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Aram Mohammed Raheem

Professor, Ph.D., Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq, 36001 AND External Lecturer, Al-Qalam University, Kirkuk, Iraq, 36001, engaram@yahoo.com

Cumaraswamy Vipulanandan

Professor, Ph.D., Civil and Environmental Engineering Department, University of Houston, Texas, USA, 77204

Mohammed Hiwa Abdullrahman

Assistant Researcher, Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq, 36001

Ali Tariq Omer

Assistant Researcher, Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq, 36001

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RESEARCH ARTICLE

Beneficial Investigation of Sustainable Recycled Waste Plastic in Treating the Consolidation Behavior of Fine Soil

Aram Mohammed Raheem [a,b,*], **Cumaraswamy Vipulanandan** [c], **Mohammed Hiwa Abdullrahman** [d], **Ali Tariq Omer** [d]

[a] Professor, Ph.D., Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq, 36001
[b] External Lecturer, Al-Qalam University, Kirkuk, Iraq, 36001
[c] Professor, Ph.D., Civil and Environmental Engineering Department, University of Houston, Texas, USA, 77204
[d] Assistant Researcher, Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq, 36001

ABSTRACT

Recycled waste plastic is one of the regular garbage utilized as a sustainable material in soil remediation. This study examines the efficacy of utilizing local recycled waste plastic as an ecological quantifiable along with soil containing fine particles to analyze the consolidation behavior. Various recycled waste plastic contents ranging from 2% to 10% were employed experimentally in two patterns where in the first pattern the recycled waste plastic were mixed as dry material with the fine soil particles while in the second pattern a sandwich layer of 10% of the recycled waste plastic was placed in the middle of the untreated soil. When subjected to the same level of stress, the recycled waste plastic-treated soil had a 165% increase in its coefficient of consolidation between the initial and subsequent loading cycles. Various nonlinear models were obtained for different consolidation aspects including a power law model for the coefficient of consolidation over time, a hyperbolic model for the deformation over time, and a second-order polynomial model for void ratio over stress. It is demonstrated that the recycled waste plastic can be utilized as an efficient sustainable substantial source for various consolidation aspects.

Keywords: Consolidation, Recycled waste plastic, Regression models, Power model, Hyperbolic model

1. Introduction

It is necessary to evaluate any work site or foundation in order to ascertain its capacity to bear the load of the structural components of the buildings [1]. Various techniques have been developed to address and minimize the impact of unstable soil conditions in order to prevent mechanical stress and foundation failures. The catastrophic damage caused by weakened soils is due to a failure to detect the seriousness of the soil's settlement or expansion at the outset of the design phase, rather than an absence of adequate engineering alternatives [2]. With an increasing proportion of projects taking place on unstable ground for both offshore and onshore constructions, geotechnical engineers are faced with the task of providing satisfactory foundation stability at a minimal expense [3–4]. The issue of soil with low shear strength is a persistent concern in the field of soil mechanics that requires continuous research. Therefore, it is necessary to improve the quality of soft soil in order to facilitate appropriate construction and expansion [5].

The growth in construction has resulted in increased demands for infrastructure development in remote places with unstable expansive soils, which are considered unsuitable [6]. Due to the substantial

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* Corresponding author.
E-mail address: engaram@yahoo.com, aram_raheem@uokirkuk.edu.iq (A. M. Raheem).

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clay concentrations, expansive soils are susceptible to instability because they tend to contract or expand in response to changes in water content. According to research conducted by several investigators, about $375 billion has been lost in the United States alone since 1973 due to the engineering difficulties associated with expansive soils [7]. Expansive soils generate ground issues in many parts of the globe, particularly in dry and semi-dry environments [8]. To analyze the properties of expansive soils, two essential metrics are utilized represented by swelling potential and swelling strain. These swelling characteristics are crucial for the construction of several types of structures, such as highways, shallow foundations, canal linings, tunnels, retaining walls, and underground pipes. In the meantime, one-dimensional oedometer experiments are employed to examine the volume change of a sample, which is measured in terms of one-dimensional length alteration as the sample is constrained horizontally. Thus, swelling soil characteristics could be quantified experimentally using an oedometer utilizing a one-dimensional consolidation test [9].

In current years, sustainable ground improvement has developed a foundation of recent infrastructure expansion, aspiring to improve the engineering performance of weak or problematic soils while minimizing environmental degradation and resource depletion [10]. One extremely effective method to achieving greater sustainability includes the utilization of recycled construction and demolition wastes, such as recycled crushed concrete, to substitute non-renewable natural aggregates in the stabilization of soft clayey soils [11]. This practice not only meaningfully improves the soil's undrained shear strength and decreases its compressibility, but it also reduces carbon footprints, cuts down project budgets, and diverts substantial waste accumulation from landfills. Furthermore, innovative and environmentally friendly additives such as nano-silica have emerged as highly viable stabilizers, recommending substantial improvements in soil cohesion, reductions in hydraulic permeability, and successful mitigation of leaching-induced settlement in highly collapsible gypseous soils [12]. To ensure these soil treatment techniques associate effectively with wider sustainable development goals, the adoption of comprehensive multi-criteria analysis frameworks is crucial to balance the interlinked environmental, social, and economic pillars of geotechnical design; such widespread evaluations demonstrate that ground improvement methods—such as lime pile treatments—frequently provide superior sustainability metrics related to conventional, resource-heavy deep foundations [13].

Cement and lime are well-known substances for treating poor soils. The excessive reliance on cement and lime has been shown to harm the environment, increasing environmental problems such as producing 8% to 10% of worldwide human-caused carbon dioxide emissions from the 4.1 billion metric tons produced each year [14]. Furthermore, carbon dioxide emissions impact considerably to worldwide warming, the loss of natural resources, and the production of waste from attributed production processes [15]. In addition to the ecological drawbacks, cement and lime are subjected to excessive plastic shrinkage and cracking, resulting in decreased durability of the stabilized soil [16]. Moreover, because of their high water content and poor hardness, some soil materials cannot be employed directly [17]. As a consequence, finding a better replacement for improving soil is very objective.

It should be recognized that following the end of the Second World War, the worldwide production of plastic has significantly expanded, rising from 1.5 million tons in 1950 to 367 million tons in 2020 [18]. Approximately 8.3 billion tons of plastic garbage has been created globally since 1950, where 60% is ended up in landfills or in the environment [19]. Countries such as India produce around 9.46 million tons of waste plastic every year, where 40% is remained uncollected and 43% is utilized for packaging purposes [20]. Plastic film wastage in China went up from 300,000 tons in 1991 to over 1.45 million tons in 2017, and this amount is expected to go above 2 million tons by 2024 [21]. The inability of recyclable plastic to biodegrade in the environment has created numerous challenges for rural and urban regions. Some common issues related to waste plastic creation include drain clogging, water stagnation, and the emission of harmful gases during open combustion [22]. The elimination and dumping of plastic garbage, on the other hand, represents a huge hazard to the environment because of its non-biodegradability. As a result, removing plastic from the environment has become an urgent priority.

Plastic substances are presented in a variety of particle sizes such as macro-plastics (greater than or equal to 5 mm in diameter), micro-plastics (less than 5 mm in diameter), and nano-particles (less than 1 μm) [23]. The correct removal of waste has become essential in many countries worldwide. For instance, efforts have been made to utilize biomedical waste to enhance the mechanical properties of cement, where such wastes can improve compressive and tensile strengths with better workability [24]. Waste from plastics is created in large amounts, such as plastic bottles made of polyethylene terephthalate (PET) and carpet and plastic sacks made of polypropylene

(PP) [25]. Polyethylene materials have been recognized as important elements of garbage in Kirkuk in Iraq. According to preliminary estimates, the population of Kirkuk city is over 1.5 million people, and the daily accumulated plastic per person is around four plastic bottles (500 cm^3 capacity), with a total created plastic garbage of 2190 million bottles per year. With the goal of protecting the ecosystem from the detrimental impact of plastic waste substances, a number of investigators have carried out experiments to identify efficient approaches to limit the contamination of these resources, including reducing waste and reusing these components in civil engineering projects. Traditional soil improvement products are not cost-effective since they require a large amount of usage. Thus, recycled plastic waste can be regarded as an inexpensive sustainable recycled byproduct utilized for soil remediation with minimal risk to the environment.

Recycled waste plastic substances can be used to stabilize soil by incorporating them as discrete fibers, which mimic the behavior of fiber-reinforced soil [26]. Multiple investigations have been conducted to examine the effects of isolated fibers produced from recyclable plastics on the characteristics of soils [27–29]. These investigators observed that utilizing plastic recyclables for soil stabilization can enhance weak soil characteristics by increasing both unconfined compressive strength and California bearing ratio, as well as decreasing the soil plasticity. Different tests, including compaction, direct shear, and California bearing ratio (CBR), were carried out to treat sandy soil with various percentages of plastic strips and size aspect ratios [29]. The study has revealed that plastic may be employed as an efficient stabilizer to address waste disposal issues as well as inexpensive alternatives for stabilizing poor soils. A study was carried out to evaluate the tensile and shear characteristics of both untreated and lime-treated plastic clay over different curing durations, extending to 300 days, utilizing triaxial tension and compression testing methods [30]. Results from triaxial tension tests show that failure occurs in a tensile mode under low confining pressure, while at higher confining pressure, it manifests in an extensional shear mode. Accordingly, the recycled waste plastic has been rarely used as a sustainable material in investigating the consolidation behavior of fine particle soils.

The novelty of this work can be presented by incorporating experimental work with mathematical modeling to evaluate the consolidation performance of soils treated with recycled waste plastic material as a sustainable material. This double practice comprehensively identifies how recycled waste plastics affect soil consolidation features, proposing empirical data and extrapolative models. The present work's originality lies in its combined experimental and modeling methodology that not only quantifies the empirical outcomes of recycled waste plastic inclusion on soil characteristics but also acquires predictive models to predict consolidation behavior. This progression allocates extra precise predictions and assessments of soil conduct for engineering purposes, supporting the utilization of sustainable materials in soil stabilization and providing ecological management efforts. Table 1 identifies a scientific assessment for current study with typical recent investigations.

As a result, recycled waste plastic is infrequently used as a sustainable material to treat fine particles of soil to examine various aspects of the consolidation behavior. In addition, the application of more than one loading cycle during experimental consolidation investigation has yet to be checked. Hence, the primary goal of the present research was to assess the effectiveness of employing local recycled waste plastic as a sustainable material and up to 10% in enhancing fine particles soil. The study's particular goal was to examine untreated and recycled waste plastic-treated fine particles of soil for one full loading and unloading cycle, followed by a half-cycle of reloading. Investigating the mechanical behavior of

Table 1. Scientific assessment for current and typical recent investigations.

Characteristics	Conventional present investigations	Current work
Main physical focus	Different industrial/agricultural wastes or main plastic combines	Recycled waste plastic as a sustainable soil additive
Evaluated geotechnical parameter	Concentrates frequently on index properties, compaction, and unconfined compressive strength (UCS)	Focuses particularly on complex consolidation and settlement functioning
Procedural approach	Thoroughly experimental and empirical laboratory tests	Dual method: incorporates extensive experimental tests with mathematical modelling
Consequence	Isolated observed data points and baseline classifications	Empirical data quantification incorporated with analytical, predictive models
Logical and engineering importance	Proves feasibility of material inclusion	Conveys high-accuracy predictive tools for long-term engineering design and environmental management

Fig. 1. The location of the soil sample on the Google map at the campus of the University of Kirkuk.

fine soil particles, both untreated and those treated with recycled plastic, under cyclic loading highlights aspects such as permanent deformation and elastic recovery when subjected to stress. This comparative study aids in measuring the extent to which plastic treatment minimizes settlement, enhances stiffness, and boosts overall geotechnical properties for sustainable engineering practices. Furthermore, several nonlinear models including hyperbolic model combined with statistical quantification have been used to predict various aspects of the consolidation behavior of untreated and recycled waste plastic-treated soils.

2. Area of study

The University of Kirkuk campus is very young, and work is currently proceeding. Thus, disturbed soil samples were obtained at the University of Kirkuk campus at the GPS coordinates of 35.392351, 44.338641, where a new building is scheduled to be erected in the near future. Fig. 1 shows the Google map for the site.

3. Methodology

In this research study, recycled waste plastic has been added to the soil in various amounts for experimental purposes. Recycled waste plastic was chopped into tiny pieces using both a shredding machine and an electric mixer before being blended with the soil. Plastic wastes were added to specimens in varying amounts of 0%, 2%, 5%, and 10%. Additionally, samples were prepared by adding 10% of recycled waste plastic as a sandwich layer to the middle of the specimen. Incorporating a 10% layer of recycled waste plastic into the soil resembles the process of soil reinforcement through discrete layers or geosynthetic materials, a concept within geotechnical engineering. This approach imitates the installation of reinforcement layers in the soil to improve characteristics such as shear strength and bearing capacity, frequently applied in foundations and pavement construction. One-dimensional consolidation tests were performed precisely according to ASTM D2435/D2435M [31].

One-dimensional consolidation tests have been performed for untreated and recycled waste plastic-treated soil samples with diameters of 20 mm and heights of 50 mm. During the testing phase, the load was incrementally increased from 1 kg (32 kPa) to 2 kg (64 kPa), then to 4 kg (128 kPa), and finally to 8 kg (256 kPa). The sample's deformation has been observed for a duration of 24 hours (equivalent to 1440 minutes) for every applied load. The testing procedure consists of a full cycle of loading and unloading, followed by a half cycle of reloading to examine the soil's mechanical behavior and material properties under conditions that simulate real-world engineering scenarios involving cyclic stress. The deformation was continuously measured for any applied load under all loading conditions for 24 hours.

4. Properties of materials

4.1. Soil

For the current investigation, disturbed soil samples were collected from a depth of 1 to 1.5 meters on

Table 2. Soil properties.

Soil property	Value	Soil property	Value
Water content (%)	8.4	Coefficient of Curvature	0.76
Specific gravity	2.746	Liquid limit	50
Effective size, D_{10} (mm)	0.1	Plastic limit	30
Coefficient of uniformity	11.8		

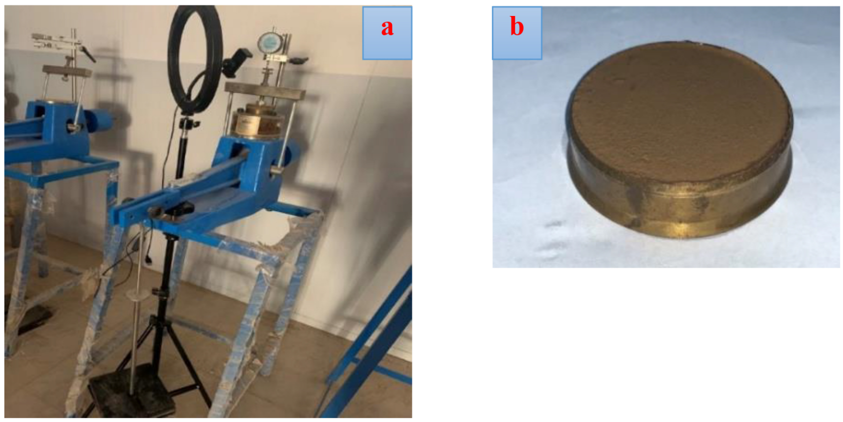

Fig. 2. (a) The consolidation device, and (b) untreated soil sample.

the University of Kirkuk campus. The engineering characteristics of the soil were evaluated using the obtained field samples. In Table 2, several test results have been presented. The fine soil particles that pass through sieve No. 200 (0.075 mm) were used to prepare the soil specimens. Fig. 2 presents both the consolidation device and untreated soil sample.

5. Recycled waste plastic

The recycled waste plastic material (polyethylene terephthalate "PET") has been collected from various local daily wastes in Kirkuk city, Iraq. The waste plastic was hashed, grinded, and passed through sieve No. 200 (0.075 mm) to be compatible with the soil's fine particle sizes. The used recycle waste plastic properties have been identified in Table 3. The recycled waste plastic-treated soil with various percentages is shown in Fig. 3. The percentage of recycled waste plastic that was tested is combined with dry soil, and an equal amount of water is added to both untreated and treated soil samples using the optimum water content value.

6. Statistical models

6.1. Linear single regression model

A single linear regression model will be used to predict consolidation soil characteristics represented by compression index (C_c) and swelling index (C_r). In terms of a number of analyzed criteria, such as recycled waste plastic content (%), swelling (mm), and swelling pressure (kPa), both C_c and C_r could

Table 3. Recycled waste plastic properties.

Material	Plastic
Size	Passing through sieve No. 200 (0.075 mm)
Color	Black
Specific gravity	1.108

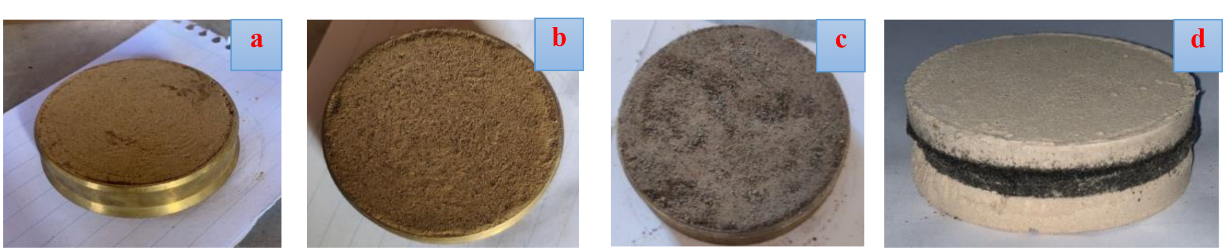

Fig. 3. Recycled waste plastic treated fine particles soil, (a) 2% plastic, (b) 5% plastic, (c) 10% plastic, and (d) 10% plastic sandwich.

be predicted. The single regression model has the following form:

$$\text{Consolidation Soil Characteristic} = A + B * \text{Investigated Factor} \quad (1)$$

Where A and B are model parameters. As the investigated factor is swelling (mm), then B unit is (1/mm). In addition, when the investigated factor is swelling pressure (kPa), then B unit is (1/kPa).

Studied elements such as the proportion of recycled waste plastic, swelling, and swelling pressure are not manageable in relation to field soil treatment or the natural behavior of soil. Furthermore, soil consolidation parameters, including C_c and C_r, require more time, effort, and crucial laboratory testing observations. Therefore, the proposed linear single regression model can be utilized to estimate C_c and C_r based on various assessed factors.

6.2. Linear multi-regression model

The overall effect of investigated parameters on C_c and C_r will be examined using a multi-linear regression model. The impacts of recycled waste plastic content, swelling, and swelling pressure are linearly added together in the model, which has the following representation:

$$\text{Consolidation Soil Property} = C + D * \text{Plastic Content}\,(\%) + E * \text{Swelling}\,(mm) + F * \text{SwellingPressure}\,(kPa) \quad (2)$$

Where C, D, E (1/mm) and F (1/kPa) are model parameters.

Both C_c and C_r may be predicted using the prescribed multi-regression model parameters depending on multiple investigated factors.

7. Results

7.1. Void ratio versus pressure relationships

The variations of void ratio versus applied stress for untreated and recycled waste plastic-treated soils have been presented in Fig. 4 (a–e). The initial void ratio for untreated and recycled waste plastic treated soils were 1.055, 1.148, 0.979, 0.838, and 0.923 for 0%, 2%, 5%, 10%, and 10% sandwich recycled waste plastic treated soils, respectively. For untreated soil and in the first loading stage from the first cycle, the void ratio has decreased by 16% as the stress has increased by 708%, while for the same stress change, the void ratio has increased by 4% for the first unloading stage from the first cycle. Nevertheless, the re-loading stage in the second cycle decreased the void ratio by 5%, resulting in a 708% stress increase. The void ratio was reduced by 15% for 2% recycled waste plastic-treated soil during the first loading stage of the first cycle as the stress increased by 708%; however, for the same stress change, the void ratio increased by 4% for the first unloading stage of the first cycle. The re-loading phase in the second cycle, on the other hand, reduced the void ratio by 5% for a 708% stress increase. During the initial loading stage of the first cycle, the void ratio of the 5% recycled waste plastic-treated soil decreased by 15%, while the stress increased by 708%. However, during the first unloading stage of the first cycle, the void ratio increased by 4% for the same change in stress. The second cycle's re-loading phase, on the other hand, decreased the void ratio by 5% for a 708% stress increase. During the first loading stage of the first cycle, the void ratio reduced by 14% for 10% recycled waste plastic-treated soil while stress increased by 708%; nevertheless, the void ratio increased by 5% for the same stress change during the first unloading stage of the first cycle. The void ratio was reduced by 5% during the second cycle's re-loading phase, resulting in a 708% stress increase. The void ratio decreased by 16% for 10% recycled waste plastic sandwich-treated soil during the first loading stage of the first cycle while stress increased by 708%; however, the void ratio increased by 8% for the same stress change during the first unloading stage of the first cycle. During the re-loading phase of the second cycle, the void ratio was decreased by 7%, resulting in a 708% increase in stress. It is clearly indicated that the recycled waste plastic works as a sustainable material with different rates.

7.2. Modelling of various consolidation characteristics

(a) C_v versus t_{50}

For each scenario under consideration, the laboratory data have been used to determine the coefficient of consolidation (C_v) vs the time for 50% consolidation (t_{50}). In addition, such C_v versus t_{50} relationship has been modeled using a nonlinear power model as follows:

$$C_v\,(mm^2/min) = L*(t_{50})^M \quad (3)$$

Where L ($mm^2/min/min^{0.5}$) and M are model parameters.

A summary of the nonlinear power model analysis for C_v vs t_{50} (Eq. (3)) is presented in Table 4. The provided model was solved using the least squares

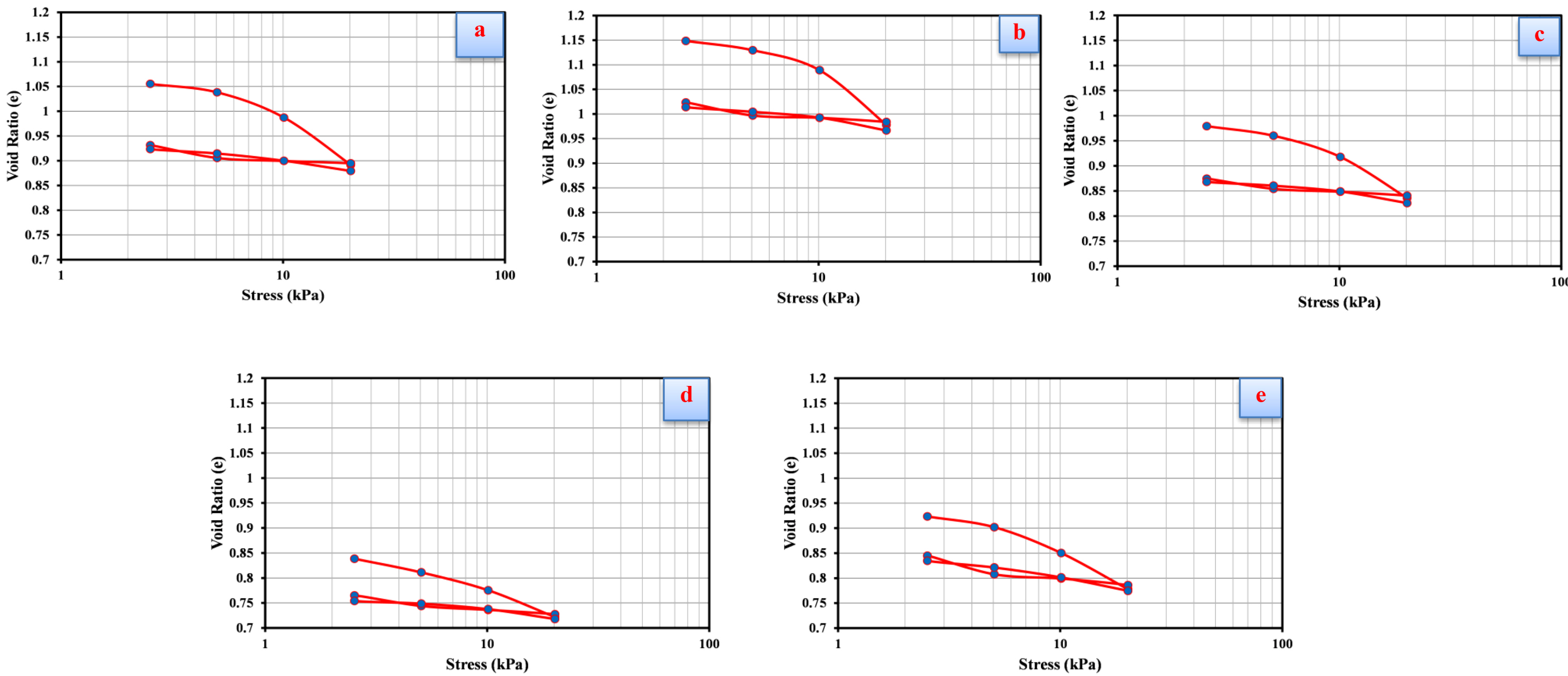

Fig. 4. The variation of void ratio versus stress for untreated and recycled waste plastic treated soils: (a) untreated soil, (b) 2% plastic treated soil, (c) 5% plastic treated soil, (d) 10% plastic treated soil, and (e) 10% plastic sandwich treated soil.

Table 4. Nonlinear power model analysis for C_v and t_{50} in untreated and recycled waste plastic treated fine grain soils.

Soil type	L ($mm^2/min/min^{0.5}$)	M	Equation	R^2	Multiple R	RMSE (mm^2/min)
Untreated Soil	16.793	–0.993	$C_v(mm^2/min) = 16.793 * (t_{50})^{-0.993}$	0.994	0.997	0.14462
2% Plastic + Soil	15.914	–0.97	$C_v(mm^2/min) = 15.914 * (t_{50})^{-0.97}$	0.994	0.997	0.06535
5% Plastic + Soil	16.115	–0.974	$C_v(mm^2/min) = 16.115 * (t_{50})^{-0.974}$	0.9906	0.995	0.08900
10% Plastic + Soil	15.265	–0.955	$C_v(mm^2/min) = 15.265 * (t_{50})^{-0.955}$	0.993	0.997	0.05535
10% Plastic sandwich + Soil	15.17	–0.97	$C_v(mm^2/min) = 15.17 * (t_{50})^{-0.97}$	0.9937	0.997	0.11236

approach. Table 4 provides a comprehensive overview of the model parameters (L and M), R^2, multiple R, and RMSE values for the suggested model. The range of the model coefficients L and M is 15.265 to 16.793 and –0.993 to –0.955, respectively. Additionally, the comparable ranges for R^2, multiple R, and RMSE values were 0.9906 to 0.994, 0.995 to 0.997, and 0.06535 to 0.14462.

As illustrated in Fig. 5 (a–e), the variation of C_v with t_{50} for both untreated and recycled waste plastic-treated fine-grain soils has been determined. The suggested nonlinear model accurately and strongly correlated the experimental results for all examined cases involving untreated and plastic-treated fine-grain soils. It is important to mention that accurate C_v values may be easily predicted based on experimental values of t_{50}. These C_v values are significant since they are utilized in subsequent consolidation analysis to determine the rate of consolidation over time.

(b) Void ratio versus stress

The variations of void ratio versus stress for untreated and recycled waste plastic-treated fine particle soils for one-full cycle loading and unloading conditions followed by one-half cycle reloading conditions have been calculated from laboratory results for each studied case. In addition, such void ratio versus stress relationship has been modeled using a nonlinear second order-polynomial model as follows:

$$e = J * LOG\left(\sigma'_v\right)^2 + K * LOG\left(\sigma'_v\right) + L \quad (4)$$

Where: e is the void ratio. J ($1/kPa^2$), K (1/kPa) and L are model parameters.

It should be remarked that the proposed model has demonstrated its effectiveness in modeling void ratio versus vertical stress for grouted soft clay soil [32]. The suggested model has been solved using the least square method. The model parameters (J, K, and L), with R^2, multiple R, and RMSE values for the proposed model, have been presented in Table 5. The model coefficients J, K, and L have a range of values from –0.000003 to 0.0003, –0.0097 to –0.0106, and 0.76 to 1.1635, respectively. In addition, R^2, multiple R, and RMSE values had corresponding ranges of 0.8646 to 0.9999, 0.9298 to 0.9999, and 0.00014 to 0.00795.

Fig. 6 (a–e) illustrates the modeling of variations in void ratio versus stress for untreated and recycled waste plastic treated fine particles of soil under a condition of full-cycle loading and unloading followed by half-cycle reloading. The proposed non-linear second order-polynomial model has accurately predicted the experimental results, demonstrating strong correlations indicated by high R^2 and multiple R values and low RMSE values across all tested cases for both untreated and recycled waste plastic-treated fine-grain soils. It needs to be pointed out that the change in void ratio with or without plastic may be anticipated accurately in terms of experimental stress values, where predicting precise void ratio values is important for final settlement evaluation or time-rate settlement response. Furthermore, the suggested model may be utilized in the field to estimate void ratio under various applied stress conditions.

7.3. Consolidation parameters correlation

Table 6 presents a summary of the associations between consolidation soil characteristics, specifically C_c and C_r, and several examined components, including recycled waste plastic content (%), swelling (mm), and swelling pressure (kPa). Correlations, both negative and positive, have been observed, with correlation coefficients ranging from –0.923 to 0.984. The C_c was correlated negatively with C_r and recycled waste plastic content (%), where the degrees of correlation were –0.389 and –0.868 respectively. However, C_c was correlated positively with swelling (mm) and swelling pressure (kPa), as the degrees of correlation were 0.694 and 0.590, respectively. C_r had a positive correlation with the recycled waste plastic content (%), with a degree of correlation of 0.783. In contrast, it had negative correlations with both swelling (mm) and swelling pressure (kPa), with degrees of correlations of –0.906 and –0.923, respectively. In addition, the recycled waste plastic content (%) was correlated negatively with both swelling (mm) and swelling pressure (kPa), with degrees of

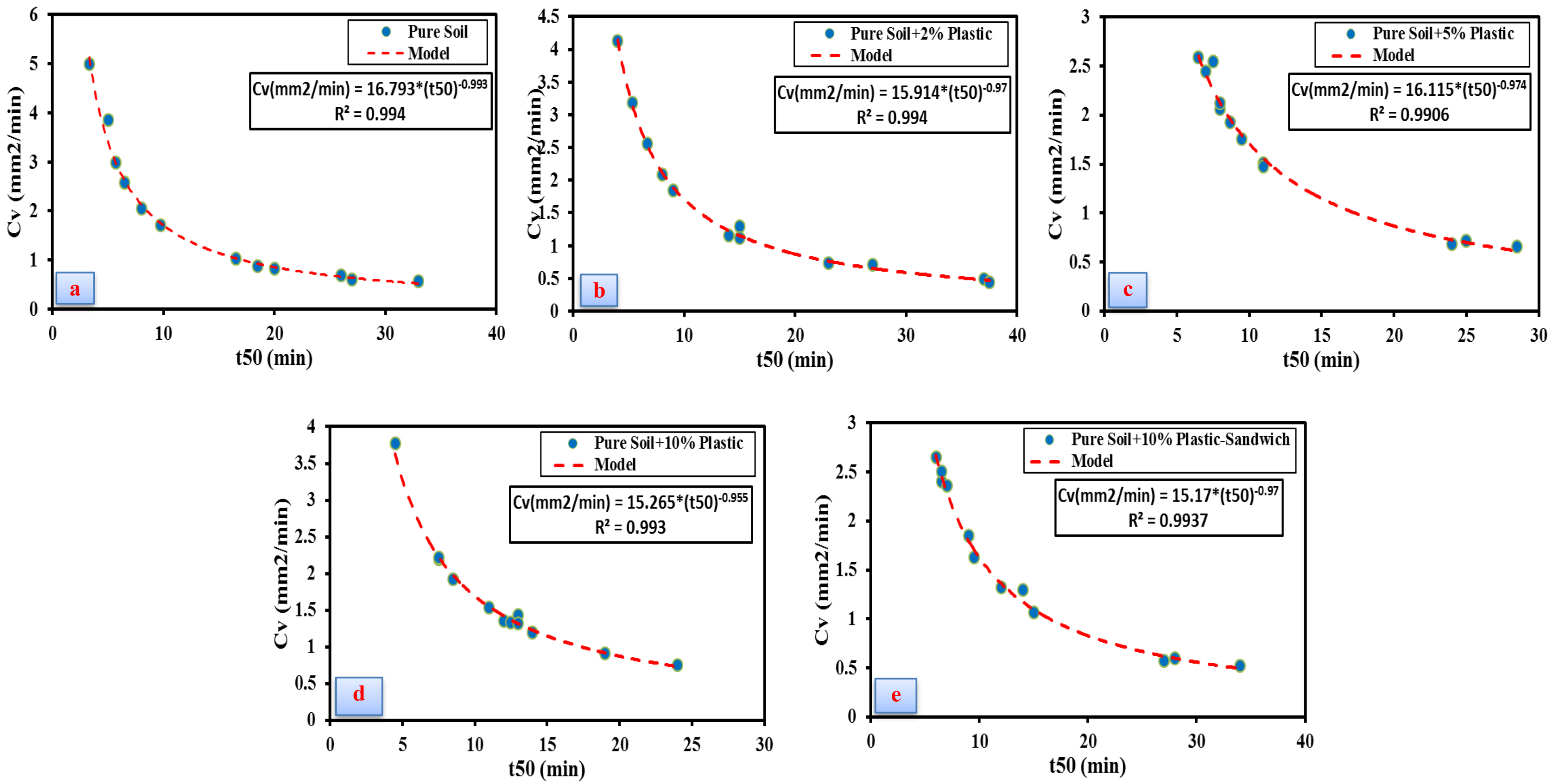

Fig. 5. The variation of C_v versus t_{50} for untreated and recycled waste plastic treated soils: (a) untreated soil, (b) 2% plastic treated soil, (c) 5% plastic treated soil, (d) 10% plastic treated soil, and (e) 10% plastic sandwich treated soil.

Table 5. Nonlinear second order-polynomial model analysis for void ratio and stress in untreated and recycled waste plastic treated fine grain soils.

Soil type	Condition	J (1/kPa^2)	K (1/kPa)	L	R^2	Multiple R	RMSE (mm)
Untreated Soil	Loading	–0.00004	–0.0086	1.079	0.9989	0.9994	0.00249
	Unloading	0.0002	–0.007	0.9431	0.8764	0.9361	0.00791
	Re-Loading	0.00006	–0.0039	0.9327	0.9999	0.9999	0.00051
2% Plastic + Soil	Loading	–0.0002	–0.0057	1.1635	0.9999	0.9999	0.00591
	Unloading	0.0002	–0.0066	1.0339	0.8646	0.9298	0.00556
	Re-Loading	0.00002	–0.003	1.0208	0.9973	0.9986	0.00129
5% Plastic + Soil	Loading	–0.000003	–0.0081	1	0.9999	0.9999	0.00065
	Unloading	0.0002	–0.0055	0.8838	0.905	0.9513	0.00795
	Re-Loading	0.00002	-0.0027	0.8745	0.9993	0.9996	0.00128
10% Plastic + Soil	Loading	0.0002	–0.0106	0.8625	0.9986	0.9992	0.00430
	Unloading	0.0002	–0.006	0.7757	0.9289	0.9637	0.00573
	Re-Loading	0.00001	–0.0023	0.76	0.9999	0.9999	0.00014
10% Plastic sandwich + Soil	Loading	0.0001	–0.0114	0.9529	0.9989	0.9994	0.00770
	Unloading	0.0003	–0.0097	0.8606	0.8868	0.9417	0.00738
	Re-Loading	0.0001	–0.0056	0.8479	0.9996	0.9997	0.00074

correlations of –0.917 and –0.845, respectively. Finally, the swelling (mm) was correlated positively with swelling pressure (kPa) with a degree of correlation of 0.984. It is clearly indicated that recycled waste plastic has a superior impact on consolidation parameters, swelling, and swelling pressure, where awareness should be considered as the soil is treated with recycled waste plastic.

7.4. Linear single regression model

Table 7 provides an overview of the consolidation features based on the proposed linear single regression model (Eq. (1)). The least squares approach was used to solve the detailed model. Table 7 shows the model parameters (A and B), R^2, multiple R, and RMSE values for the proposed model. The values of model coefficients A and B vary from 0.0006 to 0.0104 and –0.0004 to 0.0033, respectively. Furthermore, R^2, multiple R, and RMSE values ranged from 0.349 to 0.852, 0.590 to 0.923, and 0.00011 to 0.00158, respectively. The variations of C_c and C_r versus recycled waste plastic content (%) are shown in Fig. 7 (a and b). A negative association between C_c and recycled waste plastic content (%) has been observed, while a positive association between C_r and plastic content (%) has been obtained. Additionally, the variations of both C_c and C_r with swelling (mm) have been shown in Fig. 7 (c and d). There is a positively linear relationship between C_c and swelling (mm), with a noticeable negative linear relationship between C_r and swelling (mm). Moreover, the differences in swelling pressure (kPa) between C_c and C_r may be shown in Fig. 7 (e and f). An observed positive linear relationship has been found between C_c and swelling pressure (kPa). In contrast, a negative linear correlation has been observed between C_r and swelling pressure (kPa).

7.5. Linear multi-regression model

Table 8 contains details regarding linear multi-regression analysis. The linear multi-regression equation has been evaluated using the least squares method. The model coefficients (C, D, E, and F) are listed in Table 8, along with the corresponding R^2, multiple-R, and RMSE values. Based on the R^2, multiple R, and RMSE values, the recommended linear regression models accurately predicted both C_c and C_r values with a high degree of precision, as the R^2 values were greater than 0.8. The variations between the anticipated and actual consolidation characteristics, as determined by the linear multi-regression model, are illustrated in Fig. 8 (a and b). The values of C_c in Fig. 8 (a) were accurately predicted for the range below 0.008, with minor deviations for higher values. While there was significant variability for lower values, as shown in Fig. 8 (b), the predictions for C_r values were relatively precious for values greater than 0.0009.

8. Discussion

8.1. Effect of recycled waste plastic on maximum deformation

It was observed that the recycled waste plastic component of up to 10% reduces the maximum deformation of treated fine particles of soil because recycled waste plastic can modify the physical structure of fine particles of soil, preventing water from escaping from the treated soil. Furthermore, the recycled waste plastic might interact with the tiny particles, influencing the water absorption and retention processes. Moreover, the recycled waste plastic can change its responsiveness to small particles, reducing the rate of re-molding and reshaping.

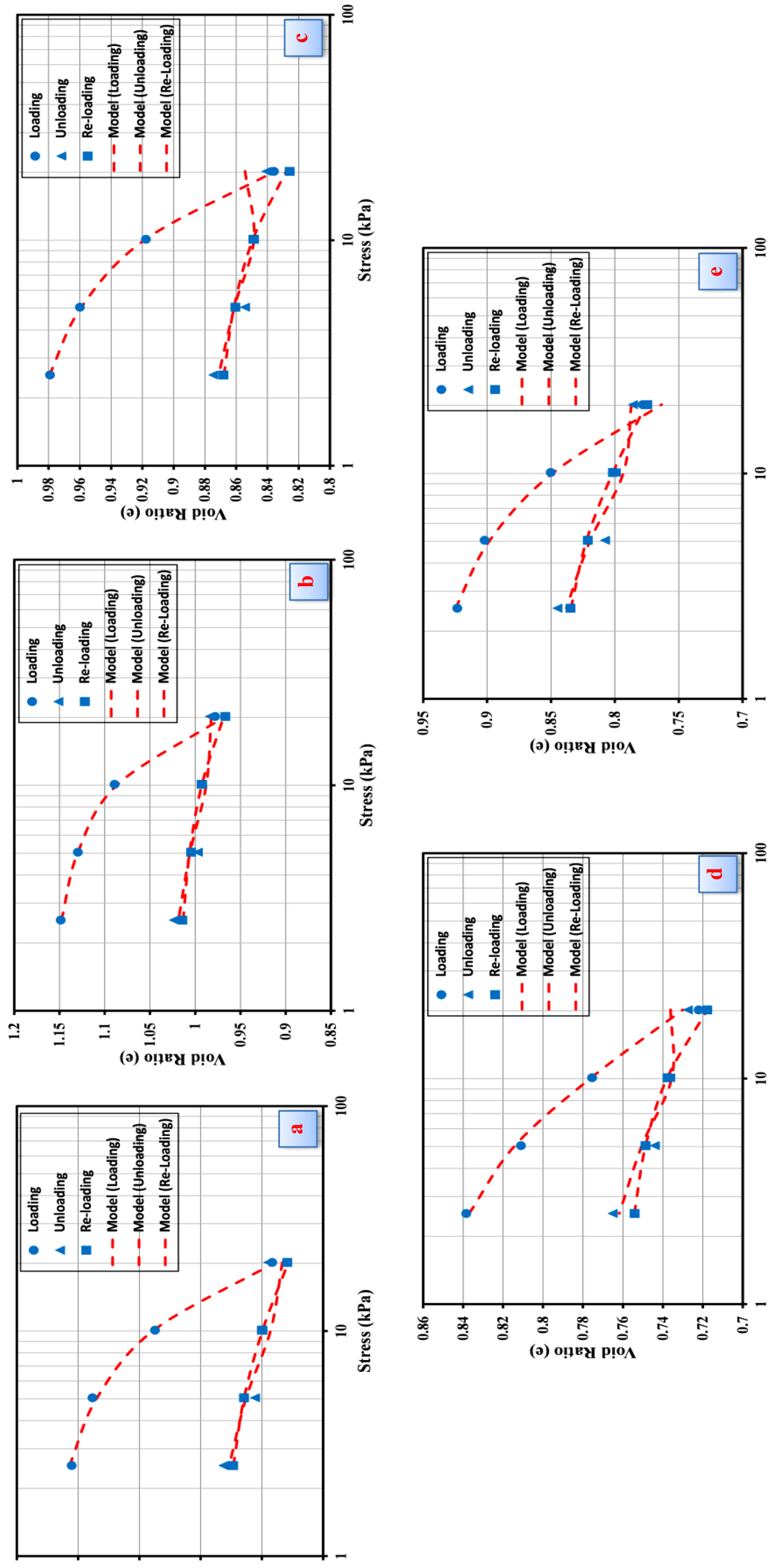

Fig. 6. Modeling the behavior of void ratio versus stress for untreated and recycled waste plastic treated soils: (a) untreated soil, (b) 2% plastic treated soil, (c) 5% plastic treated soil, (d) 10% plastic treated soil, and (e) 10% plastic sandwich treated soil.

Table 6. Correlations between consolidation parameters with various studied factors.

	C_c	C_r	Plastic Content (%)	Swelling (mm)	Swelling Pressure (kPa)
C_c	1.000				
C_r	–0.389	1.000			
Plastic Content (%)	–0.868	0.783	1.000		
Swelling (mm)	0.694	–0.906	–0.917	1.000	
Swelling Pressure (kPa)	0.590	–0.923	–0.845	0.984	1.000

Table 7. Linear single regression model analysis for consolidation characteristic.

Consolidation characteristic	Investigated factor	A	B	Equation	R^2	Multiple R	RMSE
C_c	Plastic	0.0104	–0.0004	$C_c = 0.0104 - 0.0004 * (\text{Plastic Content}(\%))$	0.754	0.868	0.00097
C_r	content (%)	0.0006	0.0001	$C_r = 0.0006 + 0.0001 * (\text{Plastic Content}(\%))$	0.613	0.783	0.00017
C_c	Swelling	0.0055	0.0004	$C_c = 0.0055 + 0.0004 * (\text{Swelling}(\text{mm}))$	0.482	0.694	0.00145
C_r	(mm)	0.0013	–0.0001	$C_r = 0.0013 - 0.0001 * (\text{Swelling}(\text{mm}))$	0.821	0.906	0.00011
C_c	Swelling	0.0057	0.0033	$C_c = 0.0057 + 0.0033 * (\text{Swelling Pressure}(\text{kPa}))$	0.349	0.590	0.00158
C_r	pressure (kPa)	0.0014	–0.0007	$C_r = 0.0014 - 0.0007 * (\text{Swelling Pressure}(\text{kPa}))$	0.852	0.923	0.00015

8.2. Effect of recycled waste plastic on void ratio-stress relationship

It was noticed that the effect of recycled waste plastic is nearly indistinguishable between the untreated soils and those treated with 2%, 5%, and 10% concentrations. The inference may be drawn that the alteration of recycled waste plastic treatment does not impact the alteration of void ratio in response to changes in stress.

8.3. Effect of recycled waste plastic on swelling displacement and swelling pressure

It is worth noting that recycled waste plastic has a significant impact on decreasing both swelling and swelling pressure, which might be useful in the field for problematic soil treatment. Recycled waste plastic presents minimal water absorption and does not experience expansion when exposed to water. Instead, recycled waste plastic functions as an impervious material that limits the absorption of water by solid soil particles. Thus, the recycled waste plastic decreases the amount of water that can induce soil swelling. In addition, the swelling pressure employed by the soil is decreased because the soil cannot swell as much or at all due to restricted access to water.

8.4. Effect of recycled waste plastic on consolidation indices

In particular, it was remarked that the recycled waste plastic content beyond 2% decreases the C_c values because of the recycled waste plastic's ability to alter the physical structure of treated fine-grain soil, which could decrease the process of water squeezing out. However, the recycled waste plastic content increased the C_r values for the first loading cycle since the void ratio has been increased in the recycled waste plastic-treated soil due to the change in the particle orientation shape in the treated medium. Because the recycled waste plastic provided additional stiffness for the plastic-treated media, the fluctuation in C_{rs} values is completely close to C_c. It should be noted that the 10% recycled waste plastic sandwich enhanced the C_{rs} value by acting as a thin layer in the middle position of the treated soil, causing an increase in the medium void ratio.

8.5. Effect of recycled waste plastic on specific volume

In general, the recycled waste plastic has a positive effect in decreasing the medium-specific volume due to its effectiveness in controlling the overall volume change, which can give better fine-grain compactness with lower expected soil consolidation.

8.6. Effect of recycled waste plastic on C_v

It is observed that increasing the C_v value with increasing recycled waste plastic content would expedite the consolidation rate, which might be attributed to the enlargement in the consolidation paths due to particle reorientation under the effect of applied stress in the presence of recycled waste plastic.

Since the recycled plastic is chemically inactive and non-cementitious, no hydration reactions happed. Instead, the stabilization mechanism is considered as a pure physical-mechanical process. The sliding friction is exhibited between the smooth PET particles and clay minerals and this interaction is known by interfacial transition zone. At low treatment content (2%), plastic particles mechanically dislocate the clay fab-

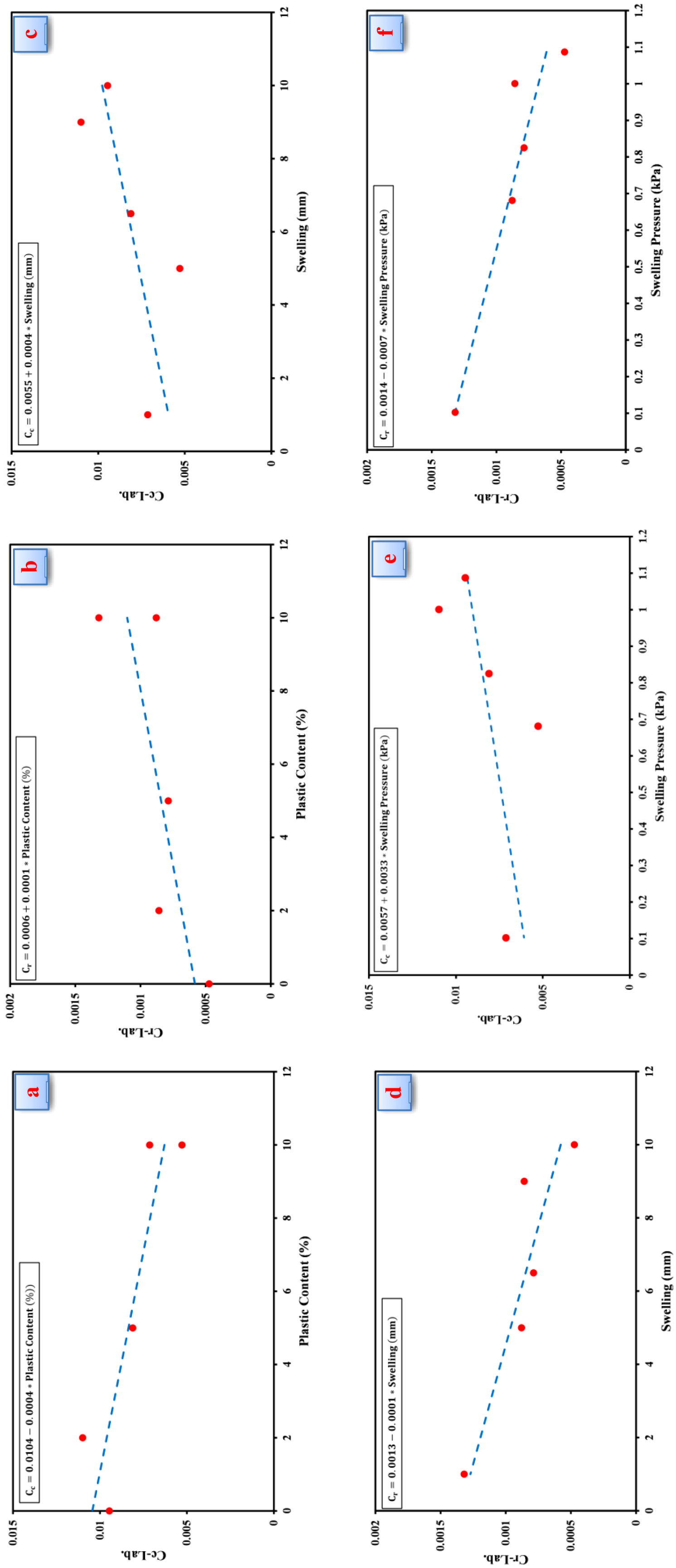

Fig. 7. The variation of soil consolidation characteristics with different investigated factors using single linear regression model: (a) C_c vs. plastic content (%), (b) C_r vs. plastic content (%), (c) C_c vs. swelling (mm), (d) C_r vs. swelling (mm), (e) C_c vs. swelling pressure (kPa), and (f) C_r vs. swelling pressure (kPa).

Table 8. Linear multi-regression analysis for consolidation characteristics.

Consolidation characteristic	Linear multi-regression model coefficients				R^2	Multiple R	RMSE
	C	D	E (1/mm)	F (1/kPa)			
C_c	0.0127	–0.0005	0.0004	–0.0052	0.828	0.910	0.00081
C_r	0.0124	0.0001	0.00005	–0.00107	0.855	0.925	0.00015

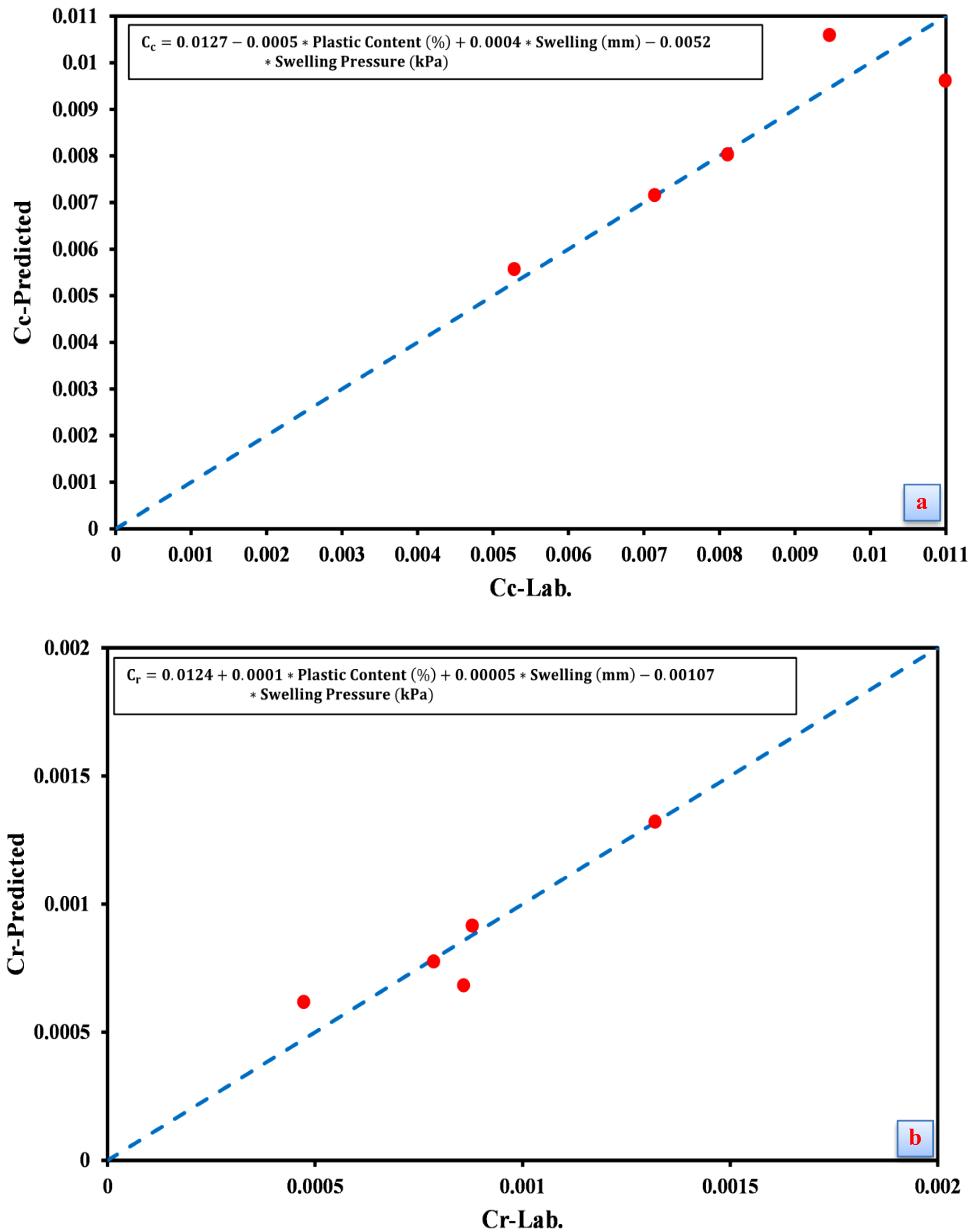

Fig. 8. The variation of predicted and laboratory soil consolidation characteristics using linear multi-regression model: (a) C_c, and (b) C_r.

ric, inflating the initial void ratio. At higher treatment content (5% and 10%), plastic particles pack into macro-pores, developing a denser composite skeleton where the rigid plastic presences cushion against compressive deformation under loading cycles while concurrently proceeding as physical blockages that increase structural tortuosity, thereby limiting the squeezing out of pore water and decreasing C_c.

9. Conclusions

In this work, the consolidation behavior of untreated and recycled waste plastic as a sustainable material treated fine-particles soil has been investigated using both experimental and mathematical models. The 0.075 mm fine particles of soil that pass through sieve No. 200 have been treated with recycled waste plastic and up to 10%. Additionally, a sandwich recycled waste plastic layer was added to the middle of the treated soil using a different recycled waste plastic treatment pattern. The experimental procedure consisted of a complete loading and unloading cycle, followed by a half-reloading cycle. Throughout the process, the deformation of the sample was continuously measured for 24 hours for each applied load. Furthermore, comprehensive theoretical and statistical models have been included alongside the experimental work. The main findings have included both experimental and theoretical modeling. It was observed that among the recycled waste plastic-treated soil samples, the soil treated with a 10% recycled waste plastic sandwich exhibited the most significant decrease in the void ratio, with a reduction of 16% compared to the initial loading stage. Experimental evidence demonstrated that the soil treated with a 10% recycled waste plastic sandwich exhibited a reduction of 90% and 91% in both swelling and swelling pressure, respectively. In addition, different variations for both C_c and C_r values have been observed in recycled waste plastic-treated soil as both C_c and C_r are increased by 16% and 82% in 2% recycled waste plastic-treated soil. However, C_c and C_r values were decreased by 14% and 67% in 5% recycled waste plastic treatment. The coefficient of consolidation of the recycled waste plastic-treated soil has experienced a 165% increase between the initial and subsequent loading cycles under the same applied stress. A nonlinear power model was used to estimate the relationship between C_v and t_{50}, with R^2 values ranging from 0.9906 to 0.994. It turned out that a nonlinear second-order polynomial model with an R^2 range of 0.8646 to 0.9999 may predict the relationship between the void ratio and stress. The study revealed that the linear single regression model accurately predicted the compression and swelling indices for different recycled waste plastic substances, as well as swelling and swelling pressure. The strongest correlation was observed between the swelling index and swelling pressure, with an R^2 value of 0.852. The study demonstrated that the suggested linear multi-regression model accurately predicted both compression and swelling indices by considering the combined factors of recycled waste plastic content, swelling, and swelling pressure. The model achieved a minimum R^2 value of 0.828 for both indices. Utilizing the recycled waste plastic as a sustainable material with any substance can have a positive effect on one or more of the consolidation factors. Alternatively, implementing recycled waste plastic soil treatment methods would have a positive impact on subsurface soil treatment and mitigate surface pollution in the ecosystem.

Ethics

There are no ethical issues with the publication of this manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's contributions

Aram Mohammed Raheem (Corresponding Author): Conceptualization, Methodology, Writing-Original draft preparation.

Cumaraswamy Vipulanandan: Supervision, Methodology.

Mohammed Hiwa Abdullrahman: Visualization, Investigation.

Ali Tariq Omer: Supervision, Validation.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

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