A comparative study on the effect of polyethylene plastic waste on sandy soils

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Abstract: Plastic pollution is one of the major global issues. Engineering measures are being undertaken to harness the non-biodegradability of plastic by converting it to a vital part of built environment. A comparative study is undertaken to evaluate the effects of the waste plastic (polyethylene) on the geotechnical properties of two locally available sands viz. Brahmaputra sand and Kulsi sand by conducting a series of direct shear tests on the two sand samples reinforced with polyethylene plastic strips. The effect of varying concentration of plastics (0.10%, 0.20%, 0.30%, 0.45%, 0.60%, 0.70% and 0.75% by weight of the sand) using different dimensions of the plastic strips is investigated. The polyethylene plastic strips' length varied from 15 mm to 45 mm and width varied from 5 mm to 15 mm. The shear strength parameters which are obtained ultimately for the composite specimens on which analysis have been done, positively reflect soil improvement due to the inclusion of polyethylene plastic waste.

Keywords: plastic pollution; polyethylene shopping bags; soil improvement; direct shear test; shear strength; sustainable development; environment.

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1 Introduction

With the increasing penetration of science and technology into our lives, there has been a great modernisation in the functioning of our day-to-day activities. The invention of plastic has been one of the major breakthroughs in the field of science and technology in the 20th century. Plastics have numerous favourable attributes like low cost, ease of manufacture, versatility and imperviousness to water which have worked as a boon in various applications and made it hugely popular among consumers. Its extensive use has consequently resulted in the unprecedented rise in the volume of plastic waste generated across the globe. There has been a huge escalation in the production of plastic from about 0.5 million tons in 1950 to over 260 million tons by 2008 with the numbers being forecast to increase with each passing year. Disposal of plastics has been one of the major concerns as plastics are generally non-biodegradable, and cause environmental as well as public health hazards. The recycling ratio of plastics has been low and this has paved the path for the continuous filling up of landfills by plastic material that has been used for only once and then discarded, with the packaging applications contributing more than 50% of the discarded plastics, one-third of which consists of plastic shopping bags (Nhamo, 2008). Plastic shopping bags are usually made from polyethylene, which is a non-biodegradable polymer made from non-renewable petroleum and natural gas resources. The unscientific methods of disposal of plastic bags have been a big contributing factor in the aggregation of plastic waste litter in the environment. It is quite an irony that the same properties that have made plastic bags so popular and successful commercially viz. low weight and resistance to degradation, have also lead to their undesirable proliferation in the environment as waste products.

All these, have escalated the need for preventing the discarded plastics from negatively affecting the biological environment. Thus, we must think of ways of taking advantage of the abundant plastic source which possesses a great versatility in terms of usage and at the same time are equally harmful to the environment and the living beings if not properly managed or disposed of. One such engineering measure to harness the non-biodegradability of plastics by minimising the impact on the biological environment would be to reuse the waste plastic and transform it into a vital part of the built environment. This study is done considering this.

This study presents a simple way of reinforcing the soil which is not fit for construction activities with waste polyethylene plastic strips and thereby making it suitable for building and construction by bringing an improvement in the geotechnical properties of the soil.

2 Background of the study

The quantity of waste generated in an overpopulated developing country like India is of mammoth proportions and so it calls for innovative ideas to achieve efficient waste management. One of the significant contributors to the rubbish produced by households is polyethylene bag. So, to tackle the problem of littering, the waste polyethylene bags must be managed efficiently. Reusing and recycling are the keystones of a sustainable future. In the recent years, a substantial amount of research is being carried out on the development of technologies or solutions for reusing the different types of wastes accumulated in order to mitigate the various environmental issues looming across the globe. Wastes such as plastic, waste tyre shreds mixed with soil behave in a similar manner to fibre-reinforced soils which encouraged several researchers to use discrete fibres like natural fibres, glass fibres, plastic fibres, polypropylene and polyester fibres to enhance the strength of the soil. All these waste materials are found in abundance but they are either disposed in landfills or incinerated which affects the environment. Instead, their unique beneficial properties can once again be used for sustainable geotechnical development.

One of the earliest research in this area was done by Gray and Al-Refeai (1986) and they established the dependency of the failure mechanism of fibre-reinforced soil on confining stress. The failure occurred by the frictional slipping of the reinforcement up to a certain value known as the critical confining stress above which, the tensile strength of the fibre governed the failure. In the recent years, researchers have shown that fibre-reinforced soil is a potential composite material that improves the structural behaviour of soil and thus can be employed (Sivakumar Babu and Vasudevan, 2008a, 2008b; Sivakumar Babu and Chouksey, 2010). Researchers have performed the tests with different types of fibres varying their proportions and also studied their effects on the improvement of the soil characteristics. An experimental study was carried out by Consoli et al. (2002, 2004) on the utilisation of the polyethylene fibres derived from waste plastic in reinforcing the uncemented and artificially cemented sand. The study showed the betterment in the stress-strain response of the plastic reinforced cemented and uncemented sand.

Researchers have established that random inclusion of discrete polypropylene fibres in soil as reinforcement materials have increased the peak shear strengths in soils (Zornberg, 2002; Consoli et al., 2007; Falorca and Pinto, 2011). Maher and Ho (1994), Santoni et al. (2001) and Miller and Rifai (2004) have thrown light towards the improvement of compressive strength and ductility of soil with the inclusion of these fibres.

Hataf and Rahimi (2006) and Yoona et al. (2008) conducted studies on the use of tyre shreds as reinforcing material. Wang (2006) and Miraftab and Lickfold (2008) used carpet waste. Sivakumar Babu and Chouksey (2011) conducted research on the recycling of plastic water bottles as a reinforcing-material in geotechnical engineering applications. The stress-strain response of the plastic waste mix was studied. The results showed an improvement in the strength and compressibility response of the plastic reinforced soil which resulted in the bearing capacity improvement and reduction of settlement in the design of shallow foundations.

One of the most recent and significant works done in the recent years in the field of soil reinforcement using polyethylene bags is that of Chebet and Kalumba (2014). Their study explored the possibility of utilising polyethylene shopping bags waste for soil reinforcement to pave way for its use in civil engineering projects such as in road bases, embankments and slope stabilisation. Inspired by all these work, we decided to test the applicability of this concept to the soil available in the North-Eastern region of India and hence selected the river sand obtained from the banks of Brahmaputra river and Kulsi river to examine their response to plastic stabilisation.

3 Materials and methodology

In our study, two types of locally available soil samples have been used – 'Brahmaputra sand' and 'Kulsi sand'. The collected sand samples were dried to negate the effect of moisture and then sieved through 425 µm sieve. The Brahmaputra sand and Kulsi sand are classified as poorly graded sand (SP) as per the unified soil classification system (USCS). The properties of both the samples are listed in Table 1.

Table 1 Engineering properties of the soils

Soil properties	*Brahmaputra sand*	*Kulsi sand*
Moisture content (%)	7.9	3.4
Mean grain size, D_{50} (mm)	0.22	0.40
Coefficient of uniformity, C_u	1.714	2.444
Coefficient of curvature, C_c	1.074	1.136
Specific gravity	2.61	2.65
Optimum moisture content (%)	13.4	14.2
Maximum dry density (KN/m^3)	17.321	18.24
Friction angle (Ø)	28.14°	33.80°

The plastic material that has been used in our study is polyethylene shopping bags, which were sourced from a local supermarket. The bags are labelled as high density polyethylene (HDPE) having a thickness of 40 micron (in accordance with the Bureau of Indian Standards (BIS) specification: IS 14534-1998). The properties of the plastic bags are given in Table 2.

Table 2 Properties of polyethylene shopping bags

Density	0.96 g/cm^3
Thickness	40 µ
Tensile modulus	0.8 GPa
Tensile strength	15 MPa

3.1 Experimental investigation

The investigation procedure included a series of direct shear tests performed on the unreinforced soil samples and the plastic reinforced soil samples to determine the strength parameters of the soil-plastic composite to investigate the effects of plastic strips. Solid strips of dimensions 15 mm × 15 mm, 30 mm × 10 mm and 45 mm × 5 mm were cut followed by their addition to the two respective sand samples. The sand samples

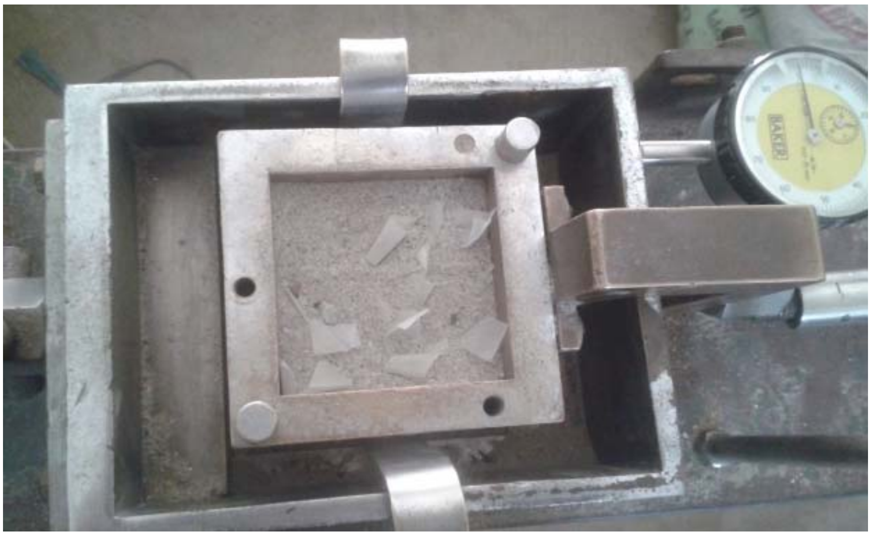
(Brahmaputra sand and Kulsi sand) were oven dried at 105°C for 24 hours so that effects of moisture were eliminated. The concentration of the plastic strips was varied from 0.10% to 0.75% of the dry weight of the sand samples. The effect of the concentration of plastics, aspect ratio (length/width) on the friction angle, shear strength parameters of the both the soil samples were studied and were compared with each other.

3.2 Shear test

Shear test of the unreinforced soil samples (Brahmaputra sand and Kulsi sand) was performed by placing the oven dried sand samples into a 60 mm × 60 mm × 25 mm shear box and compacting it to an average density of 1,543.20 kg/m^3. The tests were performed for normal stresses of 0.49 × 10^2 KPa (0.5 kg/cm^2), 1.47 × 10^2 KPa (1.5 kg/cm^2) and 2.45 × 10^2 KPa (2.5 kg/cm^2) at a shear loading rate of 1.25 mm/min. The plastic strips of the specified dimensions were mixed with the soil sample homogeneously in a bowl and were placed in the shear box. Direct shear tests were conducted on both the soil samples mixed with the plastic strips of the three dimensions maintaining the same loading condition and density. The plastic strips were added at 0.10%, 0.20%, 0.30%, 0.45%, 0.60%, 0.70% and 0.75% by weight of the soil sample. The peak stress for each condition of the soil specimen was noted including the results obtained for the control experiment in which no plastic strips were added to the soil samples.

Figure 1 A mixture of Bramhaputra sand and plastic strips (see online version for colours)

Figure 2 Soil-plastic mixture placed in shear box for testing (see online version for colours)



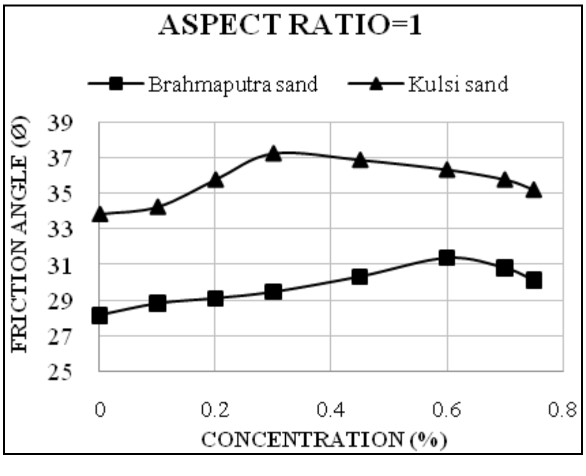
4 Results and discussions

The peak shear stresses obtained from the direct shear tests were recorded and plotted against the respective applied normal stresses to determine the angle of friction (Φ) for all the soil samples (Brahmaputra and Kulsi sands) tested. The results showed an encouraging trend of increase in friction angle for both the sands on the addition of the plastic strips. The plastic parameters yielded a distinct effect on the soils as they were varied. The relationships between the concentration of plastic strips and friction angle for a fixed aspect ratio are shown in the Figures 3, 4 and 5. For aspect ratio 1 of the plastic strips, Brahmaputra sand showed an increase in friction angle (Φ) from 28.14° to 31.38°, while Kulsi sand showed an increase from 33.80° to 37.23° (Figure 3). For aspect ratio 3, friction angle (Φ) increased from 28.14° to 34.21° in Brahmaputra sand and from 33.80° to 39.18° in Kulsi sand (Figure 4). Also, for aspect ratio 9, friction angle (Φ) increased from 28.14° to 33.02° in Brahmaputra sand and from 33.80° to 38.30° in Kulsi sand (Figure 5). The higher values of Kulsi sand corresponds to a better grading of the sand, thereby giving a higher initial shear strength. Results showed that the friction angle (Φ) in Brahmaputra sand increased with the increase in concentration from 0.1% and reached a maximum value of 34.21° for 0.6% concentration (by weight of sand) of plastic strips, followed by decrease in the friction angle with further increase in concentration of plastics up to 0.75%. Thus, 0.6% concentration of plastic strips was found to be the optimum concentration for Brahmaputra sand giving a maximum friction angle of 34.21°. On the other hand, Kulsi sand showed a peak friction angle (Φ) of 39.18° for 0.3%

concentration (by weight of sand) of plastic strips. This is due to the fact that for both the sands at their optimum concentration of plastics, the interaction between the soil and plastic is maximum which makes the friction angle maximum but as the concentration is increased, the soil-plastic interaction decreases and the plastic-plastic interaction increases which result in the slippage between the plastic strips thus decreasing the friction angle. Figure 6 shows the comparison of the effect of concentration of plastic strips of the three aspect ratios on friction angle of both the sands. In both sands, for the aspect ratio of 3, the friction angle was found to be the highest. This may be due to the fact that for the aspect ratio of 3, the surface area of the plastic strips is maximum and there occurs maximum interaction between the plastic strips and the soil particles thus making the friction angle maximum while on the other hand, as we increase the aspect ratio to 9, the plastic strips become slender and the surface area is reduced thus decreasing the soil-plastic interaction and hence the friction angle. Overall, it can be inferred that the plastic strips, when included to the soils, provide better reinforcement in Kulsi sand in comparison to the Brahmaputra sand. This is because of the better gradation of Kulsi sand.

The comparison of the variation of the friction angle with aspect ratio for a particular concentration of plastics of the two sands as shown in Figures 7, 8, 9, 10, 11, 12 and 13. The trend shows maximum friction angle for aspect ratio 3 for 0.20%, 0.30%, 0.45% and 0.70% concentration of plastic strips with Kulsi sand showing the higher friction angle in each case (Figures 8, 9, 10 and 12). This is due to the better gradation of Kulsi sand compared to Brahmaputra sand. For concentration of 0.10%, the friction angle for Kulsi sand was found to be maximum at aspect ratio 9 whereas for Brahmaputra sand, it was found to be maximum at aspect ratio 3 (Figure 7). For the concentration of 0.60%, the friction angle for Kulsi sand is highest for aspect ratio 9 whereas Brahmaputra sand shows the same trend as earlier. For the concentration of 0.75%, friction angle of Kulsi sand increases from 35.18° to 35.37° and then remains constant as the aspect ratio changes from 3 to 9.

Figure 3 Concentration of plastic strips v/s friction angle



The variation of the shear stress with the normal stress is seen for different aspect ratios and also for different concentration of plastics (Tables 3 and 4). The Brahmaputra sand showed an increase in shear stress from 0.72 kg/cm^2 to 2.08 kg/cm^2 with the change in normal stress from 0.5 kg/cm^2 to 2.5 kg/cm^2 for the aspect ratio of 3 and 0.60% concentration of plastics. On the other hand, the shear stress for the Kulsi sand increased from 0.61 kg/cm^2 to 2.24 kg/cm^2 as the normal stress was increased from 0.5 kg/cm^2 to 2.5 kg/cm^2 for 0.3% concentration of plastics having aspect ratio 3.

Figure 4 Concentration of plastic strips v/s friction angle

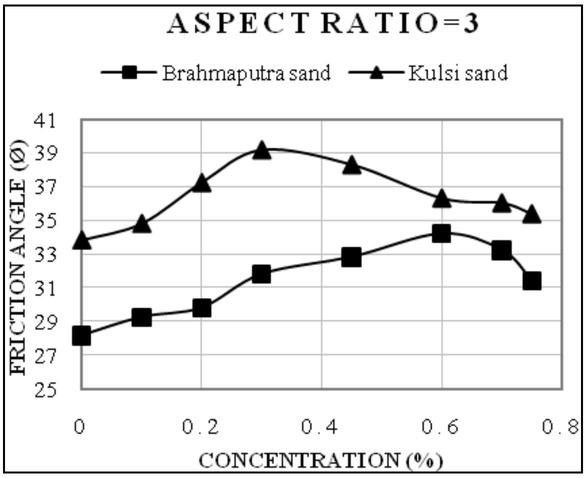


Figure 5 Concentration of plastic strips v/s friction angle

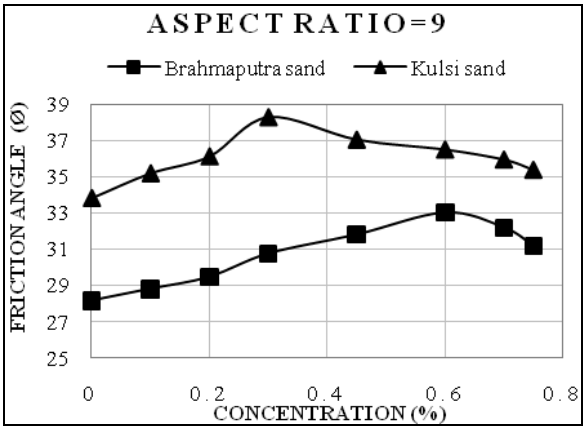


Figure 6 Comparison of concentration of plastic strips v/s friction angle

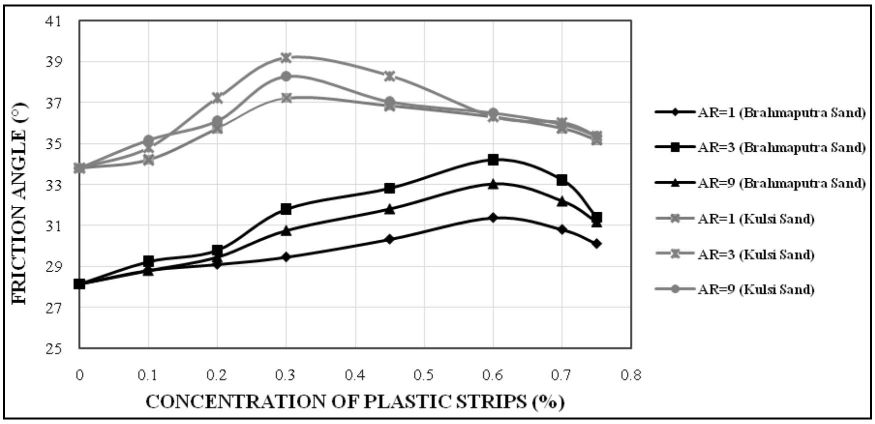


Figure 7 Aspect ratio v/s friction angle for 0.10% concentration of plastic strips

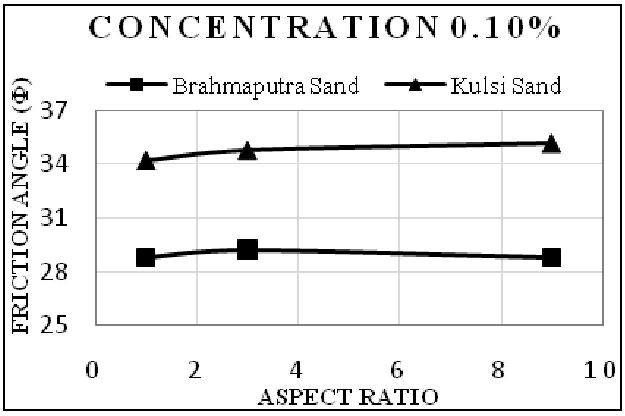


Figure 8 Aspect ratio v/s friction angle for 0.20% concentration of plastic strips

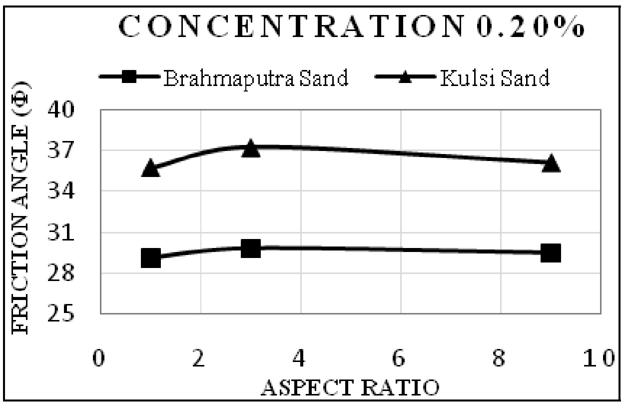


Figure 9 Aspect ratio v/s friction angle for 0.30% concentration of plastic strips

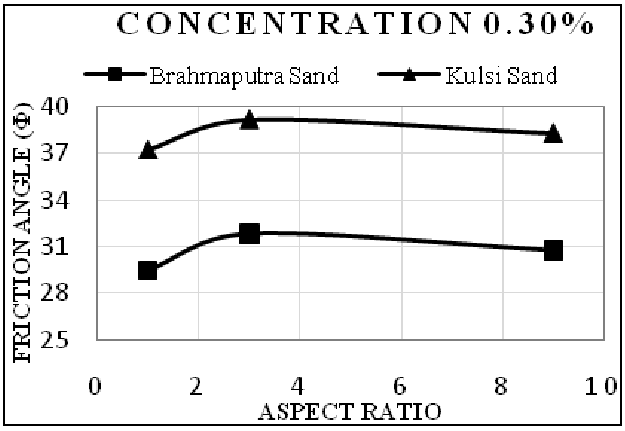


Figure 10 Aspect ratio v/s friction angle for 0.45% concentration of plastic strips

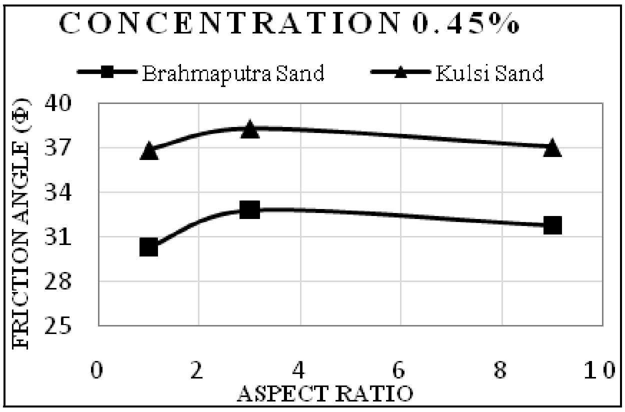


Figure 11 Aspect ratio v/s friction angle for 0.60% concentration of plastic strips

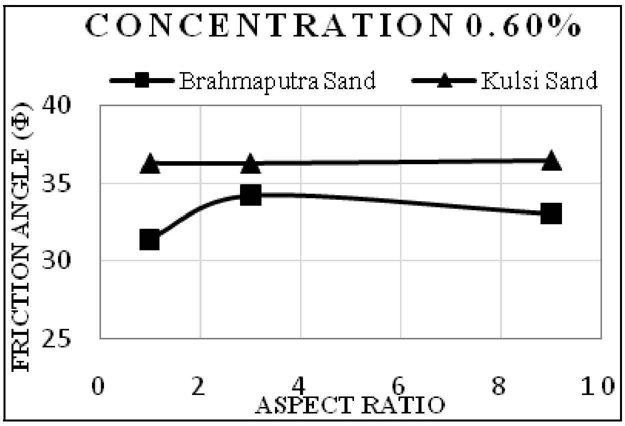


Figure 12 Aspect ratio v/s friction angle for 0.70% concentration of plastic strips

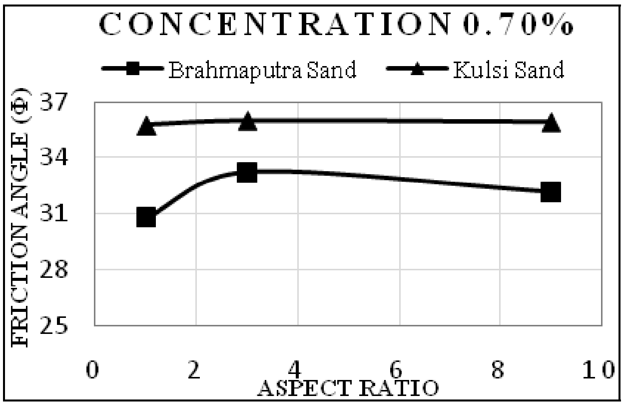


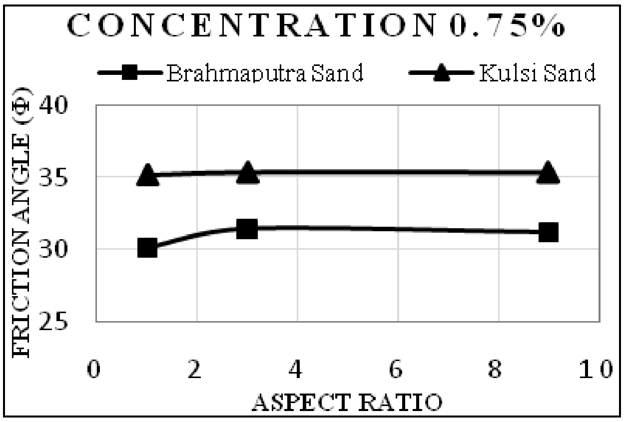
Table 3 Shear stress against applied normal stresses on Brahmaputra sand for different concentrations of plastic strips

Aspect ratio = 1								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.41	0.45	0.48	0.55	0.64	0.68	0.67	0.63
1.5	0.96	0.98	1.01	1.02	1.14	1.23	1.18	1.15
2.5	1.48	1.55	1.59	1.68	1.81	1.9	1.82	1.79
Aspect ratio = 3								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.41	0.46	0.49	0.52	0.65	0.72	0.68	0.64
1.5	0.96	1.01	1.03	1.05	1.2	1.38	1.31	1.17
2.5	1.48	1.58	1.64	1.76	1.94	2.08	1.99	1.86
Aspect ratio = 9								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.41	0.57	0.59	0.64	0.7	0.74	0.68	0.62
1.5	0.96	0.89	0.97	1.04	1.18	1.26	1.16	1.03
2.5	1.48	1.67	1.72	1.83	1.94	2.04	1.94	1.83

Table 4 Shear stress against applied normal stresses on Kulsi sand for different concentrations of plastic strips

Aspect ratio = 1								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.48	0.5	0.53	0.59	0.57	0.56	0.55	0.51
1.5	0.98	1.03	1.12	1.14	1.11	1.09	1.04	1.02
2.5	1.82	1.86	1.97	2.11	2.07	2.03	1.99	1.92
Aspect ratio = 3								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.48	0.49	0.54	0.61	0.58	0.57	0.55	0.53
1.5	0.98	1.1	1.13	1.24	1.18	1.15	1.14	1.08
2.5	1.82	1.88	2.06	2.24	2.16	2.04	2	1.95
Aspect ratio = 9								
Normal stress (kg/cm^2)	*Shear stress (kg/cm^2)*							
	0%	*0.10%*	*0.20%*	*0.30%*	*0.45%*	*0.60%*	*0.70%*	*0.75%*
0.5	0.48	0.51	0.52	0.59	0.57	0.54	0.52	0.49
1.5	0.98	0.99	1.12	1.14	1.12	1.08	1.04	1.01
2.5	1.82	1.92	1.98	2.17	2.08	2.02	1.97	1.91

Figure 13 Aspect ratio v/s friction angle for 0.60% concentration of plastic strips



5 Conclusions

In this paper, an approach for recycling plastic waste from polyethylene bags as reinforcing material in geotechnical and civil engineering applications is proposed and a comparison is made between the change in the geotechnical properties on the addition of plastic waste to Brahmaputra and Kulsi sand. A series of direct shear tests were performed to evaluate the friction angle and the shear strength parameters of the plastic reinforced Brahmaputra and Kulsi sand. The effects of the concentration of plastics, the size of the plastic strips (aspect ratio) on the friction angle, shear strength parameters were investigated. The following conclusions can be drawn from the series of direct shear tests:

- The friction angle of both the Brahmaputra and Kulsi sand increases with the inclusion of plastic strips to the soil.
- The shear strength parameters also increase with the inclusion of plastic strips for both the Brahmaputra and Kulsi sands.
- The friction angle for the Brahmaputra sand attained a maximum value of 34.21° for 0.6% concentration of plastics. 0.6% concentration of plastics is the optimum concentration of plastics and also the aspect ratio of 3 is the optimum aspect ratio giving the maximum friction angle.
- The friction angle for the Kulsi sand reached a maximum value of 39.18° for 0.3% of the concentration of the plastics strips, which is the optimum concentration of plastics. Also the aspect ratio of 3 is found to be the optimum aspect ratio giving the maximum friction angle.
- The shear stress for the Brahmaputra sand increases from 0.68 kg/cm^2 to 1.9 kg/cm^2 with the change in normal stress from 0.5 kg/cm^2 to 2.5 kg/cm^2 for 0.60% concentration of plastics having the aspect ratio 3.
- The shear stress for the Kulsi sand increases from 0.61 kg/cm^2 to 2.24 kg/cm^2 as the normal stress is increased from 0.5 kg/cm^2 to 2.5 kg/cm^2 for 0.30% concentration of plastics having the aspect ratio 3.

The results of this study suggest that plastic waste can be reused in various civil engineering and geotechnical applications of waste management. This could contribute to the development of design methodologies where this type of reinforcement material could be used resulting in a reduction in project costs. Also, a successful application in the field could lead to a reduction of plastic (polyethylene) waste disposed to landfills bringing environmental benefits and also a reduction in CO_2 emissions.

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