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Research Article

Pullout behavior of GeoStrap-reinforced Ponza-modified clay under different confinement conditions

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Abstract

Pullout behavior of geostrip reinforcement inserted in Ponza-modified clay under different confinement conditions has been studied. Natural low-plasticity clay obtained from the Al-Amiriya area in western Baghdad was used as the base soil, while Ponza a lightweight aggregate used as a granular volcanic modifier for enhancing soil–reinforcement interaction. Large pullout tests were conducted using a rigid steel box that measures 600 mm × 400 mm × 400 mm. The geostrip reinforcement was installed at 150 mm in depth, while the geostrip possessed a width of 90 mm and an embedded length of 500 mm. Three normal stress levels (173, 207, 250 kPa) were used for testing overburden pressure, with Ponza contents ranging from 0% to 50%. The pullout force and displacement were recorded continuously to determine load–displacement response, maximum pullout resistance, apparent friction coefficient, interface shear stress. The implementation of Ponza increased pullout resistance and mobilization of interface shear resistance for movement between clay and geostrip. Results showed that with increase in Ponza % and normal stress, the maximum pullout force increased to approximately 39.19 kN at 50% Ponza under 250 kPa instead of 29.42 kN. Although apparent friction coefficient decreased with increasing normal stress, the maximum interface shear stress increased. The higher Ponza content also led to large peak displacements and indicated a progression to more ductile behavior. These results show that clay modified with Ponza can significantly enhance pullout of geostrip and can be useful in application of reinforced soil structures and mechanically stabilized earth systems.

1. Introduction

Clay is historic in geotechnical engineering, leading to challenges such as low strength and high compressibility [1]. Used lightweight aggregate (LWA) is a firm, lightweight, and porous material. It aids designers and engineers in managing loads, site conditions, and cost [2]. Ponza is a porous volcanic material with low density, making it ideal for improving weak clay soils. It reduces clay plasticity, shear strength, and stability by enhancing the granular structure [3]. Moreover, geogrid–clay friction increases with normal stress. Decreases stress due to full geogrid pullout; increases stress loads to longitudinal plate pullout, with change cohesion and friction angles [4]. Geostrap make a composite with clay, build up friction, and improves pullout performance. Higher density and lower moisture increase resistance [5]. The pullout test evaluates soil- Geosynthetic interaction under tension and more closely resembles domain conditions than the direct shear test. It detects friction and interlocking resistance and yields outcomes related to soil properties and the

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reinforcement. For reinforcing soil structures, pullout test results provide important design information [5-9]. More cohesion is also observed and control of pore pressure enhances MSE wall stability. The pullout resistance was also found to be higher in static than seismic loading and Geostraps enhanced stability in this environment [10]. Standard pullout tests on geosynthetic strips applied in MSE walls showed that roughly only 45% of embedded length in the geosynthetic strips is beneficial to pullouts [6], underscoring the importance of effective anchorage length in a design. Soil consistency index significantly affects the pullout behavior. An increase in content levels causes higher perspective pullout, owing to greater cohesion in the soil [11]. Geogrids (e.g., welded straps, coated woven) possess variable pullout resistance. As an example, welded straps exhibit much greater pullout force at the higher axial stiffness [12]. Typical stress and water content affect the interaction of geogrids and the clay, where the best conditions are those of maximum pullout forces [13]. Thin granular layers around geogrids effectively improve pullout resistance. A certain ratio of thickness between sand and clay has been proposed to achieve maximal performance [12-14]. Granular material generates lateral friction, and such friction is an essential factor in the pullout force [8]. On the contrary, geosynthetic reinforcements will often enhance the pullout behavior, but too much dependence upon these materials, without considering soil characteristics and weathering may result in unexpected failures during geological interventions. Despite some research based on lightweight aggregates for Ponza-modified clay soils, the pullout behavior of reinforcement in the Ponza-modified clay soils is still very limited. How Ponza affects the shear response of the matrix to polymeric reinforcement remains underexplored. Therefore, this study investigates the pullout behavior and soil–reinforcement interaction of Geostrap-reinforced Ponza-modified clay under various normal stresses by investigating load transfer mechanism, pullout resistance and interface response.

2. Materials and Methods

2.1 Natural Soil

Soil samples were obtained from the Al-Amiriya area located in western Baghdad, Iraq, at a depth between 1.5 to 2m beneath the natural ground level. The soil used in this study was classified as CL-clay. It was prepared and tested in the laboratory of Babil Tower for studies and scientific researches to find out its physical properties, the results of these tests are presented in Table 1. Figure 1 shows the grain-size distribution, while Table 2 shows the natural clay soil's chemical composition.

Table 1. Physical characteristics of natural clay soil.

Properties of the Material	Value	Standard Specification
Specific Gravity (Gs)	2.59	ASTM D 854
Liquid Limit %	30.5	
Plastic Limit %	19.8	ASTM D4318
Plasticity Index%	10.7	
Optimum Moisture Content OMC (%)	16	ASTM D-698
Maximum Dry unit weight (kN/m3)	18.35	
Sand content %	15	
Silt content %	19	
Clay content	66	

Table 2. Chemical composition characteristics of natural clay soil

Type of test	Value	Standard Specification
PH	7.4	
Sulfate contents (SO3), %	0.103	
Gypsum contents, %	0.221	
Chloride Content (Cl^-), %	0.031	BS 1377-3: 1990
TSS, %	2.4	
TDS, mg/L, %	100	

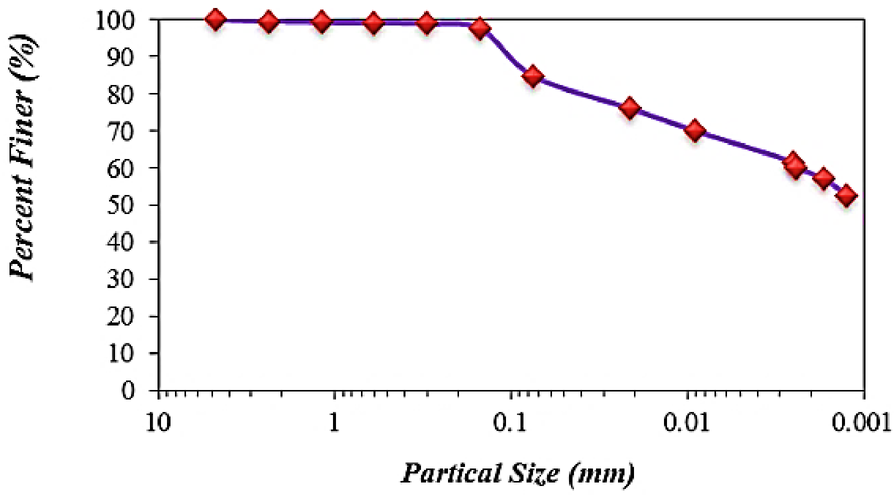


Fig. 1. Hydrometer test results for the clayey soil

2.2 Lightweight Aggregate (Ponza)

A lightweight material formed from lava and volcanic eruptions was brought from northern Iran, where it is abundant, and both physical and chemical tests were conducted on it as shown in Table 3 and 4.

Table 3. Physical characteristics of Ponza

Property	Value	Standard Specification
Absorption, %	14.830	ASTM C127-15
Specific gravity	1.931	ASTM C29
Dry unit weight, kg/m3	995	ASTM C29/C29M-17

Table 4. chemical composition characteristics of Ponza

Chemical analysis	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	Cl	TiO_2
Results	61.126	14.069	8.342	8.422	3.300	1.546	0.713	0.338	0.604	0.096	1.112

2.3 The Geostrip (Paraweb2D)

Table 5, presents the mechanical and physical properties of geostrip (Paraweb 2D) soil reinforcement strips manufactured by Maccaferri, As shown the Fig.2, which are used in reinforced soil structures. The design parameters were adopted from the manufacturer's technical data sheet. In this study, the reinforcement strips with a nominal tensile strength of 75 kN were used, and the corresponding properties were considered in all analyses and design calculations.

Table 5: Mechanical and physical properties of Paraweb 2D reinforcement strips.

Paraweb 2d	Unit	30	40	50	75	100
Mechanical Properties						
Ultimate Tensile Strength (UTS)	kN	30.16	40.20	50.27	75.40	100.54
Long Term Tensile Tc (72.4% of UTS)	kN	21.86	29.13	36.43	54.64	72.86
PHYSICAL PROPERTIES						
Strip width	mm	83 ±2	84 ±2	90 ±2	90 ±2	90 ±2
Strip weight	Kg/100 m	12.70	16.70	19.50	25.60	31.10

Fig. 2. Paraweb 2D soil reinforcement strips manufactured by Maccaferri

2.4 Experimental Work

2.4.1Pullout Test and Specimen Preparation

A pullout test was conducted to evaluate the interaction between the soil with the Paraweb 2D geostrip reinforcement to verify its properties. The experimental apparatus consists of a rigid steel box of 600 mm × 400 mm × 400 mm per ASTM D6706, a hydraulic jack to provide the pullout force, a load cell to measure the loading and a horizontal Linear Variable Differential Transformer (LVDT) to detect displacement during the testing. Normal stresses of 173, 207, and 250 kPa were applied, respectively, at a pneumatic loading system to simulate conditions of overburden pressure, which was optimized over a rectangular steel loading plate of 395 × 595 mm to provide an even distribution of stresses to the surrounding soil surface. Soil was first combined with the required optimum moisture content, and was then deposited in a series of compaction layers into a test box to generate the desired density. Specimen preparation involved a specially designed compaction hammer.

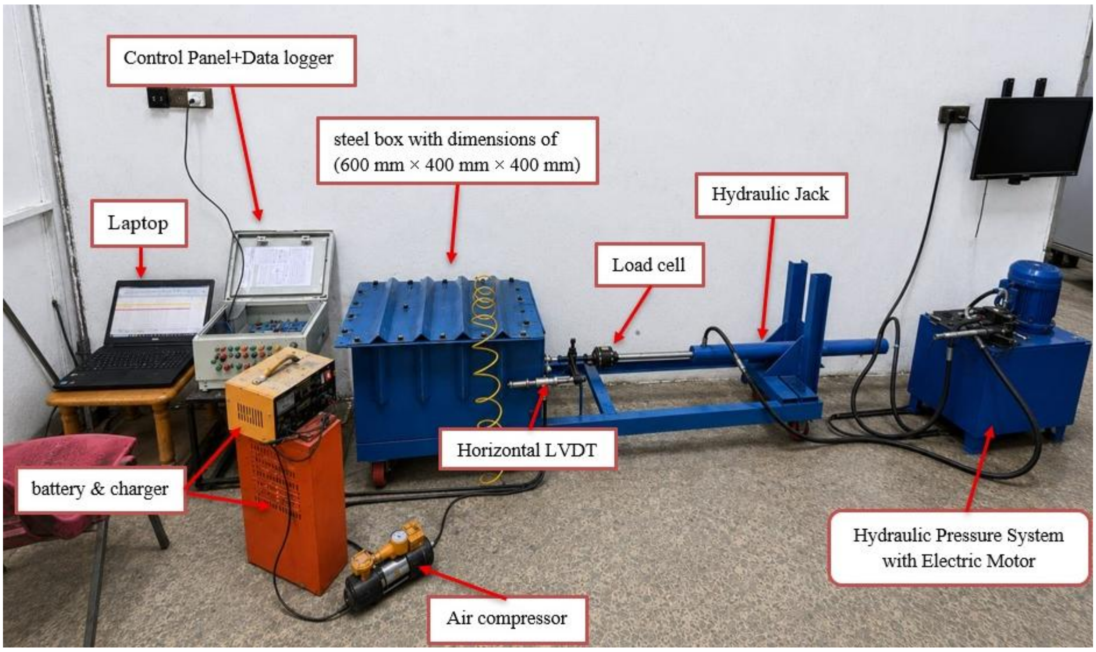


Fig. 3. Pullout test setup and specimen preparation sequence

The Paraweb 2D geostrip with 90 mm width was installed at an embedment depth of 150 mm and an embedded length of 500 mm. The reinforcement was fixed with a clamping system after deposition and compaction of the remaining soil layers. The pull-out test was carried out where horizontal displacement was applied to the geostrip at a constant rate of 1 mm per min until 100 mm was the displacement. In the procedure, pullout force and corresponding displacement were monitored on an ongoing basis to determine the soil–reinforcement interaction phenomena. Full pullout test and specimen preparation sequences are shown in Fig. 3.

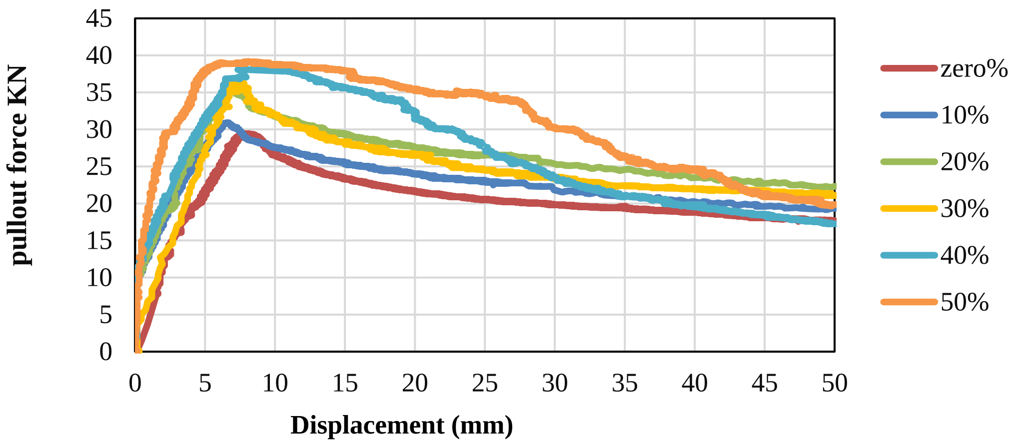
3. Result and Discussion

3.1 Analysis and Interpretation of Pullout Test Results

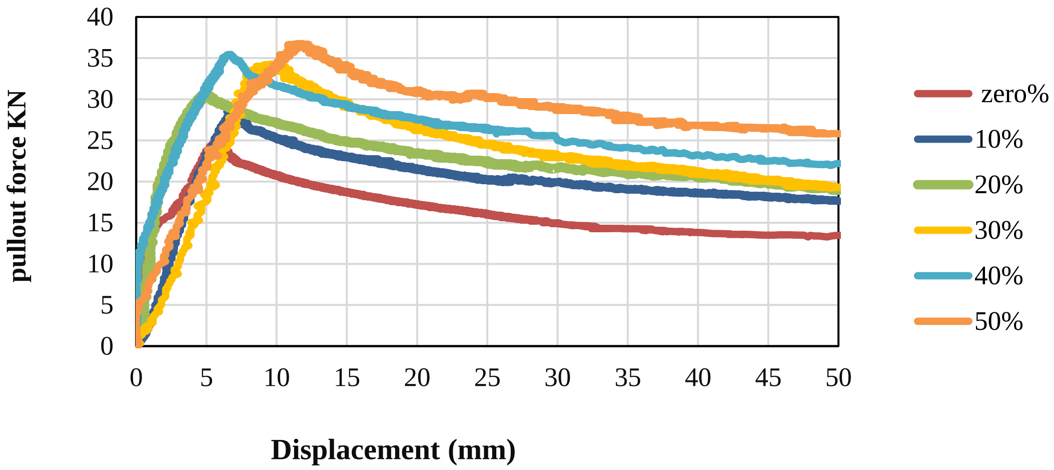
Pullout test measurements have shown that the behavior of Paraweb 2D geostrip in clay-Ponza mixes was mainly regulated by the applied normal stress and the percentage of Ponza added to the clay. The analysis was based on load-displacement response, maximum pullout resistance, maximum interface shear stress, apparent friction coefficient, and peak displacement. Generally, the results suggest the movement of interfacial behavior from adhesion to friction and provide evidence that frictional forces play a more substantial role in the tensile strength and load carrying potential.

3.2 Load–Displacement Characteristics

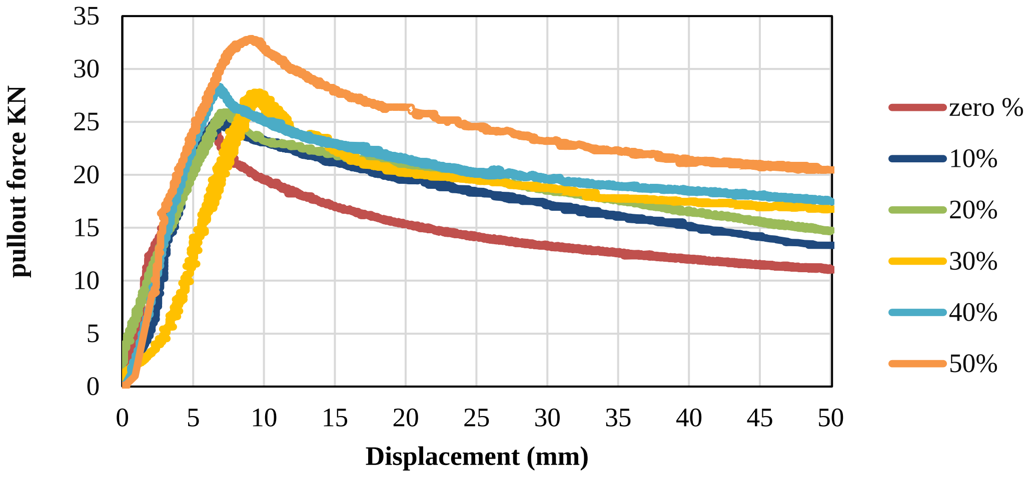
Fig. 4 presents the relationship between load and displacement of Geostrip in clay with different concentrations of Ponza, showing a progression from semi-elastic to ductile behavior. At first, the stress–strain curve reveals little deformation, indicating localized compression in the clay matrix. Nonlinear dynamics increase as loading progresses due to localized slip at the soil–reinforcement interface. Low Ponza content (0-20%) has lower peak displacements and is therefore stiffer, whereas large Ponza content (40-50%) produces more pullout loads and larger displacements, which help with friction and stress transfer. This shift toward ductile behavior at higher Ponza contents also increases energy absorption, which is beneficial for dynamic loading.



(a)



(b)



(c)

Fig. 4. Pullout force-displacement for soil-Ponza mixture under different normal stress (a) 250 kPa, (b) 207 kPa, and (c) 173 kPa

3.3 Effect of Normal Stress and Ponza Content on Maximum Pullout Resistance

Fig.5, shows that the pullout response of the Geostrip embedded in clay-Ponza mixtures is strongly influenced by both the Ponza content and the normal stress. At different stress levels, the maximum pullout resistance slowly increases. The mixes with higher Ponza contents, specifically at a 50% concentration of Ponza, have higher peak pullout resistance (Pmax) than the untreated clay. Moreover, at a uniform load of 250 kPa, the Pmax is between 29.42 kN for the untreated clay and 39.19 kN with Ponza concentration of 50%, meaning that Ponza is a good granular modifier to the clay matrix.

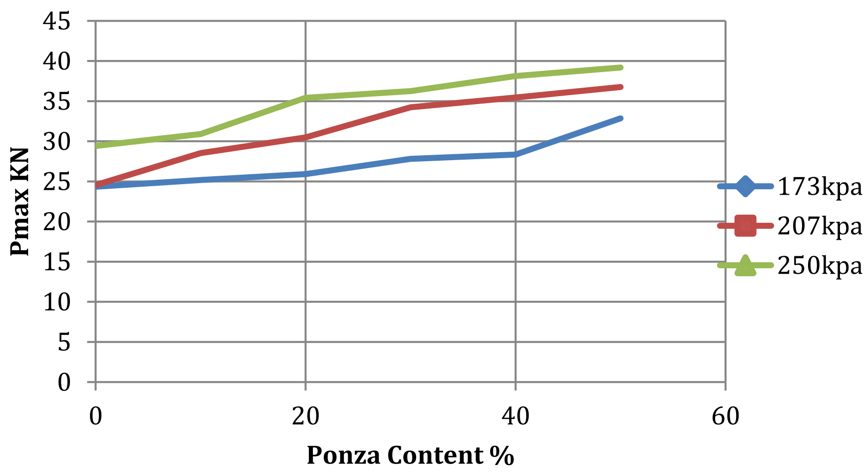


Fig. 5. Variation of Maximum pullout force (Pmax) with Ponza Content %under different normal stresses

The reason for this improvement is the rough and porous nature of the Ponza particles, which can make the mechanical entanglement better and stress transfer better at the soil-reinforcement interface. This is in line with the general structure of soil-reinforcement interaction of [15-16], where surface roughness and effective stress can be used to mobilize the interfacial shear resistance. In addition, the normal stress of the soil has a different and systematic effect on the pullout capacity. For all Ponza contents, the increase in vertical stress from 173 kPa to 250 kPa shows increasing strength gain. For 20% Ponza content, the pullout load was increased from 25.92 kN to 35.41 kN (≈37%), and for 50% Ponza content, it was increased from 32.86 kN to 39.19 kN (≈19%) as shown in Fig. 6. This behavior indicates the confinement-dependent nature of the pullout resistance, as the higher the normal stress, the more effective the contact pressure and the more frictional the reinforcement surface is. The same confinement-controlled increase in pullout capacity was obtained for reinforced soil [7,17].

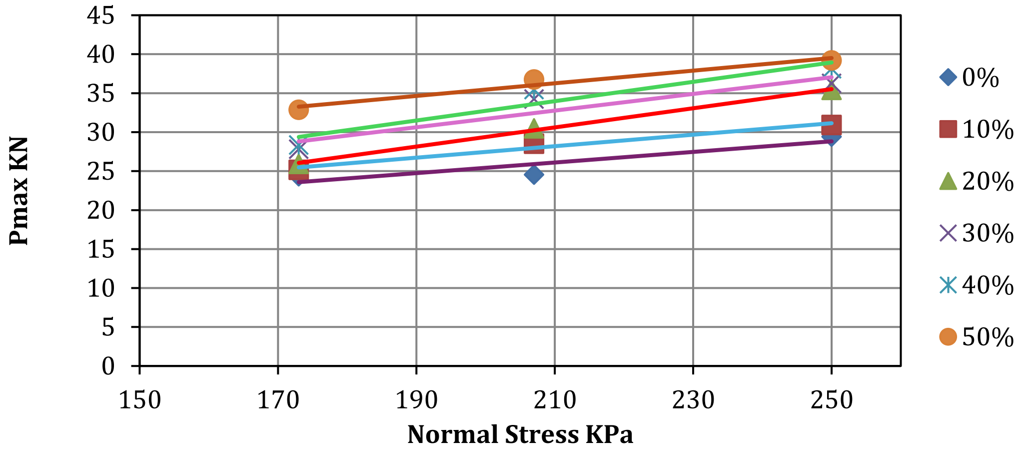


Fig. 6. Relationship between maximum pullout force and normal stress for clay-Ponza mixtures

3.4 Evaluation of Pullout Resistance Parameters

Based on the pullout test results, the maximum interface shear resistance is evaluated according to the apparent friction coefficient (ƒ*), which relates the mobilized shear resistance to the applied normal stress. The results indicate that the peak interface shear resistance increases approximately proportionally with the initial vertical stress due to the confinement-dependent nature of the pullout mechanism. The interface shear resistance parameters are determined using the calculation approach given by [18].

$$f* = \frac{P_{max}}{2 \times Lr \times Wr \times \sigma v} \quad , \tau_{max} = f^{*} \times \sigma v \tag{1}$$

The calculated results indicate a clear relationship between the normal stress (σv), the maximum interface shear stress (τmax) as shown in Fig.7, and the apparent friction coefficient (ƒ*) as shown in Fig. 8. The test data showed that τmax increases with σv and the confinement of soil reinforcement increases the effective contact pressure and mobilized shear resistance. However, the apparent friction coefficient (ƒ) decreases with the increase in normal stress. This is because τmax does not grow linearly with σv, showing the connection between interface interaction and stress. The decrease in ƒ at higher confinement levels could be due to the suppression of particle dilation and diminished relative movement about the reinforcement. Such results are consistent with confinement-dominated pullout mechanisms discussed in [17,19-20] that depend on the behavior of the interface with respect to the stress.

Fig. 9 shows that as the amount of Ponza increases (the apparent interface friction coefficient). This trend indicates that with the increase of Ponza content, soil reinforcement interface shear resistance is mobilized better. Higher ƒ* values indicate that the stress transfer mechanism, as a function of normal load, between reinforcement and treated soil is more efficient and higher mobilization of shear resistance can be obtained under normal stress. This attribution further supports Ponza inclusion improving the interfacial stress transfer effectively.

Peak displacement δpeak was also affected by Ponza content, as shown in Fig.10. The highest exertion of deformation in the system with high Ponza percentage before the point at which peak load was reached also demonstrates that an increase in Ponza percentage leads to larger displacements. This implies an enhanced capacity for deformation and a more gradual mobilization of the interface resistance. As a consequence, the increase in δpeak indicates that the pullout response shifts to a more ductile behavior with increasing Ponza content.

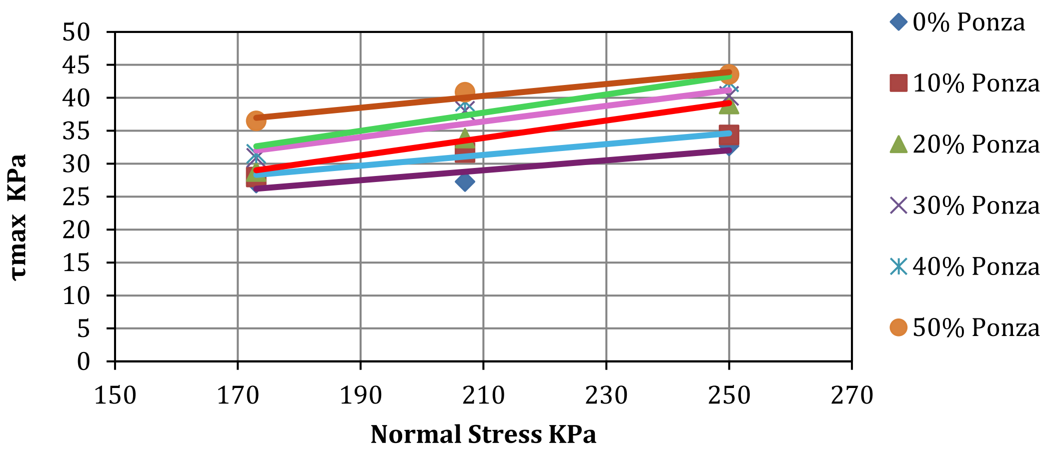


Fig. 7. Relationship between maximum Interface Shear Stress (τmax) & Normal Stress for clay – Ponza mixtures

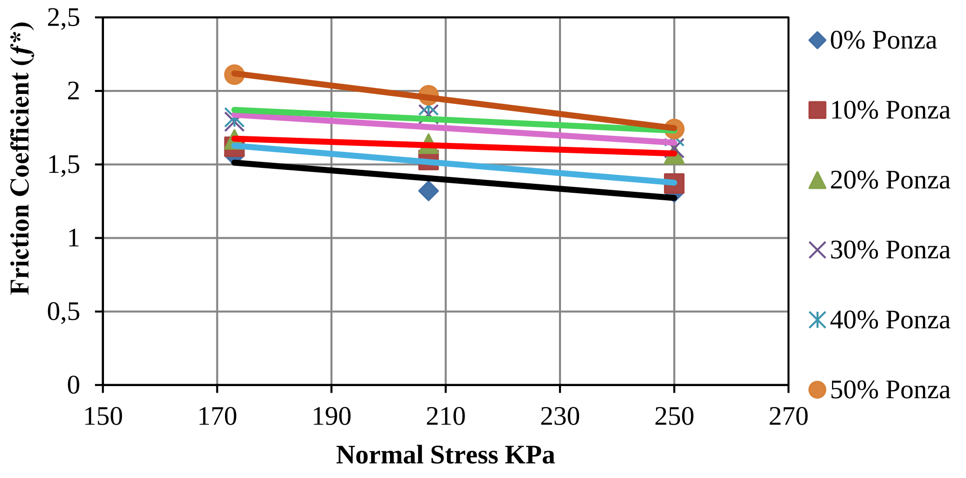


Fig. 8. Effect of normal stress on apparent friction coefficient (ƒ*) for clay –Ponza mixtures

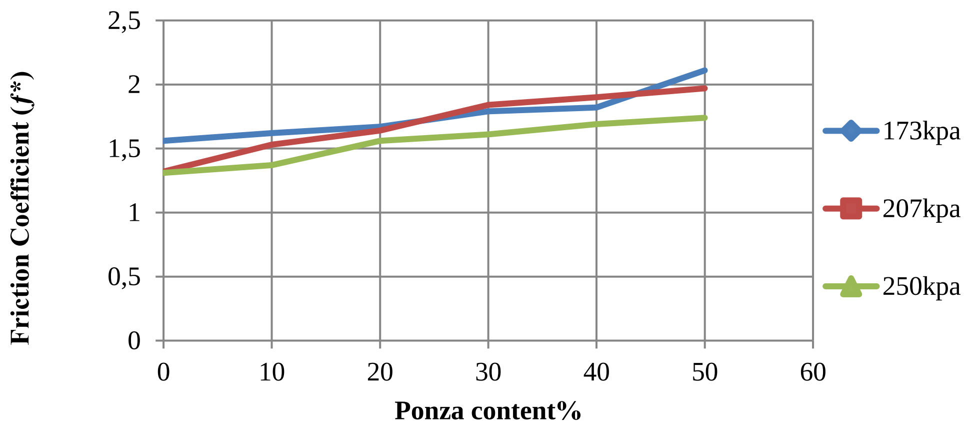


Fig. 9. Effect of Ponza content % on apparent friction coefficient (ƒ*) under different normal stresses

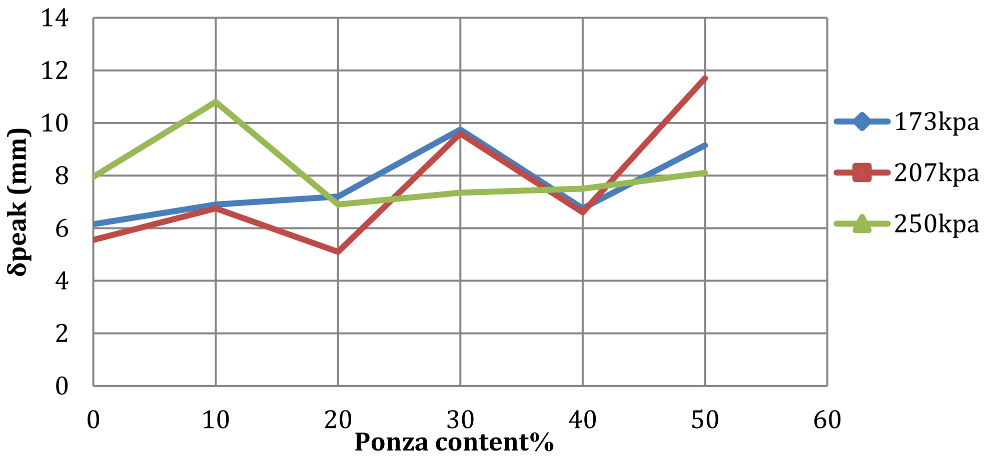


Fig. 10. Effect of Ponza content % on Peak displacement (δpeak) under different normal stresses

4. Conclusion

Based on the experimental pull-out tests conducted on Paraweb 2D geostrip reinforcement embedded in Ponza-modified clay under different normal stress levels, the following conclusions can be drawn:

- Under different normal stress levels, the pull-out strength of the geostrip in the clay–Ponza mixture is highly responsive to the Ponza content as well as to the applied normal stress (Fig. The max pull-out resistance progressively increases step by step with the amount of Ponza at different stress levels. The bulk of the thick mixed Ponza (50% Ponza concentration) has exceeded peak pull-out resistance (Pmax) in comparison to the untreated clay.
- For instance, Pmax ranges from 29.42 kN for untreated clay at 250 kPa to 39.19 kN with the uniform treatment of Ponza at about 50%, hence Ponza provides a preferred granular modification to the clay matrix. This improvement is attributed to better mechanical entanglement and stress transfer at the soil-reinforcement connect of the Ponza particles, which are rough and porous.
- Surface roughness and effective stress could potentially be utilized to mobilize interfacial shear resistance in these components. Besides, the applied normal stress has a specific and systematic effect on the pull-out capacity.
- For all Ponza contents, stepwise increase of vertical stress increasing from 173 kPa to 250 kPa shows strength improvement. In 20% Ponza content, the pull-out load increased from 25.92 kN to 35.41 kN (≈37%), and at 50% Ponza content, the pullout load rose from 32.86 kN to 39.19 kN (≈19%).
- This feature is consistent with the confinement-dependent nature of pull-out resistance with an increase of the effective contact pressure and increase in frictional mobilization on the reinforcement surface at an increased normal stress.

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