WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141892

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 3 2022

pp. 385 – 395

Research paper

Study on some of the strength properties of soft clay stabilized with plastic waste strips

Worku Firomsa Kabeta[1]

Abstract: It is well known that if plastic wastes are not well managed, it has a negative impact on the environment as well as on human health. In this study, recycling plastic waste in form of strips for stabilizing weak subgrade soil is proposed. For this purpose, a weak clay soil sample was mixed with 0.2%, 0.3%, and 0.4% of plastic strips by weight of soil, and the experimental results were compared to the control soil sample with 0% plastic. Laboratory tests on the Standard compaction test, Unconfined compression test (UCS), and California bearing ratio (CBR) were conducted according to the American Society for Testing and Materials (ASTM). The results of the study reveal that there are significant improvements in the strength of weak soil stabilized with plastic waste strips. Accordingly, the Standard Proctor test shows that there is a small increment in the maximum dry density of the soil when it is mixed with plastic strips. The result from the CBR test shows that there is a significant increment of CBR value with the plastic strip content. The unconfined compressive strength test also shows that increasing the percentage of plastic strips from 0 to 0.4% resulted in increased strength of soil by 138% with 2 cm length plastic strips. Therefore, this study recommends the application of plastic strips for improvement of the strength of soft clay for subgrade construction in civil engineering practice as an alternative weak soil stabilization method.

Keywords: plastic strips, stabilization, strength properties, soft clay

[1]MSc., Eng., Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Narutowicza 11/12, 80-233 Gdańsk, Poland, e-mail: worku.kabeta@pg.edu.pl, ORCID: 0000-0001-9792-8291

1. Introduction

Nowadays, waste management is the main concern of the world. Several researchers have been working on developing solutions for the reuse of various types of wastes generated in recent years, which has become one of the primary difficulties for environmental issues in many countries. Plastic waste is one of the common abundant waste types, especially in urban areas, as it is not biodegradable. These are the most commonly used materials in our everyday life. Plastic waste, such as plastic bottles made of polyethylene terephthalate (PET) and plastic sacks and carpets made of polypropylene (PP), is manufactured in large quantities. According to [1], the total daily production of plastic waste is estimated to be 15.4 billion pieces. The daily use of plastic products such as bottles, polythene bags, food containers and crates, pallets, kitchenware, appliances, and toys are increasing day by day, causing many environmental concerns. It has a negative impact on the environment and human health. Polyethylene products are considered to be the significant components of waste materials in Ethiopia and in 2015, the plastic consumption volume in Ethiopia reached around 172,000 tons [2]. It is expected to increase to some 308,000 tons of plastic by 2025.

On the other hand, weak soils cannot be used as a construction material as they cause excessive settlement and instability to the structures. Therefore, some treatment is required before they are used as construction subgrade. Recently, engineers have been looking for new environmentally friendly techniques to improve the geotechnical properties of problematic soils. Cement and lime, among other traditional soil stabilizers, are commonly used to improve the geotechnical properties of soft soils [3–5]. Various researchers have verified the effectiveness of these materials in improving soil properties [5–9]. However, despite of their widespread use, these products are not cost effective [10].

Recently, the usage of plastic waste materials as a soil stabilizer for construction material has been studied as an alternative to weak soil stabilizers [11, 12]. As a result, this will solve the environmental issue by reducing the amount of generated waste and recycling it to improve soil properties. The plastic strips can be used for soil stabilization [13], when mixed with soil, they act like fiber-reinforced soil. Different experimental studies have been done by various researchers on the effectiveness of soil improved by plastic waste [14–21]. They discovered that stabilizing weak soils using plastic waste materials enhances their properties by increasing unconfined compressive strength (UCS), California Bearing Ratio (CBR), and maximum dry density (MDD) while lowering soil plasticity.

Plastic waste has been also found to improve the shear, stiffness, and bearing capacity of pavements when used as a replacement for aggregate in base and subbase of road construction [22]. Choudhary *et al.* [23, 24] and [25] observed similar results, concerning improved characteristics in pavement reinforced with recycled plastic strips. Arulrajah *et al.* [26] investigated the feasibility of using plastic waste granules with demolition waste in road construction mixtures. Their study revealed that polyethylene plastic granules of about 5% content is suitable as a road construction material, when blended in supplementary amounts with demolition wastes. Their research is important because the use of plastics as a construction material, along with demolition wastes, will speed up the acceptance of recycled by-products by the construction industry. The high tensile strength of fiber contributes to the soil's ability to withstand more loads and raise its UCS [27]. To improve the compressive and tensile strength of clayey soils, Abousninal *et al.* [28] combined polyethylene waste material (water bottles) in the form of fibers with cement. The fiber contents consisted of 0.4%, 0.8%, and 1.2% of the dry soil weight, and the fiber lengths were 1.0 cm, 2.0 cm, and 3.0 cm. He found that fiber-stabilized soil was more effective in unconfined compressive strength (UCS) than tensile strength. The optimum fiber content and fiber lengths were 1.2% and 2.0 cm, respectively.

The study by Alemneh *et al.* [29] shows that the soil in Jimma town is not suitable for highway subgrade and they recommend to stabilize the soil before use. Hence, in this study, the application of plastic waste recycling for the stabilization of weak subgrade was proposed. A series of laboratory tests concerning the strength and compaction characteristics of natural soil from the campus of Jimma University and the mixtures of natural soil-plastic strips from PET bottles were considered. A variety of standard geotechnical laboratory experiments such as standard Proctor test, unconfined compression test, and California bearing ratio (CBR) were carried out to identify the effects of plastic fibers content on the mechanical properties of the improved soil.

2. Experimental program

2.1. Materials

For this study, two soil and plastic waste strips were used. The soil used was collected from Ethiopia, inside Jimma university. The geotechnical properties of natural soil were described in Table 1 below. The previous study [30] shows that the majority of the soil covering the study area was soft clay showing swelling behavior. The X-ray diffraction (XRD) pattern identified by Alemneh *et al.* [29] shows that the dominant minerals present in the soil in the study areas are illite, kaolinite, quartz, montmorillonite, and anorthite. Another material used for this study was plastic waste as shown in Fig. 1, prepared as plastic strips of length 1 cm and 2 cm with a width of 2.5 mm and 3 mm, respectively.

Table 1. Physical properties of the natural soil

Soil Properties	Results
Specific gravity (g/cm^3)	2.8
Liquid limit (%)	49
Plastic limit (%)	32
Plasticity Index (%)	17
Maximum dry density (g/cm^3)	1.51
Percentage of finer than 0.075 mm (%)	95

Fig. 1. Materials used for the study

2.2. Research methods

For this study, sufficient amount of soil sample was prepared in the laboratory. Plastic waste from water bottle plastic was collected. Plastic strips were made by cutting waste bottles and mixed thoroughly with dry soil. The following percentage of plastic content was used: 0.20%, 0.30%, 0.40% of the dry weight of the soil. Different laboratory tests, such as the Standard Proctor test, unconfined compression test, and California bearing ratio (CBR), were done according to ASTM to study the mechanical properties of both natural and stabilized soils. For all investigations, the adopted fiber material was manually blended with the air-dried soil in small increments. Great care was taken to achieve a uniform mixture. The necessary amount of water was then added according to the type of test to be conducted. The results of laboratory tests for stabilized soil were analyzed and compared with that of natural soil. Lastly, graphs and charts are used to present the outcomes.

3. Result and discussion

3.1. Compaction test

In this study, the standard Proctor test was used to compact soil samples at a given water content in a standard mold with standard compaction energy. The standard Proctor test uses a 105 mm diameter mold with the compaction of three separate layers of soil using 25 blows by a 2.5 kg hammer with compaction energy of 593.7 kJ/m^3. American Society for Testing and Materials (ASTM) standard manual was used for the test methods. As a result, the soil was first air-dried before adding water to each sample to regulate the water content. The plastic strips prepared for this test were mixed into the soil. The soil mixed with plastic strips was then deposited and compacted in three layers in the Proctor compaction mold, with each layer receiving 25 standard hammer blows. The surface of the previous layers is scratched before each new layer is placed to guarantee uniform distribution of the compaction effects. After removing and drying the sample at the end of the test, the dry density and water content of the sample are determined for each Proctor test. Plastic strips did not break after the compaction. A compaction curve was plotted based on the entire set of results. The optimum water content for the achieved maximum dry density can be determined from the curve as shown in Fig. 2.

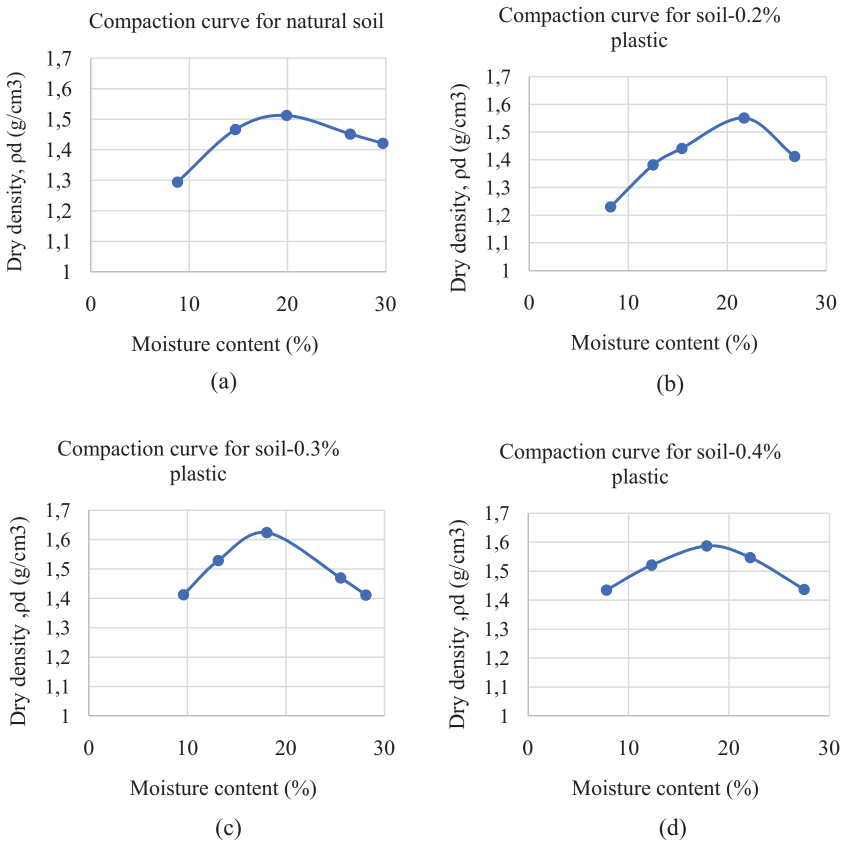

Fig. 2. Materials used for the study

Figure 2 shows the results of the compaction tests for both natural soils and soils stabilized with plastic strips at different stabilizer content ratios. Only the result of proctor test with plastic strip of 2 cm length was presented as there is no significant difference on the result for different length.

The optimum moisture content (OMC) was 19.82% for the natural soil, and the maximum dry density (MDD) was 1.51 g/cm^3. Maximum dry density was slightly increasing with the plastic content in the soil up to 0.3%. Then a small decrease was observed. This shows that there is an optimum plastic content that should be added to the soil in order to get high maximum dry density as it was already found by [6, 11, 31]. They discovered that the value of MDD reduces as the length and content of the plastic increases. The greatest reduction was obtained when the plastic component was 1% of the dry weight of the soil and the best length of plastic strip inclusion was 3.0 cm, according to the researchers. One should however note that the tests were limited to plastic content of 0.4% and we do not have data to describe an eventual further decrease of MDD with fiber content as it is suggested by other research data. The OMC of the improved soil is about 20%. No distinct tendency for OMC changes with plastic content was observed. Thus, for this study, the optimum compaction degree was assumed at 0.3% plastic waste content.

3.2. Unconfined compression strength

The Unconfined compression strength (UCS) test was aimed to find compression strength in an unconfined condition of the soil. The clayey soil samples of natural soil and soil reinforced with the strips of waste plastics had been subjected to unconfined compression test at the maximum dry density. Four samples were compacted at their MDD with 0, 0.2, 0.3, and 0.4% plastic waste strips addition, respectively. The height and diameter of the sample were 120.7 mm and 102 mm respectively. The samples were then placed in the UCS testing machine, incremental vertical load was applied to the sample, and readings were taken until the samples show visible cracks. It is noticed that the soil strength increased with plastic waste percentage. Therefore at 0.4% addition of plastic waste, the maximum unconfined compressive strength was observed.

Figure 3 shows that the addition of PE fibers considerably increased the stabilized soil strength at 0.4% of plastic content with 2 cm length by 76 kPa compared to the UCS of the natural soil. According to [32], when soils are stabilized with fibers, the applied load is transferred to the frictional interface between soil particles and fibers. The surface of the interfaces between soil and fibers increases with fiber content, improving thus friction between soil particles and fibers [33]. This blocks the movements of soil particles and improves the soil cohesion [32].

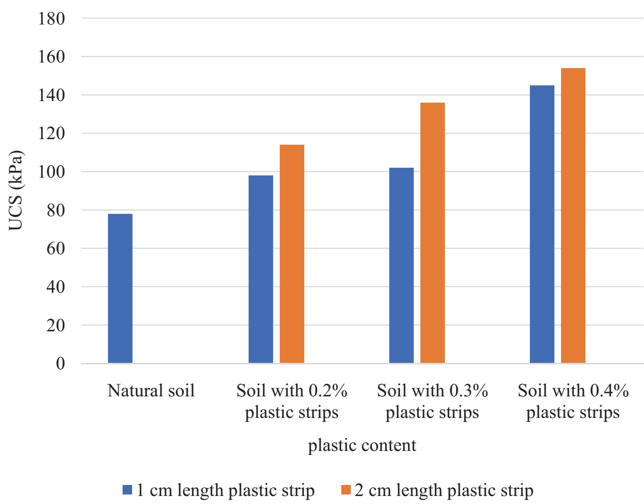

Fig. 3. UCS test results for different percentage of plastic content

It can be seen from Fig. 3 that the UCS increases with plastic content. According to [34], raising the fiber content beyond a certain percentage causes fiber panels to slip over each other and soil particles to detach, lowering the soil's strength. Such behavior was, however, not observed in this series of tests. The UCS results clearly showed that longer fiber lengths (2.0 cm) provide higher strength than shorter ones (1cm). This difference in UCS attenuates with plastic content. Several researchers have studied the effect of PE fiber length on UCS of soils providing similar results [22, 34–39]. Their findings showed that PE admixture to the natural soil significantly increases the UCS which is confirmed by the results of this study. One can also note that corresponding undrained shear strength of soil increase from 39 kPa in natural soil to 77 kPa in soil improved with 0.4% of plastic content and 2 cm length of plastic strips.

3.3. California bearing ratio

California Bearing ratio (CBR) is one of the parameters used to indicate the load-bearing capacity of subgrade soil for roadway pavement design. It is performed to evaluate the strength of soil subgrades and base course materials. This test was performed according to ASTM D1883 by measuring the pressure required to penetrate a soil sample with a plunger of standard area. The measured pressure is then divided by the pressure required to achieve an equal penetration in a standard soil. For this study, cylindrical soil sample were prepared at maximum dry density at optimum moisture content. Cylindrical mold with inside diameter 150 mm and height 175 mm was used. Loading machine with a capacity of 5000 kg and equipped with a movable base that moves at a constant rate of 1.25 mm/min and the calibrated proving ring is used to record the load. The test was conducted for both natural soil and the soil stabilized with plastic content of 0.20%, 0.3% and 0.4%. The samples were compacted at their previously obtained OMC in CBR mold, and the test was conducted till 12.9 mm of penetration. Measurements were taken and presented graphically. Fig. 4 shows CBR load versus penetration for different plastic percentages.

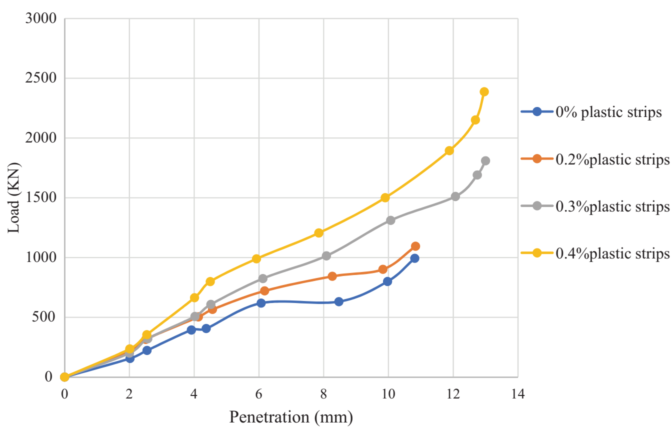

Fig. 4. Load vs. Penetration during CBR test for different plastic content

During CBR test, the load required to penetrate soil sample increased with the plastic content, leading to increase the CBR value of the improved soil as given in Fig. 5. The CBR value for natural soil indicates that the soil has a very low load-bearing capacity, implying that the soil must be stabilized before being used as a roadway subgrade. For pavement design, the CBR test is the most common method for determining and evaluating the load-bearing capacity of subgrade soil, subbase, and base materials. The CBR of subgrade soil is the most important factor in determining pavement layer thickness.

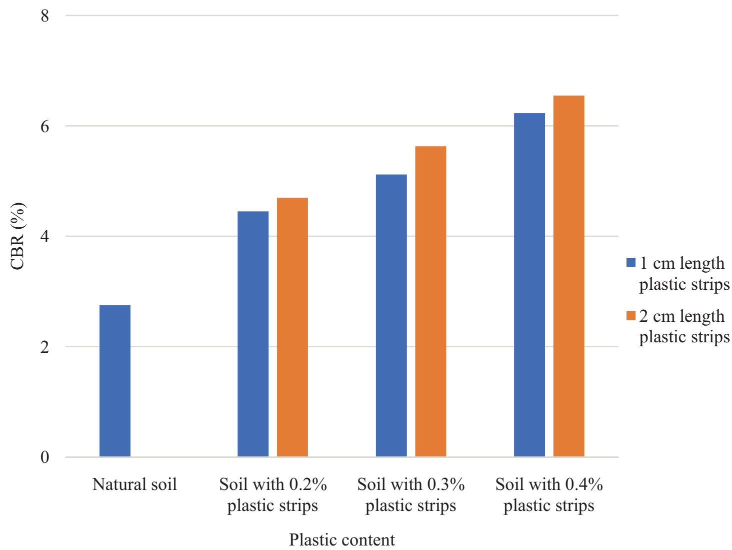

Fig. 5. CBR value with different plastic content and length

According to Ethiopian Road Authority (ERA) manual [40], which is utilized in Ethiopia to build a low-volume flexible paving system, the CBR value of most clay soils is less than 15 and the soil having CBR value less than 5 is classified as poor subgrade material and between 5 and 10, they are intermediate for subgrade material. Soils with a CBR greater than 10 are suitable for roadbeds of subgrade soil, according to Schaefer *et al.* [41]. The natural soils have low CBR value of 2.75 as shown in Fig. 5, making them unsuitable for subgrade without modification. The acquired result is consistent with research conducted in the same location [29, 42]. However, there is increase in CBR value as different plastic content and length is mixed with natural soil to improve the strength of the soil. Maximum CBR value is found at 0.4% of plastic content with 2 cm plastic length. The result also shows that, the length of plastic strips has an effect on the CBR value indicating 2 cm length plastic strips improve the soil more than plastic strips of 1cm length. The maximum dry density was however decreasing for plastic content higher than 0.3%. Thus, 0.3% plastic content can be accepted as the optimum amount of stabilizer. Hence, 0.3% plastic content with 2 cm length in the soil sample is recommended because it provides tight soil packing with a good CBR value of 5.63%.

4. Conclusions

Plastics play an important role in day-to-day activities of human beings and the amount of waste generated at the end of their use is predictable. As a result, using these plastic wastes for diverse construction applications is a realistic solution for theirs appropriate managing while promoting environmental sustainability. Thus, recycling plastic waste to improve strength of weak clay soil is proposed in this study. A series of strength and compaction tests was performed on natural soil and the clay samples with plastic content up to 0.4%. Accordingly, from the standard Proctor test, maximum dry density increases up to 0.3% plastic content and then is getting lower. The change in compaction parameter (maximum dry density) as a function of plastic content is smaller than the variation of strength parameters considered in this study. This result is similar to the finding obtained by Soltani *et al.* [43]. The unconfined compressive strength of the soil increases with plastic content. Its maximum value is 154 kPa obtained at 0.4% plastic content and 2 cm length plastic strips. It is about 138% higher than for the natural soil, where only 78 kPa is measured. While performing the CBR test, it was observed that the CBR value are increasing from 2.75% at 0% of plastic content to 7.95% at 0.4% plastic strip content and 2 cm length of plastic strip. This improvements in CBR value makes the soil from unsuitable to suitable range for subgrade in road constructions as per ERA manual [40]. From all tests, the strength of natural soil was improved as the percentage of plastic increased, except for the maximum dry density in which the optimum plastic content is observed. Hence 0.3% plastic content of the strips mixed with the natural soil can be considered as the optimum percentage in this study. At this plastic content the soil compacted at optimum moisture content is tightly packed and the soil-plastic strip mixture provides much higher strength than natural soil. Therefore, strips of plastic waste can be used as an alternative soil stabilization for the construction of roads and other civil engineering structures. From this study, it is possible to conclude that recycling plastic waste has an advantage not only in reducing environmental pollution, but they can be also used for weak soil stabilization as an alternative to traditional soil improvement methods. It can be also considered as sustainable solution with plastic wastes treated as a reliable source of materials for construction purposes.

References

[1] C. Godswill, C. Gospel, "Impacts of Plastic Pollution on the Sustainability of Seafood Value Chain and Human Health", *International Journal of Advanced Academic Research. Sciences, Technology and Engineering*, 2019, vol. 5, no. 11, pp. 2488–9849.

[2] M. Tilaye, M.P. van Dijk, "Sustainable Solid Waste Collection in Addis Ababa: the Users? Perspective", *International Journal of Waste Resources*, 2014, vol. 4, no. 3, DOI: 10.4172/2252-5211.1000158.

[3] M. Aytekin, E. Nas, "Soil stabilization with lime and cement", *Teknik Dergi/Technical Journal of Turkish Chamber of Civil Engineers*, 1998, vol. 9, pp. 471–477.

[4] J.S. Yadav, S.K. Tiwari, "Behaviour of cement stabilized treated coir fibre-reinforced clay-pond ash mixtures", *Journal of Building Engineering*, 2016, vol. 8, pp. 131–140, DOI: 10.1016/j.jobe.2016.10.006.

[5] J.S. Yadav, S.K. Tiwari, P. Shekhwat, "Strength Behaviour of Clayey Soil Mixed with Pond Ash, Cement and Randomly Distributed Fibres", *Transportation Infrastructure Geotechnology*, 2018, vol. 5, no. 3, pp. 191–209, DOI: 10.1007/s40515-018-0056-z.

[6] H.J.A. Hassan, J. Rasul, M. Samin, “Effects of Plastic Waste Materials on Geotechnical Properties of Clayey Soil", *Transportation Infrastructure Geotechnology*, 2021, vol. 8, no. 3, pp. 390–413, DOI: 10.1007/s40515-020-00145-4.

[7] J.M. Rasul, G.S. Ghataora, M.P.N. Burrow, “Permanent deformation of stabilized subgrade soils”, in *Bituminous Mixtures & Pavements VI – Proc. 6th Int. Conf. Bitum. Mix. Pavements, ICONFBMP 2015*. London: CRC Press, 2015, pp. 41–48, DOI: 10.1201/b18538-8.

[8] J.M. Rasul, M.P.N. Burrow, G.S. Ghataora, “Consideration of the deterioration of stabilised subgrade soils in analytical road pavement design”, *Transportation Geotechnics*, 2016, vol. 9, pp. 96–109, DOI: 10.1016/j.trgeo.2016.08.002.

[9] J.M. Rasul, G.S. Ghataora, M.P.N. Burrow, “The effect of wetting and drying on the performance of stabilized subgrade soils”, *Transportation Geotechnics*, 2018, vol. 14, pp. 1–7, DOI: 10.1016/j.trgeo.2017.09.002.

[10] S.Y. Amakye, S.J. Abbey, C.A. Booth, A.-M. Mahamadu, “Enhancing the Engineering Properties of Subgrade Materials Using Processed Waste: A Review”, *Geotechnics*, 2021, vol. 1, no. 2, pp. 307–329, DOI: 10.3390/geotechnics1020015.

[11] T. Kumar, S. Panda, S. Hameed, J. Maity, “Behaviour of soil by mixing of plastic strips”, *International Research Journal of Engineering and Technology*, 2018, vol. 5, no. 5, pp. 2579–2581.

[12] D.S.A. Khattab, I.M. Al-Kiki, A.H. Al-Zubaydi, “Effect of Fibers on Some Engineering Properties of Cement and Lime Stabilized Soils”, *Engineering and Technology Journal*, 2011, vol. 29, no. 5, pp. 886–905.

[13] T. Yetimoglu, O. Salbas, “A study on shear strength of sands reinforced with randomly distributed discrete fibers”, *Geotextiles and Geomembranes*, 2003, vol. 21, no. 2, pp. 103–110, DOI: 10.1016/S0266-1144(03)00003-7.

[14] G.L.S. Babu, S.K. Chouksey, “Stress-strain response of plastic waste mixed soil”, *Waste Management*, 2011, vol. 31, no. 3, pp. 481–488, DOI: 10.1016/j.wasman.2010.09.018.

[15] A. Eltayeb, “The Use of Shredded Plastic Water Bottles in Soil Stabilization”, 2021, vol. 13, pp. 37–44.

[16] E. Ahmadinia, M. Zargar, M.R. Karim, M. Abdelaziz, E. Ahmadinia, “Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt”, *Construction and Building Materials*, 2012, vol. 36, pp. 984–989, DOI: 10.1016/j.conbuildmat.2012.06.015.

[17] A. Modarres, H. Hamedi, “Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes”, *Materials and Design*, 2014, vol. 61, pp. 8–15, DOI: 10.1016/j.matdes.2014.04.046.

[18] A. Fauzi, Z. Djauhari, U. Juniansyah Fauzi, “Soil Engineering Properties Improvement by Utilization of Cut Waste Plastic and Crushed Waste Glass as Additive”, *International Journal of Engineering and Technology*, 2016, vol. 8, no. 1, pp. 15–18, DOI: 10.7763/ijet.2016.v8.851.

[19] P. Rawat, A. Kumar, “Study of CBR Behaviour of soil reinforced with HDPE strips”, *Indian Geotechnical Conference, IGC2016*, pp. 15–18. [Online]. Available: https://www.researchgate.net/publication/335946698.

[20] S. Peddaiah, A. Burman, S. Sreedeep, “Experimental Study on Effect of Waste Plastic Bottle Strips in Soil Improvement”, *Geotechnical and Geological Engineering*, 2018, vol. 36, no. 5, pp. 2907–2920, DOI: 10.1007/s10706-018-0512-0.

[21] K. Salimi, M. Ghazavi, “Soil reinforcement and slope stabilisation using recycled waste plastic sheets", *Geomechanics and Geoengineering*, 2021, vol. 16, no. 6, pp. 497–508, DOI: 10.1080/17486025.2019.1683620.

[22] M. Sai, V. Srinivas, ”Soil Stabilization by Using Plastic Waste Granules Materials", *IOSR Journal of Computer Engineering*, 2017, vol. 21, no. 4, pp. 347–354, https://www.iosrjournals.org/iosr-jce/papers/Vol21-issue4/Series-2/G2104024251.pdf.

[23] A.K. Choudhary, J.N. Jha, K.S. Gill, “Utilization of plastic wastes for improving the sub-grades in flexible pavements”, in *Paving materials and pavement analysis*. 2010, pp. 320–326, DOI: 10.1061/41104(377)39.

[24] A.K. Choudhary, J.N. Jha, K.S. Gill, S.K. Shukla, “Utilization of fly ash and waste recycled product reinforced with plastic wastes as construction materials in flexible pavement”, in *Geo-Congress 2014: Geo-characterization and Modeling for Sustainability*. 2014, pp. 3890–3902, DOI: 10.1061/9780784413272.377.

[25] A.K. Choudhary, J.N. Jha, K.S. Gill, “A study on CBR behavior of waste plastic strip reinforced soil”, *Emirates Journal for Engineering Research*, 2010, vol. 15, no. 1, pp. 51–57.

[26] A. Arulrajah, E. Yaghoubi, Y.C. Wong, S. Horpibulsuk, "Recycled plastic granules and demolition wastes as construction materials: Resilient moduli and strength characteristics", *Construction and Building Materials*, 2017, vol. 147, pp. 639–647, DOI: 10.1016/j.conbuildmat.2017.04.178.

[27] C. Tang, B. Shi, W. Gao, F. Chen, Y. Cai, "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil", *Geotextiles and Geomembranes*, 2007, vol. 25, no. 3, pp. 194–202, DOI: 10.1016/j.geotexmem.2006.11.002.

[28] R. Abousnina, *et al.*, "Effect of short fibres in the mechanical properties of geopolymer mortar containing oil-contaminated sand", *Polymers*, 2021, vol. 13, no. 17, DOI: 10.3390/polym13173008.

[29] A. Sorsa, S. Senadheera, Y. Birru, "Engineering Characterization of Subgrade Soils of Jimma Town, Ethiopia, for Roadway Design", *Geosciences*, 2020, vol. 10, no. 3, DOI: 10.3390/geosciences10030094.

[30] W. Firomsa, "Parametric Modelling on the Relationships Between Atterberg Limits and Compaction Characteristics of Fine-Grained Soils", *International Journal of Advanced Research* in *Engineering and Applied Sciences*, 2019, vol. 388, no. 7, pp. 1–20. [Online]. Available: www.garph.co.uk.

[31] R.P. Bala, P. Arun, S.A. Chandra, "A study on CBR behaviour of waste plastic (PET) on stablised red mud and fly ash", *International Journal of Structural and Civil Engineering Research*, 2013, vol. 2, no. 3, pp. 231–240.

[32] A.S. Muntohar, A. Widianti, E. Hartono, W. Diana, "Engineering Properties of Silty Soil Stabilized with Lime and Rice Husk Ash and Reinforced with Waste Plastic Fiber", *Journal of Materials in Civil Engineering*, 2013, vol. 25, no. 9, pp. 1260–1270, DOI: 10.1061/(asce)mt.1943-5533.0000659.

[33] M. Olgun, "Effects of polypropylene fiber inclusion on the strength and volume change characteristics of cement-fly ash stabilized clay soil", *Geosynthetics International*, 2013, vol. 20, no. 4, pp. 263–275, DOI: 10.1680/gein.13.00016.

[34] S.A. Naeini, S.M. Sadjadi, "Effect of waste polymer materials on shear strength of unsaturated clays", *Electronic Journal of Geotechnical Engineering*, 2008, vol. 13, pp. 10–12.

[35] A.J. Puppala, C. Musenda, "Effects of fiber reinforcement on strength and volume change in expansive soils", *Transportation Research Record*, 2000, vol. 1736, no. 1, pp. 134–140, DOI: 10.3141/1736-17.

[36] P.J. Venda Oliveira, A.A.S. Correia, J.C.A. Cajada, "Effect of the type of soil on the cyclic behaviour of chemically stabilised soils unreinforced and reinforced with polypropylene fibres", *Soil Dynamics and Earthquake Engineering*, 2018, vol. 115, pp. 336–343, DOI: 10.1016/j.soildyn.2018.09.005.

[37] A. Zukri, R. Nazir, F.N. Mender, "An experimental study on stabilization of Pekan clay using polyethylene and polypropylene", *AIP Conference Proceedings*, 2017, vol. 1892, no. 1, DOI: 10.1063/1.5005668.

[38] S. Pal, V.K. Sonthwal, J.S. Rattan, "Soil Stabilisation Using Polypropylene as Waste Fibre Material", *International Journal of Innovative Research in Science, Engineering and Technology*, 2015, vol. 4, no. 11, pp. 10459–10469, DOI: 10.15680/ijirset.2015.0411008.

[39] N. dos S.L. Louzada, J.A.C. Malko, M.D.T. Casagrande, "Behavior of Clayey Soil Reinforced with Polyethylene Terephthalate", *Journal of Materials in Civil Engineering*, 2019, vol. 31, no. 10, DOI: 10.1061/(asce)mt.1943-5533.0002863.

[40] Ethiopian Roads Authority (ERA), *Pavement Design Manual, vol. 1: Flexible Pavements*. 2013.

[41] J.L. Schaefer, R.V. White, J.D. Ceylan, H. Stevens, *Design Guide for Improved Quality of Roadway Subgrades and Subbases*. Iowa State University, 2008.

[42] J. Jibril, "In-depth investigation into engineering characteristics of Jimma Soils", Msc. thesis, Addis Ababa University, Ethiopia, 2014.

[43] H. Soltani-Jigheh, "Compressibility and Shearing Behavior of Clayey Soil Reinforced by Plastic Waste", *International Journal of Civil Engineering*, 2016, vol. 14, no. 7, pp. 479-489, DOI: 10.1007/s40999-016-0068-4.

Received: 01.01.2022, Revised: 22.03.2022