

Regression Models for Predicting the Behavior of Sand Reinforced with Waste Plastic

R. K. DUTTA

*Department of Civil Engineering, National Institute of Technology, Hamirpur, 177005-INDIA
e-mail: rkd@nitham.ac.in*

G. Venkatappa RAO

*Department of Civil Engineering, Indian Institute of Technology, Hauz Khas, New Delhi, 110016-INDIA
e-mail: gvrao@civil.iitd.ernet.in*

Received 02.11.2006

Abstract

This paper presents regression models for predicting the behavior of sand mixed with waste plastic. For this purpose, drained triaxial compression tests with strain measurements were conducted on sand mixed with waste plastic LDPE strips and HDPE strips. The joint effects of LDPE strip content (up to 0.15%), HDPE strip content (up to 2%), aspect ratio (up to 2), and confining pressure (up to 276 kPa) on the behavior of sand, using multiple regression analysis, were investigated for ground improvement. Utilizing some portion of waste plastic in this way will reduce the quantity of plastic waste requiring final disposal in landfills.

Key words: Energy absorption capacity; Deviator stress, Initial stiffness, Cohesion, Friction angle.

Introduction

Despite the ban in some Indian states, the use of plastic products, such as polythene bags, bottles, containers, and packaging strips, is increasing by leaps and bounds. As a result, open waste dumps are continuously filling up with this valuable resource. In many areas waste plastic is collected for recycling and reuse; however, the success of any recycling program will depend on the secondary market for waste plastic. At present, only a fraction of all waste plastic is used for recycling purposes. The best way to handle the increasing pressure of waste plastic on open dumps is to utilize it for ground improvement after shredding. This paper examines the utilization of waste plastic LDPE carry bag strips and used HDPE packaging strips as additives in sand. The influence of the aspect ratio, strip content, and confining pressure on the basic aspects of sand behavior, such as energy absorption capacity, deviator stress, initial stiffness, apparent cohesion, and friction angle, were studied using multiple regression analysis.

Background

Benson and Khire (1994) used cut pieces of HDPE waste milk jugs and showed that there is an increase in strength, CBR, and secant modulus of sand. They also found that the friction angle increase is as large as 18°.

Bueno (1997) conducted a laboratory study on mechanically stabilized soils with short, thin plastic strips of different lengths and contents, and reported enhanced strength and load bearing capacity.

Dutta and Venkatappa Rao (2004) conducted triaxial compression tests on sand reinforced with strips of waste plastic. The results of this study indicated that inclusion of waste plastic strips improves the performance of sand specimens.

The literature presented above indicates that there is a paucity of data concerning the influence of aspect ratio and strip content on the behavior of sand, in terms of energy absorption capacity, deviator stress, initial stiffness, apparent cohesion, and friction angle.

Laboratory Investigation

In the present work, drained triaxial compression tests were performed to evaluate the mechanical response of used HDPE packaging strips and LDPE carry bag strips in sand, in terms of energy absorption capacity, deviator stress, initial stiffness, apparent cohesion, and friction angle. Each property was quantified by measuring one or more response variables. The input variables of strip content (SC) (defined herein as the ratio of the weight of strips to the weight of dry sand, which was considered as a part of solids fraction in the void-solid matrix of the soil) and aspect ratio (AR) (length to width ratio of plastic strips) are shown in Table 1, and the range of confining pressure (CP) was selected for the triaxial tests as 5 psi (34.5 kPa), 10 psi (69 kPa), 20 psi (138 kPa), and 40 psi (276 kPa).

Table 1. Input variables and range tested.

| Input variable (X_n) | Range |
|--------------------------|-------------------------|
| Strip content, % (LDPE) | 0, 0.05, 0.10, and 0.15 |
| Strip content, % (HDPE) | 0, 0.25, 0.5, 1, and 2 |
| Aspect ratio | 1 and 2 |

Planning of experiments

Experimental planning was carried out to determine the number of tests to be performed in order to establish the necessary combinations among input variables that should be experimented with to effectively apply a statistical analysis (multiple regression analysis) to the sequence. The experimental planning required that 60 triaxial compression tests be performed. In these 60 tests, all possible combinations among the input variables [SC, AR, and CP] were tested, and the response variables were measured.

Materials used and experimental procedure

The investigation was conducted with locally available Badarpur sand, which is medium-grained, uniform quarry sand with sub-angular particles of weathered quartzite. It had a specific gravity of 2.66, maximum particle size of 1.20 mm, minimum particle size of 0.07 mm, mean particle diameter (D_{50}) of 0.42 mm, coefficient of uniformity (C_u) of 2.11, and coefficient of curvature (C_c) of 0.96. Minimum and maximum void ratios were 0.56 and 1.12, while the

corresponding dry unit weights were 16.70 and 12.30 kN/m^3 , respectively. The sand was classified as SP-SW. The angle of shearing resistance (ϕ') measured with a drained triaxial compression test on the sand was 38° . The first material used was LDPE plastic carry bags with a mass per unit area of 30 g/m^2 and a thickness of 0.05 mm. From these carry bags 12-mm wide strips were cut. These strips were then cut into lengths of 24 and 12 mm. The resulting 24 x 12 mm strips were designated as Type-I (Figure 1) and the 12 mm x 12 mm strips were designated as Type-II (Figure 2). The second material studied was used HDPE packaging strips, 12 mm wide and 0.45 mm thick, with a mass of 3.8 g/m. These were cut into lengths of 24 mm, which were designated as Type-III (Figure 3), and 12 mm, which were designated as Type-IV (Figure 4). A standard triaxial apparatus was used for testing sand with and without plastic strip. The specimen was 100 mm in diameter and 200 mm high. A standard procedure for preparing and testing samples for saturated cohesionless soil, as recommended by Bishop and Henkel (1962), was adopted. The density of the sand specimens with Type-I and Type-II inclusions were maintained at $15.08 \pm 0.18 \text{ kN/m}^3$, while the sand specimens with Type-III and Type-IV inclusions were maintained at $14.88 \pm 0.42 \text{ kN/m}^3$ for different samples. Conventional, consolidated drained triaxial compression tests were then conducted at a deformation rate of 1.016 mm/min. More details on the test materials and experimental procedure are available from Dutta and Venkatappa Rao (2004).



Figure 1. Photograph of LDPE strips (Type-I).

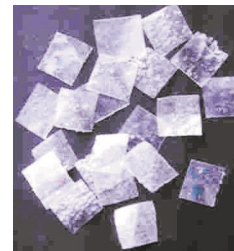


Figure 2. Photograph of LDPE strips (Type-II).



Figure 3. Photograph of HDPE strips (Type-III).

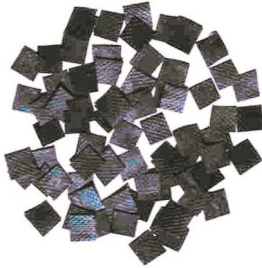


Figure 4. Photograph of HDPE strips (Type-IV).

Results and Discussion

The behavior of sand with HDPE/LDPE strips was examined by focusing on the aspects of plastic strip content influence (0%-0.15% for LDPE and 0%-2% for HDPE), AR (1 to 2), and CP (34.5 to 276 kPa). The experimental data, including the data for 0% LDPE and HDPE, was used to develop regression models using multiple regression analysis. The equations obtained from the multiple regression analysis have the general form:

$$y = a_0 + a_1.x_1 + a_2.x_2 + a_3.x_3 + \text{error} \quad (1)$$

where y is a response variable,

$a_0 \dots a_3$ are coefficients of the regression equations for each response variable evaluated, and

$x_1 \dots x_3$ are the input variables.

The equations reported in this paper are valid only over the range investigated. To check the adequacy of the regression models, the corresponding adjusted coefficients of determination (R_{adjusted}^2), standard errors, and units are also reported. The standard errors could be used to construct prediction limits for the regression models, and the R_{adjusted}^2 statistic indicates how well the model explains the variability in the response variable.

Energy absorption capacity

The area under the stress strain curve gives the energy absorption capacity of a soil; therefore, a relative measure of the improvement in toughness due to strip inclusion is provided by comparing the energy absorption capacity of the HDPE/ LDPE waste plastic strip-reinforced sand with the energy absorption capacity of the non-reinforced sand. The energy absorption capacity values were calculated by taking into consideration the area under the stress-strain curves up to an axial strain at failure. The effect of SC, AR, and CP on the energy absorption capacity is presented by the following equation for sand mixed with HDPE strips:

$$EAC = 18.99.\sigma_3 + 65.59.AR + 260.22.SC - 520.05 \quad (2)$$

($R_{\text{adjusted}}^2 = 0.933$, standard error = 480.03 kJ/m³).

For sand with LDPE waste plastic strips, the effect of SC, AR, and CP on the energy absorption capacity is presented by the following equation:

$$EAC = 17.47.\sigma_3 + 369.75.AR + 582.30.SC - 444.85 \quad (3)$$

($R_{\text{adjusted}}^2 = 0.918$, standard error = 493.97 kJ/m³).

All of the controllable factors that were investigated positively affected the energy absorption capacity of sand with and without strips. Figure 5 presents the predicted behavior obtained from the regression model for sand mixed with HDPE strips. The increase in energy absorption capacity is noticeably related to the increase in peak strength caused by SC, CP, and AR. Figure 6 presents the predicted behavior of sand reinforced with LDPE waste plastic strips obtained from the regression model. As expected, the increase in energy absorption capacity is noticeably related to the increase in peak strength caused by SC, CP, and AR. The effect was more pronounced for the strips with higher AR_s in both the figures. This may be attributed to improved anchorage of the strips.

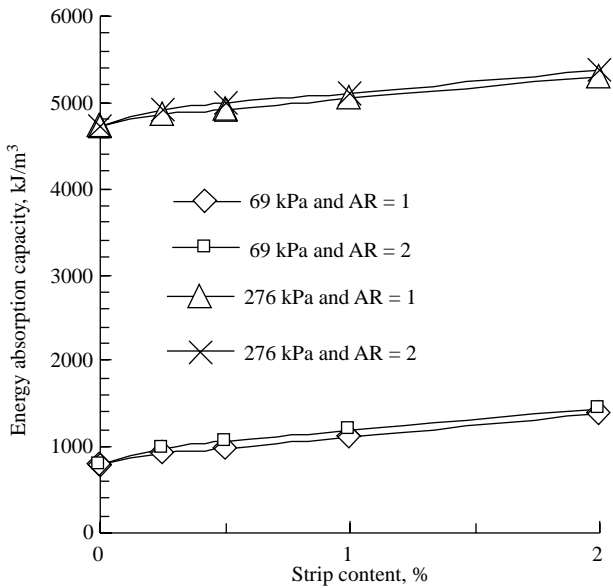


Figure 5. Effect of AR, HDPE SC, and CP on energy absorption capacity.

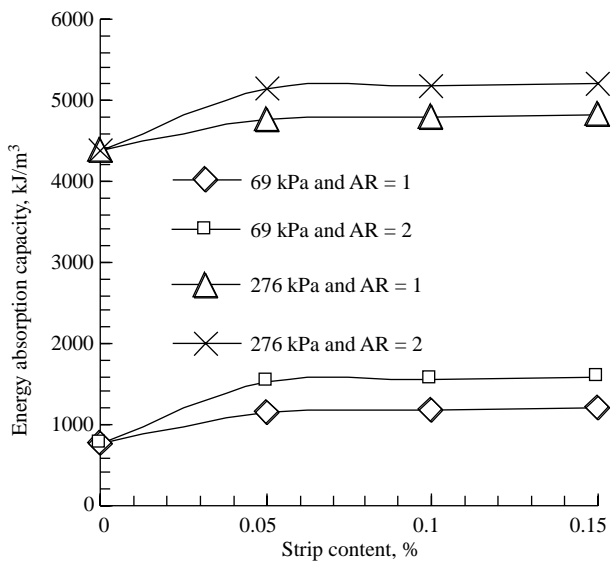


Figure 6. Effect of AR, LDPE SC, and CP on energy absorption capacity.

Deviator stress

The effect of SC, AR, and CP on the deviator stress at failure is presented by the following regression equation for sand mixed with HDPE strips:

$$(\sigma_1 - \sigma_3)_f = 3.66.\sigma_3 + 32.66.AR + 37.87.SC - 49.63 \quad (4)$$

$$(R_{adjusted}^2 = 0.984, \text{ standard error} = 44.59 \text{ kPa}).$$

For sand with LDPE waste plastic strips, the effect of SC, AR, and CP on the deviator stress at failure is presented by the following equation:

$$(\sigma_1 - \sigma_3)_f = 3.45.\sigma_3 + 22.34.AR + 377.02.SC - 19.97 \quad (5)$$

$$(R_{adjusted}^2 = 0.983, \text{ standard error} = 42.68 \text{ kPa}).$$

Figures 7 and 8 present the predicted behavior of sand mixed with HDPE and LDPE waste plastic strips, respectively, obtained from the regression model. It is evident from these figures that the deviator stress at failure was influenced by SC, CP, and AR. Upon further examination of these figures it is evident that the effect of AR, SC, and CP on the deviator stress at failure was significant.

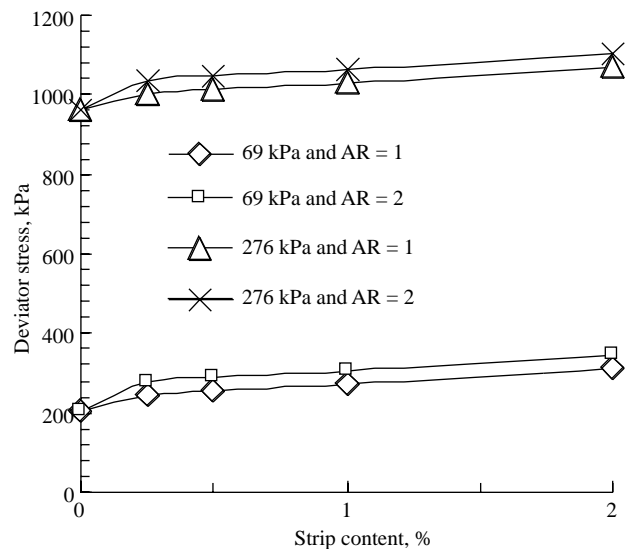


Figure 7. Effect of AR, HDPE SC, and CP on deviator stress.

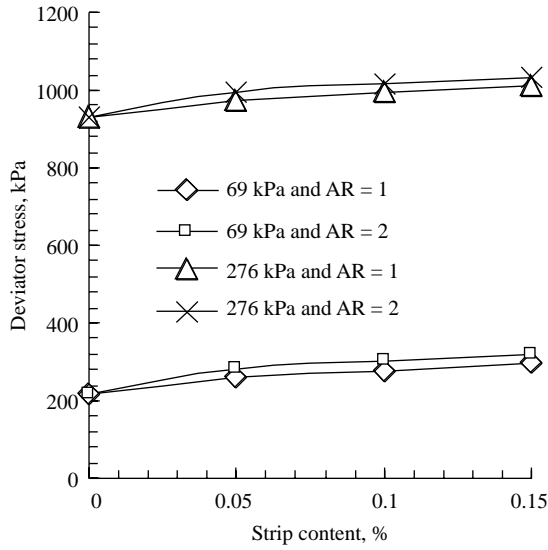


Figure 8. Effect of AR, LDPE SC, and CP on deviator stress.

Initial stiffness

The effect of SC, AR, and CP on the initial stiffness is presented by the following equation for sand mixed with HDPE strips:

$$E_i = 0.87.\sigma_3 + 9.12.AR - 6.77.SC - 11.02 \quad (6)$$

$$(R_{adjusted}^2 = 0.915, \text{ standard error} = 24.88 \text{ kPa}).$$

For sand with LDPE waste plastic strips, the effect of SC, AR, and CP on the initial stiffness is presented by the following equation:

$$E_i = 0.97.\sigma_3 - 2.93.AR + 362.63.SC - 33.93 \quad (7)$$

$$(R_{adjusted}^2 = 0.969, \text{ standard error} = 16.63 \text{ kPa})$$

Figures 9 and 10 present the predicted behavior of sand mixed with HDPE and LDPE waste plastic strips, respectively, obtained from the regression model. It is evident from these figures that the initial stiffness was influenced by SC, CP, and AR.

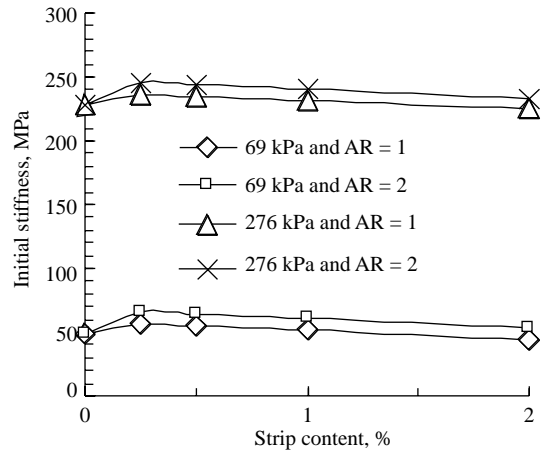


Figure 9. Effect of AR, HDPE SC, and CP on initial stiffness.

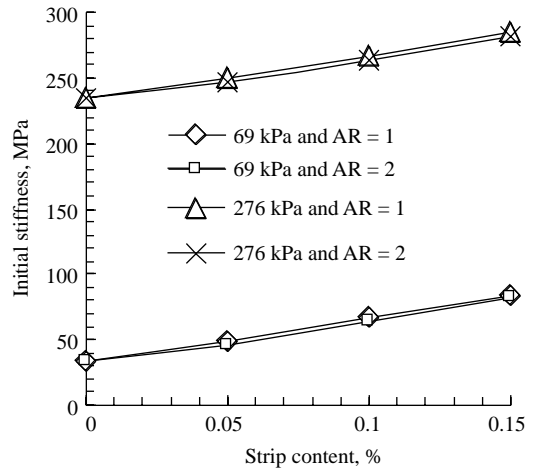


Figure 10. Effect of AR, LDPE SC, and CP on initial stiffness.

From Figure 9 it is evident that the initial stiffness increased with the increase in the value of CP and AR, whereas an increase in SC in sand decreased the value of initial stiffness. The decrease in the value of initial stiffness with the increase in SC is attributed to an experimental observation. The Type III and IV strips are relatively thick and stiffer; in fact their stiffness did not allow for good compaction as the SC was increased in the mixture. Figure 10 shows that the initial stiffness increased with an increase in CP and SC, and decreased with an increase in AR. Normally, one would expect that a higher AR would yield a higher initial stiffness, yet it was not so clearly evident from the experimental findings. It could perhaps be attributed to the fact that hyperbolic fitted lines (Figure 11) deviated from the experimental values at lower strains. These deviations

could have caused a change in the value of initial stiffness compared to observed experimental values.

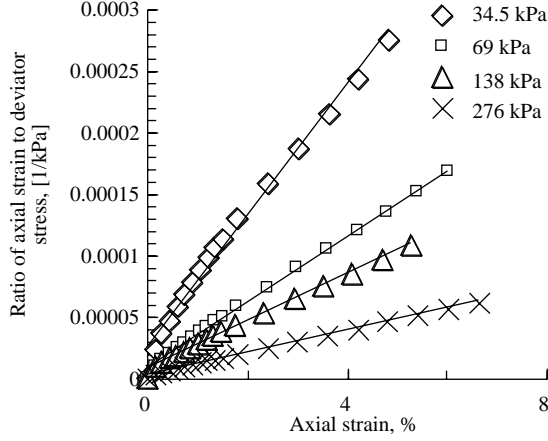


Figure 11. Hyperbolic plot for sand with 0.15% Type-I strips at different CPs.

Cohesion and friction angle

For sand with HDPE strips, the effects of SC and AR on the cohesion and friction angle are presented by the following equations. The failure envelope of the sand mixed with HDPE strips was observed to be bilinear.

$$\text{For } 0 < \sigma_c < 69 \text{ kPa}$$

$$\Phi' = 2.47.AR + 1.77.SC + 39.76 \quad (8)$$

$$(R_{\text{adjusted}}^2 = 0.80, \text{ standard error} = 1.22, \text{ Deg})$$

Figure 12 provides the predicted values of initial friction angle obtained from the regression model. As expected, the values of initial friction angle increased with an increase in SC and AR.

$$\text{For } 69 < \sigma_c < 276 \text{ kPa}$$

$$c' = 6.65.AR + 1.69.SC + 0.36 \quad (9)$$

$$(R_{\text{adjusted}}^2 = 0.70, \text{ standard error} = 3.28 \text{ kPa})$$

$$\Phi' = 0.38.AR + 1.16.SC + 38.37 \quad (10)$$

$$(R_{\text{adjusted}}^2 = 0.81, \text{ standard error} = 0.46, \text{ Deg})$$

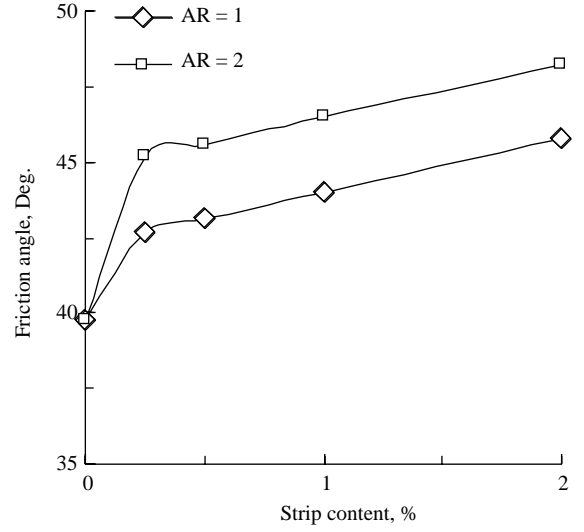


Figure 12. Effect of AR and HDPE SC on initial friction angle.

Figures 13 and 14 present the predicted values of cohesion and friction angle obtained from the regression model. As expected, the values of cohesion and friction angle were influenced by SC and AR.

The effects of SC and AR on the cohesion and friction angle are presented by the following equations for sand mixed with LDPE waste plastic strips. The failure envelope of the sand mixed with waste plastic strips was observed to be bilinear.

$$\text{For } 0 < \sigma_c < 69 \text{ kPa}$$

$$\Phi' = 1.58.AR + 32.64.SC + 39.21 \quad (11)$$

$$(R_{\text{adjusted}}^2 = 0.825, \text{ standard error} = 1.17, \text{ Deg})$$

Figure 15. Shows the predicted values of initial friction angle obtained from the regression model. As expected, the values of friction angle increased with an increase in SC and AR.

$$\text{For } 69 < \sigma_c < 276 \text{ kPa}$$

$$c' = 1.082.AR + 87.82.SC + 0.58 \quad (12)$$

$$(R_{\text{adjusted}}^2 = 0.977, \text{ standard error} = 0.82 \text{ kPa})$$

$$\Phi' = 0.57.AR + 2.91.SC + 38.34 \quad (13)$$

$$(R_{\text{adjusted}}^2 = 0.66, \text{ standard error} = 0.35, \text{ Deg})$$

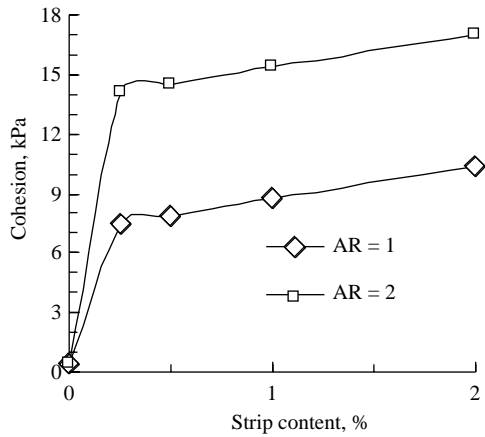


Figure 13. Effect of AR and HDPE SC on cohesion.

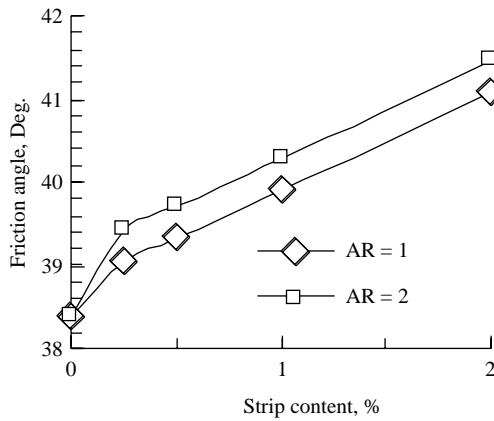


Figure 14. Effect of AR and HDPE SC on friction angle.

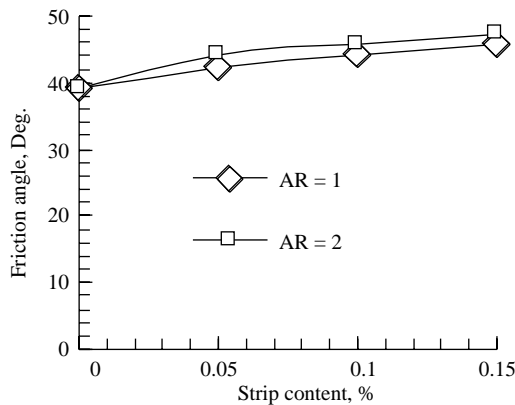


Figure 15. Effect of AR and LDPE SC on initial friction angle.

Figures 16 and 17 present the predicted values of cohesion and friction angle obtained from the regression model. As expected, the values of cohesion and friction angle were influenced by SC and AR. The authors' experience with the use of regression

models for predicting the behavior of earth materials is that a regression model with $R^2_{adjusted} \geq 0.8$ gives a fairly good prediction of the behavior of reinforced sand. The values of $R^2_{adjusted}$ for cohesion (Eq. (9)) and friction angle (Eq. (13)) are 0.70 and 0.66, respectively. These low values are attributed to the fact that the low degree of freedom inherent in the experimental design for the triaxial tests reduced the capability of the model to represent the precise influence. Secondly, cohesion and friction angle are dependent on many parameters, such as AR, SC, strip roughness, and sand type. In the present investigation, only 2 parameters were considered for developing the regression model. These regression models need further refinement by including other parameters affecting cohesion and friction angle, for which more studies are required, along with a high degree of freedom in the experimental design.

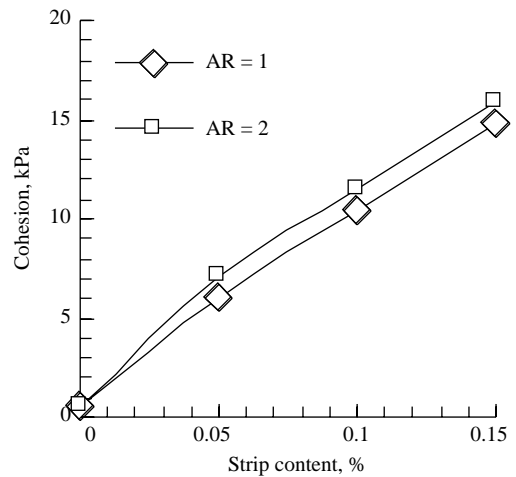


Figure 16. Effect of AR and LDPE SC on cohesion.

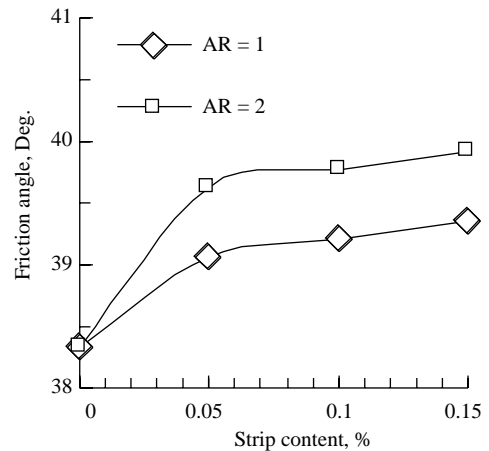


Figure 17. Effect of AR and LDPE SC on friction angle.

Conclusion

Based on the results presented above, the following conclusions are drawn.

1. The energy absorption capacity of sand mixed with HDPE/LDPE waste plastic strips was influenced by AR, SC, and CP. The energy absorption capacity increased with an increase in AR, SC, and CP.
2. The deviator stress of sand mixed with HDPE/LDPE waste plastic strips was influenced by AR, SC, and CP. The deviator stress increased with an increase in AR, SC, and CP.
3. For sand with HDPE strips, the initial stiffness increased with an increase in the value of CP and AR, whereas an increase in SC decreased the value of initial stiffness.
4. The initial stiffness of sand mixed with LDPE waste plastic strip increased with an increase in SC and CP.
5. The cohesion increased with an increase in AR and SC in the mixture.

6. Friction angle increased with an increase in AR and SC.

On the whole, the paper has attempted to provide an insight into the basic aspects of the behavior of sand mixed with waste plastic strips through multiple regression analysis. Utilizing some portion of waste plastic for ground improvement will reduce the quantity of plastic requiring waste disposal. Moreover, this type of disposal is environmentally friendly.

Nomenclature

| | |
|---------------------------|--|
| AR | aspect ratio |
| $a_0 \dots a_3$ | coefficient of the regression equations for each response variable evaluated |
| c' | cohesion |
| CR | confining pressure |
| EAC | energy absorption capacity |
| E_i | initial stiffness |
| ϕ' | friction angle |
| σ_c | critical confining pressure |
| σ_3 | confining pressure |
| $(\sigma_1 - \sigma_3)_f$ | deviator stress at failure |
| SC | SC |
| $x_1 \dots x_3$ | input variables |
| y | response variable |

References

- Benson, C.H. and Khire, M.U., "Reinforcing Sand with Strips of Reclaimed High-Density Polyethylene", *Journal of Geotechnical Engineering*, 121, 838-855, 1994.
- Bishop, A.W. and Henkel, D.J., *The Measurement of Properties in the Triaxial Test*, Edward Arnold Publishers Ltd., London, 1962.
- Bueno, B. de Souza, "The Mechanical Response of Reinforced Soils Using Short Randomly Distributed Plastic Strips", *Proceedings of Recent Developments in Soil and Pavement Mechanics*, Almeida (ed.) Balkema, Rotterdam, 401-407, 1997.
- Dutta, R. K. and Venkatappa Rao, G., "Engineering Properties of Sand Reinforced with Strips from Waste Plastic", *Proceedings of International Conference on Geotechnical Engineering*, Sharjah, UAE, 186-193, 2004.