Effect of Cement, Plastic Waste, and their Combinations on the Geotechnical Properties of Soft Clay Soil

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ABSTRACT

This study investigates soft clay soil stabilization by deploying eco-friendly, inexpensive techniques and incorporating small additions of cement and recycled Plastic Waste (PW). Ordinary Portland Cement (OPC) was used as a chemical stabilizer in quantities not exceeding 2% of dry weight of soil, which was found to be the most effective dosage. Recycled Polyethylene Terephthalate (PET) from discarded water bottles was utilized in different fractions (1%, 1.5%, 2%, and 2.5%) to fulfill this growing environmental concern. The former can be used as a soil augmentation material. A combined treatment was also studied, which involved combining the optimal 2% cement with various percentages of shredded PW. The results indicated that there were very significant improvement marks on the geotechnical properties of treated soil. The greatest UCS enhancement of 247.77% was recorded at 2.5% PW. A UCS improvement was additionally achieved when combining 2% cement with 1% PW compared to the application of cement alone. This combination exhibited the best performance regarding compressibility, having reduced the compression index (C_c) by 65.38%. The technology proposed in this work, which involves using recycled and small percentages of cement in soil stabilization to establish environmental sustainability and improved engineering performance, has been proven efficient.

Keywords-soft clay soil; plastic waste; ordinary Portland cement; shear strength; compressibility

I. INTRODUCTION

Recent alluvial deposits, likely formed within the last 10,000 years, are classified as soft clays. These soils are known for their challenges due to compression index (C_c) values ranging from 0.19 to 0.44, low undrained shear strength (20-40 kPa), and high compressibility [1]. As soil is a critical component in most civil engineering applications, encountering suboptimal soil conditions on some construction sites is often inevitable. When such soils cannot be removed, ground treatment techniques enhance the soil's engineering properties [2]. Admixture soil improvement involves modifying the behavior of soil by incorporating alternative materials with either existing or newly placed soil. This procedure may include a diverse range of materials, such as natural soils, binders, polymers, industrial by-products (such as waste or recycled materials, including fly ash, slag, and crushed glass), salts, poly-fibers, and bitumen or tar [3-8]. Chemical additives such as lime, cement, fly ash, and asphalt are used for stabilization, enhancing properties, like an increase in strength, a reduction in compressibility, improved characteristics with respect to swelling and squeezing, and enhanced durability. These enhancements represent the core objectives of soil stabilization [9-10].

Several studies have been conducted to examine the effects of the varying treatment durations of cement on soil properties and the associated chemical reactions. Typically, small quantities of cement are utilized for both economic and environmental reasons, while higher cement content leads to more significant changes in soil characteristics [11]. In [12], it was revealed that an increase in both the quantity of cement and its duration time, significantly improved the strength of the treated soil. A study involving solidification, Atterberg limits, standard proctor tests, unconfined compression tests, and consolidated-undrained triaxial tests on Aberdeen, Everett, and Palouse soils in Washington State showed that incorporating Portland cement at 2.5%, 5%, 7.5%, and 10% significantly increased the drying rate of soil. The impact was noticeable in the early stages, becoming moderate after approximately thirty minutes of treatment [13]. Approximately, 15.4 billion pieces of disposable plastic are produced each day. The consistent use of bottles, polythene bags, food boxes and containers, pallets, cookware, electronics, and toys, can lead to various ecological risks [14], since there is no place for PW disposition [15, 16]. However, PW has been proven effective for its reuse in soil engineering properties. Its incorporation helps improving load-bearing capacity, soil shear strength, durability, California Bearing Ratio (CBR) values, as well as reducing settlement [17]. To evaluate the impact of PW on key engineering properties of clay soil, PET water bottles were shredded (to sizes under 1 mm) and mixed into soil at rates of 0.5%, 1%, 1.5%, and 2% by weight. Consolidation and Unconfined Compressive Strength (UCS) tests were conducted before and after the addition of plastic and the results revealed an increase in cohesion (from 53 to 56 kPa) at an optimal PET content of 2% [18].

Many studies have explored the incorporation of cement with additive materials - especially inexpensive materials such as waste- to improve soil's properties [19]. For example, authors in [20] mixed OPC with bagasse ash and added this mixture to the soft clay soil. The experiment results demonstrated that the use of this mixture exhibited better performance than the conventional cement. In another study, cement was utilized to improve the soft clay soil properties, containing two types of minerals: kaolinite and bentonite [21]. Kaolinite was added at 5%, 10%, and 15%, while bentonite was incorporated at 30%, 40%, and 50% of cement content. Additionally, polypropylene fibers were also added at 0.1%, 0.2%, and 0.5%, along with carpet waste at 0.5%, 0.75%, and 1%. In [22], the PW from drinking water bottles was mixed in strips at 0%, 0.25%, 0.5%, and 0.75% of the dry weight of soil with cement at 1% and 1.5%. It was found that increasing the percentage of cement was effective in improving the soil when conducting the UCS test.

The primary objective of this study is to investigate methods for utilizing cement in minimal quantities to reduce expenses and mitigate environmental impact, incorporating it with shredded PW (PET) bottles. This approach aims to contribute positively to environmental sustainability, reduce costs, and enhance soil quality in terms of strength and compressibility.

II. MATERIALS AND METHOD

A. Materials

1) Soil Used

In this study, the clay soil samples were collected from Al-Zuhairat village in Diyala Governorate, about 30 km northeast of Baqubah City, and from an approximate depth of 0.5 m. The physical and chemical properties of the soil are presented in Table I.

2) Plastic Waste Material

The Plastic Waste Material (PWM) of this study was sourced from PET empty household water bottles. After being drained, the bottles were collected. The next process involved the removal of the top and bottom end, which were subsequently cut into smaller pieces with scissors. The small pieces were then fed into an industrial grinder, which further shreds them into smaller fragments of 2-4 mm, as shown in Figure 1. Finally, the shredded PWM was sifted using Sieve No. 4.

TABLE I. PHYSICAL AND CHEMICAL PROPERTIES OF CLAY SOIL

Soil property	Value	Standard
Liquid Limit (*LL*)	37	ASTM D 4318 [23]
Plastic Limit (*PL*)	17	
Plasticity Index (*PI*)	20	
Specific gravity (G_S)	2.72	ASTM D 854 [24]
Gravel (%)	0	ASTM D 422 [25]
Sand (%)	2	
Silt (%)	46	
Clay (%)	52	
Maximum Dry Density (MDD) (g/cm^3)	1.72	ASTM D 698 [26]
Optimum Moisture Content (OMC) (%)	14.8	
Classification of soil	CL	ASTM D 2487 [27]
Organic matter (%)	5.45	BS 1377 [28]
Total soluble salt (%)	0.4	
Chloride content (%)	0.02	
SO_3 content (%)	0.27	

Fig. 1. The production process of PWM.

3) Ordinary Portland Cement

OPC was employed as a chemical additive in small amounts (up to 2%) to improve the properties of the soil. This material was manufactured by the Iraqi Kabisa Factory and conforms to the standards in accordance with the Iraqi specification IQS No. 5 [29], as displayed in Table II.

TABLE II. PHYSICAL AND CHEMICAL PROPERTIES OF OPC ACCORDING TO [29]

Chemical properties		
Test	**Value**	**Limitations**
Calium oxide (CaO) %	62.6	-
Silica oxide (SiO_2) %	21	-
Aluminum oxide (Al_2O_3) %	4.92	-
Magnesium oxide (MgO) %	3.33	5(max.)
Iron oxide (Fe_2O_3) %	3.08	-
Sulfur trioxide (SO_3) %	2.16	2.8(max.)
Loss of Ignition (LOI) %	1.5	4(max.)
Insoluble residue (I.R.) %	0.6	1.5(max.)
Physical Properties		
Fineness by Blain method (m^2/kg)	348	250(min.)
Initial setting time (min)	106	45(min.- 10(max.)
Final setting time (h)	3.36	
Loading strength rate (MPa) at 2 days	12.5	10(min.)- 32.5(min.)
Loading strength rate (MPa) at 28 days	33.63	

B. Experimental Methodology

1) Soft Clay Soil Preparation

In this study, soft clay soil was prepared utilizing a trial-and-error approach. The soil was compacted into three CBR molds, each with a diameter of 15.2 cm and a height of 11 cm, using spacer. Each mold was compacted with different water contents of 18%, 20%, and 22% relative to the dry weight of the soil. Figure 2 illustrates the variation in undrained shear strength with respect to different water content percentages. Based on these results, a water content of 22% was selected for all subsequent experiments. The properties of the remolded soil at this moisture level are summarized in Table III.

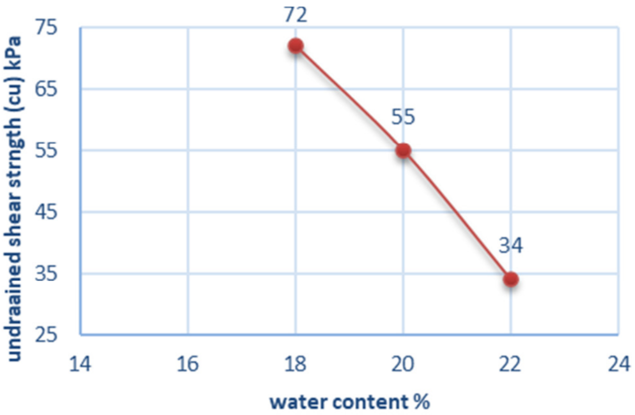

Fig. 2. The variation of undrained shear strength (kPa) with different percentages of water content%.

TABLE III. REMOLDED CLAY SOIL PROPERTIES AT 22% WATER CONTENT

Index property	Index value	Standard
Compressibility properties		
Initial void ratio, e_o	0.853	ASTM D 2435 [30]
Compression index, C_c	0.26	
Recompression index, C_r	0.026	
Volume change coefficient, m_v (m^2/kN)	1.2E-4	
Consolidation coefficient c_v (m^2/min)	2.93E-5	
Strength properties		
UCS (kPa)	28.03	ASTM D 2166 [31]

2) Unconfined Compressive Strength Test

The UCS test was carried out in accordance with ASTM D-2166 [31]. The samples were extracted after being prepared inside the CBR mold, using a cylindrical tube, and after being trimmed to a diameter of 3.8 cm and a height of 6.7 cm. The loading rate during the test was 1.56 mm/min. The test was conducted before and after the utilization of additives, all the ratios and types of which are depicted in Table IV.

3) Consolidation Test

This test was performed in accordance with ASTM D-2435 [30] standards, at pressures of 25, 50, 100, 200, 400, and 800 kPa, along with a reloading pressure of 25 kPa. The samples were extracted utilizing a metal ring with a diameter of 5 cm and a height of 2 cm. Comprehensive details regarding the mixing processes of the materials and their corresponding percentages are provided in Table IV.

TABLE IV. PERCENTAGES (%) AND CURING TIME OF ADDITIVE MATRIALS

Additive type	Additive percent %	Curing time
PW	1%, 1.5%, 2%, and 2.5%	2 days
Cement (C)	1%, 1.5%, and 2%	7days
C + PW	2% C+ 1%, 1.5%, 2%, and 2.5% PW	7 days

III. RESULTS AND DISCUSSION

A. Unconfined Compressive Strength

The results of the UCS test are presented in Table V. A gradual increase in UCS values with increasing plastic content was observed when PET PW was added to soft clay in the proportions of 1%, 1.5%, 2%, and 2.5% (by dry weight of soil). The peak strength was recorded at 2.5%, reaching a value of 97.73 kPa, which indicates an enhancement of about 247.77% when compared with the untreated soil. This has been corroborated with earlier studies [32, 33], extolling the positive role of PET waste on soil strength.

Apart from this, OPC inclusion in low percentages-1%, 1.5%, and 2%-resulted in a significant gain in soil strength with very little ecological and economic effects. The peak strength was achieved 332.27 kPa at 2% by cement content, which reinforces the idea of soft clay having a substantially uplifted UCS. To determine the extent of the effect of using the two materials as a mixture in increasing the strength of soft clay soil, the optimal percentage of cement (2%) was mixed with all the percentages of PET water bottles. The highest value of UCS was achieved when mixing cement with 1% of PW. However, beyond 1% PET, the values began to decline. Figures 3 and 4 illustrate the percentages of improvement for each type of additive.

TABLE V. RESULTS OF UCS TEST

Percentages of additives (%)	q_u (kPa)	Curing time
0	28.03	2 days
PW		
1	41.97	2 days
1.5	52.27	
2	76.7	
2.5	97.48	
C		
1	123.94	7 days
1.5	190.12	
2	332.27	
C-PW admixture		
2% C +1% PW	467.02	7 days
2% C +1.5% PW	322.88	
2% C +2% PW	200.92	
2% C +2.5% PW	110.43	

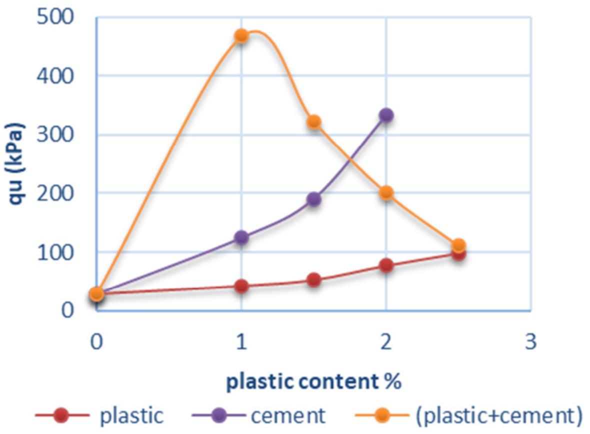

Fig. 3. Results of UCS test.

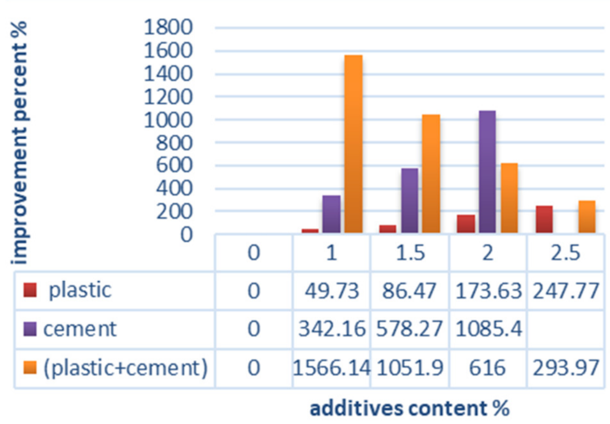

Fig. 4. Improvement percent (%) of q_u of soft clay soil with different percentages of additives.

B. Consolidation Results

TABLE VI. RESULTS OF CONSOLIDATION TEST

Percentage of additives %	C_c	C_r	Curing time
0	0.26	0.026	2 days
PW			
1	0.20	0.027	2 days
1.5	0.19	0.031	
2	0.19	0.029	
2.5	0.21	0.014	
C			
1	0.18	0.019	7 days
1.5	0.17	0.020	
2	0.13	0.014	
C-PW			
2% C +1% PW	0.09	0.013	7 days
2% C +1.5% PW	0.11	0.015	
2% C +2% PW	0.12	0.014	
2% C +2.5% PW	0.15	0.024	

All types of additives used in this research have a clear effect on reducing soil compressibility. When using a plastic shredder at rates of 1.5% and 2%, the C_c value decreased from 0.26 before treatment to 0.19 and then increased again, reaching 0.21 at 2.5%. This fluctuation between decrease and increase is consistent with the results of [34]. When utilizing only cement in small percentages (1%, 1.5%, and 2%), the values of both C_c and C_r decreased gradually as cement percentage increased, reaching 0.13 and 0.014 at 2%, respectively, which is the optimal cement percentage. This improvement was considered optimal with the use of these small percentages. The most significant improvement rate was observed when 2% cement was combined with 1% PW. The compressibility index fell to 0.09, representing an improvement of 65.38%. As the plastic percentage was increased while keeping the cement percentage constant at 2%, there was a corresponding rise in both the C_c and C_r values. Table VI and Figures 5-7 present the detailed results of C_c and C_r from the consolidation test.

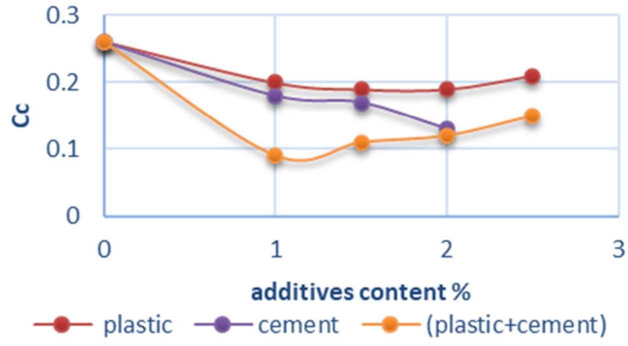

Fig. 5. Variation of C_c with different percentages of additives.

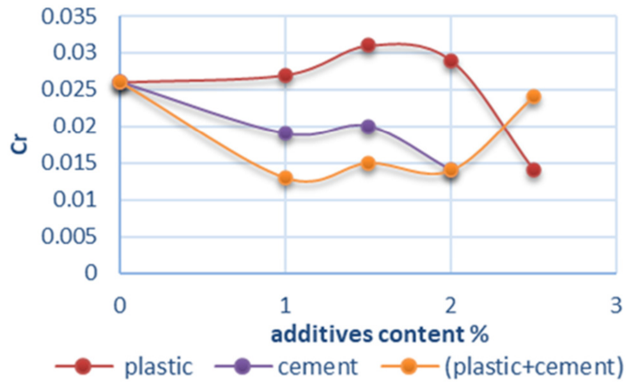

Fig. 6. Variation of C_r with different percentages of additives.

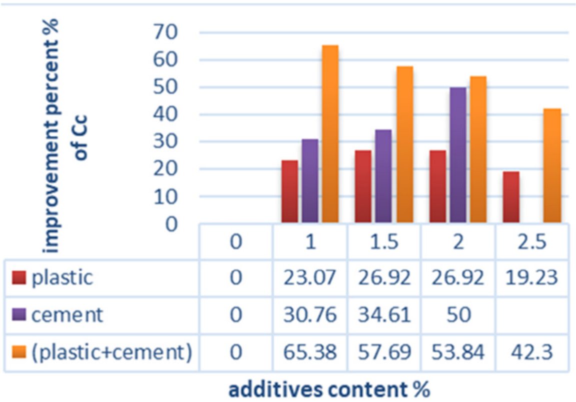

Fig. 7. Improvement percent (%) of C_c with different percentages of additives.

IV. CONCLUSION

The aim of this study was to investigate the impact of Plastic Waste (PW), Cement (C), and C-PW mixture on the properties of clay soil. The findings revealed that these additives significantly increase soil strength and decrease compressibility, thus presenting a solution for cost-effective and environmental waste management for soil stabilization. The main observations made in the current study are:

- The mixed 2.5% shredded drinking water PW improved the Unconfined Compressive Strength (UCS) by 247.77% from 28.03 kPa to 97.48 kPa in soft clay soil.
- The optimal C percentage was found to be 2%, which hugely increased this value up to 332.27 kPa for UCS.
- The highest UCS value, thus, obtained was 467.02 kPa by combining 2% C and 1% PW, which was the best treatment; however, increasing the plastic content in the combination beyond that in the 1% mix gave a reduction in strength, likely because of some interference in C-soil bonding due to too many plastic particles.
- In terms of compressibility, it was observed that adding PW at 1.5% and 2% reduced compression index (C_c) from 0.26 to 0.19, hence marking an improvement of 26.92%.
- The most effective reduction in compressibility occurred with the 2% C and 1% plastic mixture, lowering C_c from 0.26 to 0.09 and C_r from 0.026 to 0.013, achieving a compressibility improvement of 65.38%.
- While the optimal proportions of PW improved soil behavior, it was also observed that in the case of higher amounts in the C-PW blend, the performance diminishes, presumably due to the rigidity of the plastic disrupting the cementitious bonding.

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