Bulletin of the Geological Society of Malaysia, Volume 78, November 2024, pp. 29 - 37
DOI: https://doi.org/10.7186/bgsm78202404

Effect of particle gradation and rock block content on soil-rock mixture shear strength parameters

Norsyafiqah Binti Salimun*, Hisham Mohamad

Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS (UTP), Seri Iskandar 32610, Perak, Malaysia
* Corresponding author email address: norsyafiqahsalimun@gmail.com

Abstract: Soil-rock mixture (SRM) is highly inhomogeneous and loose geomaterial found in the quaternary formation, composed of a certain percentage of rock blocks, fine-grained soil, and pores. In Peninsular Malaysia, SRM can commonly be found in the granitic formation covering the mountainous areas where slope failures are prone to occur due to deep tropical weathering, heavy rainfall, and steep terrain. Numerous research studies have been conducted to investigate the mechanical behaviour of SRM, especially the influence of rock block content. However, the effect of particle size distribution has been studied in limited detail. This study uses sieve analysis, specific gravity, compaction, and direct shear box tests to determine the shear strength parameters of weathered type SRM with particle size distribution. The sample collected was divided into well-graded, poorly-graded, and gap-graded types of particle size distribution with 30%, 50%, and 70% rock block content, respectively. The percentage of rock block content is crucial in controlling the shear strength parameters. The specific gravity, dry density, optimum moisture content, and estimated porosity values measured show a considerable difference when the particle size distribution (PSD) and rock block content change. The findings also show that for a well-graded SRM, cohesion and friction angle values show a non-linear relationship against the rock block content. Meanwhile, as the rock block content increases, the cohesion decreases and inversely has an increment of friction angle for poorly-graded SRM. In contrast, the cohesion of gap-graded SRM increases when the rock block content increases. Hence, by understanding the influence of particle size distribution on the shear strength parameters of SRM, a better evaluation can be made in designing slope hazard mitigation.

Keywords: Shear strength, soil-rock mixture, particle size distribution, rock block content

INTRODUCTION

Soil-rock mixture (SRM) is distributed widely in nature which becomes a challenge in geotechnical works. SRM is a term introduced earlier by (Xu *et al*., 2011) as a geomaterial composed of a certain percentage of rock blocks with various sizes and shapes, fine-grained soils. Several types of SRM depend on their formation mechanism and the source materials (Zhou *et al*., 2017) and it has more complicated seepage characteristics than pure soil or broken rocks. Current research on the seepage characteristics of soil–rock mixtures is still limited to empirical equations. This paper presents an improved theoretical compound seepage model for the permeability coefficient of soil–rock mixtures and relative concentrations of individual constituents (i.e., pure soil and pure broken rocks. Natural SRM is commonly found in landslide deposits, colluvium, and accumulation slopes (Zhu *et al*., 2018). In Peninsular Malaysia, natural SRM are commonly found in weathered granite rock formations which show the soil-rock transition zone as shown in Figure 1. Meanwhile, artificial SRM is used as local engineering materials for constructing of embankment dams, road fillers and many more (Yang *et al*., 2015).

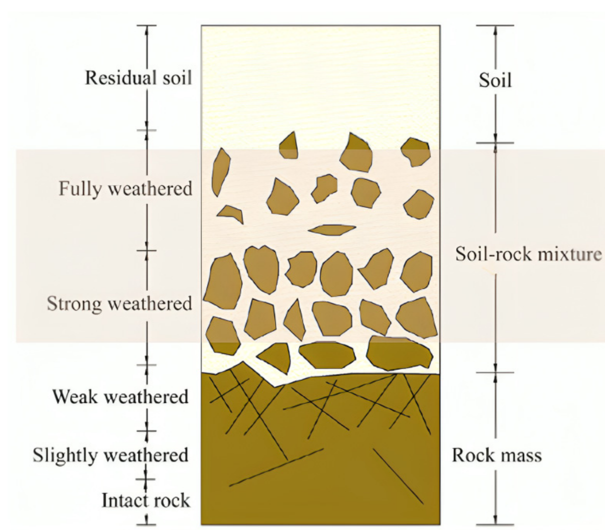

Figure 1: Soil-rock mixture illustrated in soil-rock transition zone in weathered rock (Modified from Zhou *et al*., 2017).

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

The physical and mechanical properties of SRM are complex as their natural characteristics are between soil and rock mass (Wang *et al*., 2013; Sun *et al*., 2023). However, SRM is conventionally treated as a homogenous material for ease of investigation. In Malaysia, overestimating the safety factor leads to errors in design (Jamaluddin & Deraman, 2000). A previous study stated that 80% of slope failures occurred due to design and construction errors (Akter *et al*., 2019). For the geotechnical design of the slopes, Grades I to III materials are typically treated as 'rock' and materials of Grades IV to VI as 'soil' (Chin & Sew, 2001). However, in the transition zone between these two materials, the soil-rock mixture is heterogeneous material and requires different approaches to characterise it.

Moreover, SRM landslides frequently occur worldwide because they are discontinuous materials (Xiaodi *et al*., 2023) and have complex spatial distribution (Dong *et al*., 2021). Thus, understanding the failure mechanism and determining the mechanical behaviour of SRM is a very challenging task and has gained interest from neither geologists nor engineers. Tropical countries such as Malaysia are also prone to SRM landslides caused by intense weathering due to higher rain intensity. Thus, the SRM slope's stability investigation significantly avoids geohazard events. The existing slope stability analysis has been extensively used to analyse a straight-forward case such as related to rocky or jointed rock slope (Nilsen, 2000; Raghuvanshi, 2019) and soil slope (Kasama & Zen, 2011; Rusydy *et al*., 2021).

Frequently, the estimation of slope stability uses the strength reduction method which assumes the slope is composed of homogenous material (Xian-Wen *et al*., 2020). However, soil-rock mixtures (SRM) are a complex geomaterial, which requires an integrated approach and more comprehensive analysis (Wang *et al*., 2019). Over the past decades, researchers focused on integrating physical and numerical tests for SRM slope stability analysis (Xu *et al*., 2016; Wang *et al*., 2018b). The SRM slope stability analysis numerical model developments have heightened the need for more accurate and reliable calibration between field and laboratory data (Srivastava, 2012).

There is still a lack of comprehensive and systematic data regarding SRM behaviour and failure mechanisms even though researchers and scientists have conducted certain experimental studies worldwide (Shaorui *et al*., 2019). A comprehensive study by Zhao & Guo (2014) stated that laboratory test results show that granular materials like SRM have complex structural parameters such as strength anisotropy, stress-strain relationship, and critical state. The most popular method is based on physical testing, such as in-situ shear tests (Zhang *et al*., 2016; Lv & Zhou, 2018) or large-scale laboratory triaxial tests (Huang *et al*., 2015) require a significant amount of manpower and financial resources. Yet, this method is still the best and most effective enough to measure the mechanical parameters.

Numerical tests can also characterise the strength parameters of SRM. For instance, (Yang *et al*., 2019; 2020) proposed an improved numerical manifold method (NMM) to determine the stability of SRM slopes. Moreover, digital imaging technology combined with finite and discrete element modelling is conducted to understand the soil-rock mixture engineering characteristic (Zhongfeng *et al*., 2021). These approaches are preferred to construct a heterogenous model of geomaterial such as SRM (Lianheng *et al*., 2021). Yet, it is agreed that any numerical experimental results must be tested against the physical experiments to ensure their reliability (Zhang *et al*., 2015). Thus, the physical-mechanical properties of SRM derived from in-situ and laboratory tests are required to calibrate the shear strength parameters for the numerical model.

Several factors affect the mechanical behaviour of SRM. Based on previous works, it is evident that the percentage rock block content plays a key role in controlling the shear strength parameters (Zhang *et al*., 2016; Wang *et al*., 2019; Xu & Zhang, 2021). Consistent with (Chang-Sheng *et al*., 2016), the rock block content must be greater than 30% for the shear strength of SRM to be affected. It is true that with the increment of the rock block proportion, the shear strength of the SRM increases for a known sample of a well-graded distribution. Besides, (Xu *et al*., 2011) also determined that when the rock block proportion lies in the range of 30–70%, the increment of the internal friction angle linearly increases with the increment of the rock block content. This is again followed by a study by Gong & Liu (2015), where increasing the rock content will increase the dilatation and peak shear stress of SRM.

Besides the rock block content observed from the soil-rock ratio, several other factors affect the shear strength of SRM (Xu *et al*., 2011) such as water content (Wei *et al*., 2018; Zhang *et al*., 2020), compaction rate (Yu & Wang, 2013; Qi *et al*., 2016), particle size (Xu & Zhang, 2021) and particle shape (Li, 2013). Due to the complexity of the SRM composition, the practical application involving experimental works for such materials is restricted (Dong *et al*., 2021). The SRM sample preparation for laboratory work is also affected by numerous factors as reviewed by Salimun & Mohamad (2021). However, Ren *et al*. (2018) and Xu *et al*. (2008) emphasise that particle size distribution (PSD) is the next crucial factor that affects the prediction of SRMs' physical and mechanical properties.

According to Xiaodong *et al*. (2022) the shear strength parameters of SRM are closely related to the fractal distribution of the soil and rock components. This means that the change in the particle gradation will directly affect the internal structure of SRM and lead to variations in the mechanical properties. Meanwhile, Mehdipour & Khayat (2017) stated that the void volume filled by fine-grained soil is influenced by the PSD which determines the density of soil-rock packing. Yet, there is a lack of studies to assess the influence of particle size distribution in preparing SRM samples for laboratory testing

(Li, 2020; Zhang *et al*., 2020). Limited findings also reported the effect of PSD towards the shear strength parameters of SRM despite its position as one of the crucial factors in controlling the scale effect of experimental works. Therefore, this study aimed to measure and determine the relationship between the shear strength parameters i.e., cohesion and friction angle towards the SRM rock block content and particle size distribution. The findings in this investigation are significant to enhance the effectiveness and reliability of SRM shear strength parameters for calibration of hybrid, physical and numerical slope stability studies.

METHODOLOGY

The in-situ sample acquisition for laboratory testing of SRM is challenging due to sample disturbance and the wide range of rock block sizes. Researchers use fabricated or manufactured samples for simplification compared to natural SRM samples. Thus, in this study, SRM samples are prepared in the laboratory using natural samples collected from the soil-rock transition zone for ease of repetitive testing. The samples were collected using the box sampling method from a weathered granitic hill located at Lumut Perak as pictured in Figure 2. The granite hill is selected as a study area as it is accessible to the soil-rock transition zone where the weathered type SRM is collected.

At the laboratory, the samples are first dried and sieved. Figure 3 shows the natural SRM sample prepared in this study. It is acknowledged that the grain size classification in SRM is different from the conventional standard for clay, silt, and sand (Xu *et al*., 2011). The grain size limit of the soil and rock blocks in the SRM sample also depends on the research conditions and approach. Moreover, the maximum particle diameters need to be scaled down to overcome the limitation of conventional direct shear tests. To understand the particle gradation effect of SRM, it is essential to determine the threshold that divides the soil and rock blocks (Xiaodong *et al*., 2022).

Figure 2: Weathered granitic hill located at Segari, Lumut, Perak.

Figure 3: The soil-rock mixture collected from Segari Hill, Lumut is dried before sieving.

As for this study, the soil/rock threshold was measured using the formula in equation (1) below following Medley & Lindquist (1995):

$$d_{S/RT} = 0.05L_c \quad (1)$$

given

$$d \geq d_{S/RT} = \text{rock and } d < d_{S/RT} = \text{soil} \quad (2)$$

where d represents the diameter of particles while S and RT refer to the 'soil' and 'rock' in the soil-rock mixture, respectively. Meanwhile, L_c has different definitions for different research objects depending on the engineering scale of SRM. For instance, in a direct shear test, L_c takes the height of a single shear box of the sample equal to 50 mm in this study. Thus, the $d_{S/RT}$ is 2.5 mm, which is reasonable considering the equipment's scale requirements. Following equation (2), particles less than 2.5 mm in size are defined as soil and vice versa. Particles greater or equal to 2.5 mm in size represent rock blocks. After the sieving procedure, the soil and rock components are separated according to the defined threshold. Here, the maximum rock block diameter is set to 5 mm. Then, based on a customised particle size distribution, the SRM samples with three different types of gradation which are well-graded, poorly-graded, and gap-graded are prepared.

The weight of each SRM sample prepared is 400 g for specific gravity and direct shear box test and 1.5 kg for compaction test. The rock block content for each gradation is set at 30%, 50% and 70%. The particle size distribution chart of the SRM samples with different block content prepared is shown in Figure 4. In the direct shear test, SRM samples are poured into the shear box and compacted in three layers before the shearing process occurs. The load applied is set to 100 kPa, 200 kPa and 300 kPa for gradation type and different rock block content. The horizontal displacement rate is 0.25 mm/min. The procedures described here follow the standard test in the geotechnical field as referred to in ASTM D3080-04 and adopted the pioneer research works of SRM (Xu *et al*., 2009; Xu, 2009; Xu *et al*., 2011).

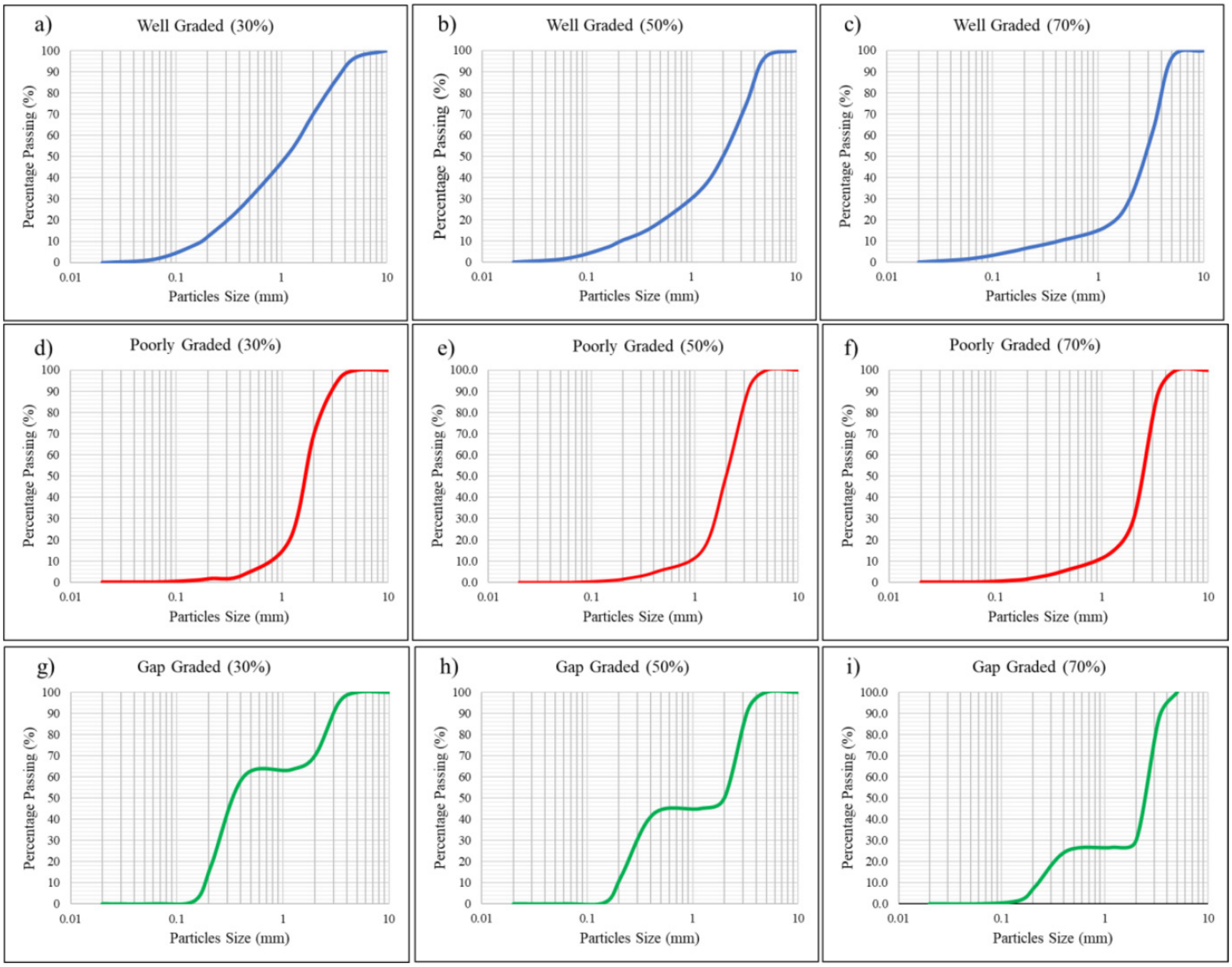

Figure 4: Particle size distribution chart for three different types of gradation.

RESULTS AND DISCUSSION

Table 1 shows all the values of the measured properties from these tests for all SRM samples. From the sieve analysis, the values of the coefficient of uniformity, Cu and coefficient of curvature, Cc, are determined and analysed. Based on these coefficient values, the type SRM gradation is then classified respectively. Higher Cu values signify the SRM sample consists of soil and rock blocks with different size ranges. Inversely, lower Cu values show a smaller range of particle size. From this investigation, the well-graded and gap-graded SRM samples have higher Cu than the poorly-graded sample, as has been presumed. According to the standard classification of granular material in the Unified Soil Classification System (USCS), the Cc values of a well-graded sample must range from 1 to 3. The range measured for the well-graded SRM sample in this study is 1.35 to 2.18 which falls within the range mentioned and confirms the gradation type.

Table 1: Properties of SRM samples with different block content.

Parameters	Well-Graded			Poorly-graded			Gap-graded		
Rock Block Content, %	30	50	70	30	50	70	30	50	70
Coefficient of Uniformity, Cu	10.21	11.11	7.64	2.90	2.88	2.05	2.35	11.67	10.67
Coefficient of Curvature, Cc	2.18	1.63	1.35	1.13	0.74	0.54	3.54	0.72	0.27

However, for the poorly-graded SRM, the Cc values only fall within the range when the rock block content is 30%. This shows that at 30% rock block content, the Cc values of poorly-graded samples do not differ much from the well-graded SRM. But as the rock block content increases, the Cu decreases for poorly-graded, but the range of Cu values is very small, which is only between 2.0 to 3.0 compared to 7.0-10.0 for well-graded and 2.0-12.0 for gap-graded SRM. It also can be observed that the Cu values are higher for gap-graded samples at 50% and 70% rock block content. Differently, at 70% rock block content, well-graded SRM samples show the lowest values of Cu compared to samples with 30% and 50% rock block content.

Before conducting the direct shear test, specific gravity and compaction tests determine each sample's particle density and optimum moisture content. Figure 5 shows the measured values against the rock block content variation for each SRM type of gradation. The specific gravity and dry density values for 30% and 50% rock block content are almost similar for all types of gradation. However, at 70% rock block content the poorly-graded SRM shows lower specific gravity values. As the soil component decreases, the density of the mixture depends on the rock block composition. The higher the rock block content, the more pore spaces present, and the density of the mixture decreases. Thus, specific gravity also decreases.

Figure 6 shows the optimum moisture content and estimated porosity from the void ratio measurement of all SRM samples obtained from the compaction test. The optimum moisture content values generally range from 14% to 17%. The range of values is relatively small, but it still can be observed that values measured for each type of SRM varied depending on the rock block content. At 30% rock block content, the poorly-graded SRM have the highest optimum moisture content and porosity. Increment in rock block content of poorly-graded SRM shows an opposing trend with the estimated porosity values. The trend also works similarly for well-graded, and gap-graded SRM. When the rock block content increases, the compaction process causes rock fragmentation, eventually forming smaller particles that fill the void spaces. Hence, the porosity of all SRM samples decreases.

Before the direct shear test of all the SRM samples, the investigation was also conducted on the original SRM soil sample collected from the field. Figure 7 shows the experiment's results, and the friction angle and cohesion values of the SRM soil sample are 29.85° and 42.30 kPa.

The overall result of the shear strength parameters of all SRM samples measured from the direct shear test is portrayed in Figure 8. Generally, it can be observed that the trendline of the shear strength parameters measured for each gradation changes as the rock block content increases. The friction angle and cohesion of the well-graded SRM

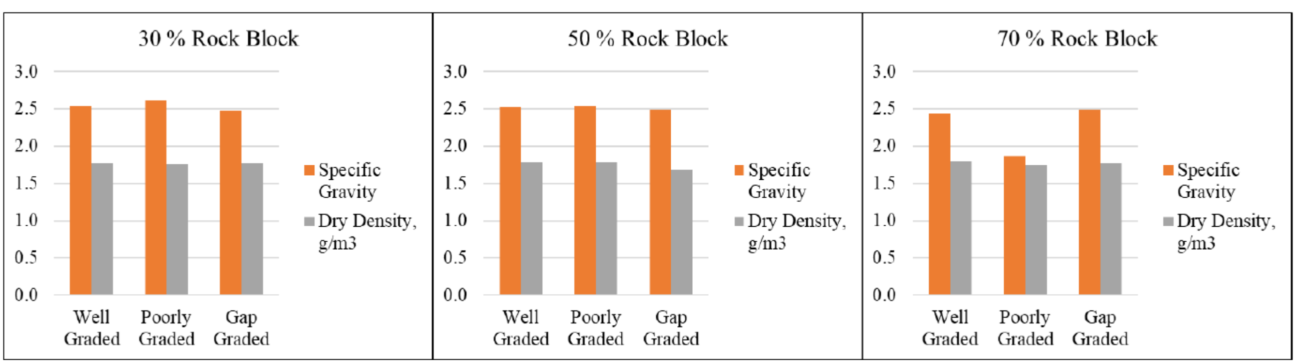

Figure 5: Specific gravity and dry density of the SRM samples with different rock block content.

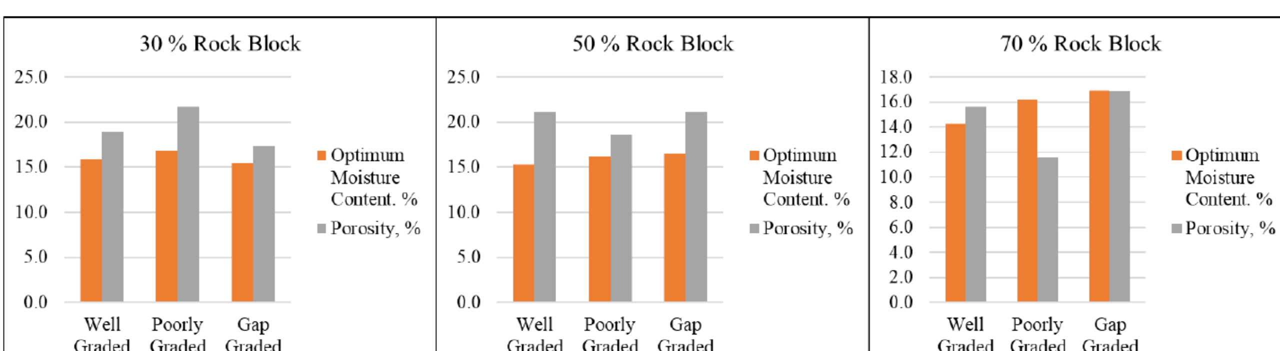

Figure 6: Optimum moisture content of SRM sample tested with different rock block content.

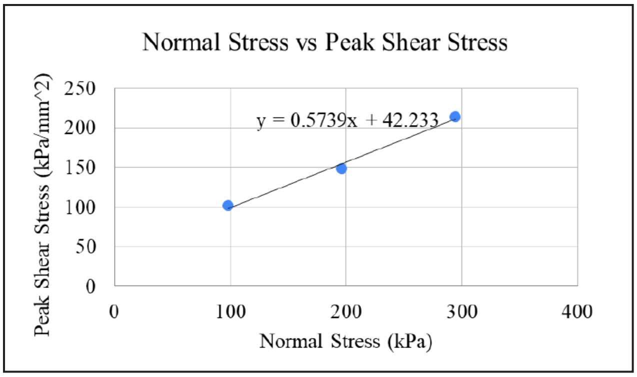

Figure 7: Normal stress and peak shear stress values of soil sample.

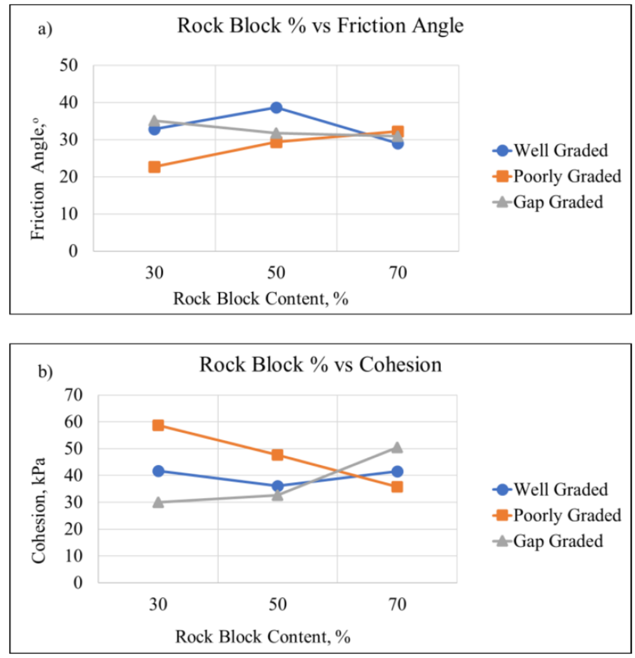

Figure 8: The shear strength parameters measured for SRM with different gradation and rock block content a) friction angle and b) cohesion.

at 30% rock block are 29.98° and 42.30 kPa which are close to the shear strength parameters of the undisturbed SRM soil sample. In comparison with the two other types of SRM, the cohesion values are highest for poorly-graded SRM at 30% rock block content. As the different particle size distribution changes, the internal structure of SRM and the load transfer mechanism will also change (Ju *et al.*, 2018). This eventually results in different mechanical characteristics due to the strength contrast between soil and rock blocks, and frictional force due to particle movement.

The friction angle of SRM is mainly influenced by the rock block's strength and composition (Xu *et al.*, 2011; Xu & Zhang, 2022). According to (Wang *et al.*, 2018a) the shear strength of SRM is higher at 50% rock block content compare to those other percentages. Yet this is true for a well-graded type SRM. For instance, in this study, the friction angle is highest at 50% rock block content, while it is the lowest value of friction angle for the gap-graded SRM. The results also show that the friction angle values of all three types of SRM gradation range from 30-35° when the rock block content is 70%. In comparison with previous work, the friction angle of grade IV granite is tabulated in Table 2. The range of values tabulated here is similar to the findings in this research, which represent the weathered type of SRM from tropical region countries.

The accumulation of rock block particles caused an interlocking effect which directly influenced the shear strength of SRM. The effect is more apparent when involving rock blocks with irregular shapes (Yao *et al.*, 2022). The rock block shape of weathered granite rock used in this research is angular. The interlocking effect is more pronounced in the poorly-graded SRM since they have a more uniform rock block size. Hence, the poorly-graded SRM show an increasing trend of friction angle as the block content increases. Poorly-graded SRM shows lower Cu values, indicating a minor soil and rock particle size range. Hence, the fine-grained material can no longer improve the soil-rock skeleton when the rock block content increases. The friction angle shows a positive increment and vice versa in the cohesion values. This shows the fine-grained component

Table 2: Friction angle values from previous work.

Reference	Friction Angle Value
(Chiu & Ng, 2014)	38°
(Saffari *et al.*, 2019)	34°

is also an important factor that controls the mechanical properties of SRM (Saffari *et al.*, 2019).

Besides, the cohesion values inversely increase when the rock block content is 70% for well-graded and gap-graded SRM. A higher rock block content will increase the rock block contact and cause collision at the particle edges during the shearing process. When the particles slide or roll over each other, they must overcome the resistance formed at the edge of adjacent particles. The rock block strength is vital in determining the friction energy, and interlocking work must overcome in this condition (Tu *et al.*, 2021). As the sample used in this investigation is a weathered type of SRM, the rock block component is weaker and easily fractured. Thus, more soil or fine-grained particles are formed indirectly through this process, eventually increasing the cohesion. This does not work the same for a poorly graded SRM because the percentage of soil components is limited to a minimal range. The percentage of finer-grained is still insignificant with additional soil formed by fracturing rock block components. Thus, the cohesion continued decreasing as the rock block content increased to 70%.

As discussed above, more interrelated factors need to be analysed to understand further the influence of rock block content and particle gradation on the shear strength parameters of SRM. The current investigation can be used as the prior works for a more comprehensive approach towards SRM characterisation, especially as a geotechnical case study in a tropical region. It is evident that the complex behaviour of SRM could be further identified for geotechnical applications by considering PSD and rock block content. The findings can be used as a reference for a more comprehensive approach towards SRM. Future work is recommended to include more comprehensive variables and other affecting factors in evaluating the mechanical behaviour of SRM.

CONCLUSION

To investigate the effect of different particle gradation and rock block content on soil-rock mixture shear strength parameters, specific gravity, compaction, and direct shear tests are conducted in this study. The variation set in the particle size distribution defined the gradation type of SRM despite having a similar rock block content percentage. The cohesion of SRM is mainly affected by the soil component which is influenced by the size range of their respective PSDs. The well-graded SRM shows non-linear relationships for both cohesion and friction angle values. Meanwhile, the cohesion decreases for poorly-graded SRM as the rock block content increases and inversely has an increment of friction angle. In contrast, the cohesion of gap-graded SRM increases when the rock block content increases. The findings of this study are significant to understand the variations of shear strength parameters with different particle size distributions and rock block content. Hence, this information is useful for geotechnical engineers and geologists in evaluating the SRM slope stability.

ACKNOWLEDGEMENT

Special thanks to the laboratory technician in the Department of Civil Engineering for their assistance in the experimental processes. We also extend our gratitude to the reviewers for their valuable comments and suggestions that helped improve the quality of this publication. This work was supported by the Ministry of Higher Education under the Fundamental Research Grant Scheme (FRGS/015MA0-154).

AUTHORS CONTRIBUTION

NS designed the study and performed the experiments. The data analysis under the supervision of HM. NS wrote the paper with input from HM.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Akter, A., Noor, M. J. M. M., Goto, M., Khanam, S., Parvez, A., & Rasheduzzaman, M., 2019. Landslide Disaster in Malaysia: An Overview. International Journal of Innovative Research and Development, 8(6), 292-302. https://doi.org/10.24940/ijird/2019/v8/i6/jun19058.

Chang-Sheng, L., Zhang, D., Du, S.S., & Shi, B., 2016. Computed tomography based numerical simulation for triaxial test of soil-rock mixture. Computers and Geotechnics, 73, 179–188. https://doi.org/10.1016/j.compgeo.2015.12.005.

Chin, T.Y., & Sew, S.G., 2001. The determination of shear strength in residual soils for slope stability analysis. Seminar Cerun Kebangsaan, Cameron Highlands, 14-15 May 2001. 18 p.

Chiu, C.F., & Ng, C.W.W., 2014. Relationships between chemical weathering indices and physical and mechanical properties of decomposed granite. Engineering Geology, 179, 76–89. https://doi.org/10.1016/j.enggeo.2014.06.021.

Dong, H., Peng, B., Gao, Q. F., Hu, Y., & Jiang, X., 2021. Study of hidden factors affecting the mechanical behavior of soil–rock mixtures based on abstraction idea. Acta Geotechnica, 16(2), 595–611. https://doi.org/10.1007/s11440-020-01045-0.

Gong, J., & Liu, J., 2015. Analysis on the mechanical behaviors of soil-rock mixtures using discrete element method. Procedia Engineering, 102, 1783–1792. https://doi.org/10.1016/j.proeng.2015.01.315.

Huang, S., Ding, X., Zhang, Y., & Cheng, W., 2015. Triaxial test and mechanical analysis of rock-soil aggregate sampled from natural sliding mass. Advances in Materials Science and Engineering, 2015(6), 1-14. https://doi.org/10.1155/2015/238095.

Jamaluddin, T.A., & Deraman, M.F., 2000. Relict Structures and Cut Slope Failures in Highly to Completely Weathered Rocks Along Jalan Tg. Siang, Kota Tinggi, Johor. Geological Society of Malaysia Annual Geological Conference 2000, September 8-9 2000, Pulau Pinang, Malaysia, 305-312.

Ju, Y., Sun, H., Xing, M., Wang, X., Zheng, J., 2018. Numerical analysis of the failure process of soil–rock mixtures through computed tomography and PFC3D models. International Journal of Coal Science & Technology, 5, 126-141. https://doi.org/10.1007/s40789-018-0194-5.

Kasama, K., & Zen, K., 2011. Effects of spatial variability of soil property on slope stability. Vulnerability, Uncertainty, and Risk: Analysis, Modeling, and Management - Proceedings of the ICVRAM 2011 and ISUMA 2011 Conferences, 92, 691–698. https://doi.org/10.1061/41170(400)84.

Lianheng, Z., Dongliang, H., Shuaihao, Z., Xiao, C., Yibo, L., & Min, D., 2021. A new method for constructing finite difference model of soil-rock mixture slope and its stability analysis. International Journal of Rock Mechanics and Mining Sciences, 138(January), 104605. https://doi.org/10.1016/j.ijrmms.2020.104605.

Li, B., 2020. Study on Shear Properties of the Soil-rock Mixture. E3S Web of Conferences, 165(63), 1–6. https://doi.org/10.1051/e3sconf/202016504079.

Li, Y., 2013. Effects of particle shape and size distribution on the shear strength behavior of composite soils. Bulletin of Engineering Geology and the Environment, 72(3–4), 371–381. https://doi.org/10.1007/s10064-013-0482-7.

Lv, X., & Zhou, H., 2018. Soil-rock mixture shear strength measurement based on in situ borehole pressure-shear tests. Journal of Geophysics and Engineering, 15(5), 2221–2234. https://doi.org/10.1088/1742-2140/aacaa8.

Medley, E., & Lindquist, E., 1995. The engineering significance of the scale- independence of some Franciscan melanges in California USA. Proceedings of the 35th US Symposium on Rock Mechanics (USRMS), Rotterdam, 907–914.

Mehdipour, I., & Khayat, K.H., 2017. Effect of particle-size distribution and specific surface area of different binder systems on packing density and flow characteristics of cement paste. Cement and Concrete Composites, 78(January), 120–131. https://doi.org/10.1016/j.cemconcomp.2017.01.005.

Nilsen, B., 2000. New trends in rock slope stability analyses. Bulletin of Engineering Geology and the Environment, 58(3), 173–178. https://doi.org/10.1007/s100640050072.

Qi, C., Li, L., Wei, J., & Liu, J., 2016. Shear Behavior of Frozen Rock-Soil Mixture. Advances in Materials Science and Engineering, 2016, Article ID 1646125, 8 p. https://doi.org/10.1155/2016/1646125.

Raghuvanshi, T. K., 2019. Plane failure in rock slopes – A review on stability analysis techniques. Journal of King Saud University - Science, 31(1), 101–109. https://doi.org/10.1016/j.jksus.2017.06.004.

Ren, M., Zhao, G., Qiu, X., Xue, Q., & Chen, M., 2018. A Systematic Method to Evaluate the Shear Properties of Soil-Rock Mixture considering the Rock Size Effect. Advances in Civil Engineering, 2018, Article ID 6509728, 9p. https://doi.org/10.1155/2018/6509728.

Rusydy, I., Fathani, T.F., Al-Huda, N., Sugiarto, Iqbal, K., Jamaluddin, K., & Meilianda, E., 2021. Integrated approach in studying rock and soil slope stability in a tropical and active tectonic country. Environmental Earth Sciences, 80(2), 1–20. https://doi.org/10.1007/s12665-020-09357-w.

Saffari, P., Nie, W., Noor, M.J.M., Zhang, X., & Liang, Q., 2019. Characterization the geotechnical properties of a Malaysian granitic residual soil grade v. IOP Conference Series: Earth and Environmental Science, 289(1), 012006. https://doi.org/10.1088/1755-1315/289/1/012006.

Salimun, N., & Mohamad, H., 2021. Review on current advances and consideration issues in preparing soil-rock mixture for laboratory testing. IOP Conference Series: Materials Science and Engineering, 1153(1), 012013. https://doi.org/10.1088/1757-899x/1153/1/012013.

Shaorui, S., Zhu, F., Wei, J., Wang, W., & Le, H., 2019. Experimental Study on Shear Failure Mechanism and the Identification of Strength Characteristics of the Soil-Rock Mixture. Shock and Vibration, 2019, Article ID 7450509, 25 p. https://doi.org/10.1155/2019/7450509.

Srivastava, A., 2012. Spatial Variability Modelling of Geotechnical Parameters and Stability of Highly Weathered Rock Slope. Indian Geotechnical Journal, 42, 179–185. https://doi.org/10.1007/s40098-012-0016-4.

Standard, A.S.T.M. 2011. D2487-11 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA.

Sun, Y., Tuo, Y., Lv, J., & Wang, G., 2023. Influence of Different Particle Size and Rock Block Proportion on Microbial-Solidified Soil–Rock Mixture. Applied Sciences, 13(3), 1325. https://doi.org/10.3390/app13031325.

Tu, Y., Chai, H., Liu, X., Wang, J., Zeng, B., Fu, X., & Yu, J., 2021. An experimental investigation on the particle breakage and strength properties of soil-rock mixture. Arabian Journal of Geosciences, 14, 840. https://doi.org/10.1007/s12517-021-07186-0/Published.

Wang, J. J., Zhang, H. P., Tang, S. C., & Liang, Y., 2013. Effects of Particle Size Distribution on Shear Strength of Accumulation Soil. Journal of Geotechnical and Geoenvironmental Engineering, 139(11), 1994–1997. https://doi.org/10.1061/(asce)gt.1943-5606.0000931.

Wang, Y., Li, C.H., & Hu, Y.Z., 2018a. Use of X-ray computed tomography to investigate the effect of rock blocks on meso-structural changes in soil-rock mixture under triaxial deformation. Construction and Building Materials, 164, 386–399. https://doi.org/10.1016/j.conbuildmat.2017.12.173.

Wang, Y., Li, C.H., & Hu, Y.Z., 2018b. X-ray computed tomography (CT) observations of crack damage evolution in soil-rock mixture during uniaxial deformation. Arabian Journal of Geosciences, 11(9), 1. https://doi.org/10.1007/s12517-018-3561-z.

Wang, S., Ji, T., Xue, Q., Shen, Z., & Zhang, Q., 2019. Deformation and Failure Characteristics of Soil-Rock Mixture considering Material Composition and Random Structure. Advances in Materials Science and Engineering, 2019, Article ID 3165096, 13 p. https://doi.org/10.1155/2019/3165096.

Wei, H.Z., Xu, W.J., Wei, C.F., & Meng, Q.S., 2018. Influence of water content and shear rate on the mechanical behavior of soil-rock mixtures. Science China Technological Sciences, 61(8), 1127–1136. https://doi.org/10.1007/S11431-017-9277-5.

Xian-Wen, H., Yao, Z.-S. S., Bing-Hui, W., Ai-Zhao, Z., & Jiang, P.-M. M., 2020. Soil-Rock Slope Stability Analysis under Top Loading considering the Nonuniformity of Rocks. Advances in Civil Engineering, 2020, Article ID 9575307, 15 p. https://doi.org/10.1155/2020/9575307.

Xiaodi, F., Zhang, B., Wang, L., Wei, Y., Leng, Y., & Dang, J., 2023. Stability prediction for soil-rock mixture slopes based on a novel ensemble learning model. Frontiers in Earth Science, 10(January), 1–13. https://doi.org/10.3389/feart.2022.1102802.

Xiaodong, F., Ding, H., Sheng, Q., Zhang, Z., Yin, D., & Chen, F., 2022. Fractal Analysis of Particle Distribution and Scale Effect in a Soil–Rock Mixture. Fractal and Fractional, 6(2), 17 p. https://doi.org/10.3390/fractalfract6020120.

Xu, W., 2009. Conception, classification and significations of soil-rock mixture. Hydrogeology & Engineering Geology, 36(4), 50–56.

Xu, W., Hu R.L, & Yue Z.Q. 2009. Genesis and stability of the Zhoujiawan landslide, Three Gorges, China. Bulletin of Engineering Geology and the Environment, 68, 47–54. https://doi.org/10.1007/s10064-008-0154-1.

Xu, W., Wang, S., Zhang, H.Y., & Zhang, Z.L., 2016. Discrete element modelling of a soil-rock mixture used in an embankment dam. International Journal of Rock Mechanics and Mining Sciences, 86, 141–156. https://doi.org/10.1016/j.ijrmms.2016.04.004.

Xu, W., Xu, Q., & Hu, R., 2011. Study on the shear strength of soil-rock mixture by large scale direct shear test. International Journal of Rock Mechanics and Mining Sciences, 48(8), 1235–1247. https://doi.org/10.1016/j.ijrmms.2011.09.018.

Xu, W., Yue, Z., & Hu, R., 2008. Study on the mesostructure and mesomechanical characteristics of the soil-rock mixture using digital image processing based finite element method. International Journal of Rock Mechanics and Mining Sciences, 45(5), 749–762. https://doi.org/10.1016/j.ijrmms.2007.09.003.

Xu, W., & Zhang, H.Y., 2021. Research on the effect of rock content and sample size on the strength behavior of soil-rock mixture. Bulletin of Engineering Geology and the Environment, 80(3), 2715–2726. https://doi.org/10.1007/s10064-020-02050-z.

Xu, W., & Zhang, H. Y., 2022. Meso and macroscale mechanical behaviors of soil–rock mixtures. Acta Geotechnica, 17(2), 3765-3782. https://doi.org/10.1007/s11440-022-01449-0.

Yang, H., Zhou, Z., Wang, X., & Zhang, Q., 2015. Elastic modulus calculation model of a soil-rock mixture at normal or freezing temperature based on micromechanics approach. Advances in Materials Science and Engineering, 2015, Article ID 576080, 10 pages. https://doi.org/10.1155/2015/576080.

Yang, Y., Sun, G., & Zheng, H., 2019. Stability analysis of soil-rock-mixture slopes using the numerical manifold method. Engineering Analysis with Boundary Elements, 109(October), 153–160. https://doi.org/10.1016/j.enganabound.2019.09.020.

Yang, Y., Sun, G., Zheng, H., & Yan, C., 2020. An improved numerical manifold method with multiple layers of mathematical cover systems for the stability analysis of soil-rock-mixture slopes. Engineering Geology, 264(May 2019), 105373. https://doi.org/10.1016/j.enggeo.2019.105373.

Yao, Y., Li, J., Ni, J., Liang, C., & Zhang, A., 2022. Effects of gravel content and shape on shear behaviour of soil-rock mixture: Experiment and DEM modelling. Computers and Geotechnics, 141, 104476. https://doi.org/10.1016/j.compgeo.2021.104476.

Yu, L.P., & Wang, Z.Y., 2013. Compactability analysis of soil-rock mixture. Applied Mechanics and Materials, 423–426, 1001–1005. https://doi.org/10.4028/www.scientific.net/AMM.423-426.1001.

Zhang, H.-Y., Xu, W., & Yu, Y.Z., 2016. Triaxial tests of soil-rock mixtures with different rock block distributions. Soils and Foundations, 56(1), 44–56. https://doi.org/10.1016/j.sandf.2016.01.004.

Zhang, S., Tang, H., Zhan, H., Lei, G., & Cheng, H., 2015. Investigation of scale effect of numerical unconfined compression strengths of virtual colluvial-deluvial soil-rock mixture. International Journal of Rock Mechanics and Mining Sciences, 77, 208–219. https://doi.org/10.1016/j.ijrmms.2015.04.012.

Zhang, Y., Zhong, X., Lin, J., Zhao, D., Jiang, F., Wang, M.K., Ge, H., & Huang, Y., 2020. Effects of fractal dimension and water content on the shear strength of red soil in the hilly granitic region of southern China. Geomorphology, 351, 106956. https://doi.org/10.1016/j.geomorph.2019.106956.

Zhao, J., & Guo, N., 2014. Bridging the micro and macro for granular media: a computational multi-scale paradigm. In: Kenichi Soga, Krishna Kumar, Giovanna Biscontin & Matthew Kuo (Eds.), Geomechanics from Micro to Macro: Proceedings of the TC105 ISSMGE International Symposium on Geomechanics from Micro to Macro, IS-Cambridge 2014. Taylor & Francis Group, London. 747–52.

Zhongfeng, Y., Yuqin, D., & Jiangong, C., 2021. Stability Analysis of Rock-soil Mixture Slope. IOP Conference Series: Earth and Environmental Science, 638(1). https://doi.org/10.1088/1755-1315/638/1/012099.

Zhou, Z., Yang, H., Wang, X., & Liu, B., 2017. Model Development and Experimental Verification for Permeability Coefficient of Soil–Rock Mixture. International Journal of Geomechanics, 17(4), 04016106. https://doi.org/10.1061/(asce)gm.1943-5622.0000768.

Zhu, F., Qian, W., Le, H., Fan, H., & Wang, W., 2018. Formation Mechanism and Mechanical Properties of Soil-Rock Mixture Containing Macropore. Advances in Civil Engineering, 2018. Article ID 1594546, 11 pages. https://doi.org/10.1155/2018/1594546.

Manuscript received 18 November 2023;
Received in revised form 13 February 2024;
Accepted 27 February 2024
Available online 30 November 2024