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Novel Remediation Technique for Stabilizing the Damaged Slopes of Kenyir Dam

Mohamed Hafez[1,], Chong You Jine[1], Zakaria Che Muda[1], Lariyah Mohd Sidek[2], Ahmed M. Yassin[3] and Mahammad Mohie Eldin[4]*

[1]Faculty of Engineering (FEQS), Civil Engineering Department, INTI-International University, Nilai, Malaysia
[2]College of Engineering, Civil Engineering Department, Universiti Tenaga Nasional, Kajang, Malaysia
[3]Higher Institute of Engineering and Technology, Civil Engineering Department, King Marriott, Egypt
[4]Civil Engineering Department, Faculty of Engineering, Beni Suef University, Beni Suef, Egypt

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Abstract: This study evaluates the engineering properties of a novel type of reinforced PVC-encased micropile made of an expanded mixture (PUCR) of polyurethane resin (PU) and crumb rubber (CR) for Kenyir dam slopes stabilization. Two types of PUCR micropiles were tested: one containing 4.0 kg/m of PU and another with 2.0 kg/m of PU, both with varying ratios of CR from 0% to 30%. Compressive and flexural strength tests were conducted. Results showed that a 1:1 ratio of Polyol to Isocyanate in PU yielded the best compressive strength. For 4 kg/m PUCR micropiles, strength decreased as CR ratio increased, while for 2 kg/m micropiles, strength increased with CR ratio up to 10%. The study concludes that PUCR micropiles demonstrate good flexural strengths and may offer installation advantages for reinforcing unstable slopes, especially in areas with space and access constraints. However, proper sizing and CR ratio optimization are crucial for enhancing structural integrity and performance.

Keywords: Polyurethane, Micropile, Crumb rubber, Transmission tower, Slope, encased, Flexural strength.

1 Introduction

Fig. 1: Landslide that disrupted the accessibility to Kenyir Dam, Malaysia.

An abnormally high volume of precipitation in 2022 resulted in a landslide that disrupted accessibility to the Kenyir Dam in Malaysia, as shown in Figure 1. Similar events occurred elsewhere and could be considered direct consequences of climate change. The landslide necessitated the temporary decommissioning of the dam for one year due to the collapse of the high-voltage tower responsible for supplying electricity to the national grid. Many slopes close to Kenyir Dam need reinforcement using robust wire mesh. Conversely, several slopes at the hill's summit have not experienced a collapse yet, allowing them to undergo stabilization processes. The use of micropiles, specifically those cast in PVC pipes, is a potentially beneficial method for enhancing the stability of unstable slopes. This technology has the advantage of being quickly produced, minimizing any disruption to the equilibrium of the slope.

1.1 Steel-reinforced PVC Encased Passive Micropile

Passive piles are a reliable and effective technique for stabilizing slopes, as they are buried in stable soil and spaced to prevent soil movement. Stability can be improved by increasing shear strength along the failure surface and reducing driving shear stress. Installing piles within the sliding soil mass reduces shear stresses, increasing the safety factor of the slope stabilized with piles. This reduction in shear stress is due to the load transfer process, or soil arching, which transfers lateral earth pressure from a yielding layer to a non-yielding or less-yielding layer in geotechnical applications. This research deals with the laboratory performance of steel-reinforced, PVC-encased passive micropiles under tension, compression, and flexural

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[*]Corresponding author e-mail: mohdahmed.hafez@newinti.edu.my

loads. The passive micropile is an innovative infrastructure made of a mixture of expanded polyurethane resin with crumb rubber (PUCR) and was tested under various configurations to analyze a single micropile's compressive and flexural resistance. The most innovative aspect of this technology lies in using less costly equipment than other pile types. In general, passive micropiles are subjected to lateral forces due to horizontal changes in the surrounding soil and are used to stabilize moving slopes or as a preventative measure for stable slopes. The novel encased reinforced (PUCR) (100mm in diameter) can be installed quickly and provides immediate strength improvements to avoid transmission tower failure and disorderly power supply. Among various supporting innovations, micropiles are the most regularly adopted (Bruce, 1989; Han and Ye, 2006; Fross, 2006), particularly for landmarks and old structures. Recently, several authors have conducted experimental and theoretical studies aiming to investigate the effects of micropiles on strain and stress (Valentino & Stevanoni, 2016; Misra et al., 2004; Juran et al., 1999; Stuedlein et al., 2008; Babu et al., 2004; Misra & Chen, 2004).

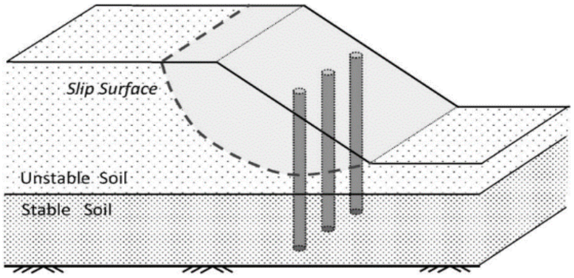


Fig. 2: Micropile stabilized slopes based on soil–pile interaction.

1.2 Polyurethane, also called PU

There are infinite uses for PU foam, and many aspects of how PU behaves have been the subject of intensive research. PU is a complex and unique polymeric substance that comprises urethane linkages to build a chain of organic units. It possesses various physical and chemical properties and is used in various applications. A substance that contains an isocyanate (-NCO) and a polyol (-OH) can be combined to produce polyurethane (PU), according to Norbaya (2017). The formation of polyurethane is given as follows:

$$R-NCO \;+\; HO-R' \;=\; R-NH-CO-O-R'$$

$$\text{(Isocynate)} + \text{(Polyol)} = \text{(Polyurethane)}$$

Rapid polyurethane (PU) production for geotechnical applications, Figure 3, requires the formation of polyurethane, which is achieved through the reaction of polyol and isocyanate. A larger percentage of isocyanate is required to manufacture stiff polyurethane foam (PU). A resin that has been properly formulated can create a very strong bond and has a shear strength that is greater than that of high-quality concrete.

Fig. 3: Rapid polyol Polyurethane foam.

1.3 Installation of Polyurethane Micropiles at the Bottom of the Slope.

The ground improvement techniques being used today have significantly shortened the time frame for preparing new land for use and, therefore, secured the economic viability of many projects (JO, Hafez, & Norbaya, 2011; Hafez & Syasirah, 2011; Asmani, Hafez, & Nurbaya, 2011). One of the primary benefits of polyurethane micropiles is their ability to be deployed in locations characterized by restricted accessibility. In contrast to larger and more intricate foundation systems, polyurethane micropiles can be positioned in restricted places and regions with limited accessibility, such as slopes at the Kenyir Dam vicinity. Installing polyurethane micropiles at the bottom of the slope is a multifaceted construction process. PUCR micropiles are 100-mm diameter piles that provide structural reinforcement, particularly in regions characterized by restricted accessibility or challenging soil conditions. The following is a comprehensive outline of the procedural stages of the installation.

1.3.1 The process of drilling and installing.

Use specialized drilling equipment to create perforations in the slope. The dimensions of the holes will depend on the individual design parameters. Place the micropile PVC casings into the pre-drilled holes. Then, insert 25 mm steel reinforcement at the center of the casing pipe. Finally, the micropiles should be grouted using polyurethane grout. This grout serves the dual purpose of enhancing the stability of the micropiles and strengthening their ability to sustain loads.

1.3.2 Load Test

Conduct load testing on the micropiles to verify their compliance with the design parameters. The typical procedure involves the application of a predetermined load to the micropiles, followed by the observation and analysis of their subsequent behavior. Figure 4 shows the details of the PUCR micropiles.

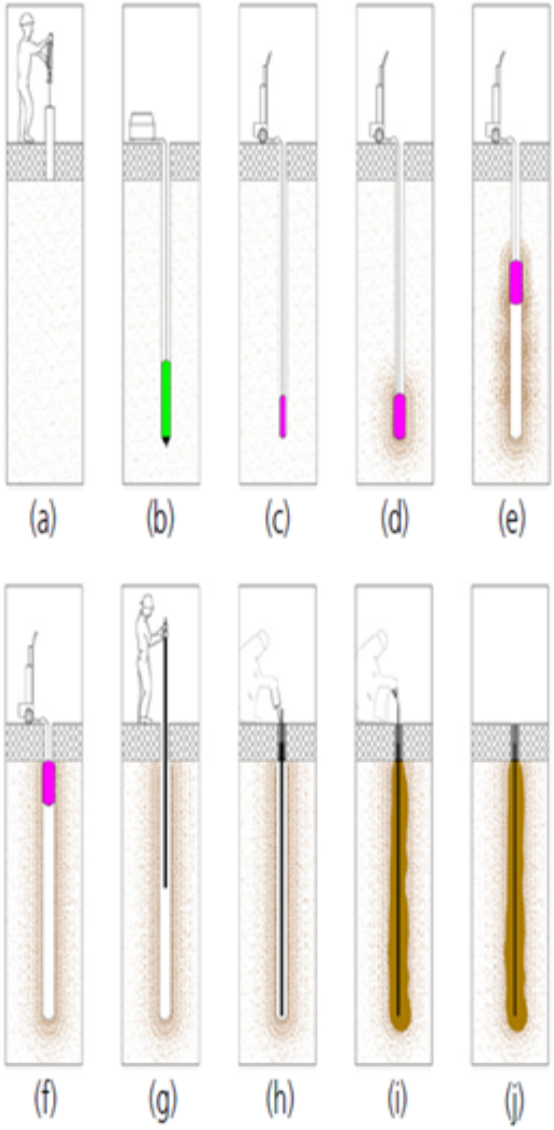


Fig. 4: Stages of the implementation method of reinforced resin micropile.

1.4 Crumb rubber as construction materials.

Crumb rubber is a substance manufactured from recycled rubber tires that have been crushed into small granules or crumbs. It has a long lifespan and high resistance to damage. This research discusses the effect of crumb rubber as coarse aggregate on the mechanical.

Properties of polyurethane grout used in steel-reinforced PVC-encased passive micropile performance. Crumb rubber particles can enhance the impact resistance of polyurethane mortar by acting as reinforcement, absorbing energy, and reducing cracking or damage. They also increase flexibility, making the mortar more suitable for applications requiring substrate movement or flexing. Additionally, it can improve adhesion, forming a stronger bond between the PU grout and surrounding materials. However, crumb rubber's presence may reduce the polyurethane grout's compressive strength, which can be disadvantageous in high-compression applications. The presence of crumb rubber may also affect the tensile strength of the PU grout, varying depending on the rubber's formulation. It can also reduce the overall density and weight of the polyurethane mortar, making it suitable for lightweight construction materials. Small-size ground rubber is typically round, while shredded and scrap rubber (size > 20 mm) are generally flaky, as shown in Figure 5 (Flores, N., Garcia, R., Hajirasouliha, I., Pilakoutas, K., & Guadagnini, M., 2018).

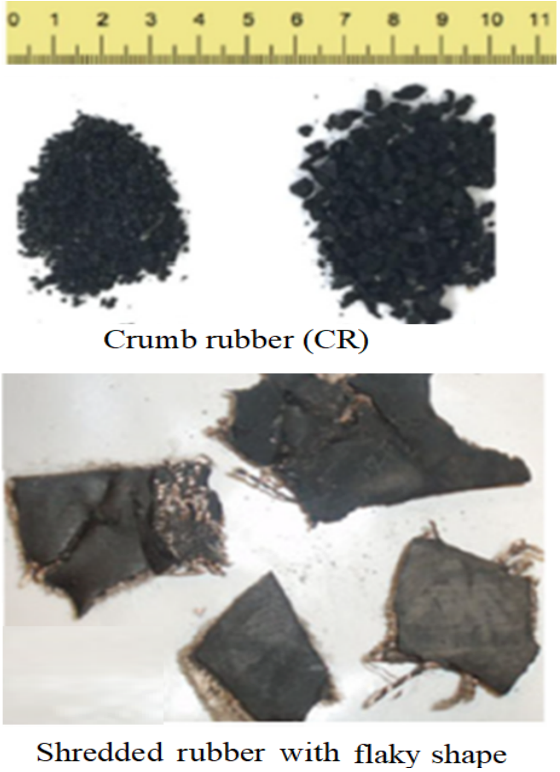


Fig. 5: Forms of rubber.

2 Micropile Design Method

The process of this research methodology was divided into the following three steps. The first worked through with polyurethane (PU) samples; it can show how the perfect balance between Polyol and Isocyanate should be. The first irrecoverable loading cycle (using a zero percent strain rate) was continued for one more step according to the BS 1377:1990 test stage. This test will provide the stress-strain diagram of where we can see the compressive strength of materials. In the third step, based on stage 2 results (PU demonstrated a higher strength ratio), PU micropile was prepared for analytical purposes, and following the DIN ISO-178 standard, a bending test of the PU micropile was done next (Procedure IV). PUCR micropiles were produced during stage five based on the third-stage PU content. During the last stage, an analysis is conducted on the sample's compressive strength and the pile's flexural strength.

2.1 Determining the Optimal Ratio between the Polyol and Isocyanate.

Table 1 Data of Polyurethane (PU) with Rapid Polyol: Isocyanate has been analyzed for various ratios employed to develop a material with maximum tensile strength as the polyurethane substance offers [16]. Rapid Polyol is chosen in this study as it is the most cost-effective option. The cost differential between Rapid Polyol, Dense Polyol, and Hard Polyol is also a factor. Rapid Poliol (BASF, Germany, 2013) is the most cost-efficient of the three types of Polyols. It has a 15 times faster reaction rate than Dense Polyol and Hard Polyol. Due to the phenomenon, Rapid Polyol is used here instead of Dense and Hard Polyol (Norbaya, 2017). The significance of polyol content justifies the fixed ratio of Rapid Polyol in this research as a determinant for growth in the composition.

On the other hand, the addition of Isocyanate enhances the strength characteristics of the composition. The experimental setup involves using a PVC pipe with established dimensions of 50.0 mm in diameter and 100.0 mm in length. The Rapid Polyol and Isocyanate substances are introduced within this sample tube by injection, followed by thorough mixing. Subsequently, the expansion of the substance inside the tube is permitted, thus encompassing both extremities of the cylinder. To create a sample of PU with 500 kg/m³, the volume of the cylinder was approximately 196.35 cm³ with a total weight of 100.0 grams for a ratio of 1:1.

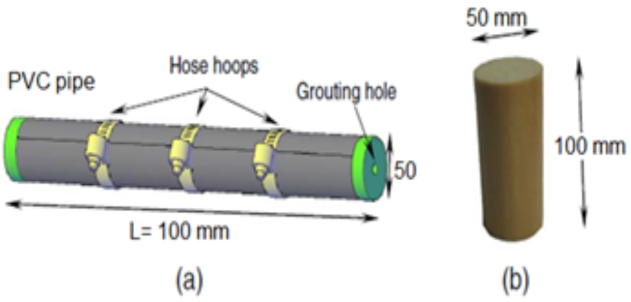


Fig. 6: Injection of polyol and isocyanate

Table 1: Different ratios for the PU samples.

No.	Rapid Polyol	gram (g)	Isocyanate	gram (g)	Number of Samples
1	1	50	1.0	50	3
2	1	50	1.1	55	3
3	1	50	1.2	60	3
4	1	50	1.3	65	3
5	1	50	1.4	70	3
6	1	50	1.5	75	3
7	1	50	1.6	80	3
8	1	50	1.7	85	3
9	1	50	1.8	90	3
10	1	50	1.9	95	3
11	1	50	2.0	100	3

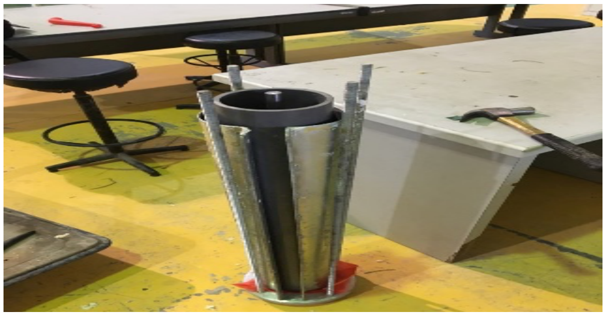
2.2 Preparing and Testing the Encased PUCR Micropile

It was established that the ratio of 1.0:1.0 demonstrated the maximum compressive strength based on the results derived from the UCT data collected during the initial stages. This experiment tested eight PUCR micropiles, each measuring one meter in length. The first batch consists of four micropiles, each containing 4.0 kg of polyurethane (PU) (2.0 kg of Polyol and 2.0 kg of Isocyanate) and a variable percentage of crumb rubber (CR) material ranging from 0% to 30%. The second batch comprises four enclosed micropiles containing 2.0 kilograms per meter (1.0 kg of Polyol and 1.0 kg of Isocyanate). Table 2 shows the CR weight in both batches. To test the encased micropiles, a PVC pipe measuring one meter in length was placed within a stainless-steel cylinder measuring 106 millimeters in diameter and 1,000 millimeters in length. After that, a steel rod measuring 16 millimeters in diameter and one meter in length was secured in the middle of the steel bottom of the mold. The mixture of Polyol and Isocyanate, along with different proportions of crumb rubber mix, was then tamped as it was slowly poured into the mold to reduce air bubbles forming. Figures 7 and 8 show the procedures for preparing and making the PUCR micropiles.

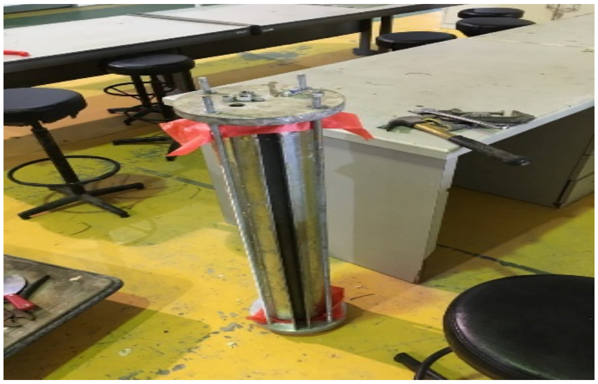
Table 2: Percentage of CR in PUCR micropiles.

Percentage of CR (%)	Weight of the CR in 4 kg PU (g)	Weight of the CR in 2 kg PU (g)
0.0	0.0	0.0
10	400	200
20	800	400
30	1200	600

(a) Insert the steel bar in the bottom cover.



(b) Install the PVC pipe.



(c) Put the top cover and screw tight.

(d) Fill up the polyol first then isocyanate.

Fig. 7: How to make a PUCR micropile.

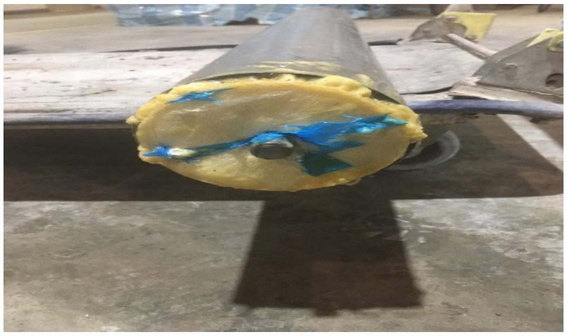
Fig. 8: Fill CR in the mold (before the Isocynate).

2.3 Testing the Encased PUCR Micropile

The capacity of the pile under lateral stress is a crucial consideration when designing micropiles for slope stabilization. Passive piles should account for the lateral shear stresses that result from slope movements. As a static load operating perpendicular to the cross-section of the micropile, the bending test is the best test to imitate the shear force induced by slope collapse. The results of these tests may help determine whether the PUCR material is suitable as a building material for passive micropiles by revealing its capacity to bear bending stresses under three-point flexural loading. Two reinforced PUCR micropiles (4 kg/m and 2 kg/m) were tested.

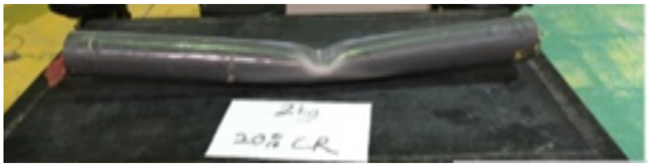
The flexural characteristics of the PUCR micropiles were measured using three specimens of each configuration, each measuring one meter in length. This information helps determine the flexural characteristics of the PUCR micropile material, such as the flexural modulus, flexural strength, and elongation at break, which are the most crucial characteristics. The maximum load applied during the test is used to calculate flexural strength. The elongation at break is the strain a specimen undergoes just before it fails. Figure 9 shows how the flexural tests were conducted. For a three-point bending strength test, a continually increasing load is applied to the center of the sample until there is a break or permanent bend in the material. A flexural test machine can apply increasing amounts of force and precisely record the amount of force at the point of breaking.

(a) Top of the pile.



(b) Bottom of the pile.

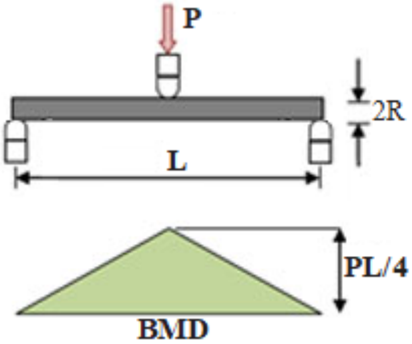
(c) During flexural testing.



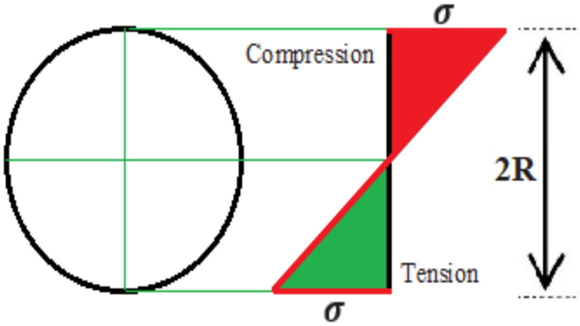
(d) After flexural testing.

Fig. 9: Conducting the three-point flexural test for 4kg PU micropile with no CR.

Figure 10 shows the bending moment diagram (BMD) and the bending stress distribution for the tested micropiles.



(a) Distribution of bending moment.



(b) Distribution of bending stresses.

Fig. 10: Distribution of bending moment and stresses.

According to Figure 10, the bending strength will be:

$$\sigma = \frac{PL}{\pi R^3} \tag{1}$$

As shown in Figure 9-c, tested micropiles are supported in the machine at (L = 30 cm), while the radius of the rigid PVC pipe is (R = 5 cm).

3 Discussion on the Pu & Pucr Micropile.

3.1 Compressive Strength of Polyurethane (PU) Sample Proportions.

Figure 11 shows the correlation between the isocyanate ratio of polyurethane (PU) and stress measured in kilopascals (kPa). The X-axis represents the isocyanate ratio, ranging from 1 to 2, and the vertical axis shows stress levels ranging between 120 kPa and 220 kPa. The graph shows a volatile pattern with several crests and troughs, with the maximum stress value recorded being 217 kPa at a ratio of 1.1 and the minimum at 122 kPa at a ratio of 1.5.

The trend line indicates a gradual rise in stress levels as the isocyanate ratio goes from 1 to 2, with varying peak and trough values. The stress behavior may be correlated with the mechanical characteristics of the polyurethane, which fluctuates depending on the isocyanate ratio. Varying ratios may impact the cross-linking density and molecular structure, influencing the material's strength and elasticity.

Comprehension of this correlation is essential for applications requiring precise mechanical characteristics, such as coatings, foams, or elastomers. Non-linear behavior suggests that other variables, such as temperature, curing time, or additional components in the formulation, may affect stress. Further research and enhancement in material design are suggested.

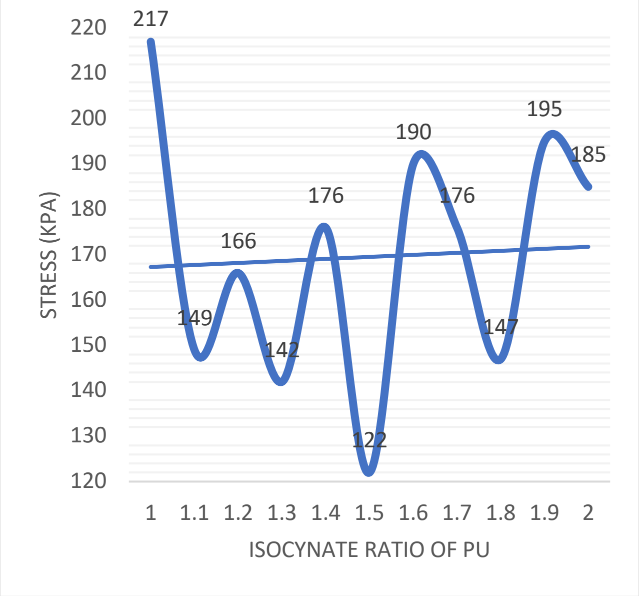


Fig. 11: Maximum corrected deviator stress vs. the isocyanate ratio of PU.

Figure 12 is a stress-strain curve plotting for multiple samples or conditions. It is commonly used in materials science and engineering to characterize the mechanical properties of materials. The graph has multiple curves, each represented by different colored lines and markers, with at least 10 visible curves. Each curve is labeled with a ratio, likely indicating different sample compositions or testing conditions.

The curves show significant variability in both maximum stress and strain behavior. Some materials reach higher peak stresses (around 200 MPa) while others peak lower (around 150 MPa). The strain at which the peak stress occurs varies considerably between samples. Some materials show more ductile behavior (continuing to strain without rapid stress decrease), while others appear more brittle (sharp drop-off after peak stress).

The different ratios likely represent varying compositions or processing conditions of a material, and the variability suggests that changing the ratio significantly affects the material's mechanical properties. However, drawing specific conclusions without more context about the ratios or the material being tested isn't easy. Despite this, the graph provides valuable information about the mechanical behavior of tested materials under compressive loading, allowing for comparisons of strength, stiffness, and deformation characteristics across different samples or conditions.

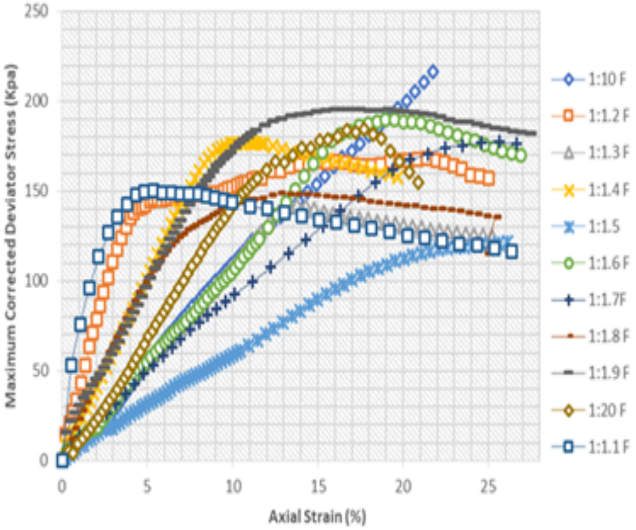


Fig. 12: Maximum Corrected Deviator Stress vs. Strain in all PU samples.

3.2 Stress-Strain analysis

When a material is loaded, its properties appear in the stress-strain diagram. As seen in Figure 13, the stress rises linearly with strain. Since this is an elastic analysis, we know that the proportional limit occurs at the terminal point of the connection. The maximum strain of 26.66 percent is recorded for a (1:1.7) ratio, while the maximum stress of 217 kPa is recorded for a (1:1) ratio.

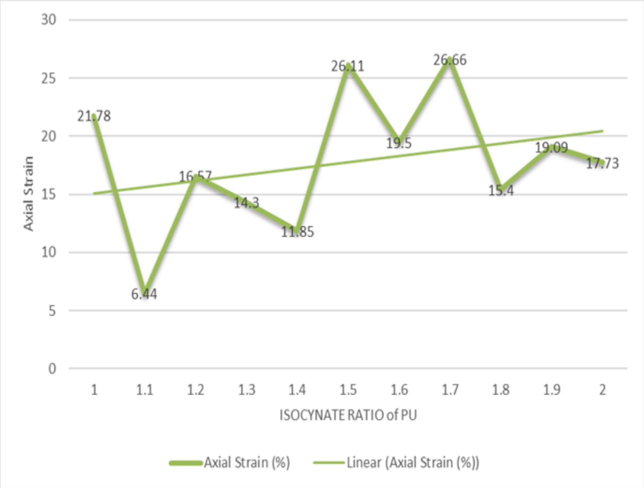


Fig. 13: Percentage of axial strain vs. the isocyanate PU ratio.

3.3 Performance of the (4.0 kg/m) Encased Micropiles.

Table 3 and Figure 14 show the flexural strength of the (4.0 kg/m) micropiles with crumb rubber (CR). The reliability and consistency of the maximum loads of the (4.0 kg/m) micropiles with crumb rubber (CR) are questionable. Based on the flexure test results, the PVC pipes did not exhibit total bending, and they should have a longer duration to achieve complete bending, as compared to the 4 kg PU micropile of (0.0%) CR.

Table 3: The 4 kg PU micropile flexural strength.

Percentage of CR (%)	Maximum load (kN)	Flexural strength (MPa)
0	52.749	40.292
10	38.599	29.484
20	39.179	29.926
30	22.130	16.904

For (10% and 20% of CR), the results exhibit a strength of just 75% of the maximum flexural capacity of (0.0% CR). On the other hand, the micropile with a (30% of CR) exhibits a higher probability of failure.

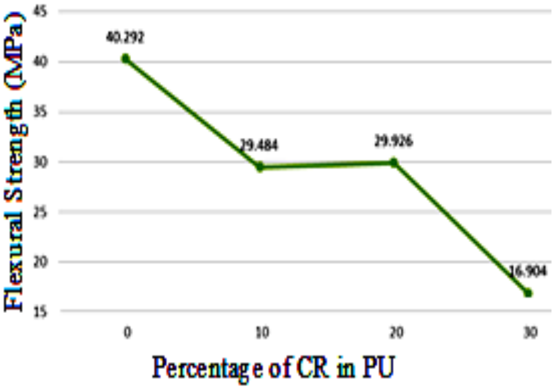


Fig. 14: Flexural strength for PU = 4 kg/m.

There are several potential explanations for the inconsistency of these results. The primary issue is the lack of reactivity between the polyol and the isocyanate, resulting in their inability to effectively blend and form a homogeneous mixture. Consequently, many empty spaces or voids are formed in the bottom section of the pipe. Furthermore, it is worth noting that the CR lacks cohesion. Another factor to be considered is the excessive bulk of the CR, which surpasses the pipe's capacity due to the combined weight of the polyol and isocyanate, amounting to 2 kg. The mass of the additive CR was recorded as 1.2 kg. Additionally, the pipe's capacity is insufficient for the proper mixing and reaction of the polyol and isocyanate. Figure 15 shows the details.

(a) PU reaction fails in the pile.

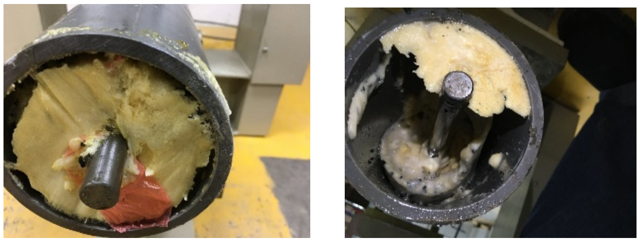
(b) Bottom of the pile. (c) Top of the pile.

Fig. 15: The 4kg PU micropile with 30% CR.

3.4 Performance of the (2.0 kg/m) Encased Micropiles.

Figure 16 shows the voids within the cross section of the 2kg PU micropiles with 10% CR, similar to the 4kg PU micropile with 30% CR shown in Figure 15.

The difference is that the tube will not be filled using 2 kg of PU. Therefore, the Polyol and isocyanate components inside the tube have space to complete their reaction and fully combine. Except for the micropile with (0.0% CR), the PU has a very spongy and gentle texture. Meanwhile, the integrity of the pipe as a whole was not compromised. Table 4 and Figure 17 show the flexural strength of the (2.0 kg/m) micropiles with crumb rubber (CR).



(a) Pile top. (b) Pile bottom.

Fig. 16: The 2kg PU micropile with 10% CR.

Table 4: The 2 kg PU micropile flexural strength

Percentage of CR (%)	Maximum load (kN)	Flexural strength (MPa)
0.0	35.607	27.198
10	40.878	31.224
20	41.041	31.349
30	41.332	31.571

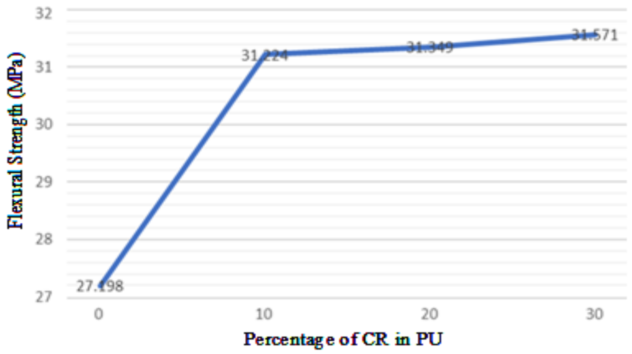


Fig. 17: Flexural strength for PU = 2 kg/m.

The graph in Figure 18 demonstrates the flexural strength of two configurations of polyurethane (PU) micropiles with different densities (2 kg/m and 4 kg/m) as the percentage of CR in PU increases from 0% to 30%. The initial strength comparison shows that the denser PU material is substantially stronger at 0% CR. As the CR percentage increases, the strength gradually increases while the density decreases. The flexural strength of both materials becomes nearly identical between 10% and 20% CR, but the 2 kg/m PU becomes stronger than the 4 kg/m PU. At 30% CR, the 2 kg/m PU is significantly stronger than the 4 kg/m PU, a complete reversal of the initial situation. Adding CR appears to strengthen the lower-density PU, possibly by improving its molecular structure or cross-linking. However, CR addition seems to weaken the material for the higher-density PU, possibly by disrupting its original structure or introducing defects. The lower density PU (2 kg/m) is more suitable for applications requiring higher flexural strength with CR additives. A higher density PU (4 kg/m) would be preferable if high flexural strength without CR is needed. The choice between these materials depends on the specific CR percentage required for other properties and the desired flexural strength.

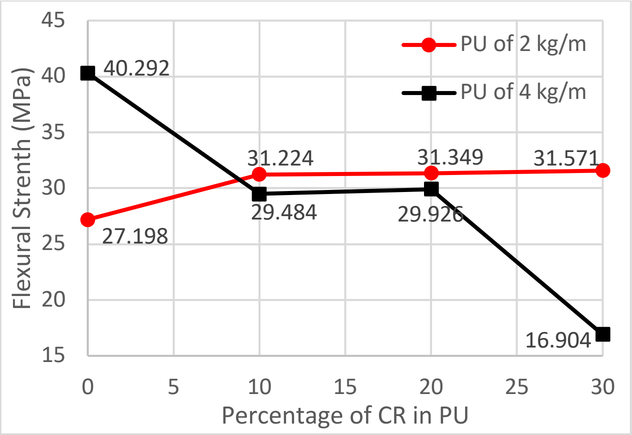


Fig. 18: Flexural Strength (MPa) for the two types.

4 Conclusions

This research evaluates the engineering properties of a new type of reinforced PVC-encased micropile made of an expanded mixture of polyurethane resin and crumb rubber. The study also explores the impact of crumb rubber as a coarse aggregate on the mechanical properties of polyurethane grout used in steel-reinforced PVC-encased passive micropile performance. Two types of PUCR micropiles were tested, with the first containing 4.0 kg/m of polyurethane and the second 2.0 kg/m.

- Upon analysis of the principal polyurethane (PU) constituents (Polyol and Isocyanate), it was shown that a 1:1 ratio of Polyol to Isocyanate yields optimal compressive strength.
- Raising the CR ratio from 0% to 30% enhances the total strength of the 2.0 kg/m micropile. While, the strength of the 4.0 kg/m micropile decreases as the CR ratio increases from 0% to 30%.
- For a micropile containing 2.0 kg/m of PU, the ideal CR percentage is 10%; exceeding this will result in marginal gains between 0.125% and 0.222%.
- The greatest flexural strength was attained without any CR for the PUCR micropile of 4.0 kg/m of PU. Nonetheless, when including CR, a 10% increment is deemed optimal, followed by a marginal rise of 1.5%, and subsequently, a substantial decline of 43.5% occurred.
- Polyurethane micropiles exhibit strong flexural strengths due to their ability to combine polyol and isocyanate. The size of the pile is crucial for increasing flexural strength.
- A limited amount of CR can reduce air voids in polyol and isocyanate compounds, enhancing pile structural integrity.
- Polyurethane micropiles can provide good installation advantages for slope reinforcement in unstable slopes and areas with space and access constraints.

References

[1] Asmani, D., Hafez, M., & Nurbaya, S. (2011). Static Laboratory Compaction Method. Electronic Journal of Geotechnical, Retrieved from http://www.csa.com/partners/viewrecord.php?requester=gs&collection=TRD&recid=16402358CE

[2] Babu, G.L.S., B.R.S. Murthy, D.S.N. Murthy, and M.S. Natraj (2004) "Bearing capacity Improvement using micropiles—a case study," Proceedings of Geosupport 2004, Drilled Shafts, Micropiling, Deep Mixing, Remedial Methods, and Speciality Foundation Systems, American Society of Civil Engineers, Orlando, Florida, 2004, Geotechnical Special Publication No.124, pp 692-699.

[3] Bruce DA. (1989). American developments in the use of small diameter inserts as piles and in situ

reinforcement. In: Proceedings of the international conference on piling and deep foundations, London, May 15–18, pp 11–22.

[4] Coppola, O., Ph, D., Magliulo, G., Ph, D., Maio, E. Di, & Ph, D. (2017). Mechanical Characterization of a Polyurethane-Cement Hybrid Foam in Compression, Tension, and Shear, 29(2), 1–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001738

[5] DIN Deutsches Institut für Normung. (2003). Din En Iso 178, (1112).

[6] FHWA. (2005). Micropile design and construction (reference manual for NHI course 132078). Federal Highway Administration FHWA-NHI-05-039, Washington, D.C., (132078), 436.

[7] Flores, N., Garcia, R., Hajirasouliha, I., Pilakoutas, K., & Guadagnini, M. (2018). Composites with recycled rubber aggregates: Properties and opportunities in construction. Construction and Building Materials, 188, 884–897. https://doi.org/10.1016/j.conbuildmat.2018.08.069

[8] Fross M. (2006). Thirty-five years of application of micropiles in Austria. In: Proceedings of the 7th international workshop on micropiles, Schrobenhausen, CD-ROM, ISM, Venetia, PA, USA, 58 pp.

[9] Hafez, M., & Syasirah, S. (2011). Study of Shear Strength on Natural Soil Using Laboratory Modeling of Static Standard Penetration Test (SSPT). Electronic Journal of Geotechnical Engineering, (2009). Retrieved from http://www.ejge.com/2011/Ppr11.118/Ppr11.118alr.pdf

[10] Hafez, M., & Syasirah, S. (2011). Study of Shear Strength on Natural Soil Using Laboratory Modeling of Static Standard Penetration Test (SSPT). Electronic Journal of Geotechnical Engineering, (2009). Retrieved from http://www.ejge.com/2011/Ppr11.118/Ppr11.118alr.pdf

[11] Han J, Ye S-L. (2006). A field study on the behavior of micropiles in clay under compression or tension. Can Geotech J 43(1):19–29.

[12] Han J, Ye S-L. (2006). A field study on the behavior of a foundation underpinned by micropiles. Can Geotech J 43(1):30–42.

[13] JO, A., Hafez, M., & Norbaya, S. (2011). Study of Bearing Capacity of Lime-Cement Columns with Pulverized Fuel Ash for Soil Stabilization Using Laboratory Model. Ejge.com, 1595–1605.

[14] Juran I, Bruce DA, Dimillio A, Benslimane A. (1999). Micropiles: the state of practice. Part II: design of single micropiles and groups and networks of micropiles. Ground Improv 3:89–110.

[15] Liu, J., Shi, B., Gu, K., Jiang, H., & Inyang, H. I. (2012). Effect of polyurethane on the stability of sand-clay mixtures. Bulletin of Engineering Geology and the Environment, 71(3), 537–544. https://doi.org/10.1007/s10064-012-0429-4

[16] Misra, A., Asce, M., Chen, C., Asce, A. M., Oberoi, R., & Kleiber, A. (2004). Simplified Analysis Method for Micropile Pullout Behavior, (October), 1024–1033.

[17] Misra A, Chen CH. (2004). Analytical solution for micropile design under tension and compression. Geotech Geol Eng 22:199–225.

[18] Naudts, A. (2003). Irreversible Changes in the grouting Industry Caused by Polyurethane Grouting: An Overview of 30 Years of polyurethane Grouting. Grouting and Ground Treatment Grouting, (519), 1266–1280. https://doi.org/10.1061/40663(2003)74

[19] Norbay binti Sidek. Dr. (Dec 2017). Chemical-modified sand soil using polyurethane (PU) for foundation improvement, PhD thesis, Universiti Teknologi MARA (UITM), Malaysia.

[20] Norbaya Sidek., Kamaruzzaman Mohamed., Ismacahyadi Bagus Mohamed Jais, M. F. M. (2014). Environmental And Sustainable Technology Using Polyurethane Foam, Annual Conference on Civil Engineering and Engineering (March 14-16 Phuket, Thailand) A1403-436, 1–9.

[21] Norbaya Sidek, Ilyani Akmar Abu Bakar, Ahmad Aftas Azman, Abdul Samad Abdul Rahman and Wizario Anak Austin "Strength Characteristic of Polyurethane With Variation of Polyol to Isocyanate Mix Ratio : A Numerical Analysis" International Conference on Automatic Control and Intelligent System (I2CACIS2017)

[22] Note, T., Fuensanta, M., Colera, M., Rodriguez, F., Iglesias, I., & Costa, V. (2017). Improvement in Adhesion, Abrasion Resistance, and Aging of Polyurethane Coatings Prepared with Polycarbonate Diol for Internal Pipelines, 29(10), 1–5. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002005.

[23] Pham, T. M., Kingston, J., Strickland, G., Chen, W., & Hao, H. (2018). Effect of crumb rubber on mechanical properties of multi-phase syntactic foams. Polymer Testing,66(September 2017), 1–12. https://doi.org/10.1016/j.polymertesting.2017.12.033

[24] Saleh, S., Zurairahetty, N., Yunus, M., Ahmad, K., & Ali, N. (2019). Improving the strength of weak soil using polyurethane grouts: A review. Construction

and Building Materials, 202, 738–752. https://doi.org/10.1016/j.conbuildmat.2019.01.048

[25] Somarathna, H. M. C. C., Raman, S. N., Mohotti, D., Mutalib, A. A., & Badri, K. H.(2018). The use of polyurethane for structural and infrastructural engineering applications: A state-of-the-art review. Construction and Building Materials, 190, 995–1014. https://doi.org/10.1016/j.conbuildmat.2018.09.166

[26] Stuedlein AW, Gibson MD, Horvitz GE. (2008). Tension and compression micropile load tests in gravelly sand. In: Proceedings of the 6th International Conference on case histories in Geotechnical Engineering, Paper 1.12, Washington D.C., 12 pp.

[27] Tuwair, H., Volz, J., Elgawady, M. A., Asce, M., Mohamed, M., Chandrashekhara, K., & Birman, V. (2016). Testing and Evaluation of Polyurethane-Based GFRP, Sandwich Bridge Deck Panels with Polyurethane Foam Core, 21(1), 1–13. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000773.

[28] Valentino R, Romeo E and Misra A. (2013). Mechanical aspects of micropiles made of reinforced polyurethane resins. Geotechnical and Geological Engineering 31(2): 463–468.

[29] Valentino, R., & Stevanoni, D. (2016). Behaviour of reinforced polyurethane resin micropiles, 169(mm), 187–200.

[30] Wei, Y., Asce, A. M., Wang, F., Gao, X., & Zhong, Y. (2017). Microstructure and Fatigue Performance of Polyurethane Grout Materials under Compression, 29(9), 1–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001954.

[31] Xiao, Y., Asce, M., Stuedlein, A. W., Asce, M., Chen, Q., Liu, H., & Liu, P. (2018), Stress-Strain-Strength Response and Ductility of Gravels Improved by Polyurethane Foam Adhesive, 144(2), 1–16. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001812.

[32] Xu, M., Liu, J., Li, W., & Duan, W. (2015). Novel Method to Prepare Activated Crumb Rubber Used for Synthesis of Activated Crumb Rubber Modified Asphalt, 27(5), 1–7. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001115.

[33] Ziari, H., Goli, A., Asce, A. M., & Amini, A. (2016). Effect of Crumb Rubber Modifier on the Performance Properties of Rubberized Binders, 28(12), 1–9. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001661.