The Asian Review of Civil Engineering
ISSN: 2249-6203 (P) Vol.1 No.2, 2012, pp.14-19

DOI: https://doi.org/10.51983/tarce-2012.1.2.2187

Effect of Waste Plastic Chips on the Strength and Swelling Pressure of Silt

Vishwas Nandkishor Khatri[1], R. K. Dutta[*2] and Gayathri Venkataraman[3]

[1&2]*Department of Civil Engineering, National Institute of Technology, Hamirpur - 177005, Himachal Pradesh, India*
[3]*Department of Civil Engineering, Institute of Technology and Management, Gurgaon, India*
E-mail: rakeshkdutta@yahoo.com
(Received on 18 August 2012 and accepted on 28 October 2012)

Abstract - **Laboratory tests were conducted to study the effect of waste plastic chips derived from used PET bottles on the strength and swelling potential of silt. The content of plastic waste was varied from 0, 0.5, 0.75 and 1 % by dry weight of silt. The size of waste plastic chips was 15 mm x 5 mm in the study. The results of this study reveal that there is significant improvement in the strength silt and considerable reduction in swell pressure with the inclusion of small quantity of waste plastic chips. Mitigation of expansive soils using waste plastic chips can be a good solution to reduce the swell potential of silt on which buildings and roads are going to be constructed.**

Keywords: **Shear strength, Silt, Swell pressure, Waste plastic chip**

I. Introduction

Researchers at present are focusing their attention to find out alternate ways to utilize wastes emerging in the society. Plastic wastes produced from used PET bottles are considered one example of such wastes. Further, in an effort to address the ever-increasing plastic waste disposal problem and to conserve our depleting landfill spaces, there has been a growing interest in recent years in for studying the geotechnical behaviour of waste materials mixed with soils. The present work is one such attempt to examine the behaviour of silt mixed with waste plastic chips derived from used PET bottles. A series of laboratory unconfined compressive strength tests, direct shear tests and swelling pressure tests were carried out by varying plastic chip content. The results obtained from these tests are presented and discussed in this paper.

II. Background

A review of the literature revealed that various laboratory investigations have been conducted on fiber-reinforced materials. The results of direct shear tests performed on sand specimens by Gray and Ohashi (1983) indicated increased shear strength, increased ductility, and reduced post peak strength loss due to the inclusion of discrete fibers. These results were supported by a number of researchers using consolidated drained triaxial tests (Gray and Al-Refeai 1986; Gray 1988; Gray and Maher 1989; Al-Refeai 1991; Stauffer and Holtz 1995; Ranjan *et al* 1996). Arteaga (1989) supported these results using both direct shear tests and consolidated drained triaxial tests, but indicated that the direct shear results were more erratic than the triaxial experiments. The inclusion of discrete fibers increased both the cohesion and angle of internal friction of the specimens. The increase in cohesion of typically cohesionless materials due to the inclusion of discrete fibers was termed the "apparent cohesion" of the material (Arteaga 1989; Stauffer and Holtz, 1995). The improvement of the engineering properties due to the inclusion of discrete fibers was determined to be a function of a variety of parameters including fiber type, fiber length, aspect ratios, fiber content, orientation, and soil properties. Attempts were made by various researchers to determine the effect of each parameter on the different engineering properties of the composite. The peak strength reportedly increased with increasing fiber content and length up to a limiting amount of each beyond which no additional benefits were observed (Gray and Ohashi1983; Gray and Al-Refeai 1986; Arteaga 1989; Gray and Maher 1989; Maher and Ho 1994; Ranjan *et al* 1996; Webster and Santoni 1997). Gray and Al-Refeai (1986) reported that reed fibers were superior to glass fibers due to greater surface friction properties. Gray and Maher (1989) and Al-Refeai (1991) reported that an increase in the coefficient of uniformity, an increase in particle roundness, or a decrease in average particle size would result in additional strength benefits due to fiber reinforcement. Al-Refeai (1991) reported that fibrillated polypropylene fibers outperformed glass fibers, and the optimum fiber length was 76mm for sands. Ahlrich and Tidewell (1994) recommended an optimum fiber content 0.5% dry weight for stabilising sands with monofilament fibers. Ranjan et al (1996) reported that reinforcement of medium sands was less effective than fine sands. Ranjan et al (1996) further reported that sands stabilised with fiber contents >2% dry weight of sand achieved no added benefit. Morel and Gourc (1997) recommended an optimum mesh content of 0.5% dry weight of sand for discrete polypropylene mesh elements. A laboratory study conducted by Webster and Santoni (1997) using varying lengths of monofilament fibers in sands indicated an optimum fiber length of 51mm and an optimum content 0.8% dry weight of sand.

Several researchers have conducted investigations to improve the physical and mechanical properties of soil by using different types of waste materials. Their research includes, for example, waste tire, waste plastic, cement kiln dust, fly and bottom ashes, blast furnace slag, stone dust, recycled carpet wastes, factory-waste roof shingles and sewage sludge ash (Benson and Khire, 1994; Baghdadi *et al.,* 1995; Miller and Azad, 2000; Montardo *et al.,* 2002; Sobhan and Mashnad, 2003; Dutta and Rao, 2004; Ghiassian, 2004; Ahmed, 2004; Hooper and Allen, 2005; Ghazavi and Sakhi, 2005; Hataf and Rahimi, 2006; Sreekrishnavilasam *et al.,* 2007; Dutta and Sarda, 2007; Ahmed *et al.,*2008; Chen and Lin, 2009). Benson and Khire (1994) reported that the reinforcing sand with of pieces of waste plastic milk jugs increased the strength, friction angle and secant modulus. Bueno (1997) reported an enhancement of strength through laboratory study on soil stabilized with short thin plastic strips of different lengths and contents. Montardo *et al.,* (2002) reported the improvement in peak and ultimate strength of fine sand with the use of fibers produced from waste plastic bottles. Dutta and Rao (2007) conducted drained triaxial tests to improve the behavior of sand reinforced with waste plastic and acceptable results for ground improvement were obtained. Dutta and Sarda (2007) studied the behavior of stone dust/fly ash reinforced with plastic strips overlying saturated clay and reported that the addition of waste plastic strips increased the CBR and secant modulus. Babu and Chouksey (2011) reported the stress-strain behavior of plastic waste mixed clay and sand. The results of this study indicated that the addition of plastic waste to soil leads to the improvement in strength. Ahmed *et al.,* (2011) reported that addition of strips of waste plastic trays to soil samples treated with recycled gypsum enhanced the compressive strength as well increased the value of secant modulus. Viswanadham *et al* (2009) examined swelling behavior of geofiber-reinforced soils, using fibers of different aspect ratios and observed a reduction in heave. The swelling pressure was the maximum at low aspect ratios at both the fiber contents of 0.25% and 0.50%.

Thus from the literature presented above, it is evident that not much work has been reported on the silt reinforced with waste plastic chips. Therefore, the present work is one such attempt to examine the behaviour of silt mixed with waste plastic chips derived from used PET bottles. A series of laboratory unconfined compressive strength tests, direct shear tests and swelling pressure tests were carried out by varying plastic chip content. The results obtained from these tests are presented and discussed in this paper.

III. Materials Used

A. Silt

The soil was collected from Solapur, Maharastra, India. The soil properties are shown in Table I. As per Universal Soil Classification System, the soil may be classified as silt with low plasticity.

Table I Properties Of Soil

Property	Soil
Specific Gravity	2.72
Liquid limit (%)	45.80
Plastic limit (%)	30.01
Plasticity index	15.79
Shrinkage limit (%)	16.83
Optimum moisture content (%)	20.15
Maximum dry unit weight (kN/m3)	16.08
Cohesion (kPa)	13.56
Friction angle (Deg.)	11.06
Unconfined compressive strength (kPa)	51.50
Differential Free Swell index (%)	50
Swell pressure (kPa)	56.96
Classification	Silt with low plasticity

B. Waste Plastic Chips

The reinforcement consisted of plastic waste derived from PET used bottles. The chip content in the mixture was kept 0, 0.5, 0.75 and 1 % by dry weight of silt. To study effect of size and shape plastic chips, chip of size 15 mm x 5 mm was used in this study. The properties of these chips are given in Table II.

Table II Properties of Plastic Chips

Property	Chip
Specific Gravity	1.4
Length (mm)	15
Width (mm)	5

IV. Experimental Procedure and Test Conducted

Dry soil of specified weight corresponding to maximum dry unit weight was mixed with required quantity of water corresponding to optimum moisture content and was kept in desiccators for moisture equilibrium. Further, the wet soil was taken out from the desiccators and the required quantity of plastic chips corresponding to dry weight of soil was distributed uniformly over the soil as shown in Fig. 1 and mixed uniformly.

Fig. 1 Mixing of chips with soil

The plastic chip–soil mixture was then filled in the standard compaction mould and compacted by static compactor to achieve the required unit weight (corresponding to max dry unit weight). This mould is then placed in a bucket filled with water for saturation. After the 3 days of saturation the specimens of 38 mm diameter and 76 mm long for unconfined compressive strength tests (UCS) were extracted using hydraulic extruder. The test was conducted as per IS-2720 Part 10 (1991, reaffirmed in 1995) and at a strain rate of 0.01 mm/min.

The specimen for direct shear tests were prepared similar to the procedure adopted for the UCS test. The static compactor mould was filled with the mixture of specified quantity of soil, water and plastic chips and compacted using static compactor. Thereafter the mould was kept for saturation for three days by immersing it in a bucket filled with water. After saturation, the specimens of size 60 mm x 60 mm x 25 mm were extracted using hydraulic extruder. The test was conducted as per IS 2720 Part 13 (1986) at a strain rate of 0.01 mm/min.

The constant volume method was used for measuring the swell pressure. The required mould of 1000 ml capacity was filled with mixture of soil, water and plastic chips (in case of reinforced soil sample) and compacted using static compactor to achieve the required dry unit weight (corresponding to max dry unit weight). The test was conducted in accordance with IS 2720: Part XLI: 1977(reaffirmed in 2002).

V. Results

The results of the unconfined compression test, direct shear test and swelling pressure were used as an index of specimen performance. The performance of test specimens relative to the performance of the control specimen, and to each other, provided a means of evaluating the effects of each test variable. The control specimen was a silt specimen prepared without any chip content. The reinforced soil specimen was prepared with the addition of 0.5 %, 0.75 % and 1 % plastic chips respectively.

A. Unconfined Compressive Strength

The axial stress-strain behavior of the silt reinforced with varying percentage of plastic chips is shown in Fig. 2. The study of Fig. 2 reveals that the peak axial stress of silt increases with the addition of plastic chips. For example, an axial stress of 51.5 kPa for the pure silt increased to 54.66 kPa when the silt specimen was reinforced with 0.5 % plastic chips. The axial stress further increased to 69.7 kPa when the content of chips was raised to 1 %. Further study of Fig. 2 reveals that the failure strain is decreasing with the increase in plastic chip content which implies that the reinforced soil is behaving in stiffer manner in comparison to pure silt.

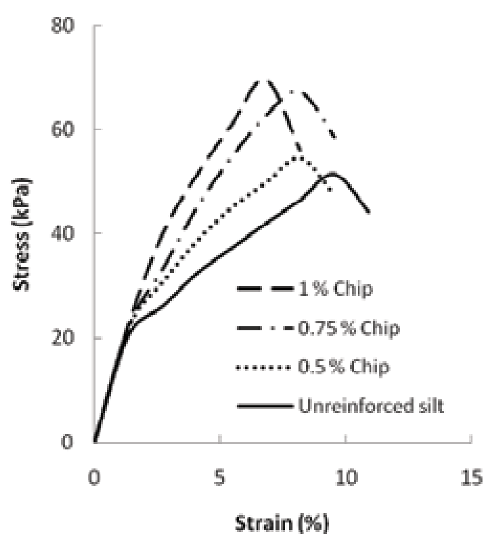

Fig. 2 Axial stress- strain behavior of silt reinforced with plastic chips

The variation of normalized unconfined compression strength (qu) for different percentage of plastic chips is shown in Fig. 5. Study of this figure reveals that the improvement in qu due to increase in plastic chip content to the soil is significant up to about 0.75 %. Beyond this, the improvement in strength is marginal.

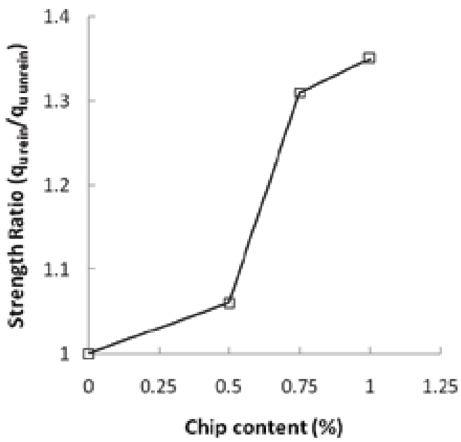

Fig. 3 Variation of normalized unconfined compression strength with percentage chip content

Thus from the above discussion it can be concluded that with the increase in plastic chip content in silt increases the unconfined compressive strength and decreases the strain at failure of the composite. Significant improvement in unconfined compressive strength is observed up to a chip content of about 0.75 %. Beyond this, the improvement in unconfined compressive strength is marginal.

B. Direct Shear

The results obtained from the direct shear tests conducted on silt and silt reinforced with varying percentage of plastic chips is shown in Fig. 4. The shear strength parameters obtained from the direct shear test are shown in Table III.

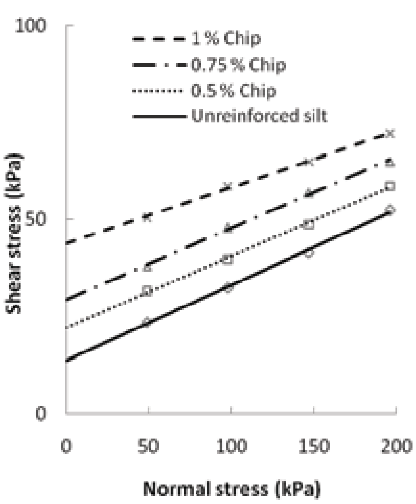

Fig. 4 Variation of shear strength of silt mixed with plastic chips

TABLE III SHEAR STRENGTH PARAMETERS FROM DIRECT SHEAR TEST

Chip content (%)	Direct shear test	
	Cohesion (kPa)	Friction angle (Deg.)
0	13.56	11.06°
0.5	22.15	10.44°
0.75	29.39	10.44°
1.0	43.85	8.28°

Study of Fig. 4 and Table III reveal that the addition of plastic chips to silt increased the cohesion. For example, the value of cohesion for the pure silt was 13.56 kPa which increased to 22.15 kPa when plastic chips of 0.5 % were added to it. The value of cohesion further increased to 43.85 kPa when the content of chips was increased to 1 % in the silt. The confinement effect by the plastic chips in soil could be a contributing factor leading to increase in cohesion of reinforced soil. Further study of Fig. 4 and Table III reveal that the value of friction angle decreases with the addition of plastic chips in silt. For example, for the pure silt, the value of friction angle was 11.060 which decreased to 10.440 when plastic chips of 0.5 % were added to the silt. The value further decreased to 8.280 when the content of the chip was increased to 1 % in the silt. This decrease in friction angle can be attributed to the easy slippage along smooth soil-chip interface for reinforced soil. Further with the increase in chip content in soil, the number of such smooth interfaces (soil-chip interface) also increases resulting a further decrease in

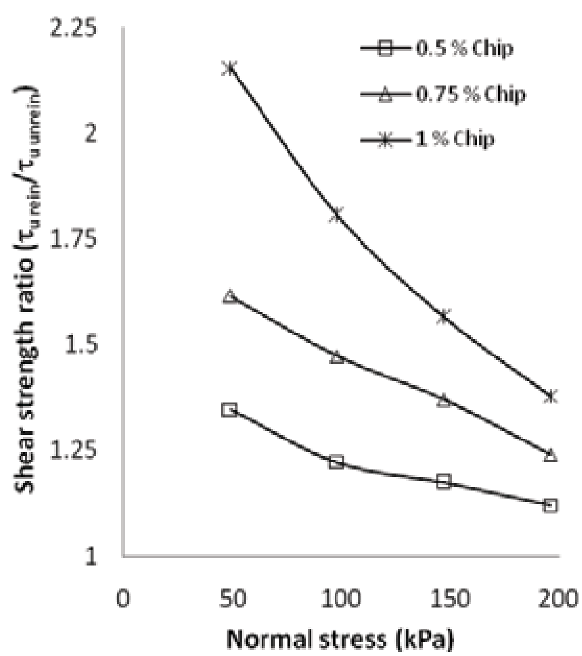

Fig. 5 Variation of normalized shear strength with normal stresses at different chip content

friction angle. Further to highlight the effect of plastic chips on the shear strength at different normal stress values, the shear strength of reinforced soil at a particular normal stress was normalized with respect to the strength of unreinforced clay at the same normal stress. The corresponding results are shown in Fig 5.

Study of Fig. 5 reveals that the improvement in shear strength of reinforced soil for particular chip content was higher at lower normal stress and vice versa. The shear strength of reinforced soil at 49 kPa with 1 % of chip content was about 2.15 times that of shear strength of pure silt which drops to 1.38 times of shear strength of pure silt as the normal stress increases to 196.2 kPa. This improvement in shear strength at lower normal stress is attributed to better interaction between the soil and plastic chip. Such effect is diminishing at higher normal stress. Thus from the above discussion it can be concluded that with the increase of plastic chip content to silt increases the cohesion and decreases the friction angle of the composite. The shear strength improvement was significant at lower normal stress and vice versa.

C. Swelling Pressure

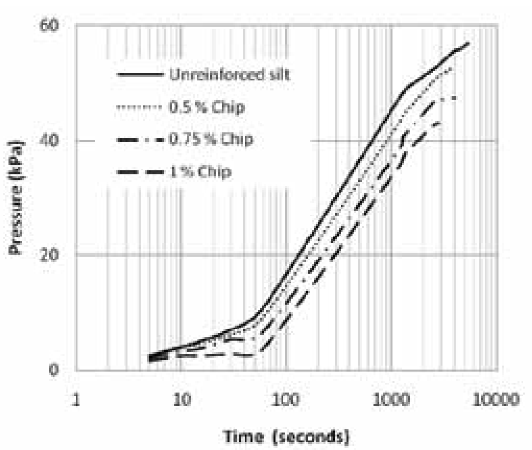

Fig 6 Variation of swell pressure with chip content

Table IV Swell Pressure for Different Chip Content

Reinforcement (%)	Swell Pressure (kPa)
0	55.71
0.5	52.82
0.75	47.45
1.0	42.91

The variation of swell pressure for different chip content is indicated in Fig. 5 and Table IV. Study of Fig. 5 and Table IV reveal that addition of plastic chips not only reduces the swell pressure but also the equilibrium time required to achieve the constant value of the same. The swell pressure of pure clay was 55.71 kPa and time require to achieve it was 5381 seconds. The addition of 1% chips lead to reduction in swell pressure to 42.91 kPa and equilibrium time to 2838 seconds. This may be attributed to interface friction at the soil-chip interface is the sole factor leading to the reduction in swell pressure.

VI. Conclusions

Laboratory tests were conducted to study the effect of waste plastic chips derived from used PET bottles on the strength and swelling potential of silt. The content of plastic waste was varied from 0, 0.5, 0.75 and 1 % by dry weight of silt. The size of waste plastic chips was 15 mm x 5 mm in the study. Based upon the results presented above, the following conclusion can be drawn.

1. The unconfined compressive strength increases with the increase in plastic chip content in silt.
2. The strain at failure decreases with the increase in plastic chip content in silt.
3. The unconfined compressive strength increases up to a chip content of about 0.75 %. Beyond this, the improvement in unconfined compressive strength is marginal.
4. The cohesion increases with the increase in plastic chip content in silt.
5. The friction angle decreases with the increase in plastic chip content in silt.
6. The improvement in shear strength was significant at lower normal stress and vice versa with the increase in plastic chip content in silt.
7. There is considerable reduction in swell pressure with the increase in plastic chip content in silt.

The observations noted in the present study are useful in the reuse of plastic waste and contribute better practices in geotechnical aspects of waste management. Further it provides an efficient and reliable technique for improving the strength and stability of soils. Mitigation of expansive soils using waste plastic chips can be a good solution to reduce the swell potential of silt on buildings and roads are going to be constructed.

References

[1] R. C. Ahlrich and L. E. Tidewell, "Contingency airfield construction: Mechanical stabilization using monofilament and fibrillated fibers," Tech. Rep GL-94-2, U.S. Army Engr. Waterways Experiment Station, Vicksburg, Miss. 1994.

[2] A. Ahmed, M.Shehat and S. Easa, "Enhancing the Strength of Roadway Subgrades Using Factorywaste Roof Shingles," The proceeding of CSCE 2008 Annual Conference, pp. 10-13, Québec, Canada, June 2008.

[3] A. Ahmed, K. Ugai and T. Kamei, "Investigation of recycledgypsum in conjunction with waste plastic trays for ground improvement," *Construction and Building Materials,* Vol. 25,No. 1, pp. 208-217, 2011.

[4] A. Ahmed, "Utilization of Shredded Waste Tires in the Strengthening of Unpaved Roads Over soft Clay," Ph. D. Thesis, Civil Eng. Dept., Faculty of Engineering, El-Mina University, El-Minia, Egypt, 2004.

[5] T. Al-Refeai, "Behavior of granular soils reinforced with discrete randomly oriented inclusions," *Geotextiles and Geomembrane,* Vol. 10, pp. 319-333, 1991.

[6] C. B. Arteaga, "The shear strength of Ottawa sand mixed with discrete short length plastic fibers," Thesis, Mississippi State University, Mississippi State, Miss, 1989.

[7] Z. A. Baghdadi, MN. Fatani and NA. Sabban, "Soil modification by cement kiln dust," *Material Civil Eng.* J., Vol. 7, No. 4, pp. 218-222, 1995.

[8] C. H. Benson and M. U. Khire, "Reinforcing Sand with Strips of Reclaimed High-Density Polyethylene," *Journal of Geotechnical Engineering,* Vol. 120, No. 5, pp. 838-855, 1994.

[9] A. W. Bishop and D. J. Henkel, "The measurement of properties in the triaxial test," Edward Arnold Publishers Ltd, London, 1962.

[10] B. Bueno and De Souza, "The Mechanical response of reinforced soils using short randomly distributed plastic strips," Recent developments in Soil and Pavement Mechanics, Almeida (Ed.) @ Balkema, Rotterdam, ISBN 9054108851, pp. 401-407, 1997.

[11] L. Chen and D. Lin, "Stabilization treatment of soft subgrade soil by sewage sludge ash and cement," *Journal of Hazardous Materials,* Vol. 162, No. 1, pp. 321-327, 2009.

[12] R. K. Dutta and V. K. Sarda, "CBR Behaviour of Waste Plastic Strip-Reinforced Stone Dust/Fly Ash Overlying Saturated Clay," *J. Turkish Eng. Env. Sci.,* Vol. 31, pp. 171 - 182, 2007.

[13] M. Dutta, (Ed), "Waste disposal in Engineered landfills," Narosa Publishing House, New Delhi, pp. 3-4, 1997.

[14] R. K. Dutta, and G. Venkatappa Rao, "Engineering Properties of Sand Reinforced with Strips from Waste Plastic," Proceedings of International Conference on Geotechnical Engineering, Sharjah, UAE, pp. 186-193, 2004.

[15] R. K. Dutta and G. Venkatappa Rao, "Regresson model for predicting the behaviour of sand reinforced with waste plastic," *Turkish Journal of Engineering and Environmental Sciences,* Vol. 31, No. 2, pp. 119-126, 2007.

[16] C. S. Fletcher and W. K. Humphries," California Bearing ratio improvement of remolded soils by the addition of polypropylene fiber reinforcement," Transportation Research Record 1295, Transportation Research Board, D. C. Washington, pp. 80-86, 1991.

[17] M. Ghazavi, and M. A. Sakhi, "Influence of Optimized Tire Shreds on Shear Strength Parameters of Sand," *Int. J. of Geomechanics,* ASCE, Vol. 5,No. 1, pp. 58-65, 2005.

[18] H. Ghiassian "Soil Reinforcement with Recycled Carpet Wastes," *Waste Management & Research* J., Vol. 22, No. 2, pp. 108-114, 2004.

[19] M. Giles, "Freeze–Thaw Processes and Soil Chemistry," Special Report pp. 95-12, US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, 1995.

[20] Global Environmental Technology Promotion Committee, (GETPC), "Recycling in Japan," Technical Report, Osaka University, Technology Center, 2003.

[21] Gopal Ranjan, R. M. Vasan, & H. D. Charan, "Probabilistic analysis of randomly distributed fiber-reinforced soil," *Journal of Geotechnical Engineering,* Vol. 122, No. 6, pp. 419-426, 1996.

[22] D.H.Gray and M.H. Maher, "Admixture stabilization of sand with discrete randomly distributed fibers," Proc. XII Int. Conf. on Soil Mech. Found. Eng., Rio de Janeiro, Brazil, pp. 1363-1366, 1989.

[23] D. H. Gray and H. Ohashi, "Mechanics of fiber reinforcing in sand," *Journal of Geotechnical Engineering,* Vol. 109, No. 3, pp. 335-353, 1983.

[24] D. H. Gray, "Constitutive behavior of fiber-reinforced sands," Tech. Rep. AFOSR-TR-88-1007, Bolling Air Force Base, Washington, D. C, 1988.

[25] D. H. Gray and T. Al-Refeai, "Behavior of fabric-vs fiber-reinforced sand," *Journal of Geotechnical Engineering,* Vol. 112, No. 8, pp. 804-820,1986.

[26] N. Hataf and M. M. Rahimi, "Experimental Investigation of bearing Capacity of Sand Reinforced with Randomly Distributed Tire Shreds," *Construction and Building Materials Journal,* Vol. 20, No. 10, pp. 910-916, 2006.

[27] R. D. Holtz and W. D. Kovac, "An Introduction to Geotechnical Engineering", Prentice Hall, New Jersey, 1981.

[28] F. Hooper and M. Allen, "Effects of Reclaimed Asphalt Shingles on Engineering Properties of Soils," ASCE Geotechnical Special Publication No. 127, Corp, A. Aydilek and J. Wartman (eds.), pp. 137-149, 2005.

[29] N. N. Khoury and M. M. Zaman, "Environmental effects on durability of aggregates stabilized with cementations materials," *J. Materials in Civil Eng.,* ASCE, Vol. 19, No. 1, pp. 41–48, 2007.

[30] M. H. Maher and Y. C. Ho, "Mechanical properties of kaolinite/fiber soil composite," *Journal of Geotechnical Engineering,* Vol. 120, No. 8, pp. 1381-1393, 1994.

[31] G. A. Miller and S. Azad "Influence of soil type on stabilization with cement kiln dust," *Construction and Building Materials J.,* Vol. 14, pp. 89-97, 2000.

[32] J. P., Montardo, P. D. M. Prietto and G.S. Pasa, "Engineering behavior of a sand reinforced with plastic waste," *J. Geotech. and Geoenvir. Eng.,* Vol. 128, No. 6, pp. 462-472, 2002.

[33] J. C. Morel, and J. P. Gourc, "Mechanical behavior of sand reinforced with mesh elements," *Geosynthetics International.,* Vol. 4, No. 5, pp. 481-508, 1997.

[34] G. L. Sivakumar Babu and S. K. Chouksey, "Stress–strain response of plastic waste mixed soil," *Waste Management,* Vol. 31, No. 3, pp. 481-488, 2011.

[35] K. Sobhan and M. Mashnad "Mechanical stabilization of cement soil-fly ash mixtures with recycled plastic strips," *J. Envir. Eng.,* ASCE, Vol. 129, No. 10, pp. 943-947, 2003.

[36] A. Sreekrishnavilasam, S. Rahardja and M. Santagta, "Soil Treatment Using Fresh and Landfilled Cement Kiln Dust," *Const. and Building Materials J.,* Vol. 21, No.2, pp. 318-327, 2007.

[37] S. D. Stauffer and R.D. Holtz, "Stress-strain and strength behavior of staple fiber and continuous filament-reinforced sand," Transp. Res. Rec. 1474, Transp. Res. Board, Washington D.C., pp. 82–95, 1995.

[38] K. Ugai and A. Ahmed, "Evaluation of Using Gypsum Waste Plasterboard in Ground Improvement," In Proceeding of the Workshop on Recycling Waste Plasterboard, Memorial Hall, Chuo University, Tokyo, Japan. March 13, 2009,

[39] B. V. S. Viswanadham, B. R. Phanikumar and R. V. Mukherjee, "Swelling behaviour of a geofiber-reinforced expansive soil," *Geotextiles and Geomembranes,* Vol.27, No.1, pp. 73-76, 2009.

[40] S. L. Webster and R. L. Santoni, "Contingency airfield and road construction using geosynthetic fiber stabilization of sands," Tech. Rep GL-97-4, U.S. Army Engr. Waterways Experiment Station, Vicksburg, Miss. 1997.