Strength and Compressibility Response of Plastic Waste Mixed Soil

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ABSTRACT

Recycling plastic waste from water bottles has become one of the major challenges worldwide. The present study provides an approach for the use plastic waste as reinforcement material in soil. The experimental results are presented in the form of stress-strain-pore water pressure response and compression paths. Based on experimental test results, it is observed that the strength of soil is improved and compressibility reduced significantly with addition of a small percentage of plastic waste to the soil. A model based on critical state concept is proposed which enables prediction of stress-strain response based on plastic waste content and type of waste. The experimental results of stress-strain and pore water pressure response of all percentages of plastic waste match adequately with proposed model.

1. INTRODUCTION

The bottled water is the fastest growing beverage industry in the world. According to the international bottled water association (IBWA), sales of bottled water have increased by 500 percent over the last decade: 1.5 million tons of plastic are used to bottle water every year, unfortunately the recycling process is messy and inefficient. Plastic bottle recycling has not kept pace with the dramatic increase in virgin resin polyethylene terephthalate (PET) sales and the last imperative in the ecological triad of reduce / reuse / recycle, has emerged as the one that needs to be given prominence. The general survey shows that 1500 bottles are dumped as garbage every second. PET is reported as one of the most abundant plastics in solid urban waste. In 2007, it is reported a world’s annual consumption of PET drink covers of approximately 10 million tons and this number grows about up to 15% every year. On the other hand, the number of recycled or returned bottles is very low. Hence, there needs to be concerted efforts in the reuse of plastic waste from water bottles and this study is in this direction.

This study presents simple way of recycling plastic water bottles in the field of civil engineering as reinforcing material. The plastic waste mixed soil behaves as reinforced soil, similar to fiber reinforced soil. The concept of soil reinforcement has dramatically changed the function of soil as a construction material. The introduction of the soil reinforcing techniques has enabled engineers to effectively use unsuitable in-situ soils as reliable construction materials in a wide range of civil engineering applications. Reinforced soil construction is an efficient and reliable technique for improving the strength and stability of soils. It is noted that, in the literature very few studies are available on the use of plastic mixed soil. The possible advantages of using the plastic wastes are that the plastic waste can be consumed in useful geotechnical engineering applications. The plastic waste results in improvement of soil response in the case of roads and embankments, soil being a natural resource, the quantity of soil can be reduced. Thus, it offer two advantages; one is the reuse of plastic waste materials and the other is the reduction in consumption of natural material like soil. In the present study, an approach for recycling of plastic water bottles in the field of geotechnical engineering as reinforcing material is proposed and illustrated with a simple example.

Experimental results reported by various researchers (Consoli et al., 2002, Sivakumar Babu & Vasudevan 2008a, b; Sivakumar Babu & Chouksey 2010) showed that the fiber reinforced soil is a potential composite material which can be advantageously employed in improving the structural behavior of soils. Consoli et al. (2002) carried out an experimental study of the utilization of the polyethylene fibers derived from plastic wastes in the reinforcement of...
uncemented and artificially cemented sand and showed that the plastic waste improved the stress-strain response of unceemented and cemented sands. Consoli et al. (2003) proposed a field application for such materials designed for increasing the bearing capacity of spread foundations when placed on a layer of fiber-reinforced cemented sand built over a weak residual soil stratum. Consoli et al. (2004) carried out triaxial compression test on cemented and uncemented sand reinforced with various types of fibers to study the effect of fibers on mode of failure, ultimate deviator stress, ductility and energy absorption capacity. They observed that the inclusion of fibers changed the mode of failure from brittle to ductile.

2. MATERIALS, SAMPLE PREPARATION AND TESTING

A series of consolidated undrained (CU) and one dimensional compression tests at different confining pressures were performed to determine stress-strain-pore water pressure and compression behavior of plastic waste mixed soil and observe the influence of plastic waste on shear strength of soil with various percentages. The basic properties of soil are presented in Table 1. The soil had liquid limit of 39%, plasticity index of 26% and tests were conducted at initial water content of 17.8% and bulk density of 19.9 kN/m³. Plastic water bottle wastes in the form of chips (12mm long and 4mm in width) have been used in the study. Plastic waste at different percentages (0%, 0.5%, 0.75% and 1.0% by dry weight of soil) is mixed with soil and tests were conducted. To avoid segregation during sample preparation, plastic waste chips were distributed as evenly and randomly as possible throughout the soil. Figures 1a, b show the plastic waste chips and the plastic waste mixed soil respectively.

3. PROPOSED MODEL

Sivakumar Babu and Chouksey (2010) proposed a constitutive model for the prediction of stress-strain and pore water pressure response based on critical state soil mechanics framework. The stress ratio for unreinforced soil is expressed as (Eq. 1):

\[ \eta = \frac{q}{p} \] (1)

where, the deviatoric stress and mean effective stress are given by \( q = (\sigma_1' - \sigma_3') \) and \( p = (\sigma_1' + 2\sigma_3')/3 \).

It is observed from experiments that deviatoric stress and stress ratio are functions of plastic waste present in soil. A typical observation of stress ratio (\( \eta \)) versus strain (in %) is presented in Figure 2 for plastic waste mixed soil at confining pressure of 100kPa. Similar results are obtained for 50 and 100 kPa plastic waste mixed soil.

![Fig. 2: Stress Ratio vs. Strain Response (100 kPa)](image)

The experimental observations of stress ratio with strain show that up to a certain strain level, stress ratio increases and becomes constant. Hence, to model the behavior of plastic waste mixed soil, it can be assumed that the stress ratio increases and subsequently becomes constant with increase in strain. This can be expressed as an exponential form as a function of plastic waste as follows (Eq. 2):

\[ \eta = \frac{q}{p} \left(2 - e^{-\chi\mu}\right) \] (2)

where \( \chi \) is percentage of plastic waste present in soil (\( \chi = 0.0, 0.50, 1.0 \) and 2.0) and \( \mu \) is material constant.

Eq. (2) can be rewritten as in Eq. (3)

\[ \eta p' = q(2 - e^{-\chi\mu}) \] (3)

Therefore, taking differentials both sides,

\[ p'dp + \eta dp' = (2 - e^{-\chi\mu})dq + (q\mu e^{-\chi\mu}d\chi) \] (4)

Let us assume that the slope of the yield curve at any point \((p', q)\) in Figure 3 be \( \Psi \). Since \( q \) decreases with \( p' \), the sign of \( \Psi \) is negative (Eq. 5).
Strength and Compressibility Response of Plastic Waste Mixed Soil

Substituting value of \( dq \) in Eq. (4) and simplifying we get

\[
\frac{dq}{\eta + (2 - e^{\eta})} \psi' \frac{dp'}{\eta + (2 - e^{\eta})} \psi' = \frac{(q e^{-\mu \chi} d \chi)}{\eta + (2 - e^{\eta})} \psi' \frac{dp'}{\eta + (2 - e^{\eta})} \psi'.
\]

The Eq. (6) defines a yield locus. Since for this model, the successive yield loci are geometrically similar, \( \psi' \) is a function of \( \eta \) (stress ratio) only. Therefore, any yield curve passing through a known point can be obtained by integrating Eq. (6).

\[
\int_0^{\psi} \frac{dq}{\eta + (2 - e^{\eta})} \psi' \frac{dp'}{\eta + (2 - e^{\eta})} \psi' \int_0^{q e^{-\mu \chi} d \chi} = \int_0^{\eta + (2 - e^{\eta})} \psi' \frac{dp'}{\eta + (2 - e^{\eta})} \psi'.
\]

Here in the Eq. (7) \( \psi' \) is function of stress ratio. Now, our objective is to find the \( \psi' \) in terms of stress ratio. The value of \( \psi' \) is obtained by energy dissipated equation. (Wood, 1990)

\[
\psi' = \frac{M^2 - \eta}{2 \eta} = \frac{(p' M)^2 - q^2}{2 p q}
\]

Multiplying numerator and denominator by \((2 - e^{\eta})\)

\[
\psi' = \frac{M^2 - \eta^2}{2(2 - e^{\eta})} \eta.
\]

Substituting value of \( \psi' \) (Eq. 8) in Eq. (7) and on simplification,

\[
\ln \left[ \left( 1 + \frac{q^2}{M^2 p^2} \right) \frac{p'}{p_0} \right] = \frac{2 q^2}{M^2 p^2 + q^2} - \ln \left( 2 - e^{\eta} \right)
\]

On further simplification of Eq. (8a) with expanding exponential series and assuming higher terms are neglected, final expression turns to Eq. (9):

\[
q = M p' \left( \frac{p_0}{p} \right) \exp \left[ 2 \ln \left( 2 - e^{\eta} \right) \right] - 1 - \left[ 2 \ln \left( 2 - e^{\eta} \right) \right].
\]

Thus, Eq. (9) represents the equation for deviatoric stress which incorporates behavior of plastic waste under different loading conditions. When the plastic wastes are ignored, it reduces to standard form of the modified cam clay model i.e. when plastic waste \( \chi = 0 \), above one changes to Eq. (10):

\[
q = M p' \left( \frac{p_0}{p} \right) - 1
\]

The proposed model requires the same parameters as the modified cam clay model. These parameters are frictional constant \( M = 6 \sin \phi' / (3 - \sin \phi') \), compression index \( \lambda \), recompression or swelling index \( \kappa \), \( p' \) is mean effective stress \((\sigma' + 2 \sigma')/3\) and \( p_0' \) is a pre-consolidation pressure. All these model parameters are obtained from standard triaxial and one dimensional compression tests. The compression and recompression indices \( \lambda \) and \( \kappa \) are obtained from the compression test results shown in Figure 4.

The slope of loading path in e-log p curve is given by \( \lambda \) and the slope of unloading path is given by \( \kappa \). The summary of model parameters used for the validation of proposed model is presented in Table 2 for the plain and plastic waste mixed soils respectively.

### Table 2: Summary of Model Parameters

<table>
<thead>
<tr>
<th>S.No</th>
<th>F.c %</th>
<th>( \phi' )</th>
<th>( \lambda )</th>
<th>( \kappa )</th>
<th>( M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>23.20</td>
<td>0.150</td>
<td>0.014</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>0.50</td>
<td>24.10</td>
<td>0.131</td>
<td>0.013</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>25.25</td>
<td>0.120</td>
<td>0.011</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>26.70</td>
<td>0.092</td>
<td>0.0087</td>
<td>1.06</td>
</tr>
</tbody>
</table>

The average values of material constant (\( \mu \)) used for prediction of stress-stain and pore water pressure behavior is taken as 0.52 for analysis in the present study. It can be noted from the results that, the compression parameters \( \lambda \) and \( \kappa \) decrease and frictional constant \( M \) parameter increase as percentage of plastic waste increases. The
experimental results clearly point out that the plastic waste mixed soil improves stress-strain behavior. The response of the plastic waste mixed soil obtained from experiments is discussed in relation to the results obtained from analytical model in the following sections.

4. MODEL PREDICTIONS

To validate the proposed analytical model, experimental results are compared with predicted results. Figures 5a, b show the comparison of stress-strain and pore water pressure response for various percentages of plastic waste at confining pressure for 100 kPa.

**Fig. 5:** (a) Comparison of Experimental and Predicted Results for Stress Strain Response (100 kPa)

**Fig. 5:** (b) Comparison of Experimental and Predicted Results for Pore Water Pressure (100 kPa)

It can be seen that the proposed model gives reasonably good agreement with experimental results. It is clear from the results presented that the stress-strain and pore water pressure response of the plastic waste mixed soil can be well represented using the proposed model for different confining pressures. This agreement is attributed to the main feature of the proposed constitutive model that the critical state soil mechanics framework has been extended to include the effect of plastic waste. The proposed model requires material constant ($\mu$). For the best fitting of experimental results with proposed model, material constant ($\mu$) is taken as 0.52.

5. CONCLUSIONS

In this paper, an approach is presented to model stress-strain behavior of plastic waste mixed soil. To investigate the effects of plastic waste mixed in strength of soil, series of triaxial compression and one dimensional consolidation tests have been performed with various percentages of plastic waste in soil at different confining pressures. The conclusions emerge from the present study are as follows:

1. The experimental results show that there is a good improvement in the strength of soil with inclusion of plastic waste. This increase in strength of soil is due to increase in friction between soil and plastic waste as results development of tensile stress in the plastic waste. The tensile stress developed in the plastic waste is responsible for improved strength in plastic waste mixed soil.

2. Based on experimental observations a simple generalized constitutive model is proposed, which is extension of critical state soil mechanics framework. The experimental results are compared with analytical model, and the agreement is satisfactory.

REFERENCES


