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RESEARCH ARTICLE-CIVIL ENGINEERING

Experimental Study on the Mechanical Properties and Durability of Sand Using a Semicrystalline Hydrophobic Fluoropolymer

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Abstract

There has been an inclination towards using sustainable and environmentally friendly soil stabilizers to reduce the carbon footprint resulting from the production process of ordinary Portland cement. Polymers soil stabilizers have proven to be effective towards improving the strength of marginal soil. Despite this significant improvement, certain polymers are susceptible to the action of wetting, which results in a loss in strength. Thus, this study aims to investigate the mechanical properties and the durability of polymer-modified dune sand. Poly(vinylidene fluoride) (PVDF) polymer was used as the soil stabilizer in varying concentrations of 3, 6, 9, and 12%. The efficacy of the polymer was evaluated by conducting unconfined compressive strength (UCS) and direct shear tests. The durability test was divided into two categories: constant soaking and cyclic wetting–drying. Changes in the morphology of the sand as a result of polymer inclusion were investigated by scanning electron microscopy (SEM). The result showed that the UCS, shear strength and cohesion increased with polymer concentrations, while the frictional angle did not change significantly. The polymer-modified sand specimens lost about 60–75% of their strength after being submerged in water for 7–21 days. However, there was no reduction in strength for specimens subjected to 3 and 7 wetting–drying cycles. The action of drying following each wetting cycle reactivated the bond properties of the PVDF polymer. SEM confirmed the presence of the polymer links between the sand grains after constantly soaking. The loss of strength, in this case, can be linked to the presence of water molecules within the structure of the polymer-sand matrix. In conclusion, the PVDF polymer exhibits potential as an effective stabilizer against water susceptibility and elevated temperature.

Keywords Durability · Friction · Polymer · Soaking · Strength · Wet–dry

1 Introduction

Windblown sand possesses no cohesive strength because of its non-plastic nature and loose structure, which makes it susceptible to dispersal by wind or flowing water. It poses a significant economic problem to infrastructures and industrial facilities such as roadways, pipelines, and railways in desert regions characterized by a higher evaporation rate, a lower precipitation rate, and high wind velocity. Thus, sand tends to accumulate around and over these facilities quickly, preventing easy accessibility. This often requires frequent sand removal, consequently incurring additional cleaning costs. Furthermore, large settlements that occur rapidly may arise because of the free-drainage structure of sand, which can lead to a failure in the foundation of structures. Because of these shortcomings, researchers are keen on improving the mechanical properties of windblown and marginal soil using sustainable and eco-friendly stabilization techniques. Compared to selecting a new building site location, modifying the design to accommodate unsuitable soil, or excavating and replacing the unsuitable soil with a higher quality alternative, soil stabilization is typically the more economically viable approach for addressing soil-related foundation issues in construction projects [1].

The techniques for achieving soil stabilization can be classified into mechanical, chemical, biological and thermal [2, 3]. Chemical stabilization, which uses both conventional and unconventional stabilizers, is the most common method for

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Table 1 Basic properties of sand

Specific gravity, Gs	e_{min}	e_{max}	D_{50} (mm)	D_{10} (mm)	Coefficient of uniformity, C_u	Coefficient of curvature, C_c	pH
2.66	0.506	0.761	0.15	0.085	1.99	0.88	8.33

e_{min} and e_{max}, minimum and maximum void ratio respectively; D_{50} and D_{10}, average and effective particle size

altering the engineering properties of different soil [4]. Traditional stabilizers such as cement, lime, fly ash, bitumen, gypsum, slag, alum, kiln dust, and stone dust have been employed by several researchers to improve the geotechnical properties of soil over the years. However, some of these stabilizers have a negative impact on the environment. Ordinary Portland cement and lime are the most used traditional chemical stabilizer for soil improvement. Cement stabilization can be applied to a broad spectrum of soils. However, it is particularly effective for stabilizing well-graded, granular soils such as gravel and sand with only small quantities of silt or clay [5]. Lime is effective for the stabilization of plastic clay [6]. However, the production process of cement and lime has been reported to account for a considerable amount of carbon dioxide emission and high energy consumption [7–9]. Some of the current non-traditional soil stabilizers are polymers, bio-enzymes, salts, sulfonated oil, and bio-mediated techniques. Polymers are promising, sustainable eco-friendly stabilizers that can achieve significant strength at much lower concentrations. The utilization of polymer stabilizers has the potential to tackle the issues linked with conventional methods, such as greenhouse gas emissions and groundwater pollution [9]. The application of polymer to marginal soil has been reported to improve the strength [4, 10–15, 15–20], reduce hydraulic conductivity [10, 14, 21–23], and significantly improve the resistance of sand to wind and water erosion [14, 21, 22, 24–26]. Liu et al. [21] reported an increase in the UCS of cohesionless sand to approximately 150 kPa after modification with 40% (w/w) water-based polyurethane soil stabilizer. In another study, Wang eta al. [27] applied polyurethane polymer prepared from a mixture of poly-oxypropylene diol, poly-oxyethylene glycol, polycaprolaclone glycol, and toluene di-isocyanate to improve the geotechnical properties of silty sand. A UCS value of approximately 1200 kPa was reported with 4% polymer concentration (by the weight of dry silty sand) after 2 days of curing. Significant strength (1366 kPa) was achieved for poorly graded sand modified with 4% of an aqueous acrylic polymer solution and cured for three days [28].

Most of these studies focus extensively on utilizing certain types of polymers and evaluating their effects on the geotechnical properties of modified sand. However, only a few have assessed the influence of environmental conditions on the durability of polymer-stabilized soil. The durability of polymer-stabilized soil is of utmost concern, and it must be considered when evaluating its behavior and mechanical properties. Thus, this paper aims to improve the mechanical properties of sand using a less explored hydrophobic poly(vinylidene fluoride) (PVDF) polymer as a nonconventional chemical stabilizer. Thus, this study aims to investigate the mechanical properties and the durability of dune sand using a less explored hydrophobic polymer. A series of UCS and direct shear tests were conducted to investigate the effectiveness of the PVDF polymer as a soil stabilizer. The durability of the polymer-modified sand was examined under a constant soaking condition and after a series of wetting–drying cycles under laboratory conditions. Moreover, the reinforcement mechanism and interaction between the polymer and the sand particles were assessed using SEM images.

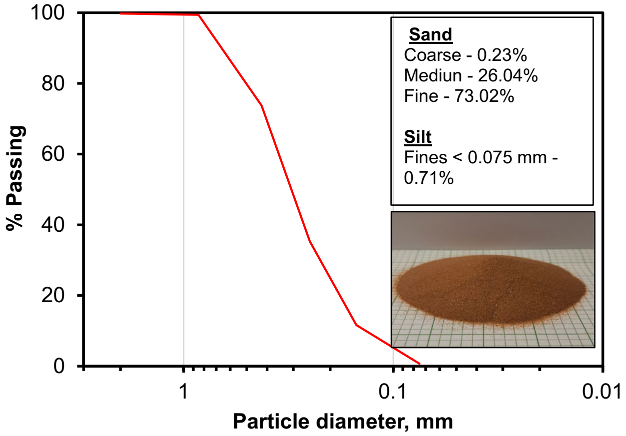


Fig. 1 The particle size distribution curve of sand

2 Materials

2.1 Soil

The soil used in this study was obtained from Thadiq, a city located on the outskirts of Riyadh province, Saudi Arabia. The basic properties of the soil obtained following the American Society of Testing Materials (ASTM) are presented in Table 1. The grain size distribution of the sand used in the study is shown in Fig. 1. According to the unified soil classification system, the soil was classified as poorly graded sand (SP).

Table 2 Properties of PVDF stabilizer

Properties	Values
Vapor pressure	15 mmHg (@ 32 °C)
Quality level	100
Form	Powder
Molecular weight	Average M_w ~ 534,000 by GPC
Refractive index	*n*20/D 1.42
Transition temperature	T_g—38 °C T_m—171 °C
Density	1.74 g/mL at 25 °C

GPC global product classification, *Tg* glass transition temperature, *Tm* melting temperature

2.2 Polymer

PVDF polymer was used as the nontraditional stabilizer to improve the properties of dune sand. The polymer was obtained from Sigma Aldrich. It is a semicrystalline polymer made up of linear chains in the $(CH_2–CF_2)_n$ sequence [29]. It has extreme hydrophobicity and water insolubility due to the presence of fluorine in the side group [30]. It is a thermoplastic fluoropolymer typically utilized in a wide range of applications that require the highest purity, strength, and resistance to solvents, acids, bases, and heat, and minimal smoke generation in the event of fire [31–33]. The properties of the polymer used in the study, as reported by the manufacturer, are presented in Table 2.

3 Experimental Methods

3.1 Specimen Preparation

The polymer stabilizer solution was prepared by dissolving the required amount of polymer powder in an organic solvent. The solution was mixed using a magnetic stirrer at approximately 50 °C until a homogeneous mix was achieved. A temperature of 50 °C (< the transition melting point) was selected to ensure that the chemical structure of the polymer is not changed. PVDF polymer solution with a varying concentration of 0, 3, 6, 9, and 12% was prepared to stabilize the poorly graded sand. The polymer concentration, P_c, is defined as the proportion of the polymer (w_p) to that final weight of the solution (w_s), expressed as follows:

$$P_c = \frac{w_p}{w_s} * 100\%$$

The sand used for the experiments underwent a series of preparations. First, it was air-dried, then screened using a sieve with a 1.18 mm aperture diameter to eliminate any foreign and unwanted material such as boulders, shafts, leaves and sticks. Afterwards, the desired amount of sand was meticulously mixed by hand with the polymer solution to produce the test specimens for both UCS and direct shear test. The polymer solution content was set as 10% by the weight of dry sand used to prepare the samples for both tests.

The UCS specimens having a diameter of 36 mm and a height of 72 mm, were fabricated using a cylindrical steel mold. The thoroughly hand-mixed polymer-sand admixture was compacted lightly in three layers and compressed between two endplates using a hydraulic jack to achieve a wet density of about 1.63 g/cm^3. The direct shear specimens having a dimension of 62.5 mm by 62.5 mm by 20 mm were prepared using a prefabricated mold. The polymer-sand admixture was placed in three layers and compacted lightly by ten blows to achieve a wet density of 1.60 g/cm^3. All the specimens were cured in an oven at a temperature of 40 °C. The UCS specimens were cured for 3, 7, 14, and 28 days, while the direct shear specimens were cured for only three days before testing based on the result obtained from the UCS test. Table 3 shows the test matrix of soil stabilized with the PVDF polymer. In addition, the procedure adopted to prepare the PVDF polymer-modified specimens is shown in Fig. 2. To ensure the repeatability of the test, two to three samples were prepared for each test condition under consideration.

3.2 UCS Test

The UCS test was conducted to obtain the strength of the PVDF polymer-modified sand at varying concentrations and curing periods. The test was conducted following ASTM

Table 3 Test matrix for UCS and direct shear tests for the modified sand

Test	Wet density (g/cm^3)	P_c (%)	C_p (day)	Tests/Pc	Total no of specimen
UCS	1.63	3, 6, 9, and 12	3, 7, 14, 28	3	3 × 4 × 4 = 48
Direct shear	1.60	3, 6, 9, and 12	3	2	2 × 4 × 1 × 3* = 24
					= 72

*, 3 normal stresses of 50, 100 and 200 kPa were considered; Pc, polymer concentration; Cp, curing period

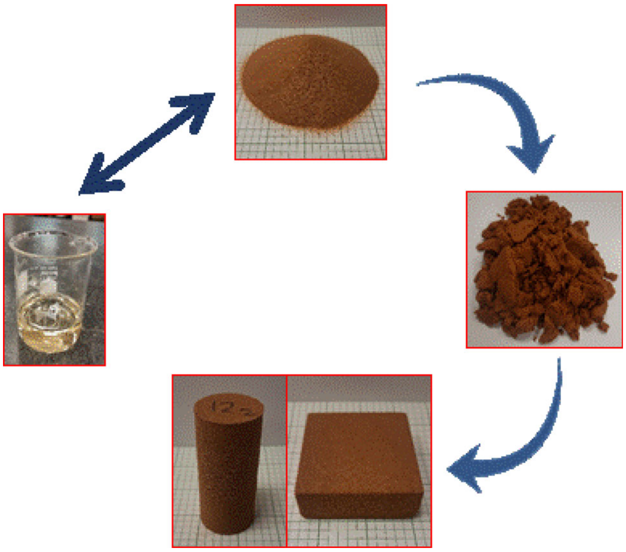


Fig. 2 PVDF polymer modified sand specimen preparation procedure

D2166 [34], which specifies the standard test method for the UCS of cohesive soil. Shearing of the modified specimens was conducted at a strain rate of 0.5 mm/min. The test was performed on triplicate specimens, and the average value was reported. The compressive strength of the modified sand specimens was evaluated by dividing the peak load by the cross-sectional area of the cylindrical test specimen.

3.3 Direct Shear Test

The direct shear test was conducted to evaluate the shear strength, τ, as well as the shear strength parameters (cohesion and internal friction angle) of PVDF polymer-modified specimens at varying concentrations and cured at a temperature of 40 °C for three days. The test was performed following the instructions given by ASTM D3080 [35]. The test was performed utilizing an automated direct shear testing system by VJ Tech. During the test, the upper half of the shearing box was fixed, while the lower half was subjected to horizontal displacement at a constant shear rate of 0.6 mm/min until a strain of 15% was achieved or failure occurred. Normal stresses of 50, 100, and 200 kPa were applied in this study to obtain three peak shear strengths. The three peak shear strengths and the applied normal stresses were used to fit a straight line from which the cohesion could be evaluated from the intercept on the y-axis and the internal frictional angle from the slope of the line.

3.4 Durability Test

The durability of polymer-modified soil is of utmost concern and should be one of the many factors required to determine the effectiveness of polymers as soil stabilizer. In this study, the durability test was conducted to assess the impact of water and elevated temperature on the UCS of modified sand with varying PVDF polymer concentrations. This study adopted two durability test procedures: soaking and wet-dry cycles. The soaking test was conducted by simulating a condition where the soil was submerged. The wet-dry cycle represented a scenario of the rainy season followed by exposure to heat. The test matrix for the durability test is presented in Table 4. The specimens for the durability test were allowed to be cured for seven days before the commencement of the test. The soaked samples were tested at 7 and 21 days, translating to a total curing period of 14 and 28 days, respectively. In the case of wet-dry cycles, since there is no standard test method for polymer-modified soil. Thus, a modification of the test method, ASTM D559 [36], for compacted soil-cement mixture was followed. The procedures are similar to those by Rezaeimalek et al. [19]. The specimen was soaked in water for 24 h and placed in the oven for 48 h at a temperature of 70 °C, representing one wet-dry cycle. As shown in Table 4, the specimens were subjected to 3 and 7 wet-dry cycles. The impact of soaking and wet-dry cycles was examined by conducting a UCS test on both weathered and control samples.

4 Experimental Result and Discussion

4.1 Effect of Polymer Concentration and Curing Period on UCS

Figure 3 presents the result of the UCS test performed on PVDF-modified sand at varying concentrations of 3, 6, 9, and

Table 4 Test matrix for the durability tests on modified sand

Durability test	Test conducted	P_c (%)	C_p (day)/no. of cycles	Tests/Pc	Total no of specimen
Soaking	UCS	3, 6, 9, and 12	7, and 21	3	$3 \times 2 \times 4 \times 2^a =$ 48
Wet-dry cycles			3, and 7	3	$3 \times 2 \times 4 \times 2^a =$ 48
					= 96

a, specimens for both control and weathered condition; Pc, polymer concentration; Cp, curing period

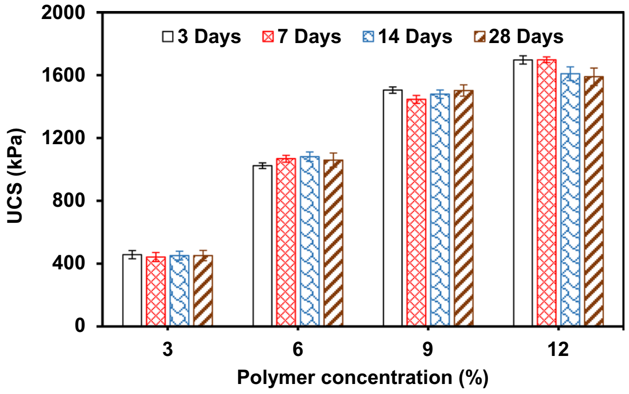


Fig. 3 UCS of PVDF polymer modified sand with respect to polymer concentration and curing time

12% and cured for 3, 7, 14, and 28 days. The results show that varying the duration of the curing from 3 to 28 days did not significantly impact the UCS. For instance, at a polymer concentration of 9%, the UCS obtained was 1505, 1446, 1479, and 1503 kPa at a curing period of 3, 7, 14, and 28 days, respectively. Most of the strength gained happened on or before the three days curing periods. Thus, an extended curing period beyond three days did not significantly contribute to strength gain. This can be attributed to moisture evaporation from the modified soil following curing at 40 °C.

The UCS of the modified sand was observed to increase with an increase in the concentration of PVDF polymer from 3 to 12%. For instance, after a curing period of 7 days, the UCS increased from approximately 442 to 1698 kPa as the polymer concentration increased from 3 to 12%. This signifies an increase in strength of about 284% (around 3.84 times). In general, after seven days of curing, an increase in the polymer concentration from 3 to 6% yielded an increase in the UCS by 142%. However, the rate of increase in UCS decreased as the polymer concentration increased from 6 to 12%. An improvement of 35% and 17% were obtained as the polymer concentration increased from 6 to 9% and 9 to 12%, respectively. A similar report on the increase in UCS of polymer-modified cohesionless soil with polymer concentration was observed by Almajed et al. [11] using styrene-butadiene rubber emulsion; Park et al. [37] and Rezaeimalek et al. [19] using styrene-acrylic emulsion; and Liu et al. [4, 18, 21, 38]; and Rezaeimalek et al. [39] using polyurethane emulsion. In addition, in another study by Fu et al. [40], which utilized PVDF polymer as a mass ratio of the soil, the UCS was reported to reach optimum at 8%, with a further increase in the PVDF concentration leading to a reduction in the UCS. However, increasing the polymer concentration beyond 9% only slightly increased the UCS. The decline in UCS growth with a further increase in the polymer concentration was suggested by Liu et al. [21] to be caused chiefly by the unavailability of pore spaces between loosened sand particles at a particular dry density at which the specimens were prepared.

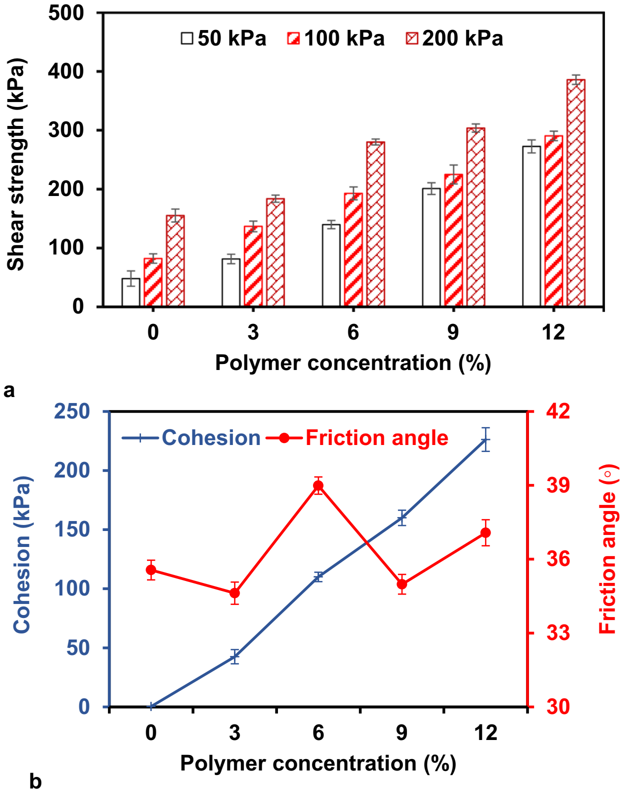


Fig. 4 **a** Shear strength and **b** shear strength parameters of PVDF polymer-modified sand

The PVDF polymer can be considered an effective soil stabilizer since the incorporation of 3% into the cohesionless sand yielded a UCS value of 442 kPa, which is greater than the minimum strength increment requirement of 345 kPa specified by ASTM 4609 [41] for effective soil stabilizers.

4.2 Effect of Polymer Concentration on Shear Strength and Parameters

The direct shear test was conducted to investigate the effect of PVDF polymer on the shear strength parameters of dune sand. Varying polymer concentrations of 0, 3, 6, 9, and 12% were employed. A curing period of three days was selected since there was no significant improvement in the UCS of the modified sand after this period. The shear strength and shear strength parameters of sand modified with PVDF polymer are presented in Fig. 4a. The results showed that the shear strength of the modified sand under normal stresses of 50, 100, and 200 kPa increased with an increase in the concentration of the PVDF polymer. The cohesion of unmodified sand was 0.31 kPa. However, the addition of polymer had a significant impact on the development of cohesion. At a PVDF polymer concentration of 3, 6, 9, and 12%,a cohesion of

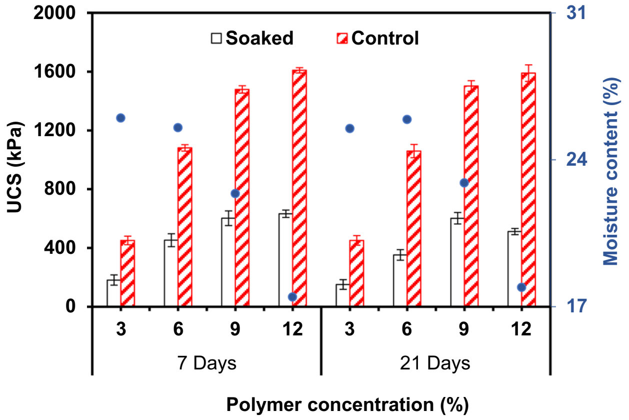


Fig. 5 Comparison of UCS for control and soaked sand specimen after 7 and 21 days; and the moisture content of soaked samples after testing

42.50, 110.00, 160.00, and 226.25 kPa was observed, respectively. This indicates an improvement of approximately 137, 355, 516, and 730 times that of unmodified sand. This result agrees with the report by Almajed et al. [11], Liu et al. [4, 18, 21, 42], and Ozhan [43].

Also, no significant changes were observed in the internal frictional angle of modified sand specimens compared to the unmodified sand, as shown in Fig. 4b. The frictional angle was observed to range between 34° and 39°. This finding corresponds with that of Liu et al. [21] on sand treated with polyurethane, where the internal frictional angle ranges between 30° and 34°. The effect of the polymer on the shape and size of sand particles was not evident on the internal frictional angle.

4.3 Durability Test

4.3.1 Soaking Test

Figure 5 shows the result of the soak test conducted on PVDF polymer-modified sand and the control specimens after 7 and 21 days. The result showed a reduction in the strength of the soaked specimens compared to the control specimen. For instance, after seven days of soaking, the UCS of the sand specimens modified using a PVDF polymer concentration of 3, 6, 9, and 12% were approximately 181, 453, 602, and 632 kPa, respectively, while that of the control specimens were 451, 1081, 1479, and 1609 kPa, respectively. All polymer concentrations exhibit a strength decrease of around 60%. Moreover, the strength was reduced by around 60–68% after soaking in water for 21 days. Notably, extending the soaking duration from 7 to 21 days did not significantly impact the UCS. This result conforms with reports by Zandieh and Yasrobi [20] on sand modified with polyvinyl acetate, where the UCS was reported to reduce by 57–70%. Similarly, Liu et al. [42] reported a reduction in the cohesion of sand modified with polyurethane as the immersion time was increased from 1 to 216 h. In another study, Naeini and Ghorbanali [44] reported a reduction of about 41,18 and 2% in the UCS of sand modified with epoxy resin-polyamide emulsion submerged in water for seven days as the concentration varied as 3, 4, and 5%.

Table 5 presents the durability index of the soaked specimens compared to those that were not soaked (control). The durability index (D.I) defines the resistance of the weathered specimen and can be expressed as follows:

$$D.I = \frac{UCS_w}{UCS_c}$$

where UCS_s is the compressive strength of the weathered specimen and UCS_c is the compressive strength of the control specimen.

The D.I. obtained for the soaked specimen after 7 and 21 days were below 0.5, which signifies a loss of more than 50% of the strength. For instance, after soaking the modified sand specimen for 21 days, the D.I. value ranged from 0.32 to 0.40. The presence of water within the pores of the polymer-sand matrix resulted in a loss of strength. The moisture content of the modified sand at the time of the test is also presented in Fig. 5. It was observed that the moisture content decreased with an increase in the polymer concentration. This reduction may result from the availability of more polymer filling up the voids, leaving less room for moisture.

4.3.2 Wet–Dry Cycles

Figure 6 presents the images of the PVDF polymer-modified sand specimen during the 7th wet cycle. All the samples remained stable after being subjected to 7 wet-dry cycles. The UCS result of the PVDF polymer-modified sand compared to the control after 3 and 7 wet-dry cycles are presented in Fig. 7. From the result, it was observed that a series of wet-dry cycles had no significant impact on the UCS of the PVDF polymer-modified specimens compared to the control specimen. For instance, after seven wet-dry cycles, the UCS of the modified sand specimens were 451, 1159, 1506, and 1500 kPa, while that of the control specimens were 451, 1060, 1503, and 1590 kPa at concentrations of 3, 6, 9, and 12%, respectively. The effect of cyclic drying of the specimen at a temperature of 70 °C did not negatively impact the UCS because fluoropolymers are thermally stable, which is attributed to the strength of the C–F bond [45]. The ther-

Table 5 Durability index for weathered sand specimens modified with PVDF polymer

P_c (%)	Durability index (D.I)			
	Soaked		Wet–dry	
	7 days	21 days	3 cycles	7 cycles
3	0.40	0.34	1.00	1.00
6	0.42	0.33	0.94	1.09
9	0.41	0.40	1.03	0.87
12	0.39	0.32	1.06	0.94

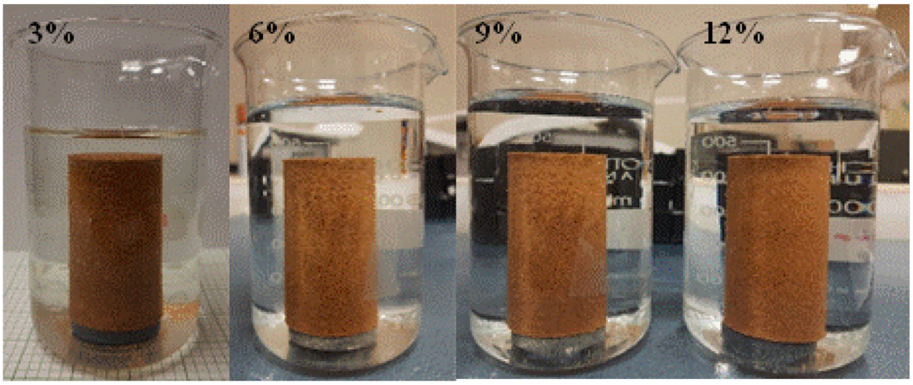


Fig. 6 PVDF polymer modified sand specimen during the 7th wet cycle

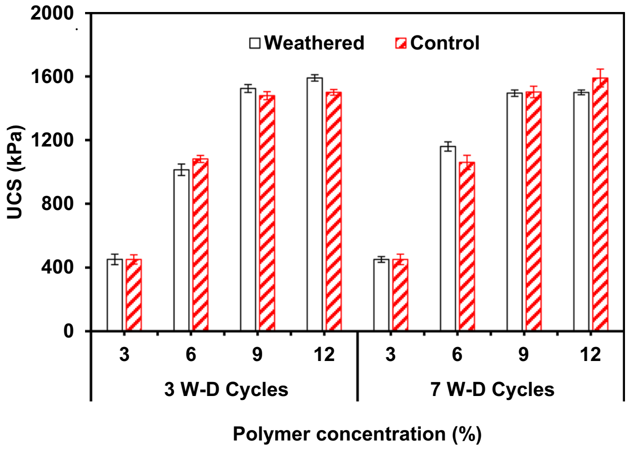


Fig. 7 Comparison of UCS for control and soaked sand specimen after 3 and 7 wet–dry cycles

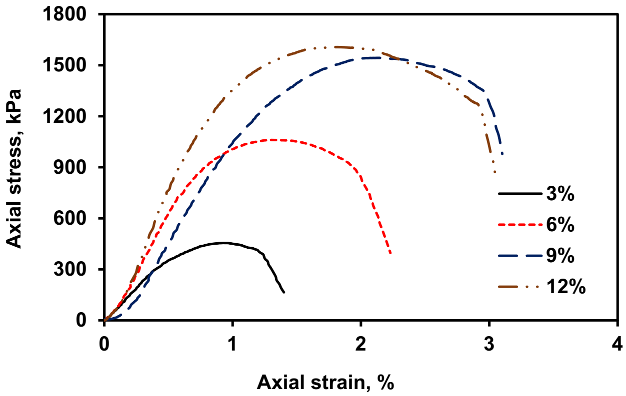


Fig. 8 Typical axial stress–strain of PVDF polymer modified sand after 7 days curing

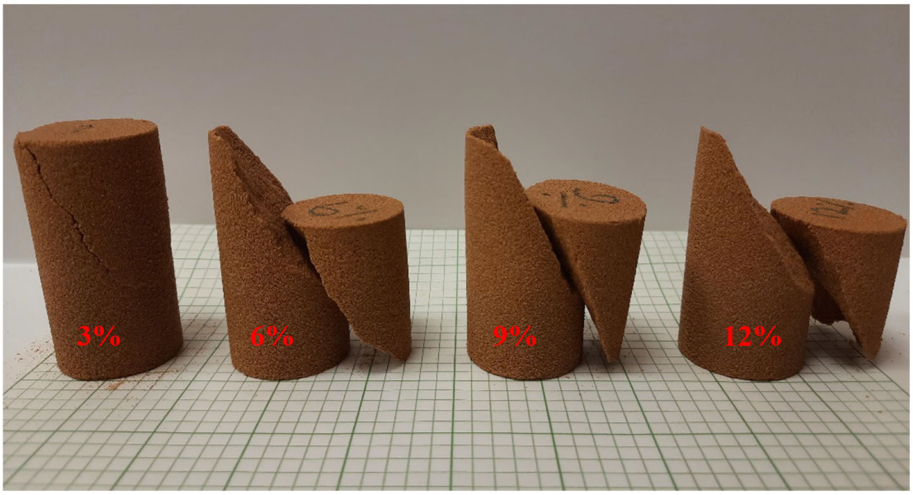
mal degradation of PVDF primarily occurs in the range of 400–510 °C [46]. Rezaeimalek et al. [19] reported a reduction of approximately 39% in the UCS after subjecting sand specimens modified with styrene-acrylic emulsion to 24 wet-dry cycles. Similarly, another study by Rezaeimalek et al. [39] reported about 85% of UCS retention after subjecting sand modified with hydrophobic polyurethane polymer emulsion to 24 wet-dry cycles.

The D.I. of the PVDF polymer-modified sand specimens subjected to 3 and 7 wet-dry cycles is also presented in Table 5. The result shows a D.I. of approximately 1, which signifies no loss in UCS and, thus, confirms the effective soil stabilizer against wet-dry cycles.

4.4 Failure Mechanism

Figure 8 shows a typical stress-strain relationship modified sand specimens after seven days of curing. As expected, the axial stress increased monotonically with increased strain until the peak strength was reached. The straight line at the initial stage of the stress-strain curve for each specimen represents the elastic deformation region. After the peak stress was reached, the stress began to decrease gradually increased

Fig. 9 Failure mode of PVDF polymer modified sand after UCS test



strain. Thus, the specimens showed a semi-brittle failure pattern. The images of the modified sand specimens after the UCS test are presented in Fig. 9. After the test, all the samples were found to have undergone a shear along an inclined failure plane. This type of failure is classified as a brittle faulting, according to Hatibu and Hettiaratchi [47]. However, the stress-strain behavior of the modified sand specimen showed that the decrease in stress after the ultimate strength was reached was not abrupt but gradual. Thus, the mode of failure demonstrated by the modified sand specimens can be characterized by a semi-brittle behavior.

4.5 Reinforcement Mechanism

The SEM image of the unmodified and modified sand specimens are presented in Fig. 10. The unmodified sand specimen is characterized by dispersed sand grains with noticeable pockets of voids, as shown in Fig. 10a. There was no bond existing between the sand grains, which explains the non-cohesive nature of the sand used in this study. Adding the PVDF polymer to the cohesionless sand resulted in the aggregation of the soil grains, as seen previously in Fig. 2. Figure 10b shows noticeable alterations in the morphology of the sand modified with 12% of PVDF polymer. The polymer filled up the void between the sand particles, with a few of the sand particles being enwrapped, thus forming a more stable structure compared to the unmodified sand specimen. This polymer structure formed within the matrix of the sand specimen improved the bond and interlocking force among the sand particles and reduced the void. The improvement in the UCS, shear strength and cohesion of the modified specimen can be attributed to the formation of a PVDF polymer membrane within and around the particles of the sand. The morphological changes in the sand specimen modified with 9% PVDF polymer and subjected to 21 days of soaking are depicted in Fig. 10c. From the image, it is apparent that the polymer membrane structure remains in place and has not been depleted by the action of water molecules. However, the reduction in UCS of the soaked sand specimen is not linked to the destruction of the polymer-sand structure or bond. Although may result from the presence of water molecules within the matrix of the modified sand.

5 Conclusions

Sand specimens modified with different concentrations of PVDF polymer were assessed by conducting the UCS and direct shear tests to evaluate the efficacy as a soil stabilizer. In addition, the durability of the stabilized sand was evaluated against water susceptibility and exposure to a series of wet-dry cycles. The resistance to weathering was measured through the UCS test. Based on the obtained results, the following conclusion can be drawn:

1. Stabilizing the sand used in this study with the PVDF polymer yielded increased UCS, shear strength and cohesion with polymer concentration. However, the internal friction angle remained relatively the same, with values between 34° and 39°.
2. Prolonging the curing duration from 3 to 28 days did not affect the UCS, given that the entire strength development was attained within the first three days of curing.
3. When the modified sand specimens were soaked in water for 7 and 21 days, the strength was reduced by 60–75% compared to the control. Although the sand specimen structure remained intact, the presence of water molecules negatively impacted the UCS.
4. The UCS of the modified sand specimen remained unchanged after being subjected to wet-dry cycles, indicating that the PVDF polymer was effective in resisting cyclic wetting and drying.

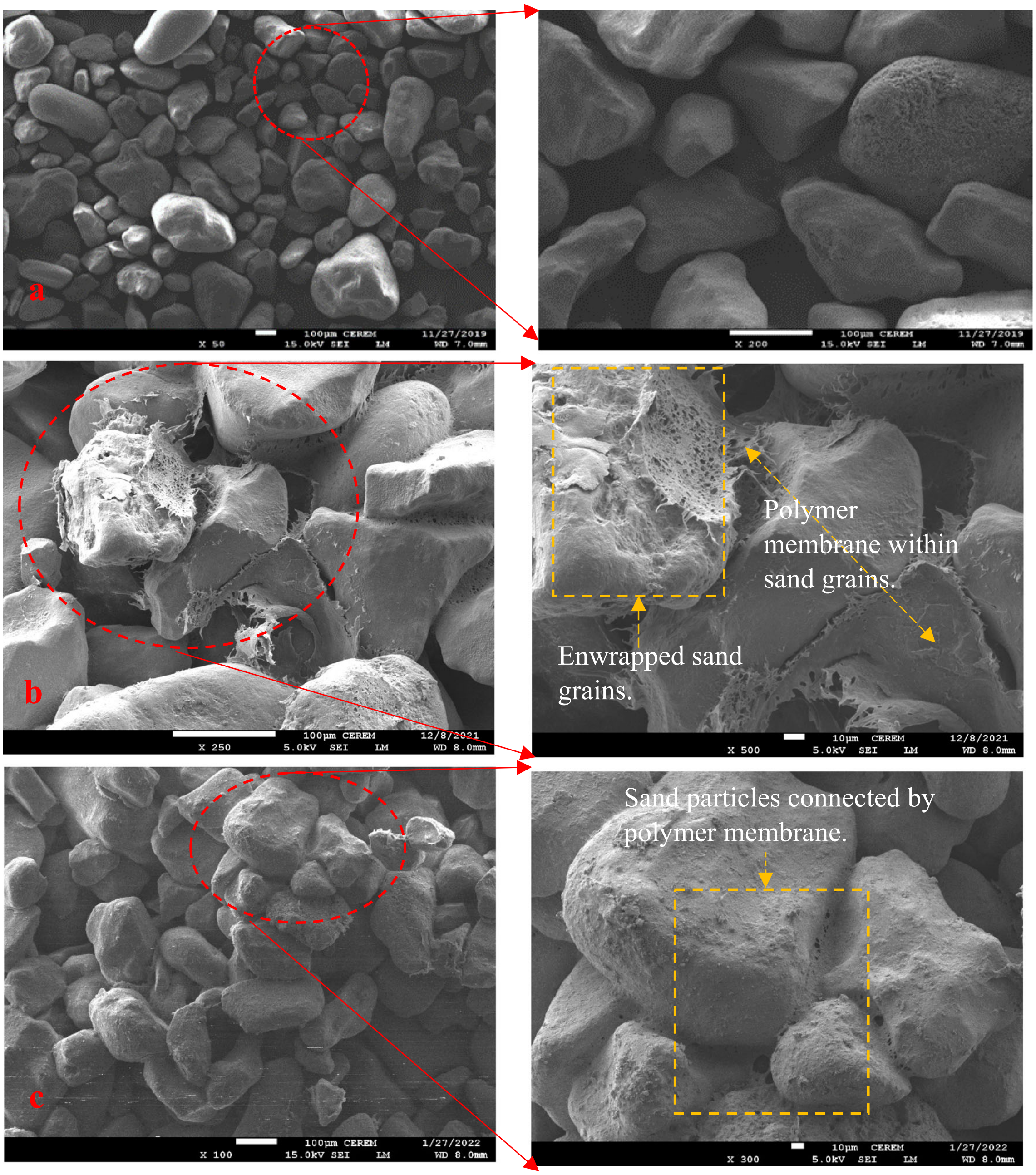


Fig. 10 SEM images of **a** unmodified sand specimen; **b** 12% PVDF polymer modified sand specimen; and **c** 9% PVDF polymer modified sand subjected to 21 days of soaking

5. SEM images showed that the sand particles were coated with a PVDF polymer that formed a membrane, which acted as a crucial bond to create a durable sand-polymer composite structure. Furthermore, the PVDF polymer structure was still evident around and within the sand particles after the modified sand sample was immersed in water for 21 days.

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Author Contributions Conceptualization: KL, AA; Methodology; Formal analysis and investigation; and Writing—initial draft preparation: KL; Writing—review and editing: AA; Funding acquisition: AA; Resources: KL, AA; Supervision: AA.

Data Availability The data collected and analyzed during this study are available upon request from the corresponding author.

Declarations

Conflict of interest The authors state that no known competing financial interests or personal relationships could appear to have influenced the work described in this study.

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