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The Effect of Polyester Resins on the compressive and shear strength of Clayey Sand Soil: An Experimental Study

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Abstract

One of the soil improvement methods is to use appropriate materials and additives to enhance the geotechnical properties such as strength, hardness, ductility, and bearing capacity. In recent years, polymers have attracted significant attention as soil stabilizers and have been proposed as an environmentally friendly method for enhancing the geotechnical properties of soils. In this article, the effect of liquid Polyester Resin on the strength parameters of clayey sand (SC) was studied. For this purpose, the soil was first characterized and then uniaxial compressive strength and direct shear tests were performed on the specimens without additives and those consolidated with different percentages of polymeric resin at different curing times. The purpose of this research is to investigate and compare the resistance parameters of soil reinforced with Polyester Resin polymer to those of unreinforced soil materials. In this study, 0.5, 1, 2, 3, and 4 percent of Polyester Resin was added to the clayey sand and the soil properties were studied immediately after mixing and after 1, 3, 7, and 14 days of curing. The changes in the soil strength parameters at different percentages of the polymeric additive were determined at different curing times. Based on the results, the optimum percentage of Polyester Resin was 3% so that further increase in the additive did not increase the soil strength parameters. The effect of curing time in the presence of the polymeric additive indicated that the maximum strength was obtained after 7 days of curing. Increasing Resin content and curing time led to enhancements in the uniaxial compressive strength, shear strength, cohesion and internal friction of the consolidated specimens. The results of this study suggest that with increasing the percentage of Polyester Resin, in addition to increasing the peak strength, the ultimate strength initially increased and then decreased.

Keywords: Clayey sand soil, Polyester Resin, Uniaxial strength test, Direct shear test.

1.Introduction

Improvement of the physical and mechanical properties of soils is an important issue faced by geotechnical engineers. Geotechnical engineers have recently been limited to carrying out construction work on weak soil because of rapid infrastructure development, population growth, and land cost. Thus, they are always looking for new ways to solve existing problems or those that arise during implementation. The improvement of the mechanical properties of these soils which do not meet the engineering requirement has to be considered before construction activities commence. Low-quality soil materials typically have an enormous destructive potential. For example, low strength parameters and load-bearing capacity contraction potential and high swelling are among the disadvantages of this type of soil. Soil improvement can alter the engineering properties of soil such as strength, density, liquefaction potential, compressibility, swell and shrinkage behavior, permeability, etc. The various geotechnical techniques used for improving the characteristics of the soil include compaction, drainage methods, vibroflotation, pre-compression and consolidation, stone columns, grouting and injection, chemical stabilization, soil nailing and reinforcement, geotextiles and geomembranes, thermal methods, construction of moisture barriers, prewetting, or the replacement of unsuitable soils. Chemical stabilization refers to the addition of a chemical admixture to the soil to enhance the engineering properties (Kestler, 2009).

Many studies on soil improvement and stabilization using chemical additives have been conducted in recent years. For example, Shourijeh et al., (2023) examined the effect of magnesium oxide and lime on enhancing clay soil contaminated with methyl tert-butyl ether.

Recently, polymers have attracted widespread interest as soil stabilizers and are proposed as an ecologically acceptable means for enhancing the geotechnical properties of soils. They have found profound applications in diverse fields such as the food industry, textile, medicine, agriculture, construction, and many more. Various polymers are proven to increase soil shear strength, improve volume stability, promote water retention, and prevent erosion, at extremely low concentrations within soils through the formation of a polymer membrane around the soil particles upon hydration. Polymers are made up of extremely large molecules that are multiples of smaller chemical components known as monomers. Polymers examined to improve soil engineering characteristics can be divided into two types: natural and synthetic polymers. (Tingle et al., 2007)

The use of polymer additives and resins in soil improvement has not a long history. Gopal et al., (1983) used urea-formaldehyde and polymers of the same family in blown sand improvement. Hazirbaba and Gullu (2010) studied the improvement of the bearing capacity of fine-grained soils by adding polypropylene and liquid synthetic resins. Ahmad et al., (2010) used butadiene styrene resin to improve the geotechnical properties of fine-grained soils. The results showed that the addition of 2.5% polymeric resin increased the soil strength by 17.8% while reducing the plasticity index by 13.5 percent. Tadayonfar et al., (2014) showed that the use of polymers decreases the permeability of silty soils. Modarres and Nosoudy (2015) studied the changes in the strength parameters of clay by adding lime and coal waste. Their results showed that with the addition of the above additives, the plasticity limit of the soil decreased but its compressive strength increased. Gilazghi et al., (2016) studied the effect of liquid polyurethane (of methylene diphenyl diisocyanate family) as an alternative to cement stabilizers in clay soils. Their results showed that 90% of the ultimate soil strength was obtained after 4 days. However, the soil strength slightly increased after 4 days. Vakili et al., (2019) evaluated the effect of macro steel fiber (SF), micro glass fiber (GF), and micro polypropylene fiber (PF) in lightweight aggregate concrete, (LWAC) beams reinforced with glass fiber reinforced polymer (GFRP) bars. Sabri et al., (2021) studied the soil injection technology using an expandable polyurethane resin and then demonstrated the advantages and limitations of this technology in practical applications. they also explored the existing finite element models used to calculate the strength and stiffness parameters, evaluating the bearing capacity of the composite (soil-resin) and the settlement after the injection process. Soltani Jigheh et al., (2022) investigated the effect of polyester polymer resin on the physical and mechanical properties of fine-grained bentonite soil with a high paste by performing Atterberg and uniaxial compressive tests. the results showed that the addition of different amounts of polyester polymer resin decreases the fluidity limit, increases the pasty limit, and consequently decreases the pasty range of bentonite soil. Also, this additive improved the uniaxial resistance of the soil several times and reduced its deformability. Mansourghanaei et al. (2023) explored the application of geopolymer concrete (GPC) as an environmentally friendly and sustainable alternative to traditional concrete. In their study, GPC was formulated using granulated blast furnace slag (GBFS) and reinforced with 0-2% polyolefin fibers (POFs) and 0-8% nanosilica (NS) to enhance its structural performance. The findings demonstrated the clear advantages of GPC over conventional concrete in terms of both sustainability and structural properties.

Heravi and Cheshomi (2023) studied the effects of a vinyl acrylic polymer emulsion on the dry density, optimum moisture content, uniaxial compressive strength, and modulus of elasticity of aeolian sand sands in the Khuzestan plain. The results indicate that, after drying, the polymer solution enhances the strength and modulus of the sand by forming bonds and bridges between the sand grains. Spagnoli et al., (2023) investigated the mechanical behavior of sands mixed with acrylate and polyurethane resins. Kömürlü et al., (2024) investigated the values of uniaxial compressive strength of a sand-type soil reinforced with polypropylene fibers and silicate resin additives with different amounts. Microgrid fiber (MGF) was tested as a new polypropylene fiber additive in the experiments to compare it with a widely used polypropylene fiber type geosynthetic product used in soil fill improvement applications. The obtained results showed that the new MGF-type fibers usually increase the resistance values at higher rates compared to the conventional fiber product. Makarchian (2024) studied the combined effect of stabilization and reinforcement of sandy soil by polyethylene fibers and epoxy resin polymer on standard density and unconfined compressive strength. According to the results adding epoxy resin to the samples up to 6% increased the strength, decresed the failure strain, and increased the stiffness of the specimens. Also, adding polyethylene fibers to the optimum percentage of additives to the specimens caused increasing the unconfined compressive strength and the failure strain, and decreased the stiffness of the specimens. Table 1 presents some synthetic polymers and the geotechnical properties of soil it has been used to improve.

Considering the continuous development of construction projects and the necessity for stable foundations, it is essential to focus on soil resistance parameters. Consequently, soil amendment should be undertaken when necessary.This research addresses the cost-effectiveness of soil amendment using certain polymer additives. Specifically, it examines the impact of polyester polymer additives on soil resistance parameters. A review of the literature indicates that there have been limited studies on the modification of sandy clay soils with Polyester Resin polymer, particularly regarding the comparative behavior of this type of additive in the soil. Notably, the effects of curing time have not been thoroughly investigated in these studies. Therefore, this research aims to address this gap and investigate the effect of curing time on the properties of soil using polyester additives.

Table 1. Summary of polymer used to improve geotechnical properties of soil

Soil	Test	Considered Factor	Polymer Type	Main Conclusions	Reference
Silty Clay	Water erosion	Infiltration depth	Aqua-dispersing-nano-binder Water stability (ADNB)	-The polymer stabilizer could be applied to improve the erosion resistance of the slope topsoil and reduce soil loss.	Zhou et al., (2019)
Clay	- Atterberg limit - Compaction - CBR	Polymer content	CBR Plus	- Improvement of the soilengineering properties	Mousavi et al., (2021)
Sand	- Ultrasonic pulse - velocity - UCS	- Polymer content - Curing time	Epoxy resin	- Significant improvement of UCS of the sensitive sandy soils	Ateş (2013)
Clay	- UCS - Triaxial - Split tensile strength - Compaction	- Polymer content - Curing time - Curing condition - Freezing thaw	Epoxy resin	- Noticeableimprovement of the soil strength after a curing period of 90 days	Anagnostopoulos (2015)
Silt	- UCS - Durability	- Polymer content - Curing time - Curing condition	Polyacrylamide (PAM)	- Enhancement of UCS with increasing PAM content - A significant decrease in the strength and durability of samples, when the soil samples are exposed to the freeze-thaw phenomenon, especially after the first cycle.	Soltani et al., (2019)
Clay	- Free/volumetric swelling - Atterberg limits - Oedometer - Cyclic wetting & drying - Crack intensity - Compaction - UCS	- Polymer content - Curing time	Polyacrylamide (PAM)	- Improvement of the mechanical behavior	Soltani et al., (2018)
Clay	- Soil reactivity - Direct shear - UCS	- Polymer content - Curing time - Capillary rise	Polyacrylamide (PAM)	- Significant improvement inUCS and increase incohesion and internal friction angle.	Padmavathi et al., (2021)
Sand	- Fatigue test - UCS	- Polymer content - Curing time	Methylene Diphenyl	- Enhancement of the strength of stabilized sand by increasing the amount of polymer	Rezaeimalk et al., (2017)

			Diisocyanate (MDI)		
Silty sand	- UCS - Durability - CBR - Compaction	- Polymer content - Curing time - Curing condition - Freezing thaw	Polyacrylamide (PAM)	- Soil properties including fracture patterns, strain capacity and overall strength, undergo significant changes due to the presence of polymer stabilizers. -Enhancement of the UCSand CBR	Park et al., (2020)
Sand	- Penetrationresistance - Wind erosion - Moistureretention - Compaction - Moisture retention	Polymer content	Polyacrylamide (PAM)	- Significant increase in water storage capacity of refined sand - Reduction shell thickness with higher stabilizer concentrations	Ding et al., (2020)

Table 1. Cont.

Soil	Test	Considered Factor	Polymer Type	Main Conclusions	Reference
Sand	- Durability - Penetrationresistance	- Polymer content - Wet-dry cycles - Temperature U.V aging	Polyacrylamide (PAM)	- The applied polymers have an excellent ability to withstand wetting, high temperature, and long-term UV exposure. - Higher solution viscosity resulted in better crust strength and dust erosion resistance when applied on red sand surface.	Ding et al., (2019)
Clay	- Atterberg limits - Compaction - CBR - Direct shear - Oedometer	Polymer content	Polyethylene (PE)	- Improvement of CBR and maximum dry density, - Reduction of the Atterberg Limits, swelling potential, and swelling pressure	Bekkouche and Boukhatem (2016)
Clay	- Swelling test - Sorption test	Polymer content	Polyethylene oxide (PEO)	- Effective on stabilizing clay against swelling	Inyang et al., (2007)
Clay	- UCS - Density - Durability - Soaking - Density	- Polymer content - Curing time Polymer content	Polyvinyl alcohol (PVAO)	- Significant improvement of UCS - Significant increase of the stability of wetter samples - Increased durability of PVA-stabilized samples when subjected to soaking.	Mirzababaei et al., (2018)
Clay	- Compaction - UCS - CBR	Polymer content	SoilTechMKIII	-Improvement ofthe mechanical behavior	Giridhar et al., (2017)
Sand	- Free swell - Direct shear - Tensile strength - UCS - Permeability	- Polymer content - Density - Fiber content - Polymer content - Curing time	Polyurethane (PU)	- Enhancement of UCScohesion, and tensile strength of samples with the same dry density with increasing polymer concentration	Liu et al., (2018) Liu et al., (2018) Liu et al. (2018)
Clay	. Atterberg limits . Direct shear . UCS . Triaxial . Oedometer	Polymer content	Polyvinyl acetate (PVA)	- Improvement of the mechanical behavior	Ghasemzadeh et al., (2021)
Sandy clay	- Atterberg limit - Compaction	Polymer content	Polyvinyl acetate (PVA)	- Improvement ofthe mechanical behavior	Zumrawi and

	- Free swell index - UCS				Mohammed (2019)
Sand	- Direct shear - Modulus rupture - Durability - UCS	- Polymer content - Fiber content - Temperature - Polymer content - Fiber content	Styrene-butadiene rubber (SBR) emulsion	- Slight reduction of the internal friction - Significant increase in cohesion - Enhancement of the Cohesion and UCS - Increasing the amount of recycled hemp fibers had a detrimental effect on the modulus of rupture, UCS, and shear strength.	Almajed et al., (2021)
Sand	- Compaction . CBR . Direct shear	- Polymer concentration	Styrene-butadiene rubber (SBR) emulsion	-Optimimum moisture reduction Enhancement of the maximum dry density, CBR, friction angle and the cohesion	Ahmed and Radhia(2019)
Clay	- Atterberg limits - Compaction - Oedometer - Hydraulic - conductivity UCS	- Polymer content - Curing time	Vinyl copolymer	- Reducing the swelling potential - increasing the unconfined compressive strength - a several thousand-fold increase in k	Taher et al., (2020)

2. Materials

In this study, a synthetic soil containing 70% sand and 30% kaolinite produced in the laboratory was used. The density of the sand used in this study was 2.7 g/cm3 with fine-grained particles of less than one percent. The sand composition and clay specifications are shown in Tables 2 and 3. Figure 1 and Table 4 show the grading curve and some characteristics of the soil used in thisstudy, respectively.

The polymer used in this research is an orthophthalic Polyester Resin polymer, which means the face is liquid. Unsaturated Polyester Resins are widely used all over the world. The main polymeric chain of the studied Polyester Resin has ester linkages, which are prepared from the condensation reaction of a multi-factor alcohol compound and a multi-factor acid such as glycol and fumaric acid. Therefore, by designing the formula and Control of saturated and unsaturated acids, catalysts, temperature, and reaction time, a complete set of Polyester Resins can be produced that are suitable for different applications. Polyesters are materials that in structure Chemically, they have an ester group. Unsaturated Polyester Resin is the most widely used resin in the composite industry. This Resin is made from the reaction of one or more dihydric alcohols with one or more dihydric acids Provided.

The purpose of this research is to investigate and compare resistance parameters of soil reinforced with Polyester Resin polymer and comparing the results with unreinforced soil materials. To this end, two main tests, including the uniaxial compressive strength test (ASTM D 2166-87) and theDirect cutting test (ASTM 3080D) have been conducted.

Table 5 shows the physical and chemical characteristics of the polymers used in this study. The main reason for selecting this type of polymer as an additive is its convenient properties including low price, good tensile and flexural strength, and high hardness.

In this study, the uniaxial compressive strength and direct shear tests were conducted on the soil without additives and the specimens containing 0.5, 1, 2, 3, and 4% Polyester Resins. The changes in the uniaxial compressive strength, shear strength, adhesion, and internal friction coefficient were studied immediately after mixing and after 1, 3, 7, and 14 days.

Table 2. Composition of the used sand in this study

SiO_2	Fe_2O_3	Al_2O_3	K_2O	CaO	MgO	L.O.I
97.5	0.85	0.95	0.19	0.27	0.24	0.00

Table 3. Specifications of the used clay in this study

Chemical analysis (%)	L.I.O	9 ± 1
	SiO_2	63 ± 1
	Al_2O_3	24 ± 1
	Fe_2O_3	0.55 ± 0.1
	TiO2	0.04 ± 0.01
	CaO	1.2 ± 0.2
	MgO	0.55 ± 0.06
	Na_2O	0.4 ± 0.1
	K_2O	0.3 ± 0.1
	SO_4	-
Mineralogical analysis (%)	Kaolinite	64 ± 2
	Quartz	27 ± 2
	Calcite	2.1 ± 0.5
	Total feldspars	-
	Other	6 ± 1
Particle size distribution (%)	>μ150	0.00
	>μ40	0 – 0.5
	<μ20	99
	<μ2	47 ± 3

Table 4. Some properties of the used soils in this study.

UCS (kg/cm^2)	Compression		Atterberg limits	Direct shear test	
1	γd max (gr/m^3)	1.92	NP.	Friction angle (φ)	30.9
	$\omega_{opt\ (\%)}$	10.78		Cohesion (Kg/cm^2)	0.014

Table 5. Characteristics of PolyesterResins used in this study (http://www.polymeriran.com)

Characteristics	Amount
Appearance	Liquid
Color	Colorless
Density (g/cm3)	1.13 ± 0.5
Viscosity	200-500
Tensile strength (MPa)	60-70
Tensile modulus (GPa)	3-4

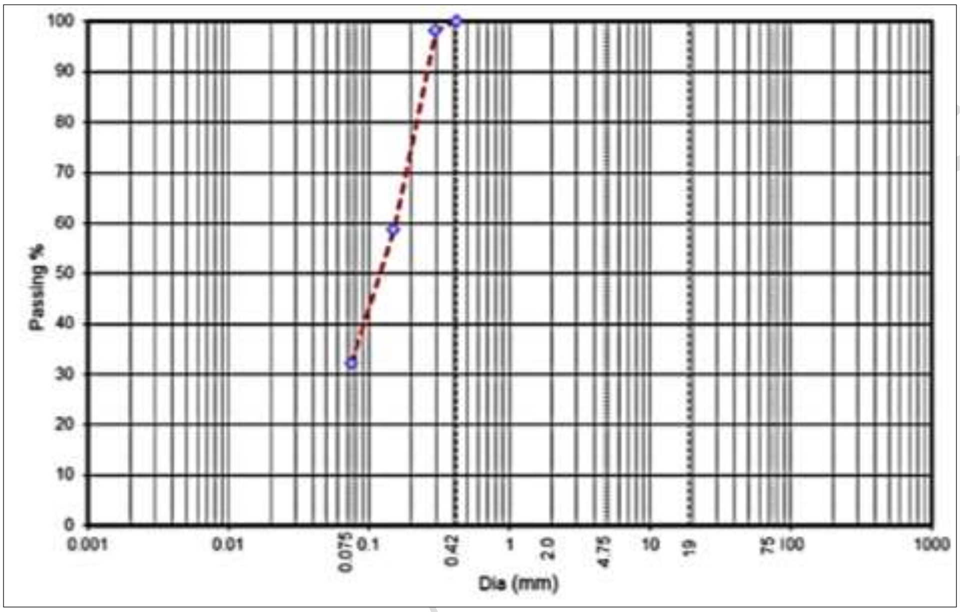


Fig 1. Particle-size distribution of the studied soil.

3. Methods

In this study, the uniaxial compressive strength tests were conducted on the specimens with a relative density of 1.92 g/cm^3 prepared with an optimal moisture content of 10.78%. The cylindrical specimens with a diameter of 50 cm and a height of 100 mm were used in all experiments. The specimens were compressed using the reduced density method where the density is controlled by changing the layer thickness. At a constant weight of the soil and cross-section of layers, each layer was compressed at a thickness greater than the design thickness to obtain an equal thickness for all layers. The first layer with the highest reduced density has the highest thickness. The thickness linearly changes to the lowest thickness (0%) for the last layer with the ultimate density of the specimen.

The reinforced and unreinforced compacted soil specimens were prepared by manual mixing of dry soil, polymer and water. For proper mixing of the samples, the Polyester Resin was mixed with water and then gradually added to the soil to achieve a homogeneous mixture.

Then the mixture was divided into three equal parts and compacted in the molds to achieve the desired density. After molding the soil samples, they were placed in an enclosure with no airflow at room temperature to apply curing conditions. After the desired time, the uniaxial compressive strength tests were conducted on the soil specimens according to ASTM D2166-87.

In this experiment, the axial strain has been calculated with an accuracy of 0.1% using the equation.(1)

$$\varepsilon_1 = \frac{\Delta L}{L_0} \quad (1)$$

In this relation, ΔL is the change in the length of the sample read from the strain gauge and L_0 is the initial length of the samples (mm).

The average cross-sectional area of the samples is calculated using the equation (2).

$$A = \frac{A_0}{(1-\varepsilon_1)} \quad (2)$$

A_0, isthe initial average cross-sectional area of the sample (mm2), and ε_1 is the axial strain at the desired load (%). The compressive axial stress is calculated using equation (3).

$$\sigma_c = \frac{P}{A} \quad (3)$$

P, the force applied to the sample (N)

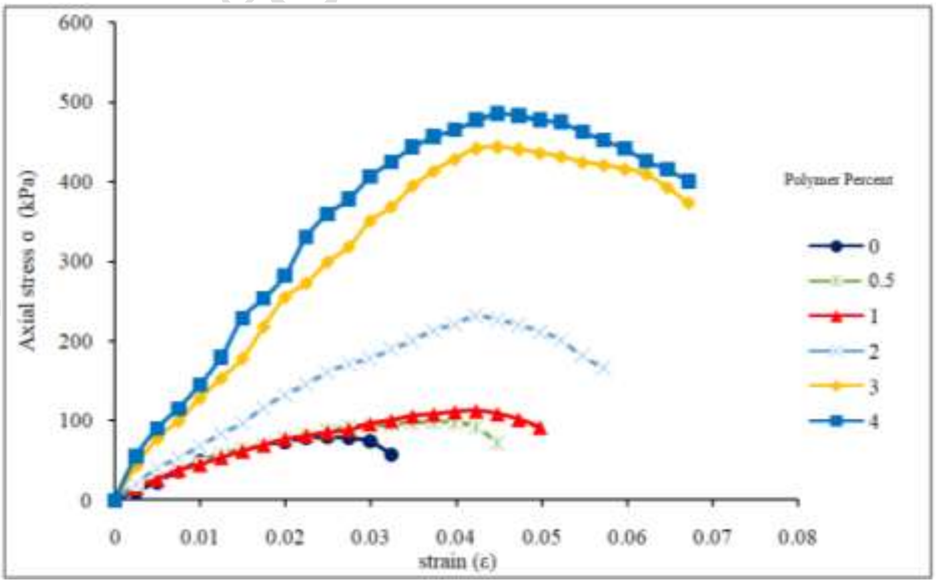
A, the cross-sectional area of the sample at the time of loading P obtained from equation (3).

To investigate the changes in ductility and soil strength in the presence of polymer, the consolidated-drained (CD) direct shear test was conducted according to ASTM D 3080. For this purpose, as mentioned earlier, the dry soil, polymer and water were combined homogeneously. Then cut the box It is ready and installed in its place and the porous plate is placed on the bottom of the cutting box. Sample in box The cut is placed and each layer is pounded until the entire mass of soil is placed in the cut box A certain volume is condensed. Then the samples were prepared and compressed according to the desired density based on different percentages of the polymer in 10×10 shear molds with a height of 2.3 cm. The vertical stresses of 50, 100 and 150 kPa and an optimum moisture of 10.78 (according to the density test) were used. The cutting speed of the sample in this test should be low enough to avoid drainage conditions It should be ensured that the speed of 0.05 mm/min was used in this research. As mentioned earlier, the aim of this study is the improvement of clayey sand soil with the addition of 0.5, 1, 2, 3 and 4 percent Polyester Resins at different curing times.

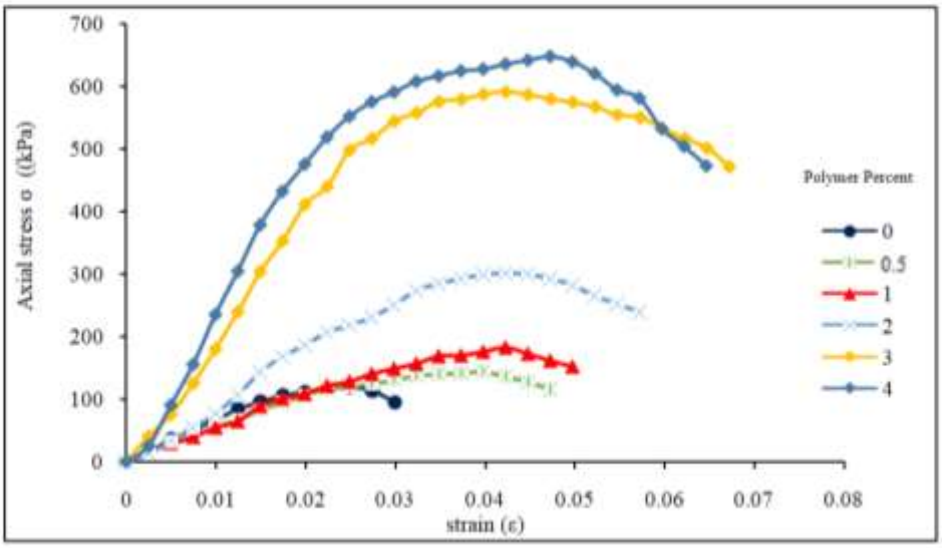
3. Results and Discussion

Figure 2 shows the stress-strain curves at different curing times. According to the Figures, with increasing the percentage of the polymeric additive, the specimens endure higher axial stress and axial strain. In other words, the specimens consolidated with higher percentages of Polyester Resin are more elastic. As can be seen, the optimal polymer content is 3%. In other words, further increase of the polymeric additive did not lead to a significant change in the uniaxial strength. According to these Figures, after 7 and 14 days of curing, due to moisture absorption by the polymer and hardening of the specimens, deformation and elasticity decrease and the specimens immediately fail after the ultimate stress.

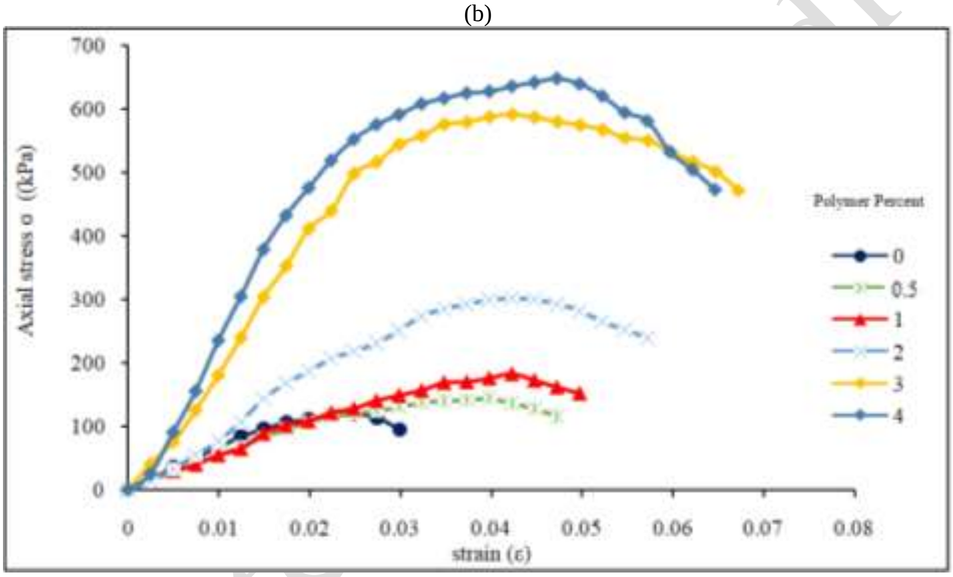
The vertical distance between the charts in Figure 4 shows the effect of polymer content on the specimens. As is clear, the stress-strain curves for 3 and 4 percentages of the polymeric additive are very close to each other. In other words, the optimal content of fibers is equal to 3% and further increase causes a slight change in the peak strength and thus is not economically affordable. Figure 4 also shows that the stress-strain curves become closer with increasing the curing time. This reflects the impact of the curing time on the stress-strain curve. Accordingly, the charts become very close to each other after 7 and 14 days of curing.



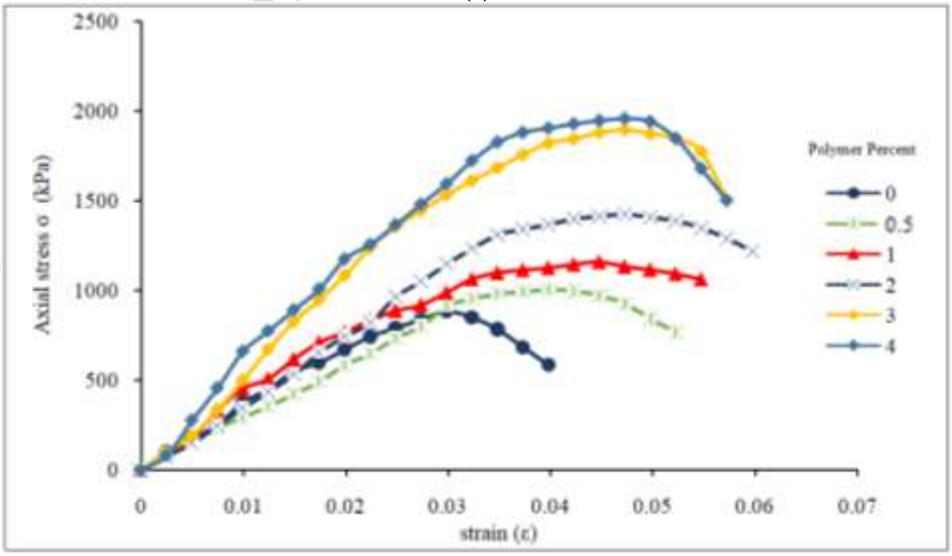
(a)


Axial stress σ ((kPa)
strain (ε)
Polymer Percent
0
0.5
1
2
3
4
0
100
200
300
400
500
600
700
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

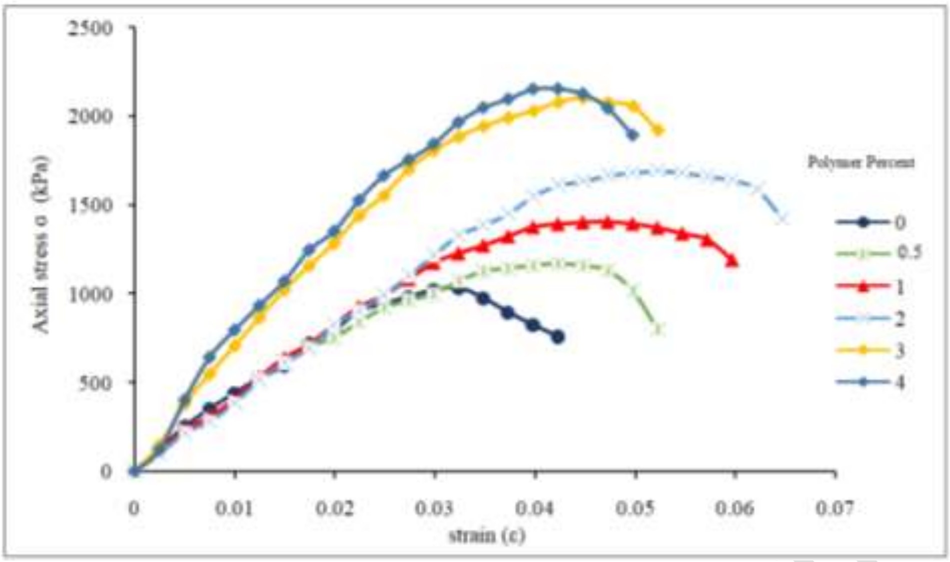
(b)


Axial stress σ ((kPa)
strain (ε)
Polymer Percent
0
0.5
1
2
3
4
0
100
200
300
400
500
600
700
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

(c)


Axial stress σ (kPa)
strain (ε)
Polymer Percent
0
0.5
1
2
3
4
0
500
1000
1500
2000
2500
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

(d)



(e)

Fig 2. Axial stress-strain curves of specimens containing different percentages of Polyester Resins at different timesa) Immediately b) 1day c) 3 days d)7 days e)14 days

Figure 3 shows the changes in the uniaxial compressive strength at different percentages of the polymeric additive. As can be seen, the uniaxial compressive strength increases with increasing the percentage of polymer and curing time. The optimal uniaxial compressive strength is observed by adding 3% of the Polyester Resin.

According to Figure 4, the uniaxial compressive strength of the specimens increases with increasing the curing time. However, the maximum effect of curing time on the strength is observed after 7 days of curing. In other words, a further increase in the curing time has an insignificant impact on increased soil strength. The large vertical distance between 2 and 3 percentages of the polymeric additive reflects the impact of 3% polymeric additive compared to other percentages. As shown, with increasing the polymeric additive, the compressive strength changes further over time. In other words, the polymer has a significant impact on the soil strength after 3 days of curing. With increasing the percentage of polymeric additive (up 3 percent), the impact of the Polyester Resin on the compressive strength increases.

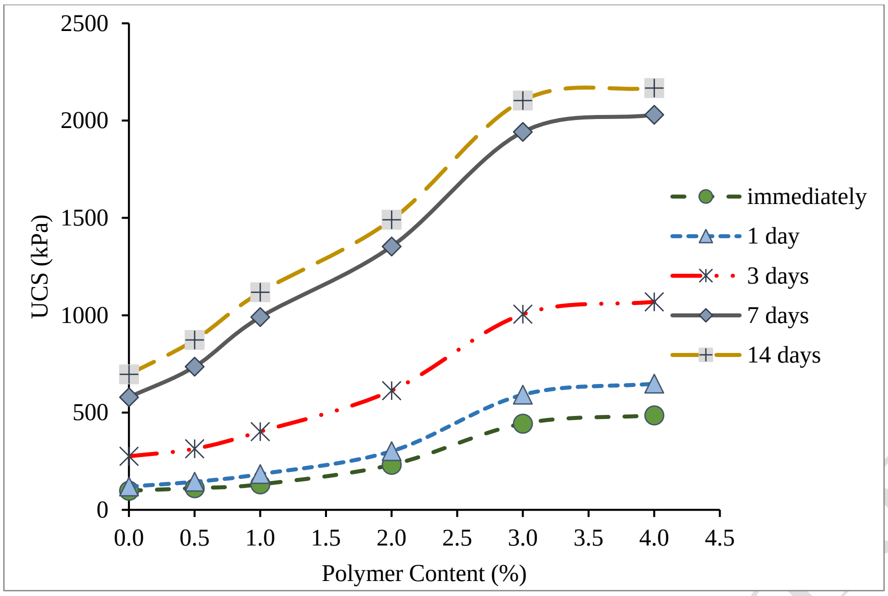


Fig 3. Uniaxial compressive strength as a function of Polyester Resinsadditive at different curing times

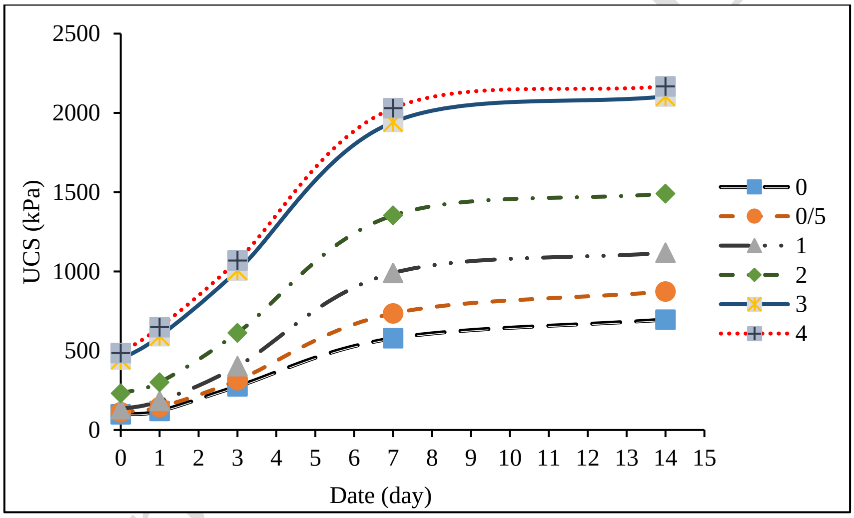


Fig 4. Uniaxial compressive strength versus the different curing times

The changes in the uniaxial compressive strength of soil with different amounts of additives, in curing times of 1, 3, 7, and 14 days, are shown in Figure (5). Comparing the curves in Figure (5) shows that increasing the amount of Polyester Resinhas always increased soil resistance. The rate of increase in resistance increased up to 3% ofPolyester Resinand after that up to 4% of additive, this increase continues at a lower rate. In other words, increasing the studied additive doesnot lead to an increase in resistanceat the same rate. Increasing the curing time also leads to an increase in the strength of the samples, but increasing the curing time from 1 to 14 days increases the strength of the samples. Anyway, according to Figure 6, the peak increase in compressive strength in different percentages of additives was related to the curing time of 7 days. In other words, the additive has shown its effect in improving resistance in a short time.

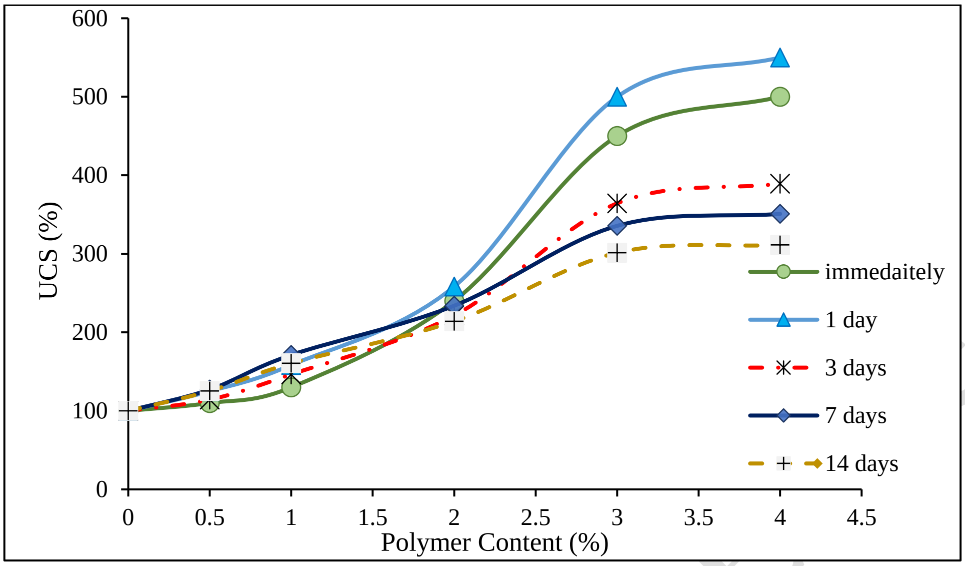


Fig 5. Percentage increase in uniaxial compressive strength as a function of Polyester Resins additive at different curing times

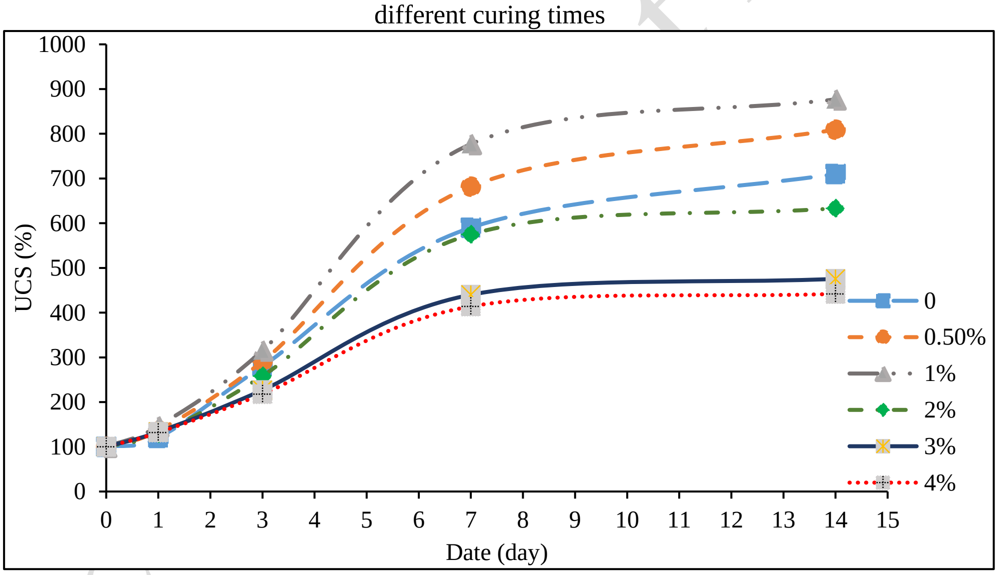
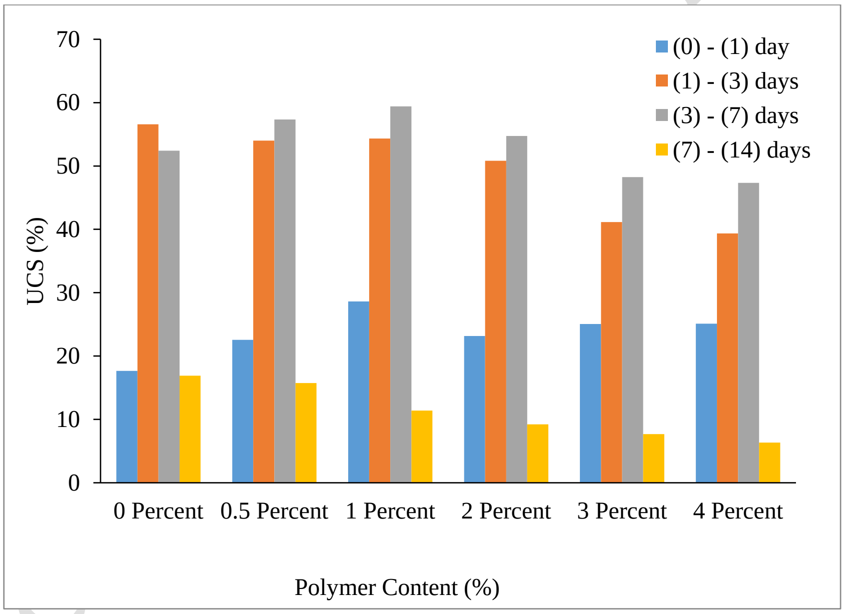


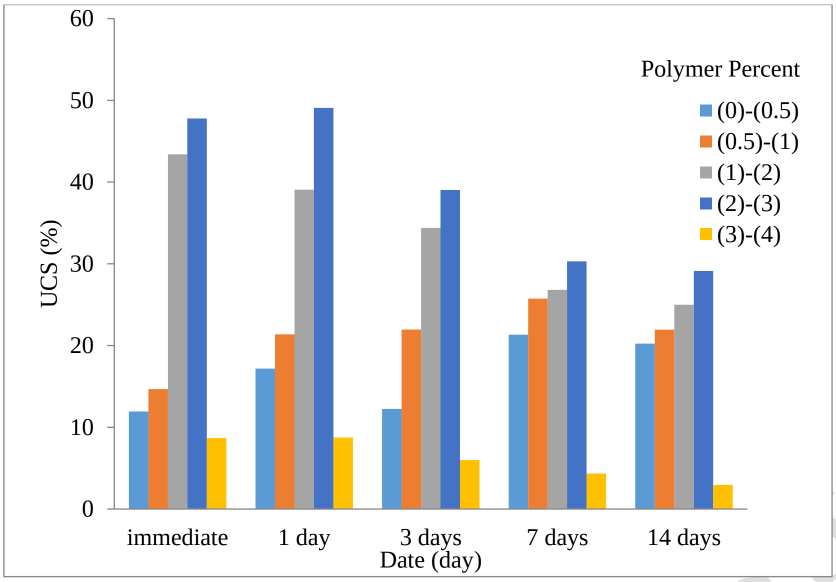
Fig 6. Percentage increase in uniaxial compressive strength versus the curing times

Figure 7a shows the changes in the soil strength versus polymer percentage at different curing times. Accordingly, the polymeric additive has the greatest impact on the strength after 3 to 7 days of curing. It is clear from this Figure that the initial setting ofthe Polyester Resin is obtained after 3 days. This setting rate continues up to 7 days and then the rate of strength increase is reduced. A review of previous studies suggests that additives such as cement, lime, pozzolan, and similar materials enhance soil strength over time by promoting chemical reactions between soil particles and the additives, resulting in a gradual increase in soil resistance. However, the results of this study indicate that Polyester Resin does not exhibit this property and instead functions as an adhesive. Over time, Polyester Resin loses its cohesion, leading to fracturing and ultimately a reduction in soil strength. In samples with higher Polyester Resin content and longer curing periods, it appears that soil particles become more separated, with the added Polyester Resincontributing to structural failure and thereby affecting soil resistance. Figure 7b shows the changes in the soil strength versus the curing time at different additive percentages. The greatest impact of the polymeric additive is seen in the range of 2 to 3 percent. Accordingly, the optimal impact of fibers is obtained by adding 3% ofthe Polyester Resins additive. A further increase in the polymeric additive is not economically affordable.

To evaluate the effect of additives on the soil strength parameters, the direct shear tests were used in addition to uniaxial strength tests. For this purpose, additive-free specimens and soil specimens containing 0.5, 1, 2, 3, and 4% of Polyester Resin were prepared in the 10×10 shear molds with an optimal moisture content of 10.78.



(a)



(b)

Fig 7. Uniaxial compressive strengthversus the curing time at different percentages of Polyester Resins (a), and versus different percentages of Polyester Resins at different curing times (b)

Figure 8a shows the adhesion variation with polymer percentage at different times. As shown, adhesion and therefore shear strength increases with increasing the percentage of polymer. On the other hand, adhesion significantly increases with increasing the curing time. According to Figure 8a, an optimal polymer content of 1% after 7 days of curing resulted in 90% of maximum soil adhesion. The polymer has an insignificant impact on the soil strength parameters after 0 and 1 days. The initial and ultimate setting of additives occurred after 3 and 7 days of curing, respectively.

As a result, the additive-free soil showed an adhesion of 1.372 kPa immediately after the addition of Polyester Resin. With the addition of 3% Polyester Resin and after 7 days of curing, adhesion increased to 12.74 kPa, i.e. about 22.14 times the initial adhesion. As shown in Figure 8b the internal friction angle did not significantly change with the addition of Polyester Resin. In other words, the internal friction angle of the specimen without the polymeric additive is 30.867°. By adding 4% Polyester Resin, the friction angle increased to 32.810° (2 degrees increase) after 14 days of curing.

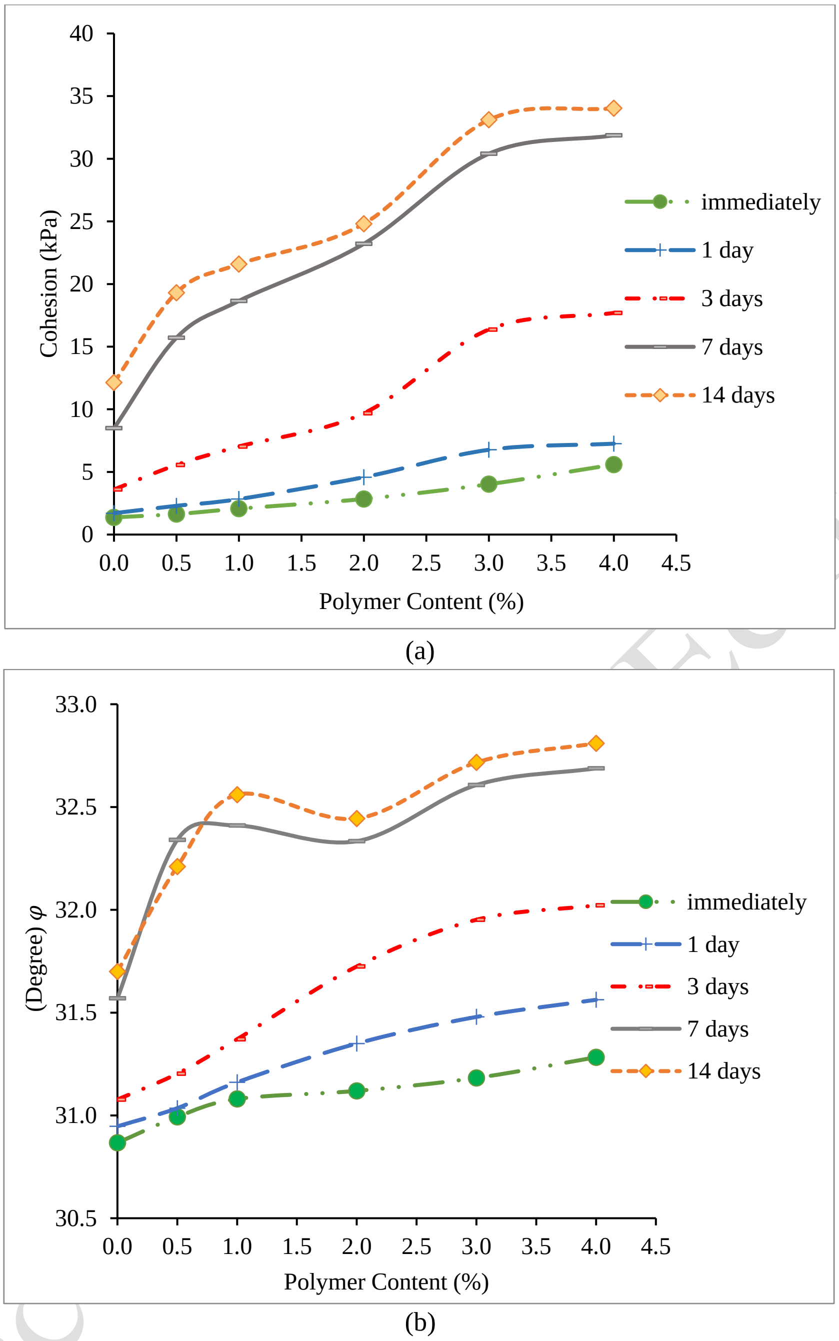


Fig 8. The shear strength parameter versus Polyester Resins present at different curing times, a) changes in soil cohesion, b) changes in internal friction angle

5. Conclusion

Consolidation of clayey sand soils with an orthophthalic Polyester Resin was experimentally studied. For this purpose, the uniaxial strength and direct shear tests were conducted on specimens with 0, 0.5, 1, 2, 3, and 4% ofPolyester Resins at curing times of 0, 1, 3, 7, and 14 days. The results are summarized as follows:

1. An increase in the polymer content and curing time increased the uniaxial compressive strength, shear strength, adhesion, and internal friction of consolidated specimens. The

improvement in the resistance characteristics of the soil in the presence of Polyester Resin can be attributed to the Resin's ability to penetrate between soil particles. This penetration creates effective interactions that enhance adhesion among the particles.

2. The addition of Polyester Resin enhances the uniaxial strength of the soil, with the rate of increase depending on the amount of the additive and the curing time. The studied additive demonstrates its effectiveness in improving resistance over a short period; however, as time progresses, the increase in sample resistance occurs at a slower rate. Specifically, the addition of 1, 2, 3, 4, and 5 Polyester Resin after 14 days of curing resulted in increases in uniaxial strength of 125, 160, 214, 301, and 311 percent, respectively.

3. Curing time is more effective than the percentage of polymeric additive in increasing the compressive and shear strength of the reinforced soil. By adding 4% PolyesterResinimmediately after mixing, the uniaxial compressive strength did not change significantly. However, the ultimate strength increased about 19 times after 7 days of curing while soil polymerization.

4. With the addition of the polymer at curing times of less than 3 days, in addition to increasing the peak strength, the ultimate strength increased leading to a more ductile specimen. The peak strength increased at curing times of more than 3 days while the ultimate strength decreased and hardness increased leading to a more brittle specimen. The specimens consolidated with 4% polymer showed a high strength after 7 or 14 days of curing. After the peak strength, the specimens quickly failed and completely destroyed.

5. In general, curing time (even in specimens with no additives) caused an increase in strength because of the consolidation and integration of the specimens. For this reason, it is considered one of the effective factors in soil improvement.

6. An optimal polymer content of 3% after 7 days of curing caused the maximum increase in soil strength parameters. Further, an increase in the polymeric additive was not economically affordable. In this condition, the specimen reached 90% of its maximum strength.

Field surveys have shown that the results of this study can be used in road-building projects to improve the roadbed. It is worth mentioning that this study was conducted ona laboratory scale. Since homogeneous mixing of soil in local conditions is associated with many problems, the results of this study should be used with caution in local conditions.

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