

Effect of polyvinyl chloride waste granules on the uniaxial compressive strength of clayey soils

Melik Bekhiti^{1,2a} and Abdelhalim Bensaada^{*3}

¹Department of Civil Engineering, University of Djelfa, Algeria

²Civil Engineering and Environmental Laboratory, Sidi Bel Abbes University, Algeria

³Civil engineering and environmental protection laboratory (LGPE), Civil Engineering Department, Faculty of Technology, University of Medea, Algeria

(Received January 19, 2025, Revised April 13, 2025, Accepted April 14, 2025)

Abstract. This study aims to investigate the impact of polyvinyl chloride (PVC) waste granules from discarded pipes on the uniaxial compressive strength (UCS) of two clayey soils using various mixing ratios. Soil 1 and Soil 2 were sourced from El-Idrissia and central Djelfa, Algeria, respectively. PVC granules (0%, 0.5%, 1%, 2%, and 10%) were mixed with dry clay soil, and UCS tests showed that PVC granules enhanced soil strength. Adding 0.5% and 5% PVC to Soil 1 increased UCS by 6.84% and 46.58%, respectively, making these values 1.5 times higher than unreinforced soil. For Soil 2, UCS increased by 14.62% and 88.46% with the same PVC proportions, over twice the strength of soil without PVC. PVC granules improved the compressive strength and resistance of clayey soils, enhanced their ductility noticeably, and prevented crack propagation and soil deformation. Microscopic analysis revealed significant interactions between PVC surfaces and clay particles, positively impacting soil behavior. Stabilizing clay soil with PVC waste produced isotropic materials with fewer desiccation cracks, improving compressive strength. This study offers practical applications for reinforcing weak soils in infrastructure, foundations, and road materials, providing significant economic and environmental benefits.

Keywords: clay soil; ductility; PVC Waste granules; reinforcement; uniaxial compressive strength

1. Introduction

In road construction, enhancing soil properties is crucial. Recently, using local materials like polyvinyl chloride (PVC) waste from used pipes has garnered attention from practitioners and researchers. PVC waste represents a major environmental problem at the local level due to its non-biodegradability, damage to ecosystems, recycling difficulties, pollution from incineration, and health risks. It also puts pressure on waste management infrastructure and affects the local economy. Recognized as a versatile polymer, increased PVC consumption has led to more waste entering the environment. Recycling PVC helps mitigate pollution from land filling, dumping, and incineration. Recycled plastic aggregates from crushed PVC pipes are increasingly used in civil engineering for hydraulic structures and lightweight and bituminous concrete. This eco-friendly approach protects the environment and promotes well-being (Sadat *et al.* 2011, Kou *et al.* 2020). Furthermore; it was shown that polymers in general can stabilize soils. In this context, Bekhiti *et al.* (2019) conducted a study to examine the effect of waste tire rubber fibers on the behavior of clay soils. They found out that incorporating 0.5% and 2% of rubber fibers into clay soils

caused their uniaxial compressive strength (UCS) to increase by 35.75% and 94.57%, respectively, while their dry density was reduced when stabilized with 10% of cement. Other authors have used polymers, such as used tire rubber powder and lime, to strengthen sandy soils. They found that sandy soils containing these materials showed higher axial compressive strength than unreinforced soils.

It is important to note that the experiments were conducted using a three-component mixture of rubber powder (8%), sand (90%), and lime (2%). These ratios represent the ideal mixture for achieving the highest strength in tensile and compressive conditions at 7, 14, 28, and 60 days (M 90-02-08) (Bekhiti *et al.* 2020). Furthermore, various authors, including Reddy and Marella (2001), have conducted numerous experimental studies to explore the potential use of shredded tire waste in concrete for structures and pavements. Cabalar *et al.* (2017) investigated the effect of xanthan gum biopolymer on uniaxial compressive strength (UCS) and observed that increasing the xanthan gum content led to higher UCS. A group of scientists explored the enhancement of clay or soft soil properties using sand, fibers, waste materials like pulverized glass, polypropylene fibers, calcium sulfoaluminate cement and phosphogypsum, lime - and cement, cement dust or various biopolymer types (Bensaada *et al.* 2023, Benathmane *et al.* 2024, Artoshi *et al.* 2024, Sommart *et al.* 2023, Khalid *et al.* 2022, Anna *et al.* 2025, Laith *et al.* 2025, Radhi *et al.* 2024, Zhanbo *et al.* 2021). They concluded that incorporating these materials improves the soil's strength, cohesion, and durability.

*Corresponding author, Associate Professor

E-mail: bensaada.abdelhalim@univ-medea.dz

^aAssociate Professor

Research in civil and geotechnical engineering has focused on soil stabilization, the use of waste materials in construction, and improving soil properties. Specific topics include stabilizing soil with rice husk ash and enhancing soil strength through reinforcement techniques (Najmun *et al.* 2022).

Furthermore, they also noted that increasing the curing time leads to higher UCS values. It is also noteworthy to mention that various types of polymers, such as polypropylene and polyester, have been extensively researched by several authors as well (Tomar *et al.* 2020, Correia *et al.* 2021, Komal *et al.* 2021, Sengul *et al.* 2023, Changizi *et al.* 2015, Chaduvula *et al.* 2017, Zhang *et al.* 2019). Researchers found that adding PVC waste granules up to 7.5% increased the compressive strength of soil samples. Specifically, incorporating 7.5% of PVC waste doubled the soil's compressive strength, with the UCS value being twice that of unreinforced soil (Karboua *et al.* 2023). It should also be mentioned that the investigation of polyvinyl chloride (PVC) waste granules was limited solely to the geotechnical field. The primary objective of this study is to develop a method to enhance the uniaxial compressive strength of clay soils by incorporating waste polyvinyl chloride (PVC) granules, which can be utilized in road construction or foundations.

Clay soils pose significant challenges in civil engineering due to their unique properties, which impact the stability and quality of infrastructure. In our study, we examine two types of local clay soils and it is worth noting that the most important problems these local soils create in construction include poor bearing capacity, expansion and contraction due to moisture, structural instability of buildings, cracks in building structures, and increased costs for construction projects.

Our research begins in the first part with an experimental study to examine the basic properties of the materials of both soil (1 & 2) and PVC granules. In the second part, we evaluate the effect of PVC granules on both Uniaxial Compressive Strength and Ductility Index. In the last part, we perform microscopic analyses to evaluate the effect of PVC granules on the cohesive strength of PVC particles and clay soil. These tests provide quantitative data on the strength and reveal the microscopic changes and interactions between PVC granules and clay particles. This approach aims to understand the mechanical behavior and potential applications of PVC-reinforced clay soil in engineering and construction.

2. Research significance

Assessing the effect of polyvinyl chloride waste granules on the uniaxial compressive strength of clayey soils is very important in infrastructure construction (both foundations and roads). Also, these promising results highlight the environmental potential of the technique, enabling the recycling and valorization of PVC waste on a global scale, while improving the geotechnical properties of clay soils, and assessing the uniaxial compressive strength of clay soil.

3. Experimental study

In this experimental investigation, identical clay test specimens were meticulously prepared with consistent water content and density. Initial compressive strength tests (reference tests) were conducted on two types of clay soil samples, denoted as Soil 1 and Soil 2, utilizing a slow compression device to ensure precise results. The clay soil utilized in this study was sourced from the El-Idrissia region and the town of Djelfa, both situated in the province of Djelfa in Algeria. Subsequently, a series of tests were conducted on clay soil mixtures containing PVC granules to qualitatively assess the influence of PVC pipe granules on compressive strength.

4. Materials and methods

The samples containing recycled PVC granules were stored in a controlled temperature and humidity box dry cabinet, following the Standard Test Method ASTM D 0854, for durations of 3, 7, and 14 days prior to conducting the compression tests. All granule samples under study were maintained in the laboratory for a total of 14 days at a temperature of (20 ± 2) °C and a relative humidity of (50 ± 5) % (ASTM D0854. 2010). Axial compression tests were performed on selected samples, applying controlled axial stress with deformation as per Standard (ASTM D 2166. 2000). Each sample had dimensions of 35 mm in diameter and 70 mm in height. A Compression Testing Machine (CTM) was utilized to apply a loading force along the axial direction at a loading rate of 1 mm/min. The values of the applied load were continuously recorded during the tests, which proceeded until the peak axial compression strength was reached. Subsequently, testing continued post-peak until failure.

4.1 Soil properties

Two distinct soil types, each with different origins and physical properties, were chosen for this study. The first sample (Soil 1) was obtained from the El-Idrissia region, situated in the north-southwestern part of the province of Djelfa, Algeria. This clay soil has been implicated in various structural disorders observed in buildings and civil engineering structures within the region. The second sample (Soil 2) was sourced from the central region of Djelfa. The characteristics of these two soils are detailed in Table 1. Subsequently, both soil types underwent several laboratory identification tests following standard procedures recommended by ASTM standards (ASTM D 4318. 2010, ASTM D 698. 2021, ASTM C 117. 2013, ASTM C 136. 2005, ASTM D 5102. 2009). Fig. 1 depicts the particle size distribution curves of Soil 1, Soil 2, and the PVC granules.

On the basis of the results obtained in Table 1 and according to the USCS (Unified Soil Classification System), soil 1 is classified as a clay soil with high plasticity (CH), and soil 2 is classified as a clay soil with

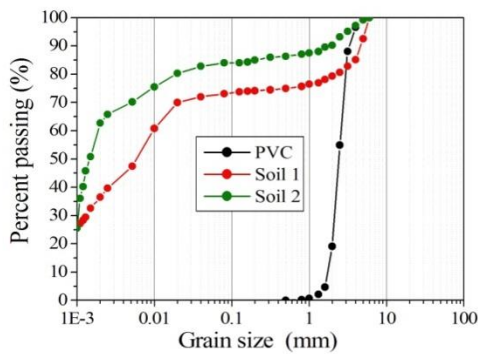


Fig. 1 Grain size curves of the two clays (soil 1 and 2) and PVC granule

Table 1 Characteristics of the clays used

Test	Soil 1 (%)	Soil 2 (%)
Granulometry	% < 2.5 mm	93.2
	% < 2 mm	91
	% < 0.08 mm	84
	% < 0.015 mm	50.8
	% < 0.001 mm	26
Atterberg Limits	W _L (%)	80
	W _p (%)	30
	I _p (%)	50
Compactibility	γ _d (g/cm ³)	2.5
	W _{op} (%)	17.5
Density	g/cm ³	2.74

Table 2 Physical and mechanical characteristics of PVC granules

Property	Value
Density (gr/cm ³)	1.4
Melting temperature (°C)	80-125
Compressive strength (MPa)	20-50
Elasticity limit	40
Young's modulus (GPa)	2 to 3
Elongation at break (%)	20 to 70

low to medium plasticity (CL), Soil 1 exhibits a maximum dry density (MDD) of 2.5 g/cm³ and optimal moisture content (OMC) of 17.5%, whereas soil 2 has a maximum dry density (MDD) of 1.83 g/cm³ and optimum moisture content (OMC) of 14.4%. Soil 1 exhibits a much greater maximum dry density compared to soil 2, along with a higher optimal moisture content (OMC), as increased water is required to facilitate particle softening for compaction.

The PVC plastic granules utilized as aggregates in the mixtures were sourced from PVC pipes. Some key properties of polyvinyl chloride are summarized in Table 2, as cited by Traore (2018). These PVC granules are sufficiently small, with approximately 98% of them capable of passing through a 5 mm sieve, as illustrated in Fig. 2.



Fig. 2 PVC granules used



Fig. 3 PVC granules mixed with soil

Fig. 3 depicts the mixture of PVC granules and clay under study.

4.2 Mix proportions and sample preparation

For this study, the clay soils were dried at approximately 105°C and then mixed with polyvinyl chloride (PVC) waste granules. The PVC proportions added were 0%, 0.5%, 1%, 2%, 5%, and 10% of the sample's weight. Special attention was given to achieving a homogeneous distribution of PVC granules within the mixtures.

The following abbreviations are used to represent the components of the mixture: "Soil 1" for the El-Idrissia clay, "Soil 2" for the central Djelfa clay, and "PVC" for the polyvinyl chloride waste granules.

The mixtures (PVC - Soil) were prepared with optimal water content for each sample, in accordance with ASTM D698 standards. To ensure uniform dry density, the samples were compacted statically in five layers using a standard Proctor mold. Due to the varying physical properties of the soils and PVC granules, an additional 1 kPa stress was applied. Static compaction facilitates achieving the corresponding dry density.

After the compaction of the mixtures, a hydraulic press was used to extrude the cylindrical samples, whether reinforced or unreinforced. The samples were then wrapped in plastic to prevent water evaporation.

5. Results and discussion

5.1 Uniaxial compressive strength



Fig. 4 Uniaxial compressive strength test



Fig. 5 The sample after compression testing

The mixtures under investigation were all formulated to achieve their maximum dry density and optimum water content. Unconfined compression tests were conducted on the specimens, applying a meticulously controlled axial load by Standard ASTM D 2166, ensuring consistent and reliable experimental conditions. For assessing compressive strength, each cured sample was positioned between the press plates, and a compressive load was progressively and continuously applied to it at a constant speed of 1 mm min^{-1} until the sample was completely crushed (Fig. 4).

Figs. 6 and 7 depict the variation of uniaxial compressive strength (UCS) concerning axial deformation for both Soil 1 and Soil 2, as well as for soil samples mixed with PVC granules sourced from used pipes, at concentrations ranging from 0.5% to 10%. The maximum UCS was recorded as 375 kPa for Soil 1, while for Soil 2; the highest UCS attained was 277 kPa, observed at a PVC content of 10%. Notably, the final UCS of samples containing different percentages of PVC granules exhibited an increasing trend, with axial deformation remaining constant. Figs. 6 and 7 unmistakably demonstrate the exceptional effectiveness of PVC granules in augmenting the compressive strength of Soils 1 and 2. It was observed that, for both soils, UCS progressively increased with higher PVC granule content. The maximum measured compressive strength (UCS) values are summarized in Table 3.

It is noteworthy that, for Soil 1, the uniaxial compressive strength increased by approximately 20.08% with the inclusion of 1% PVC granules in the mixture.

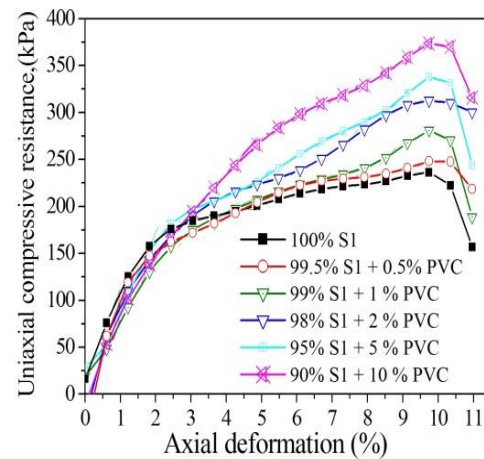


Fig. 6 Variation of uniaxial compressive strength as a function of axial deformation for mixtures -soil 1

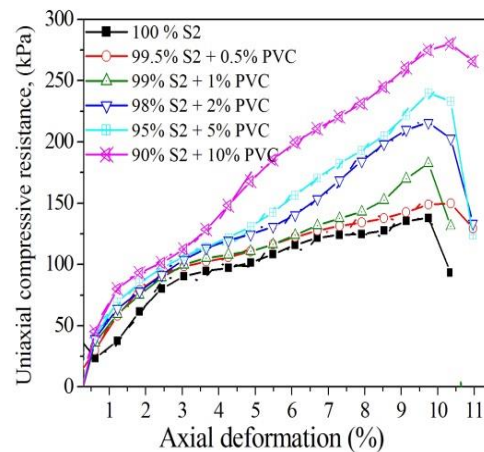


Fig. 7 Variation of uniaxial compressive strength as a function of axial deformation for mixtures -soil 2

Particularly significant was the finding that the UCS value surged by 46.58% with a 5% PVC granule content and by 60.25% with a content of 10% PVC granules. This leads to the conclusion that, for both types of soil, the higher the percentage of PVC granules, the greater the enhancement in compressive strength. In the case of Soil 2 incorporating 1% PVC waste granules, a notable increase of approximately 34.61% in uniaxial compressive strength was observed, with even more significant gains of 88.46% recorded for a 5% PVC granule content. It is worth emphasizing that the inherent hardness of PVC significantly contributed to the observed increase in compressive strength.

The incorporation of Polyvinyl Chloride (PVC) waste granules affected the Uniaxial Compressive Strength (UCS) of Soil 1 and Soil 2, albeit the extent of strength enhancement differed markedly between the two soils. This disparity can be ascribed to the inherent physical and chemical characteristics of the base soils, the interaction processes between soil particles and PVC granules, and the nature of load transfer within the altered soil matrix.

Table 3 Summary of uniaxial compression tests

Samples	PVC granule (%)	UCS max (kPa)	Increase in resistance R	Axial strain at peak strength (%)	Ductility D
Soil 1	0	234	1,00	9.29	1
	0.5	250	1,07	9.64	1.03
	1	281	1,20	9.64	1.03
	2	312	1,33	10	1.07
	5	343	1,47	10	1.07
	10	375	1,60	10	1.07
Soil 2	0	130	1,00	9.29	1
	0.5	149	1,15	9.29	1
	1	175	1,35	9.64	1.03
	2	214	1,65	9.64	1.03
	5	245	1,88	9.64	1.03
	10	277	2,13	10	1.07

5.2 Effect of PVC Granule content on the uniaxial compressive strength

Fig. 8 clearly demonstrates that the maximum uniaxial compressive strength of PVC granule-reinforced specimens increased with higher PVC percentages ranging from 0.5% to 10%. Specifically, for Soil 1, an increase in PVC granule percentage from 0.5% to 1% resulted in a respective augmentation of 6.84% and 33.33% in uniaxial compressive strength (UCS).

Notably, the compressive strength of the mixture at 1% PVC content was 1.6 times that of unreinforced Soil 1. Similarly, for Soil 2, the compressive strength increased by 14.61% and 34.61% for PVC granule proportions of 0.5% and 1%, respectively. In this case, the resulting mixture exhibited a compressive strength equal to 2.13 times that of unreinforced Soil 2. This significant increase in UCS can be attributed to the hardness of PVC granules, which enhances interaction with clay soil particles.

Hence, the maximum UCS values for Soil 1 samples, incorporating 0.5%, 1%, 2%, 5%, and 10% of PVC granules, were recorded as 250 kPa, 281 kPa, 312 kPa, 343 kPa, and 375 kPa, respectively.

Conversely, the corresponding values for Soil 2 samples, with 0.5%, 1%, 2%, 5%, and 10% PVC granules, were measured as 149 kPa, 175 kPa, 214 kPa, 245 kPa, and 277 kPa, as depicted in Fig. 8.

These results align closely with previously reported findings. In their experimental study investigating the compressive strength of expansive clay soil reinforced with

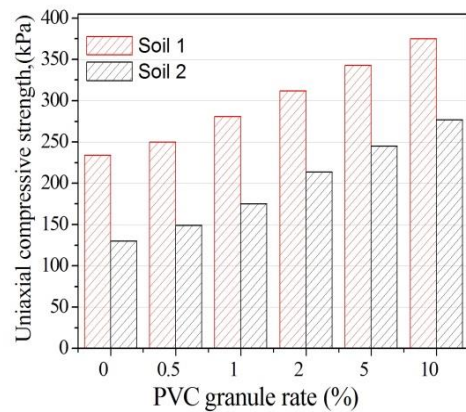


Fig. 8 Effects of PVC granule content on the UCS of mixtures

rubber aggregates from discarded tires and bentonite from the Maghnia region in the province of Tlemcen (Northwestern Algeria), it was noted that increasing the cement content from 5% to 7.5% in concrete mixtures reinforced with small fibers or granules (3-10 mm in length) at 0% and 1% contents resulted in respective increases of 4.46% and 5.53% in compressive strength (Bekhiti *et al.* 2019).

Similarly, another research team conducted an experimental study to assess the impact of rubber powder derived from used tires on the compressive strength of sandy soils, with lime added as well. Their findings revealed that incorporating 8% and 12% of rubber powder alongside 2% and 3% of lime led to increased compressive strength values. Furthermore, after 60 days of curing, the compressive strength of samples rose from 3 kg/cm² for the reference samples (M 100-00-00) to 6.2 kg/cm² for samples with optimal contents (M 90-02-08).

These findings are consistent with observations that UCS values increased with tire rubber fiber content up to 2%, beyond which they began to decrease (Akbulut *et al.* 2007). Similar outcomes were reported, demonstrating that UCS increased with higher polymer content. It was further noted that soils stabilized with 4% polymer exhibited greater compressive strength values compared to those with lower polymer percentages (Naeini *et al.* 2012).

Additionally, it was observed that soil samples stabilized with 5% polymer exhibited a lower UCS than those with 4% polymer. Moreover, the UCS values of samples incorporating 0% and 7.5% of PVC waste aggregates were measured as 180.24 kPa and 341.03 kPa, respectively (Karboua *et al.* 2023).

(Jiasheng *et al.* 2023) showed that the incorporation of 1% PET strips significantly enhanced the strength and stiffness of the expanded soil, as evidenced by UCS and MR, due to the bridging effect and the 3D network structure formed by the PET strips within the soil matrix.

Therefore, the observed increase in UCS can be attributed to the greater hardness of PVC waste granules compared to clay, leading to enhanced interaction between the PVC grains and clay soil particles.

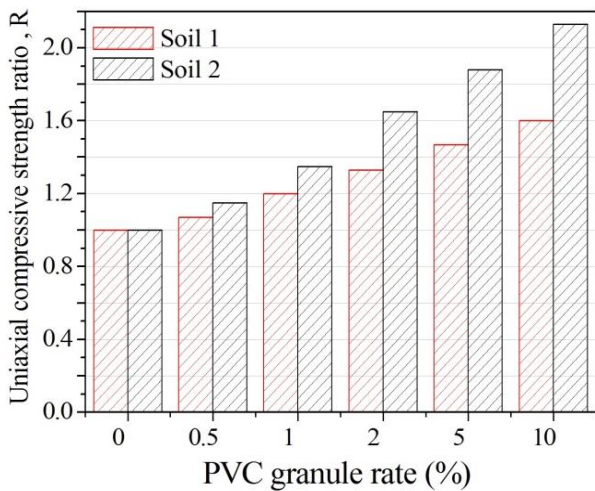


Fig. 9 Influence of PVC granule content on the uniaxial compressive strength ratio R

5.3 Influence of PVC granule content on the uniaxial compressive strength ratio

The uniaxial compressive strength ratio (R) was calculated, using Eq. (1), for the purpose of investigating the impact of PVC granule content on the increased ratio of the UCS, for both types of soil, i.e., Soil 1 and Soil 2. The ratio R of UCS for the samples reinforced with PVC granules to that of unreinforced samples is given by the following equation.

$$R = \frac{UCS_{(PVC\ granules=0,0.5,1,2,10)}}{UCS_{(No\ PVC\ granules)}} \quad (1)$$

Fig. 9 illustrates the trend of the increased ratio of uniaxial compressive strength (R) for both Soil 1 and Soil 2 as the content of PVC granules increases. It's evident that the ratio R shows a consistent upward trend with the addition of PVC granules for both soil types.

Particularly for Soil 2, the ratio R peaked at a value of 2.13, observed at a PVC granule percentage of 10%. Conversely, for Soil 1, the maximum R-value of 1.6 was attained with samples containing the same PVC granule content of 10%.

In a related study, researcher's utilized polymers such as rubber fibers or polyvinyl alcohol (PVA) combined with dune sand or clayey soil reinforced with cement. They discovered that the ratio R reached 3.5 for a mixture containing 1% PVA and 6% cemented sand, and 1.62 for a mixture incorporating bentonite clay with 0.15% fibers and 12% lime.

Notably, the R values were significantly higher in samples reinforced with a polymer containing cement (with fibers or PVA) compared to unreinforced samples (Byung *et al.* 2004).

5.4 Axial strain and ductility index

Fig. 10 illustrates the axial strain results at peak strength

for both types of soil reinforced with PVC granules, namely Soil 1 and Soil 2.

This figure indicates that the axial strain at peak strength tends to increase with higher PVC granule content. Specifically, incorporating 0.5% and 10% of PVC granules into the mixture resulted in increases in the axial strain at peak strength of 3.6% and 7.1% for Soil 1 and Soil 2, respectively. Notably, the axial strain values at peak strength were nearly identical for both types of soil (Byung *et al.* 2004).

In the realm of structural materials, ductility refers to the ability of materials or structural systems to undergo inelastic deformation before failure without experiencing significant loss in strength (Sung 2011). Sung-Sik noted that the addition of polymer fibers can have varied effects, particularly in mixtures containing 2% of cement (Sung 2011).

Furthermore, research has shown that fiber-reinforced cemented sand with 2% cement exhibited strength three and a half times greater than that of cemented sand without fiber reinforcement.

Hence, the ductility index (D) in this study can be calculated using Eq. (2) provided below. This index serves as a useful metric for evaluating the ductility of PVC granule-reinforced clayey soils (Soil 1 and Soil 2).

$$D = \frac{\Delta_{(PVC\ granules)}}{\Delta_{(No\ PVC\ granules)}} \quad (2)$$

Where $\Delta_{PVC\ granule}$ and $\Delta_{No\ PVC\ granule}$ are the axial strain values at peak strength in PVC granule-reinforced and unreinforced soils, i.e. Soil 1 and Soil 2, respectively.

The results obtained from the calculation of the ductility index D, for both types of clay soil (Soil 1 and Soil 2), reinforced with 0, 0.5, 1, 2, 5, and 10% PVC granules, are reported in Table 3, and illustrated in Figure 11.

It is clearly observed, in this figure, that the value of D for Soil 1 reinforced with PVC granules increased from 1.03 to 1.07, when the PVC granule content rose from 0.5% to 10%. As for Soil 2, this D value augmented from 1 to 1.07, with the same PVC content increase.

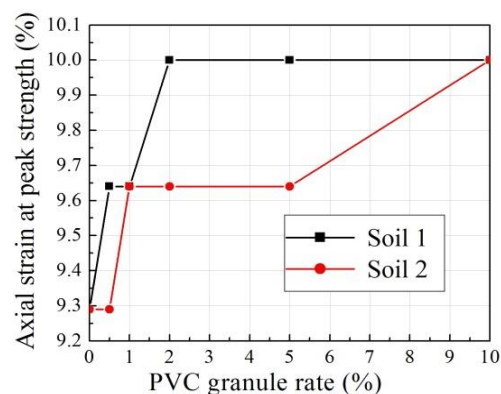


Fig. 10 Effects of PVC granule content on axial strain at peak strength for soil 1 and 2

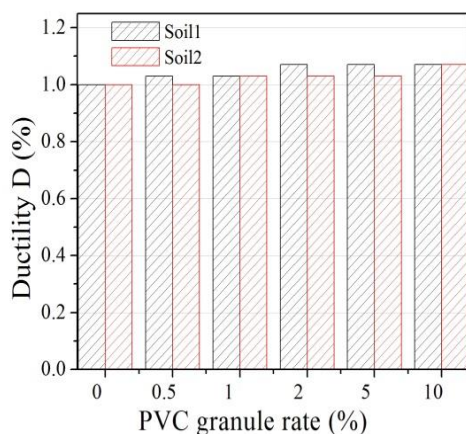


Fig. 11 Effects of PVC granule content on the ductility D for soil 1 and 2

In this regard, it was found that in fiber-reinforced cemented clay with 10% cement, the value of D increased from 1.8 to 5 as the tire rubber fiber (TRF) rate augmented from 0.5% to 2% (Bekhiti *et al.* 2019).

As for Sung-Sik Park, he indicated that the ductility index (D) value for fiber-reinforced cemented sand, with 6% cement and 1% PVA (Polyvinyl alcohol), was about 4.5 (Sung, 2011).

This is higher than the minimum value (1.07) obtained for Soil 1 and Soil 2 reinforced with PVC granules, as reported in Table 3.

This index can correspond to the toughness level of PVC granules when added to the clayey soil. It can also be used in choosing suitable PVC granules for a specific soil. It was also noted that PVC granules cause a strong frictional interaction between them and clay soil particles.

5.5 Microscopic analysis of soils mixed with PVC granules

Multiple samples were meticulously prepared and examined using a specialized microscopic device to confirm the impact of PVC granules on the soils under investigation. It was determined that Soil 1, being more expansive than Soil 2, would yield more precise and insightful results. Thus, Soil 1, fortified with PVC granules under optimal water content conditions, was scrutinized using a material analysis microscope, as depicted in Fig. 12. Optical microscope images of the mixture comprising clay Soil 1 and PVC granules, magnified to 600 \times , are presented in Figs. 12(a) and 12(b). Notably, Fig. 12(b) exhibits Soil 1 particles encircling the PVC granules, demonstrating their affinity to adhere to these granules. This is primarily due to the hydrophilic nature of both substances, particularly clay. Consequently, the presence of water amplifies the adhesion between these elements. It is crucial to emphasize that the robust adhesion between the PVC granules and clay soil particles, further enhanced by water, fortifies the clay soil with PVC granules. As the PVC granules share a significant surface area with the clay in the mixture, they offer

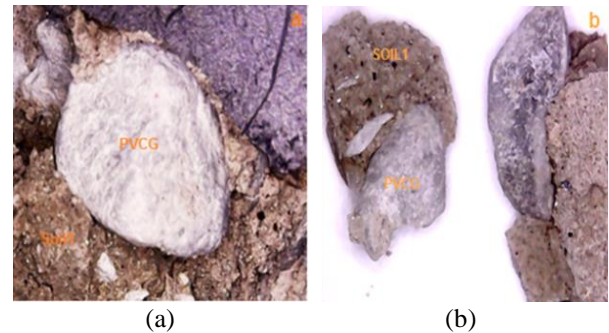


Fig. 12 Microscopic analysis at 600 \times Magnification of a sample containing 10% PVC granule of soil 1. (a) Top view of the sample and (b) Inner section of the sample

enhanced reinforcement, thereby augmenting the mixture's strength. Moreover, the robust reinforcement between the soil particles and PVC granules enhances the tensile strength of samples containing 10% or more PVC granules. Remarkably, similar findings and visual observations were reported when rubber granules were introduced into clayey soil. These authors observed substantial cohesion between the rubber granules and soil particles, suggesting an increase in mixture strength. It is pertinent to note that the precise calculation and evaluation of the adhesion between clayey soil and PVC granules warrant further investigation and thorough scrutiny (Akbarimehr *et al.* 2020).

6. Conclusions

Several tests were carried out for the purpose of studying the effect of PVC granules on the uniaxial compressive strength of clay soils. The findings allowed drawing the following conclusions:

Adding PVC granules to clay soil increases its uniaxial compressive strength and stiffness. Adding 10% PVC granules increases the uniaxial compressive strength (UCS) of Soil 1 from 234 kPa to 375 kPa (60.25% increase) and Soil 2 from 130 kPa to 277 kPa (113.07% increase). This demonstrates that PVC granules significantly enhance the hardness and cohesion of the soil samples.

Deformability and ductility index (D) increase noticeably with higher PVC granule content, peaking at 10%, regardless of soil type.

PVC granules can enhance soil stability and reinforcement and absorb up to 3% of their weight in water.

Microscopic examination shows that the adhesion between clay and recycled PVC granules improves the performance of the mixtures.

The results of this study can be generalized to clayey soils with low plasticity (CL) and high plasticity (CH) mixed with varying amounts of PVC particles in any region.

In conclusion, PVC granules enhance the uniaxial compressive strength, stiffness, and hardness of soil samples, prevent tension cracks and deformation, and improve mechanical behavior through interactions with clay grains. Stabilized clay soils with PVC granules are isotropic, exhibit high compressive strength, and have fewer desiccation cracks.

References

- Akbarimehr, D., Eslami, A. and Aflaki, E. (2020), "Geotechnical behavior of clay soil mixed with rubber waste", *J. Cleaner Product.*, **271**(6), 122-132. <https://doi.org/10.1016/j.jclepro.2020.122632>.
- Akbulut, S., Arasan, S. and Kalkan, E. (2007), "Modification of clayey soils using scrap tire rubber and synthetic fibers", *Appl. Clay Sci.*, **38**(1-2), 23-32. <https://doi.org/10.1016/j.clay.2007.02.001>.
- Artoshi, I.M.K., Abdulateef, L.A., Farman, I.H. and Ahmed, A.M. (2024), "Efficiency and durability assessment of soil stabilization using waste tire shreds", *Eng., Tech. Appl. Sci. Res.*, **14**(1), 13012-13016. <https://doi.org/10.48084/etasr.6740>.
- ASTM C 117. (2013), "Test Method for Materials Finer Than 75- μ m (No.200) Sieve in Mineral Aggregates by Washing", Annual Book of ASTM Standards.
- ASTM C 136. (2005), "Test Method for Sieve Analysis of Fine and Coarse Aggregates", Annual Book of ASTM Standards.
- ASTM D 2166. (2000), "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil", Annual Book of ASTM Standards.
- ASTM D 4318. (2010), "Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", Annual Book of ASTM Standards.
- ASTM D 5102. (2009), "Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures", Annual Book of ASTM Standards.
- ASTM D 698. (2021), "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³))", Annual Book of ASTM Standards.
- ASTM D0854. (2010), "Test Methods for Specific Gravity of Soil Solids by Water Pycnometer", Annual Book of ASTM Standards.
- Bekhiti, M., Ghrieb, A. and Zaitri, R. (2020), "Valorization of dune sand treated with lime and scrap tyre rubber powder as a road foundation material", *J. Mater. Eng. Struct.*, **7**(3), 487-500.
- Bekhiti, M., Trouzine, H. and Rabehi, M. (2019), "Influence of waste tire rubber fibers on swelling behavior, unconfined compressive strength and ductility of cement stabilized bentonite clay soil", *Const. Build. Mater.*, **208**, 304-313. <https://doi.org/10.1016/j.conbuildmat.2019.03.011>.
- Benathmane, B., Younes, A., Sadok, F., Sidali, D., Turgay, B. and Achref, C. (2024), "Effect of Xanthan gum biopolymer combined with fibre as soil-stabilization binder of dune sand in Southern Algeria", *Geomech. Eng.*, **39**(2), 115-127. <https://doi.org/10.12989/gae.2024.39.2.115>.
- Bensaada, A., Chougache, B. and Zaitri, R. (2023), "Influence of the incorporation of alluvial sand on the mechanical behavior of marl soil", *Eng. Tech. Appl. Sci. Res.*, **13**(2), 10363-10366. <https://doi.org/10.48084/etasr.5712>.
- Cabalar, A.F., Wiszniewski, M. and Skutnik, Z. (2017), "Effects of xanthan gum biopolymer on the permeability, odometer, unconfined compressive and triaxial shear behavior of a sand", *Soil Mech. Found. Eng.*, **54**, 356-361. <https://doi.org/10.1007/s11204-017-9481-1>.
- Chaduvula, U., Viswanadham, B.V.S. and Kodikara, K. (2017), "A study on desiccation cracking behavior of polyester fiber-reinforced expansive clay", *Appl. Clay Sci.*, **142**, 163-172. <https://doi.org/10.1016/j.clay.2017.02.008>.
- Changizi, F. and Haddad, A. (2015), "Strength properties of soft clay treated with mixture of nano-SiO₂ and recycled polyester fiber", *J. Rock Mech. Geotech. Eng.*, **7**(4), 367-378. <https://doi.org/10.1016/j.jrmge.2015.03.013>.
- Cheng, Z. and Geng, X. (2021), "Soil consistency and interparticle characteristics of various biopolymer types' stabilization of clay", *Geomech. Eng.*, **27**(2), 103-113. <https://doi.org/10.12989/gae.2021.27.2.103>.
- Correia, S.N., Andrade, S.R. and Rocha, P.C. (2021), "Shear strength behavior of clayey soil reinforced with polypropylene fibers under drained and undrained conditions", *Geotext. Geomembranes*, **49**(5), 1419-1426. <https://doi.org/10.1016/j.geotextmem.2021.05.005>.
- Ehrenstein, G.W. and Montagne, F. (2000), *Polymer materials: structures, properties and applications*, Editions Hermes, Paris.
- Ibdah, L., Owusu, K., Behdad, A. and Eun, J. (2025), "Effects of freeze-thaw cycles on the unconfined compressive strength of lime- and cement-stabilized soils", *Geomech. Eng.*, **41**(1), 59-70. <https://doi.org/10.12989/gae.2025.41.1.059>.
- Jo, B.W., Tae, G.H. and Kwon, B.Y. (2004), "Ductility evaluation of pre-stressed concrete beams with CFRP tendons", *J. Reinf. Plast. Comp.*, **23**(8), 843-859. <https://doi.org/10.1177/0731684404033492>.
- Karboua, L., Bekhiti, M. and Zaitri, R. (2023), "Optimizing the mechanical behavior of clay using cement and PVC aggregates with the application of a mixture design method", *Constr. Build. Mater.*, **208**, 304-313. <https://doi.org/10.1016/j.conbuildmat.2023.133343>.
- Khalid, W.A., Mohammed, Y.F. and Mudhafar, K.H. (2022), "Compressibility and strength development of soft soil by polypropylene fiber", *Int. J. Geomate*, **22**(93), 91-97. <https://geomatejournal.com/geomate/article/view/3206>.
- Komal, K., Bawa, S. and Kantharma, S.J.M.T.P. (2021), "Laboratory investigation on the effect of polypropylene and nylon fiber on silt stabilized clay", *Mater. Today Proceedings*, **52**, 1368-1376. <https://doi.org/10.1016/j.matpr.2021.11.123>.
- Kou, S.C., Lee, G., Poon, C.S. and Lai, W.L. (2009), "Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes", *Waste Management*, **29**(2), 621-628. <https://doi.org/10.1016/j.wasman.2008.06.014>.
- Loskutova, A., Kim, J., Satyanaga, A. and Moon, S.W. (2025), "Sustainable soil stabilization using calcium sulfoaluminate cement and phosphogypsum", *Geomech. Eng.*, **41**(1), 1-10. <https://doi.org/10.12989/gae.2025.41.1.001>.
- Naeini, S.A., Naderinia, B. and Ehsan, I. (2012), "Unconfined compressive strength of clayey soils stabilized with waterborne polymer", *KSCE J. Civil Eng.*, **16**(6), 943-949. <https://doi.org/10.1007/s12205-012-1388-9>.
- Najmun, N., Alex, O.O. and Zakaria, H. (2022), "Influence of the initial setting of cement on the shear strength of rice husk ash stabilized soil", *J. Agricult. Eng.*, **53**(4), 1411. <https://doi.org/10.4081/jae.2022.1411>.
- Park, S.S. (2011), "Unconfined compressive strength and ductility of fiber-reinforced cemented sand", *Const. Build. Mater.*, **25**(2), 1134-1138. <https://doi.org/10.1016/j.conbuildmat.2010.07.017>.
- Radhi, M.A., Kawkab, S. and Ayad, H., (2024), "Effect of rate of strain on the strength parameters of clay soil stabilized with cement dust by product", *Geomech. Eng.*, **37** (4), 419-429. <https://doi.org/10.12989/gae.2024.37.4.419>.
- Reddy, K.R. and Marella, A. (2001), "Properties of different size scrap tire shreds: Implications on using as drainage material in landfill cover systems. Philadelphia, PA, USA", *Proceedings of the 17th Int. Conf. on Solid Waste Tec and Manag.*, 1-19.
- Sadat-Shojai, M. and Bakhshandeh, G.R. (2011), "Recycling of PVC wastes", *Polym. Degrad. Stabil.*, **96**(4), 404-415. <https://doi.org/10.1016/j.polymdegradstab.2010.12.001>.
- Sengul, T., Akray, N. and Vitosoglu, Y. (2023), "Investigating the effects of stabilization carried out using fly ash and polypropylene fiber on the properties of highway clay soils", *Constr. Build. Mater.*, **400**, 132-590. <https://doi.org/10.1016/j.conbuildmat.2023.132590>.
- Swadi, S., Iyaruk, A., Promputtangkoon, P. and Lukjan, A. (2023), "Compressive and tensile strength behaviors of sand

- reinforced with fibers and natural Para rubber”, *Geomech. Eng.*, **32**(4), 361-373. <https://doi.org/10.12989/gae.2023.32.4.361>.
- Tomar, A., Sharma, T. and Singh, S.J.M.T.P. (2020), “Strength properties and durability of clay soil treated with mixture of nano silica and Polypropylene fiber”, *Mater. Today: Proceedings*, **26**, 3449-3457. <https://doi.org/10.1016/j.matpr.2019.12.239>.
- Traore, B. (2018), “Elaboration and characterization of a composite structure (sand and recycled plastic waste): Improvement of resistance by clay fillers”, Thesis from the University of Felix HouphouëtBoigny, Cote d'Ivoire.
- Zhang, G.S., Zhang, F.X. and Li, X.T. (2019), “Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment”, *Sci. Total Environ.*, **670**, 1-7. <https://doi.org/10.1016/j.scitotenv.2019.03.149>.
- Zhu, J., Saberian, M., Li, J., Maqsood, T. and Yang, W. (2023), “Performance of clay soil reinforced with PET plastic waste subjected to freeze-thaw cycles for pavement subgrade application”, *Cold Reg. Sci. Technol.*, **214**, 103957. <https://doi.org/10.1016/j.coldregions.2023.103957>.