrison 1997). Because it functions as a support, the pillar must have considerable strength. The pillar strength itself depends on the stress experienced by the pillar. The greater the stress on the pillar, the greater the potential for the pillar to failure (Hoek and Brown, 1980; Hamid, 2017).

Because of these problems, a research to increase pillar strength and prevent the pillars to failure is needed. One way to increase the pillar strength is by installing a reinforcement system on the pillar (Hoek, Kaiser, and Bawden, 1995). Problems regarding the reinforcement system on pillars have been investigated by experts, including Wojtkowiak, Rai and Bonvallet (1985) who conducted research on Rock and Soil Reinforcement and Support, Ringwald and Brawner (1989) who proved that the strength increase experienced by pillar with rock bolt reinforcement strongly influenced by confining pressure which arises because the faceplate attached to both ends of the rock bolt is tightened, Waclawik, Snuparek and Kukutsch (2017) who proved that the bolting support of the ribs is loaded very strongly and its proper design has a decisive effect on the decrease of deformation and strengthening of pillars. Likewise, the results of a research conducted by Ozturk and Guner (2017) show that thin spray-on liners with a thickness of >20% (TSL thickness to core diameter ratio) had a significant influence on increasing the pillar strength.

Based on the results of these research, a further verification or research related to the influence of reinforcement system on pillars is required. This research was conducted using pillar physical models with three different strengths and two reinforcement systems, namely rock bolt and shotcrete. The rock bolt used was made of stainless steel with a diameter of 2 mm, while the shotcrete used was made from a mixture of cement and water with a ratio of 1:1. In this research, each pillar with different strengths will be given different treatments, namely pillar without reinforcement, pillar with rock bolt reinforcement, pillar with shotcrete reinforcement and pillar with combination of rock bolt and shotcrete reinforcement (Figure 1). Furthermore, each pillar was tested with a uniaxial compressive strength machine to observe the effect of the reinforcement system on the pillar strength (Ringwald and Brawner, 1989).

E-ISSN 2541-2116
ISSN 2443-2083

RESEARCH METHODS

Pillar sample preparation

In this study, physical model of the pillar was made of the mixtures of sand, cement and water (Table 1) with strengths resembling coal strength in Indonesia.

Table 1. Cement, sand and water ratio for each pillar

No	Pillar	Ratio (cement : sand : water)
1	High strength pillar	1:2:1.3
2	Medium strength pillar	1:3:1.3
3	Low strength pillar	1:5:1.3

The three types of pillars with different strengths (Table 1) were then given different treatments, namely pillar without reinforcement, pillar with rock bolt reinforcement, pillar with shotcrete reinforcement and pillar with combination of rock bolt and shotcrete reinforcement (Figure 1). After that, the dimension of each pillar was measured. The measurement results show that the pillars used in this research have an average height of ±170mm, diameter of ±84mm and thickness of ±8mm for the shotcrete layer.

a b c d

Figure 1. Pillar Physical Models (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement)

Testing

1. Physical Properties Test

In geotechnics the physical properties of the material that must be recognized are natural density(ρ_n), dry density (ρ_d), saturated density (ρ_s), natural water content (W), degree of saturation (S), porosity (n) and void ratio (e) (Rai, Kramadibrata, and Wattimena, 2013). Table 2 shows the results of the physical properties test on pillar and shotcrete materials which was conducted in the Laboratory of Geomechanics and Mine Equipment of Bandung Institute of Technology.

Table 2. Physical properties of pillar and shotcrete materials

No	Sample		ρ_n (g/cm^3)	ρ_d (g/cm^3)	ρ_s (g/cm^3)	W %	S %	n %	e
1	**Pillar**	High strength pillar	1.71	1.67	1.96	2	13	28	0.41
		Medium strength pillar	1.66	1.58	1.92	5	24	33	0.50
		Low strength pillar	1.50	1.34	1.79	12	34	45	0.83
2	**Shotcrete**		1.29	1.15	1.67	13	28	52	1.10

2. Mechanical Properties Test

a. Rock bolt

To obtain the mechanical properties of rock bolt material, a tensile test was carried out in the Production Engineering Laboratory of Bandung Institute of Technology. The test results can be seen in Table 3.

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Table 3. Mechanical properties of the rock bolt used for testing

No	Mechanical Properties	Value
1	Tensile Capacity (MN)	0.003
2	Young's Modulus, E (MPa)	6994.76

b. Shotcrete

To obtain the mechanical properties of shotcrete material, a uniaxial compressive strength (Jaeger, Cook and Zimmerman, 2007; Rai, Kramadibrata, and Wattimena, 2013) test was conducted using the HT-8391 Computer-Controlled Servo Hydraulic Concrete Compression Testing Machines in the Laboratory of Geomechanics and Mine Equipment of Bandung Institute of Technology. Table 4 shows the mechanical properties of shotcrete material obtained from the results of uniaxial compressive strength test.

Table 4. Mechanical properties of the shotcrete used for testing

No	Mechanical Properties	Value
1	uniaxial compressive strength, σ_c (MPa)	13.84
2	Young's Modulus, E (MPa)	2935.50
3	Poisson ratio, υ	0.23

c. Pillar

To find out the mechanical properties of the pillars (Table 5), a triaxial test and uniaxial compressive strength (UCS) test using HT-8391 Computer-Controlled Servo Hydraulic Concrete Compression Testing Machines were conducted. Triaxial test was conducted to obtain cohesion value (c) and internal friction angle (ϕ) of each pillar material, while UCS test was performed to obtain uniaxial compressive strength value ($\sigma_c = \sigma_1$), Young's modulus (E) and Poisson ratio (υ).

Table 5. Mechanical properties of the pillars used for testing

No	Type of Pilar	c (MPa)	ϕ (...°)	σ_1 (MPa)	E (MPa)	υ
1	High strength pillar	5.83	23.00	17.62	3239.39	0.26
2	Medium strength pillar	2.70	29.60	9.28	1950.89	0.21
3	Low strength pillar	1.36	35.90	5.33	1647.92	0.17

Based on the triaksial's test, it was obtained three Mohr Coulomb Failure envelopes. Those three failure envelopes latter would be used to estabilish the value of equivalent confining pressure appearing due to the installation of reinforcement system to the pillars (Ringwald and Brawner, 1989; Rai, 1981; Wojtkowiak, Rai, and Bonvallet 1985).

RESULTS AND DISCUSSION

Laboratory Test Results

a. Strength Increase

Based on the UCS test results (Figure 6) summarized in Table 6 and Figure 2, it is known that shotcrete reinforcement has a greater effect on increasing the pillar strength compared to rock bolt. Increased pillar strength happens because the shotcrete layer resists the horizontal displacement across the pillar wall surface, while the rock bolt reinforcement only restrains the horizontal displacement at the point where the faceplate is installed. From the test results, it can also be seen that the combination of rock bolt and shotcrete reinforcement gives a more significant effect on the pillar strength, because it combines two reinforcing materials which together serve to resist the horizontal displacement on the pillar wall surface in one pillar sample. Thus, the pillar will experience a greater increase in strength compared to the pillar with rock bolt reinforcement only or pillar with shotcrete reinforcement only. This can

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be seen in the percentage of strength increase in each pillar, where the percentage of strength increase on high strength pillars is 34.67%, medium strength pillars is 44.40% and low strength pillars is 53.85%.

In addition to increasing strength, the research results also show an increase in Young's modulus of each pillar with shotcrete reinforcement, rock bolt reinforcement and combination of rock bolt and shotcrete reinforcement as seen in Table 6 and Figures 3, 4 and 5.

Table 6. Strength increase on each pillar

NO	Type of Pillar	Pillar Treatment	σ_1 (MPa)	σ_1 Increase (%)	E (MPa)	E Increase (%)
1	High strength pillar	Pillar	17.62	0	3239.39	0
		Pillar + Rock Bolt	20.25	14.93	4093.03	26.35
		Pillar + Shotcrete	21.40	21.45	4617.49	42.54
		Pillar + Rock Bolt + Shotcrete	23.73	34.67	4885.03	50.80
2	Medium strength pillar	Pillar	9.28	0	1950.89	0
		Pillar + Rock Bolt	10.79	16.27	2533.47	29.86
		Pillar + Shotcrete	11.12	19.83	2601.26	33.34
		Pillar + Rock Bolt + Shotcrete	13.40	44.40	3185.44	63.28
3	Low strength pillar	Pillar	5.33	0	1647.92	0
		Pillar + Rock Bolt	6.03	13.13	1809.78	9.82
		Pillar + Shotcrete	7.26	36.21	1851.67	12.36
		Pillar + Rock Bolt + Shotcrete	8.20	53.85	1993.85	20.99

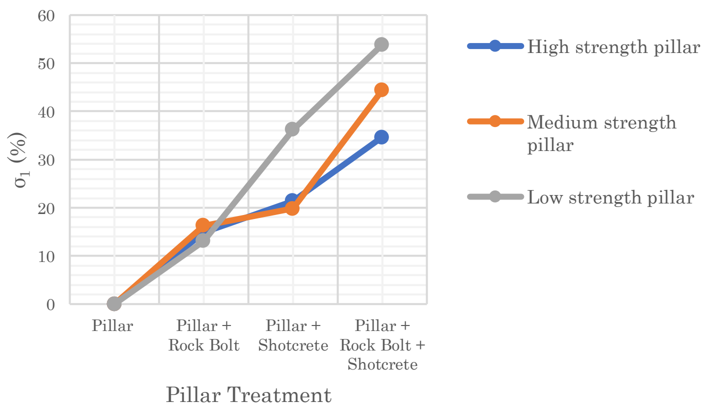

Figure 2. Pillar strength increase percentage

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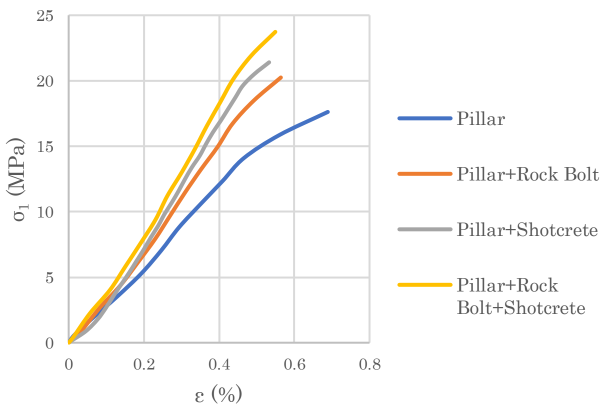

Figure 3. Stress vs strain curve for high strength pillars

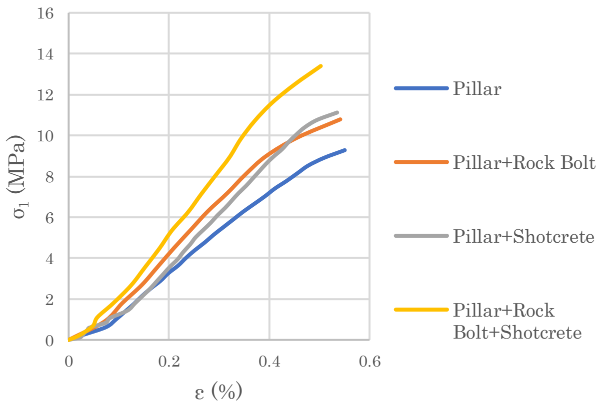

Figure 4. Stress vs strain curve for medium strength pillars

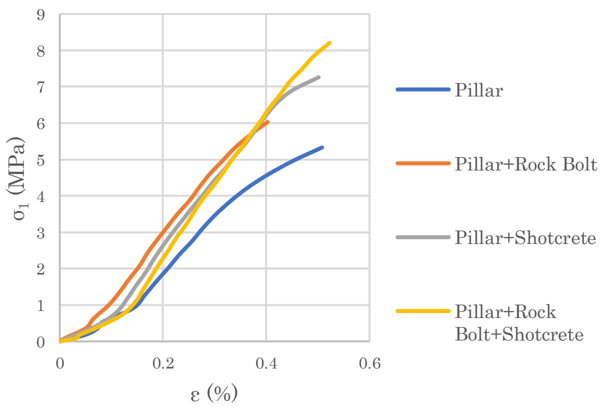

Figure 5. Stress vs strain curve for low strength pillars

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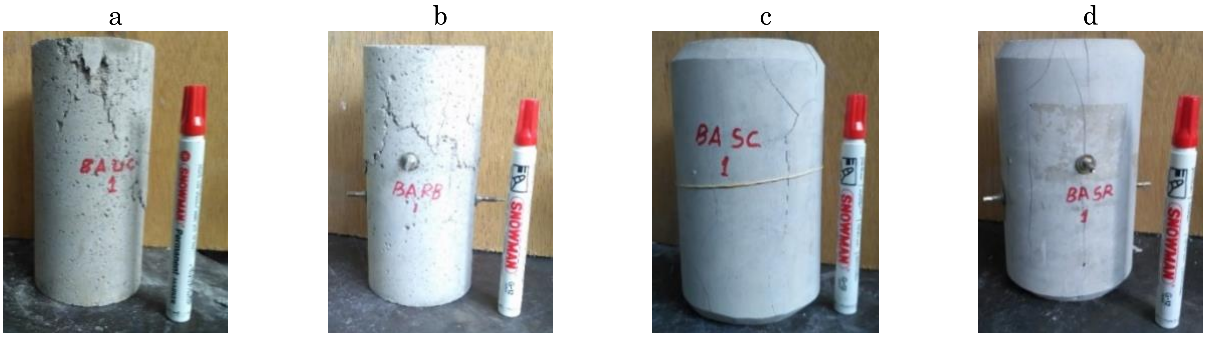

Figure 6. Examples of failure modes on pillars (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement)

b. Horizontal displacement (u_i)

Horizontal displacement (u_i) measurement was carried out at half the height of the pillar which aims to see the effect of reinforcement on the horizontal displacement (u_i) that occurs at the half height of the pillar. Based on the test results, it was found that the installation of reinforcement on the pillar generated a smaller horizontal displacement of the pillar wall compared to the horizontal displacement that occurred on pillar without reinforcement (Table 7). This can be seen in horizontal displacement percentage decrease as shown in Figure 7.

Table 7. Horizontal displacement (u_i) of each pillar wall

No	Type of Pillar	Pillar Treatment	Horizontal Displacement (m)	Decrease (%)
1	High Strength Pillar	Pillar	3.03×10^{-4}	0
		Pillar + Rock Bolt	2.13×10^{-4}	29.70
		Pillar + Shotcrete	1.94×10^{-4}	35.97
		Pillar + Rock Bolt + Shotcrete	1.72×10^{-4}	43.23
2	Medium Strength Pillar	Pillar	2.01×10^{-4}	0
		Pillar + Rock Bolt	1.70×10^{-4}	15.42
		Pillar + Shotcrete	1.65×10^{-4}	17.91
		Pillar + Rock Bolt + Shotcrete	1.55×10^{-4}	22.89
3	Low Strength Pillar	Pillar	1.28×10^{-4}	0
		Pillar + Rock Bolt	1.25×10^{-4}	2.34
		Pillar + Shotcrete	1.17×10^{-4}	8.59
		Pillar + Rock Bolt + Shotcrete	1.12×10^{-4}	12.5

Figure 7 shows that the percentage decrease in horizontal displacement (u_i) on the pillar wall surface is greater in the pillar with combination of rock bolt and shotcrete reinforcement compared to the pillar with rock bolt reinforcement only or pillar with shotcrete reinforcement only.

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ISSN 2443-2083

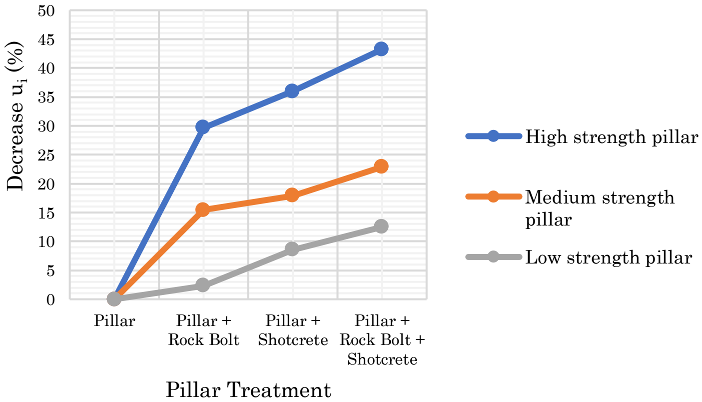

Figure 7. Percentage of decrease in horizontal displacement (u_i) caused by various reinforcement systems

c. Equivalent confining pressure

Equivalent confining pressure is the confining pressure arising because the horizontal displacement on the surface of the pillar wall is detained by shotcrete and faceplate on the rock bolt so that the pillar as if experiencing confining pressure (Ringwald an Brawner, 1989). The equivalent compression pressure value can be determined by inputting Mohr's semicircular line from point σ_1 ($\sigma_c = \sigma_1$) up to alluding failure envelope (obtained from the triaxial test) then the left leg of the half Mohr's circle is the equivalent confining pressure value or σ_3 ' (Figures 8, 9, 10) that appears due to reinforcement system installation on the pillar (Rai, 1981; Wojtkowiak, Rai, B and onvallet 1985; Das, Sobhan 2014).

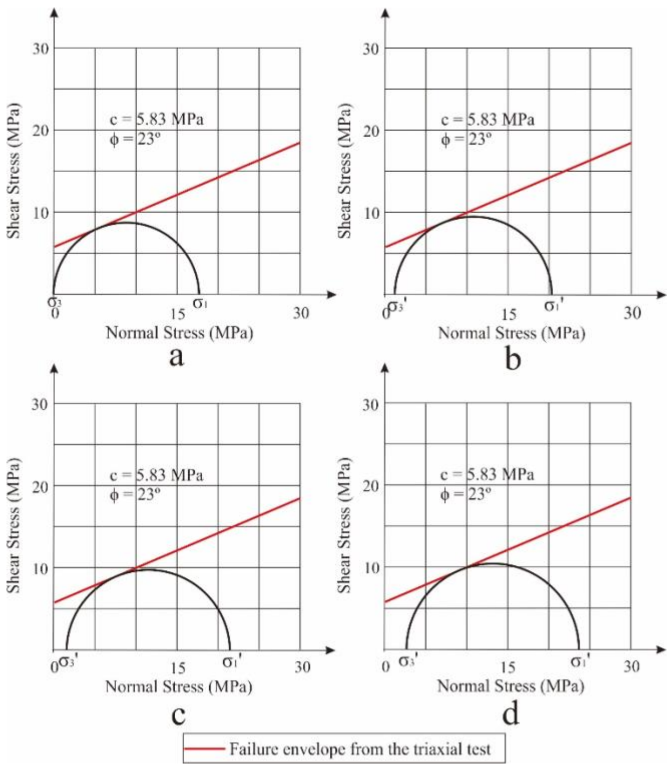

Figure 8. Representation of Mohr Coulomb curve on high strength pillar to find a equivalent confining pressure (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement)

E-ISSN 2541-2116
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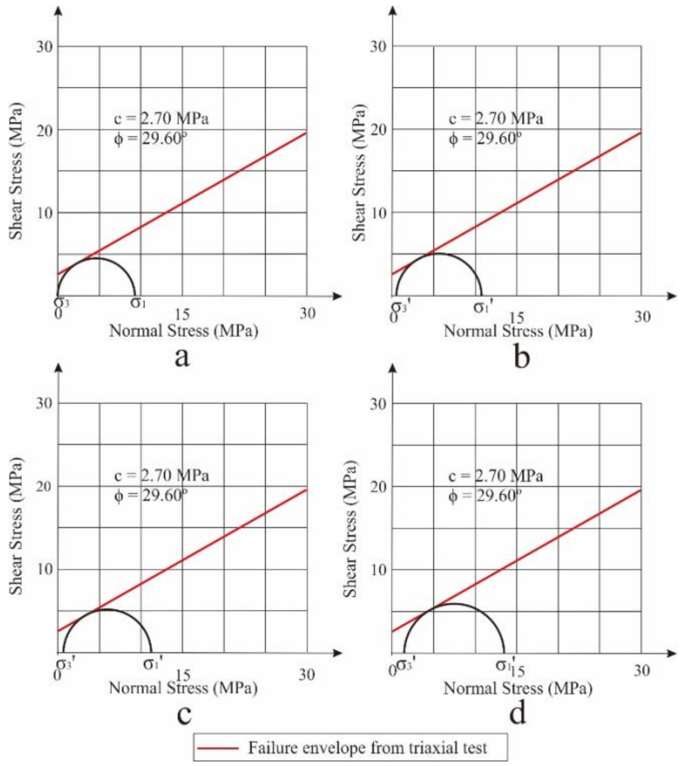

Figure 9. Representation of Mohr Coulomb curve on medium strength pillar to find a equivalent confining pressure (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement)

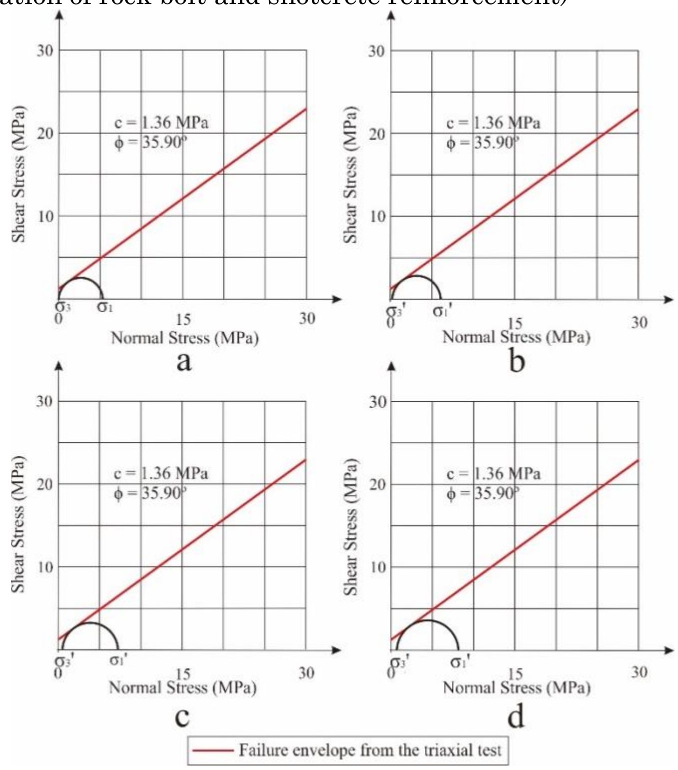

Figure 10. Representation of Mohr Coulomb curve on low strength pillar to find a equivalent confining pressure (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement)

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ISSN 2443-2083

Table 8. Equivalent confining pressure on each pillar

No	Type of Pillar	Pillar Treatment	σ_3'(MPa)
1	High strength pillar	Pillar	0
		Pillar + Rock Bolt	1.15
		Pillar + Shotcrete	1.66
		Pillar + Rock Bolt + Shotcrete	2.68
2	Medium strength pillar	Pillar	0
		Pillar + Rock Bolt	0.50
		Pillar + Shotcrete	0.61
		Pillar + Rock Bolt + Shotcrete	1.39
3	Low strength pillar	Pillar	0
		Pillar + Rock Bolt	0.18
		Pillar + Shotcrete	0.50
		Pillar + Rock Bolt + Shotcrete	0.75

Based on Figure 11, it can be seen that the equivalent compression pressure (σ_3') that arises due to the installation of shotcrete reinforcement shows a greater value compared to the equivalent compression pressure that arises on the pillar with rock bolt reinforcement. As explained earlier, shotcrete which is installed on the entire pillar wall surface will resist the occurrence of horizontal displacement across the entire pillar wall surface, so that it will automatically cause the appearance of a greater equivalent confining pressure (σ_3') compared to the rock bolt which only restrains the occurrence of horizontal displacement at a certain point. Likewise, on the pillar with combined rock bolt and shotcrete reinforcement, the arising compression pressure shows a greater value compared to the pillar with rock bolt reinforcement only and pillar with shotcrete reinforcement only. This happens because of the influence of two reinforcements, each of which has the function of restraining the displacement in horizontal direction. The function of both reinforcements are combined into one on one pillar.

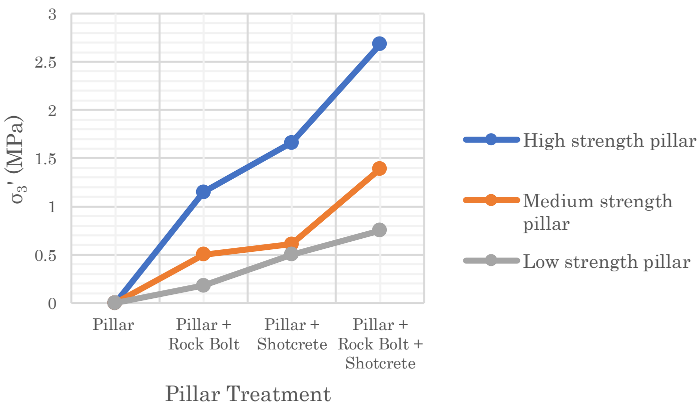

Figure 11. Equivalent confining pressure on each pillar

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Numerical Modeling

Three-dimensional numerical modeling was performed using RS3 2.0 software (rocscience). Model I was made to follow the pillar model during laboratory testing (Figure 12), while model II was made by inputting the equivalent confining pressure value (Figure 13) obtained from Table 8.

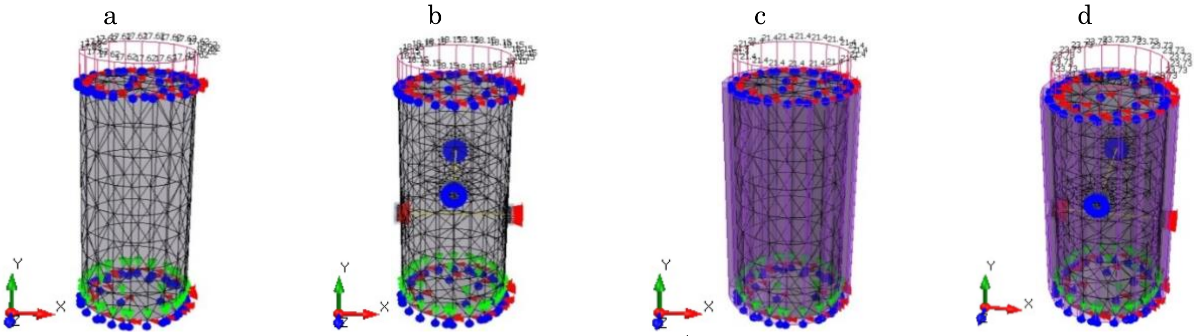

Figure 12. Example of boundary conditions in model I (a. Pillar without reinforcement, b. Pillar with rock bolt reinforcement, c. Pillar with shotcrete reinforcement, d. Pillar with combination of rock bolt and shotcrete reinforcement).

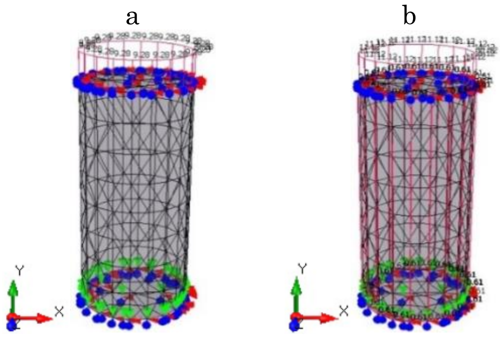

Figure 13. Example of boundary conditions in model II (a. Pillar without reinforcement, b. Pillar with reinforcement)

a. Pillar strength increase

To determine whether the modeled pillar is a failure or not, it can be seen in the strength factor (SF) value in the numerical model. If the strength factor value = 1 in most elements in the pillar, then the pillar is declared to be a failure.

Based on the results of numerical modeling with RS3, it is known that the installation of a reinforcement system has a significant influence on increasing the pillar strength. This can be seen in Table 9. Model I shows a different value of σ_1 with a value of σ_1 resulting from laboratory tests (Table 6), with the percentage increase in strength as shown in Figure 14. While model II shows the value of σ_1, which is equal to the value of σ_1 in laboratory test results (Figure 15).Therefore, it can be concluded that model II is closer to the results of laboratory tests compared to model I.

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ISSN 2443-2083

Table 9. Pillar strength increase resulting from numerical modeling with RS3

No	Type of Pilar	Pillar Treatment	σ1 Model I (MPa)	σ1 increase (%)	σ1 Model II (MPa)	σ1 increase (%)	SF
1	High strength pillar	Pillar	17.62	0	17.62	0	1.00
		Pillar + Rock Bolt	18.15	3.01	20.25	14.93	1.00
		Pillar + Shotcrete	21.40	21.45	21.40	21.45	1.00
		Pillar + Rock Bolt + Shotcrete	23.73	34.67	23.73	34.67	1.00
2	Medium strength pillar	Pillar	9.28	0	9.28	0	1.00
		Pillar + Rock Bolt	9.65	3.99	10.79	16.27	1.00
		Pillar + Shotcrete	12.95	39.54	11.12	19.83	1.00
		Pillar + Rock Bolt + Shotcrete	13.50	45.47	13.40	44.40	1.00
3	Low strength pillar	Pillar	5.33	0	5.33	0	1.00
		Pillar + Rock Bolt	5.65	6.00	6.03	13.13	1.00
		Pillar + Shotcrete	8.35	56.66	7.26	36.21	1.00
		Pillar + Rock Bolt + Shotcrete	8.70	63.23	8.20	53.85	1.00

Note: *The pillars modeled aresimilar to the physical model of the pillar in the lab test, **Pillars are modeled by including equivalent confining pressure on the entire surface of the pillar wall.

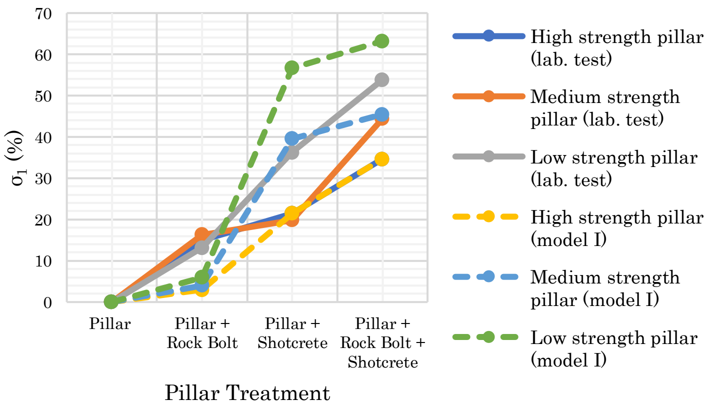

Figure 14. Pillar strength increase percentage on model I and laboratory test results

E-ISSN 2541-2116
ISSN 2443-2083

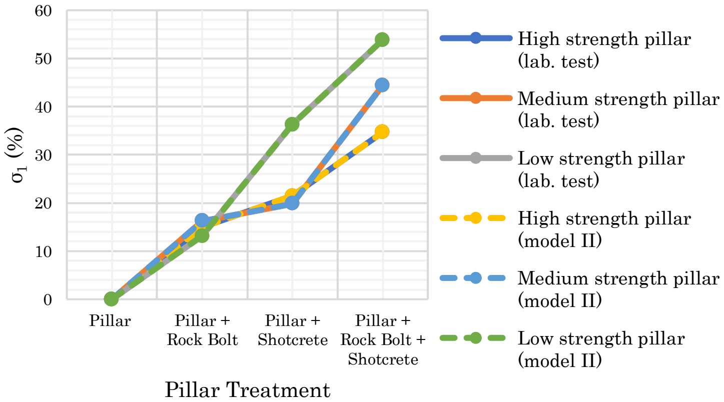

Figure 15. Pillar strength increase percentage on model II and laboratory test results

b. Horizontal Displacement (u_i)

In numerical modeling, horizontal displacement (u_i) at half the height of the pillar can be determined by looking at the color contour indicating the horizontal displacement that occurs at the measurement point.Where based on the results of numerical modeling results obtained that the reinforcement system causes horizontal displacement on the surface of the wall of the pillar to be smaller. Table 10 shows a decrease in the horizontal displacement of each pillar.

Model I shows a very different decrease percentage in horizontal displacement (u_i) with the decrease percentage in horizontal displacement that occurs on the pillar during laboratory testing (Figure 16), while model II shows the decrease percentage in horizontal displacement that approaches the decrease percentage in horizontal displacement that occurs on the pillar during laboratory testing (Figure 17). Therefore, it can be concluded that the model II is closer to the results of laboratory tests compared to model II.

Table 10. Horizontal displacement (u_i) at half the height of the pillar resulting from numerical modeling

No	Type of Pillar	Pillar Treatment	Total Horizontal Displacement			
			Model I (m)	Decrease (%)	Model II (m)	Decrease (%)
1	High strength pillar	Pillar	2.60×10^{-4}	0	2.60×10^{-4}	0
		Pillar + Rock Bolt	1.65×10^{-4}	36.54	1.78×10^{-4}	31.54
		Pillar + Shotcrete	1.20×10^{-4}	53.85	1.50×10^{-4}	42.31
		Pillar + Rock Bolt +Shotcrete	1.38×10^{-4}	46.92	1.46×10^{-4}	43.85
2	Medium strength pillar	Pillar	1.66×10^{-4}	0	1.66×10^{-4}	0
		Pillar + Rock Bolt	1.58×10^{-4}	4.82	1.36×10^{-4}	18.07
		Pillar + Shotcrete	1.19×10^{-4}	28.31	1.35×10^{-4}	18.68
		Pillar + Rock Bolt +Shotcrete	1.10×10^{-4}	33.74	1.25×10^{-4}	24.70
3	Low strength pillar	Pillar	0.91×10^{-4}	0	0.91×10^{-4}	0
		Pillar + Rock Bolt	0.88×10^{-4}	3.30	0.84×10^{-4}	7.69
		Pillar + Shotcrete	0.88×10^{-4}	3.30	0.86×10^{-4}	5.50
		Pillar + Rock Bolt +Shotcrete	0.80×10^{-4}	12.09	0.82×10^{-4}	9.89

Note: *The pillars modeled are similar to the physical model of the pillar in the lab test, **Pillars are modeled by including equivalent confining pressure on the entire surface of the pillar wall.

E-ISSN 2541-2116
ISSN 2443-2083

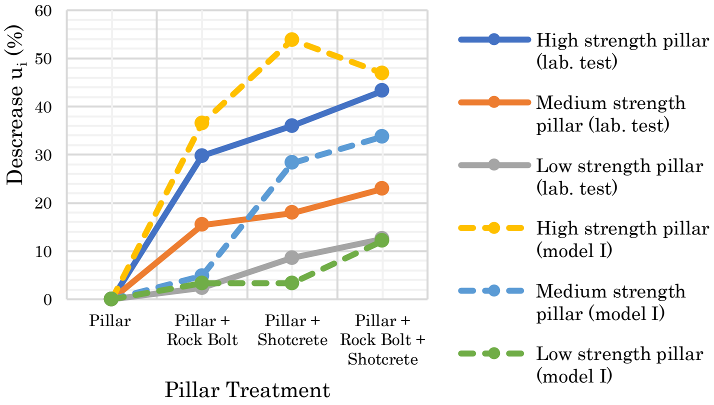

Figure 16. Horizontal displacement (u_i) decrease percentage on model I and laboratory test results

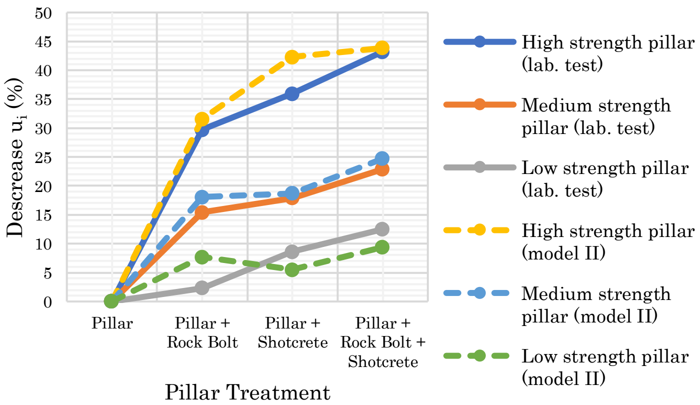

Figure 17. Horizontal displacement (u_i) decrease percentage on model II and laboratory test results

CONCLUSION

Based on the results of research conducted in the laboratory, the installation of rock bolt, shotcrete and combination of rock bolt and shotcrete reinforcement system causes an increase in uniaxial compressive strength (σ_1) and Young modulus (E) on a pillar.High strength pillar shows a strength increase of 14.93% on pillar with rock bolt reinforcement, 21.45% on pillar with shotcrete reinforcement and 34.67% on pillar with combination of rock bolt and shotcrete reinforcement.Medium strength pillar shows a strength increase of 16.27% on pillar with rock bolt reinforcement, 19.83% on pillar with shotcrete reinforcement and 44.40% on pillar with combination of rock bolt and shotcrete reinforcement.Low strength pillar shows a strength increase of 13.13% on pillar with rock bolt reinforcement, 36.21% on pillar with shotcrete reinforcement and 53.85% on pillar with combination of rock bolt and shotcrete reinforcement.

The results of laboratory testing and numerical modeling indicate that the increase in strength occurs because the horizontal displacement on the surface of the pillar wall is detained by shotcrete and faceplate on rock bolt, so that the pillar seems to be confining pressure throughout the pillar wall surface, which is called equivalent confining pressure.

ACKNOWLEDGEMENT

The researcher is very grateful to the head of the laboratory and technicians of the Laboratory of Geomechanics and Mine Equipment as well as Production Engineering Laboratory of the Bandung Institute of Technology for supporting this research activity.

E-ISSN 2541-2116
ISSN 2443-2083

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