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Utilizing solid plastic wastes in subgrade pavement layers to reduce plastic environmental pollution

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ABSTRACT

The present study investigated the utilization of plastic wastes as reinforcement to improve the strength and swelling behavior of weak subgrade expansive soils and reduce plastic pollution. Expansive soils are known for their volume change during different seasons, while plastic waste is the most hazardous waste pollutant material that causes damage to the environment and organisms. Utilizing plastic wastes in subgrade construction reduces the quantity of waste and improves the problematic behavior of expansive soils.

The studied soil is categorized as expansive clay soil according to the AASHTO soil classification system. Various geotechnical laboratory tests were conducted by varying the plastic strip sizes with treatment percentages of 0%, 0.25%, 0.5%, 1%, 1.5% and 2%. The study found that swelling percentages and compaction parameters were decreased with an increase in plastic waste strips. As percentages of plastic strips increase, CBR values increase while unconfined compressive strength increases up to 0.5% addition of plastic strips and then slightly decreasing. The cohesion of the soil increases up to 1.5% of plastic strips addition. The study recommends that the utilization of plastic waste in subgrade road construction is the best alternative to improve the strength of expansive soils and reduce environmental pollution.

1. Introduction

Expansive soil, the most difficult soil working with, is found in most countries around the world, including Ethiopia. The volume of expansive soil swells during the wet season, and shrinks during the dry season. The condition of shrinking and expanding of expansive soils leads to bearing capacity failure and excessive settlement, which might lead to huge damage to infrastructures (Rao, 2000). In recent years, expansive soils have became the cause of the destruction of many projects in Ethiopia (Uba, 2017).

Studies recommend that expansive soils must be treated before starting the construction of any structures on them. Stabilizations, blending, soil reinforcement, and replacing the soil with coarse material are some of the techniques used to overcome the problem of expansive soils. Stabilization is a method by which the engineering properties of weak soils can be improved and become suitable for construction. Stabilization improves the strength of the soil and reduces swelling properties significantly. From an economic point of view, stabilization saves the enormous cost required for replacing weak soil. Stabilization may be mechanical or chemical such as cement, lime, thermal, bituminous, grouting, and electrical stabilization (Seco et al., 2011).

More than 100 million tons of plastics are manufactured, and 200 billion pounds of new plastic material are foamed across the world per year. In addition to this, more than one million plastic bottles are purchased per minute and more than five trillion plastic bags per year (Teshome, 2020). According to research conducted in 2015, Ethiopia had over 486 plastic manufacturing enterprises, with 66% of them confirmed to have breached the rules in proclamation number 513/2007 (Regassa et al., 2017). Due to a lack of awareness of the society on the adverse effects of plastics, they threw away in the open areas and water bodies after use. Thus, plastic waste ranked third next to food and paper wastes by polluting the environment. The complex behavior of plastic wastes is their durability as it takes a long time to decompose (Kassahun et al., 2019).

Soil stabilization with waste materials such as demolished construction materials, bricks, fly ash, and factory byproducts are becoming popular. The most hazardous waste to the environment is plastic waste because it takes too much time to decompose. There are a needs of developing new methods to waste plastic disposal (Asgedom and Abraha, 2012). Using these trash, as a road layer material is the most cost-effective, reduces pollution, and improves the unpredictable properties of weak soil (Aamir et al., 2019) following the stabilization

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standard procedures (Nair, 2008). Many researchers have found that the use of plastic fibers significantly improves the engineering properties of soils. Studies have revealed that, the addition of waste plastic strips with cement kiln (Shafat, 2019), waste plastic strips with lime (Venkata et al., 2017), waste plastic strips with brick powder (Amena, 2021), waste brick powder mixed with lime (Reddy et al., 2018), and randomly distributing fiber as reinforcement (Rabindra Kar, 2011) caused an increase in strength properties, swelling potential, and frictional resistance of fine-grained soil. The studies on the effect of HDPE plastic waste on some soil concluded that constructing flexible pavement to improve the subgrade soil of pavement using waste plastic bottles chips is an alternative method (Niteen, 2018).

A series of researchers found that HDPE plastic waste improves the CBR and UCS values of black cotton soil. Studies done on polyethylene, bottles, and shopping bags as reinforcement mixed with lime and rice hush ash (Muntohar et al., 2013), and crushed waste glass (Fauzi et al., 2016) found that the unconfined compressive strength and CBR values improved slightly. The study done by mixing waste plastic High-density Polyethylene (HDPE) and waste crushed glass as reinforcement for subgrade strength improvement shows that engineering properties of samples such as plastic index, compaction characteristics, and strength properties are improved (Muntohar et al., 2013).

Although many studies were done, adequate plastic strip sizes, shapes, and percentages were not specified and fixed. The present study was conducted using rectangular plastic strip sizes of 5*8 mm, 8*15 mm, and 15*25 mm at 0.25%, 0.5%, 1%, 1.5%, and 2% percentages of plastic waste strips to introduce the usage of plastic waste chips as a reinforcement to improve the strength of the flexible pavement's subgrade layer. This study introduces the utilization of plastic waste in road construction in an environmentally friendly way that highly contributes to pollution reduction and enhances the strength of pavement layers. This utilization of plastic waste improves the permeability of the embankment, which highly minimizes the development of pore water pressure, it makes the embankment lightweight that reduces the weight of the fill material to minimize the settlement and increase the durability by improving the bonding of the mixing.

2. Materials and methods

2.1. Materials used in the study

A representative soil sample was collected from a selected site in Jimma town, Ethiopia. Particle size distribution, atterberg limit tests, specific gravity, compaction parameters, strength parameters, and soil test swelling properties were carried out to characterize the soil sample. Plastic wastes, mainly plastic water bottles, were collected from open spaces. The collected plastic waste is cut into strips with specified width and length manually.

2.2. Grain size analysis

The objective of grain size analysis is to determine the percentage of soils passing different sieve opening sizes. A wet sieve, the test for cohesive soils to disintegrate sticky soil particles into their original particle size by soaking and washing in water and sieving the retained portion mechanically as per the standard, was conducted (ASTM D6913M-17, 2017). The test results in Fig. 1 show that above 50% of the entire soil samples passed a sieve of 0.075 mm, which indicates that the selected soil sample was categorized under fine-grained soils according to the Unified Soil Classification System (Howard, 1984).

2.3. Atterberg limits

The purpose of conducting Atterberg limit test is to know the plasticity properties of soil and to use it as input index parameters for soil classification. The liquid limit of the soil was determined by using the Casagrande method. The plastic limit is the value of moisture content at which soil changes from the plastic state to the semisolid state; it is obtained by rolling a soil paste on glass into 3 mm diameter until it begins crumbling (ASTM D4318-17, 2017). The result shows that the liquid limit is 88.5%, while the plastic limit is 43.6%.

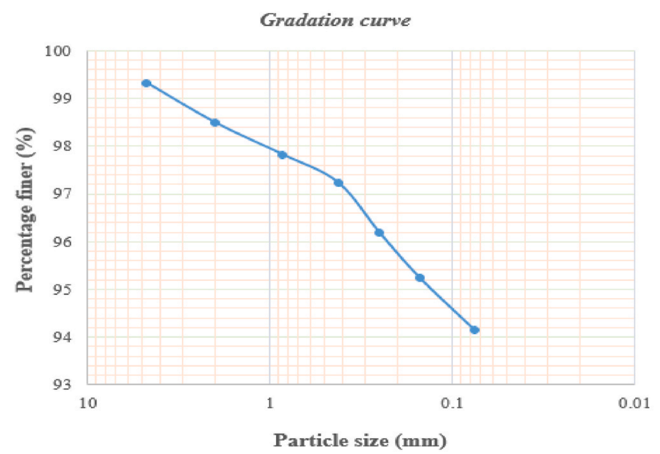

Fig. 1. Gradation curve of soil sample.

2.4. Compaction characteristics

The soil's compaction characteristics (maximum dry density and optimum moisture content) were determined using a standard compaction test (ASTM D698-12, 2012). At least three trials of air-dried soil samples were compacted with 25 blows at three layers. After compaction, the top of the mold is trimmed, and the mass of the compacted soil is measured. The moisture content of the compacted soil is measured as well. Using the densities and moisture contents of the compacted soil trials, a graph of dry density versus moisture content is drawn from which MDD and OMC values are obtained. The test results show the maximum dry density of the soil is 1.375 g/cc at the optimum moisture content of 37.5%.

2.5. Unconfined compressive strength

An unconfined Compressive Strength test was carried out using samples collected from the chosen location according to the standard (ASTM D2166-16, 2016). As a result, the soil's peak strength determined from this test is 80 kPa. The soil is classified as medium stiff clay soil with this UCS value.

2.6. Californian bearing ratio (CBR)

The soaked CBR test was carried out to measure the strength of the subgrade soil at the worst condition of the ground (ASTM D1883-16, 2016). The bearing ratio is calculated by dividing the loads obtained at 2.54 mm, and 5.08 mm penetrations by their corresponding standard loads, 13.24 KN and 19.96 KN respectively. Using the value of CBR for each point, the graph of CBR to dry density is plotted. The value of CBR of the soil at 97% MDD (1.333 g/cc), was taken as 1.98%. This value indicates that the bearing resistance of the soil sample is poor. According to the Ethiopian roads authority standard, soil with a CBR value of 1.98% cannot be used as a subgrade layer material.

2.7. Free swell test

The complex behavior of expansive soils is their volume fluctuation with seasonal changes. During the wet season, the moisture content of the ground is high, which initiates the swelling of the soil. During the dry season, the moisture content decreases with a shrinking volume of the soil. When water meets expansive soils, it breaks the bond between soil particles penetrating the layers. The free swell test was carried out to measure the swelling percentage of the soil sample. The series of tests were conducted according to ASTM standards by varying plastic waste strips sizes and percentages (ASTM D4546 - 21, 2021). Accordingly, the free swell of the soil alone is observed to be 134%, which is categorized under highly expansive soil.

3. Results and discussion

3.1. Effect of plastic waste strips on swelling properties

The purpose of this study is to overcome the swelling problem of expansive soils. The volume of expansive soil increases with an increase in moisture content and vise versa. During free swell tests, some percent of plastic strips are added to the soil to alter the swelling of soil volume. A good improvement is observed in the value of free swell with the addition of plastic strips.

As the sizes and percentage addition of plastic strips increases, the free swell values of the soil decrease. An increase in the size of the plastic strips creates a large gap between soil particles that alters interaction between soil particles. In the same way, the mass of the soil decreases as the percentages of plastic increase waste which leads to a reduction in swelling potential. Since plastic strips are chemically inactive to react with soil, there is no chemical reaction. As plastic strips alter the interaction between the soil particles so that swelling potential decreases.

A shown in Fig. 2, better improvement is obtained when 2% of 8*15 mm plastic strip is added to the soil. This shows a 57.83% improvement, which changes the state of the expansiveness of the study soil. Generally, as the percentages and sizes of the plastic waste strips increase, the swelling percentage of the soil decreases. The past researches proved the decrease of the swelling percentage of the soil with the addition of the plastic strips and fibers but the decrement percentage obtained in this study is better comparatively (Entesar, 2019; Kassahun et al., 2019; Soğancı, 2015).

3.2. Effect of plastic waste strips on compaction parameters

The suitability of plastic strips for the improvement in engineering properties of soil is observed in terms of compaction characteristics, i.e., maximum dry density and optimum moisture content. Series laboratory compaction tests trials are done to measure the compaction parameters by varying the mixing proportion and strip sizes.

The addition of plastic waste strips at various percentages revealed a decrease in OMC. As shown in Fig. 3, the minimum value of OMC obtained at 2% addition of plastic strip sizes 5 × 8 mm, which resulted in a

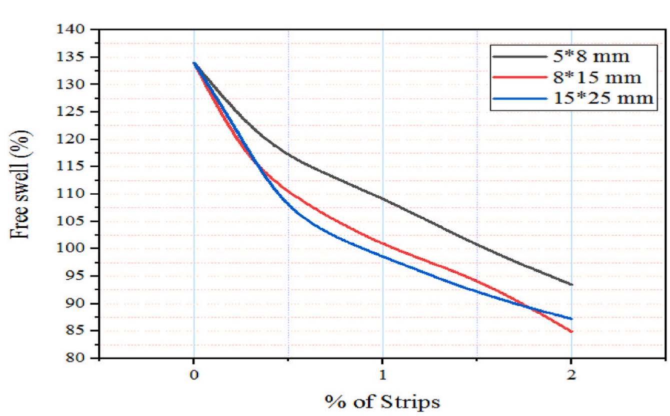

Fig. 2. Comparison of free swell values at different sizes and percentage of strips.

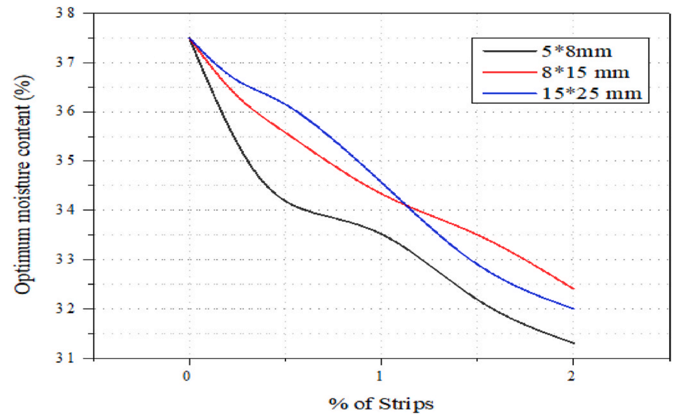

Fig. 3. Comparison of Optimum moisture content at different treatment levels.

19.8% decrease in moisture content. The fundamental reason for this drop in moisture content is that, the plastic strip's water absorption capacity is poor compared to soil materials. Almost similar trends of decrease in OMC were observed in research done using plastic fibers and strips (Choudhary and Jha, 2012; Hassan and Rasul, 2021; Saravanan et al., 2020; Rather and Bhat, 2021).

Fig. 4 reveals that the maximum dry density of soil slightly decreases as the percentages and sizes of the plastic wastes increase. Density decrease due to the replacement of some volume of the soil by lighter plastic waste strips for the constant volume. The minimum value of MDD is obtained at 2% addition of plastic strip with size of 8 × 15 mm. As a result, a 9.48% decrement in maximum dry density is observed. Some researches prove that the addition of plastic fibers resulted in a decrease in maximum dry density, while others suggest that it depends on the addition percentages (Hassan and Rasul, 2021; Sai and Author-Anonymous, 2019.; Rather and Bhat, 2021).

Generally, the addition of lighter materials such as plastic to a denser material results in a reduction in density. In this situation, the drop in maximum dry density might be balanced by the decrease in optimum moisture contents. Such decreases in density have an advantage in lightweight embankment construction, effective plastic waste disposal as landfill, and so on.

3.3. Effect of plastic waste strips on unconfined compressive strength

The unconfined compressive strength laboratory test of the soil without treatment is obtained to be 80 kPa, which shows the soil is categorized as medium stiff. After treatment, all sizes and percentages of

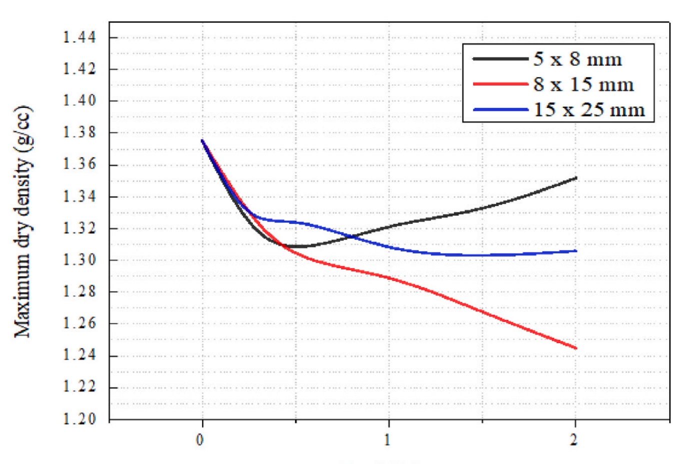

Fig. 4. Comparison of maximum dry density at different treatment levels.

the strips demonstrated better values of UCS after mix compared to the soil alone. The maximum value of unconfined compressive strength obtained is 192.8 kPa at 0.5% addition of 8 × 15 mm size of strips.

The increase in UCS values was obtained at small and medium-size strips. After 8*15 mm strip size addition, the value of UCS started decreasing. As the percentage and size of the strips increase beyond 8*15 mm, it starts making weak shear planes along which the soil can fail quickly. The formation of weak planes may be due to the smoothness of the surface of the plastic strips, which significantly affects the UCS values. The smooth surface has a low resistance to the shear component of the applied force.

As shown in Fig. 5, the optimum UCS value is obtained for 8*15 mm at the addition of 0.5%, 1%, and 1.5% from which 0.5% plastic strip addition gives peak improvement. In Fig. 5, the comparison of values of UCS obtained at different sizes and percentages of plastic strips is shown.

3.4. Effect of plastic waste strips on California bearing ratio

Soaked CBR was conducted to consider the worst condition of the site at which the soil was fully saturated. It also helps to understand the effect of water on the strength of expansive soil. Fig. 6 shows that as the percentage and size of plastic strip increases, the CBR value increases. The CBR value for a 5*8 mm plastic strip increased by 44.67% from 1.97 to 2.85. Similarly, for 8*15 mm strip size, the CBR value increased from 1.97 to 3.32, while it increased from 1.97 to 3.85 for 15*25 mm strip size as shown in Fig. 6.

The study shows that as the percentage and sizes of plastic waste strips increase, CBR values increase for addition up to 1.5%. Beyond 1.5% addition of plastic waste strips, the CBR values start slightly decreasing. The decrease in CBR values beyond 1.5% shows that the plastic strips have a low resistance to penetration and load exerted by the plunger. According to this study, an addition of 1.5% of plastic waste strips gives better results. The investigation done using plastic fibers found that the addition of plastic fibers resulted in CBR increases for 8*16 mm, 8*24 mm, and 8*8 mm, up to an addition of 1% only (Saravanan, 2020). According to (Rather and Bhat, 2021), CBR value has been increasing up to 4% plastic fibers and beyond that, it started to decrease. The research was done using plastic strips of 1 cm and 2 cm fibers demonstrated that the addition of plastic strips improves the deformation and strength of the soil with the addition of 4% (Hassan and Rasul, 2021).

3.5. Effect of plastic waste strips on direct shear test

The shear strength parameters of the treated soil directly depend on the arrangement of the plastic waste strips in the direct shear test box.

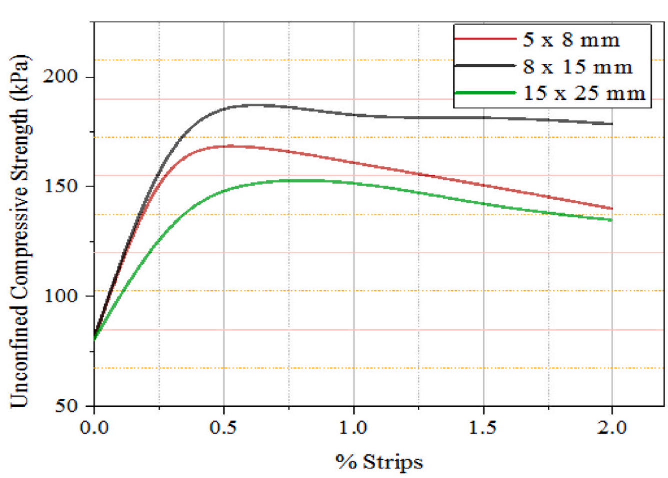

Fig. 5. Comparison of UCS values at different percentages and sizes of strips.

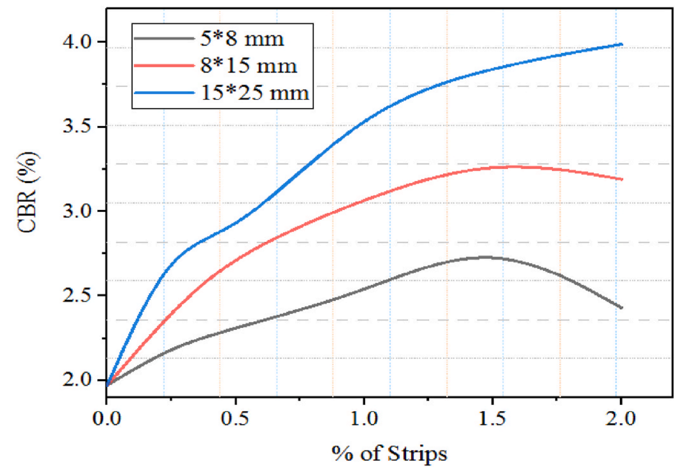

Fig. 6. Comparison of CBR values at different percentages and sizes of strips.

When the plastic waste strips are placed horizontally, i.e. parallel to the shear failure plan, it facilitates the failure due to the smooth surface of the plastic strips. When the plastic waste strips are placed vertically perpendicular to the failure plane direction, the sample withstands large shear force due to the stiffness of the plastic. For this study, the plastic waste strips were placed by randomly mixing the strips with soil.

As observed from direct shear test results, shear strength parameters increased with the addition of plastic waste strips. The cohesion and angle of internal friction of the untreated soil were found to be 35.1 kPa and 6.32^0.

Cohesion value increases as plastic strip percentage increases up to 1.5% and beyond that, it starts decreasing as shown in Fig. 7. The decrease in cohesion beyond 1.5% plastic strips addition implies that as the percentage of plastic strips increases it enhances the failure forming a weak sliding plane along the smooth surface of the plastic strips. As shown in Fig. 8, as the quantity of plastic strips increases, the friction between plastic strips and soil particles increases, which increases the angle of internal friction of the soil.

4. SWOT analysis on the utilizing plastic waste as subgrade material

Packaging reuse and packaging avoidance are better than recycling or utilizing for other purposes because it saves the energy needed to remanufacture and shape plastic waste into the required forms. It also plays a great role in reducing waste by saving the raw materials needed for plastic production. Opportunities to avoid packaging include delivering in bulk, changing the design of packaging, and searching for alternative distribution and handling methods. The opportunities for

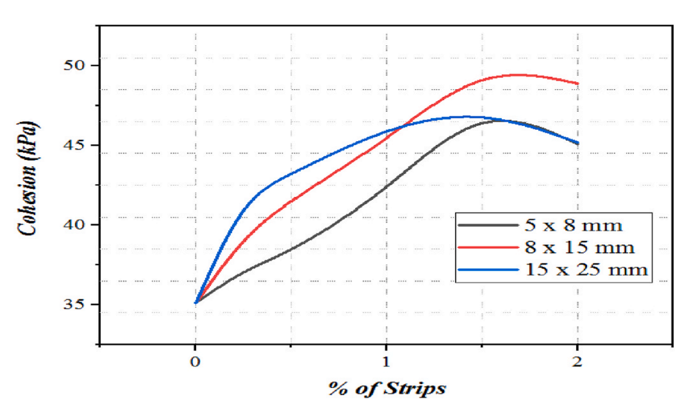

Fig. 7. Variation of Cohesion of the soil with a variation of plastic strips.

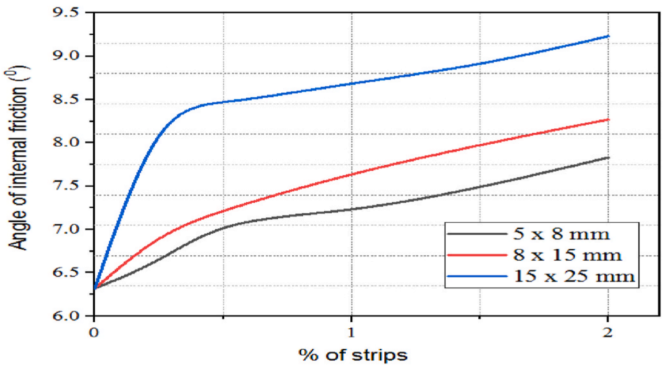

Fig. 8. Variation of the angle of internal friction of the soil with a variation of plastic strips.

package reuse can be achieved by making reuse packaging available within the company itself, suppliers, and other community groups. Reuse packaging can reduce material and disposal costs. However, it is difficult to control plastic pollution generated from users thrown away after use. All around the world, many urban areas and water bodies are highly polluted by plastic, which is an indicator of this. So that the best alternative for the throw-away plastic waste is utilizing in road construction rather than recycling.

The proposed plan for plastic waste utilization in road construction can be analyzed in terms of strengths, weaknesses, threats, and opportunities using SWOT analysis. SWOT analysis for this study helps to know the conditions that affect the study and to understand the ways and potentials required to implement the system effectively. The strengths and weaknesses are related to internal conditions, while threats and opportunities are to external conditions that affect the study. The detail of SWOT analysis is shown in Fig. 9.

4.1. Strengths

The addition of the plastic waste strips in subgrade pavement layers facilitates the flow of water in the embankment layer, which minimizes porewater development. The utilization of plastic waste in such an environmentally friendly way reduces the plastic environmental pollution that saves the life of many living organisms. It helps to minimize the cost of construction by preventing the replacement of weak soil with selected materials. It also reduces the dead weight of the embankment making a lightweight pavement layer that helps to minimize settlement of foundation loads. It also minimizes earthquake risks since the earthquake force depends on the weight of the structures.

4.2. Weakness

The smoothness and hydrophobic surfaces of plastic waste reduce the adhesive strength between plastic waste and soil particles. In addition to this, plastic waste and soil are made up of material with different grades and types, which might result in non-isotropic performance. All kinds of plastics have different physical and chemical properties, which might become a challenge in utilizing plastic waste in pavement construction. There is no standardized optimum percentage of plastic waste required to stabilize the weak soil. The environmental impacts and long-term performance of the plastic waste utilization method are not understood yet, which affects the usage and acceptance of this method. To understood in depth it needs deep investigation to examine its environmental impacts and long-term performance.

4.3. Opportunities

The program provides employment opportunities for local waste collectors and for those who work in circulation centers. It creates the establishment of a center where plastic wastes are collected. In addition, it needs government/non-governmental organization supports and public participation, which create public awareness on plastic waste management. It promotes the sustainable waste management system in the construction industry that the construction industry practices the usage of construction waste.

4.4. Threats

Cutting large volumes of plastic waste may require advanced technology that might be expensive. The cost of collecting, transporting, energy consumption, and recycling technology required has to be

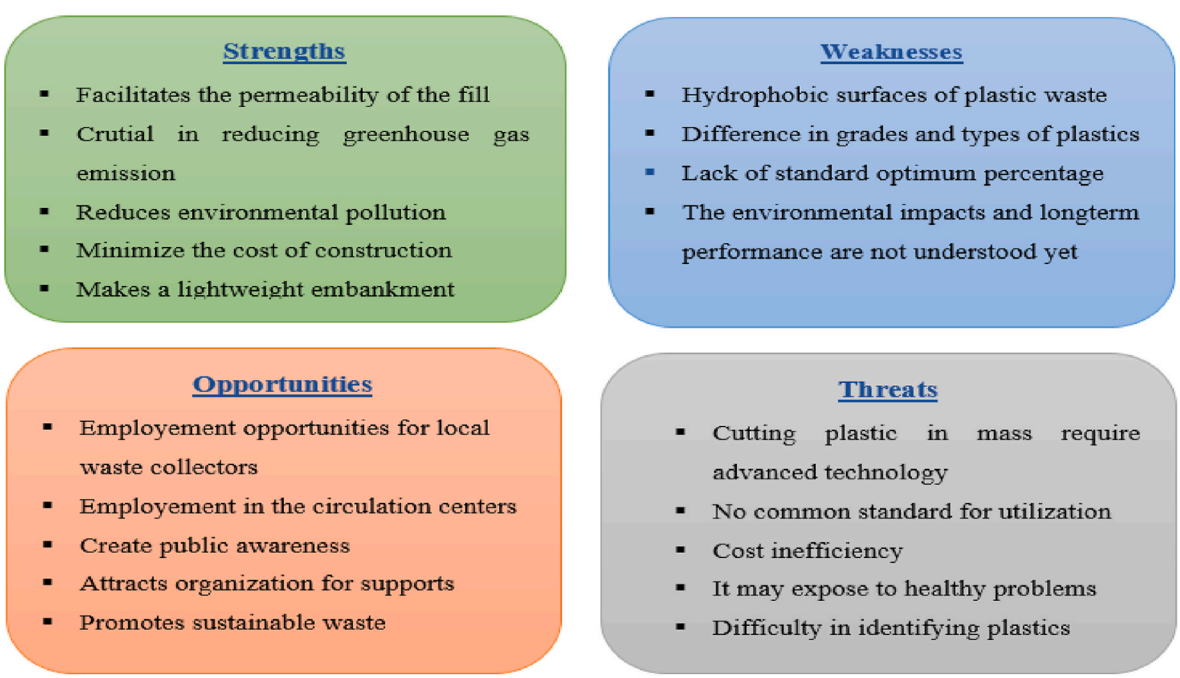

Fig. 9. Graphical presentation of SWOT analysis.

compared with the usage of the local selected materials. There is no fixed common standard for the application of plastic waste utilization in pavement construction yet. Identifying the suitable and unsuitable plastics for utilization in road construction is difficult. During plastic waste collection and identification, it may expose workers to health problems if safety is not assured.

5. Conclusion

This study aims to improve the strength of the expansive soils and reduce pollution by utilizing the waste plastic strips for the subgrade layer of the road pavements. The study can have two purposes. One, creating a proper disposal method of plastic wastes and the second is to improve the subgrade layer properties of road pavements. Based on the analysis and interpretations of the following conclusions are drawn.

When plastic strips of different sizes and percentages were added to soil, a reduction in both MDD and OMC was observed. Decrement in the density of pavement layer materials has an advantage in some engineering works, such as lightweight embankment construction.

As the percentage of strips increases, the swelling potential of the soil significantly decreases. This may be due to the replacement of an equal mass of the soil with a plastic strip. The addition of plastic waste strips improves the UCS value of the soil significantly. Comparatively, the values obtained for 8*15 mm strip size are more significant; the size above 8*15 mm starts forming weak planes along which the soil can easily exposed to shear failure. Huge CBR value improvement was observed from the study. The increments in CBR values were obtained as the percentage of the strip increased.

Generally, based on the results of UCS, CBR, and swelling percentages to improve the difficulty of expansive soil properties, one can use 8*15 mm plastic size as an average. The study found that utilizing plastic waste strips as subgrade pavement material can open a door for proper plastic waste disposal methods and good soil improvements.

Conflict of interests

The author declares that there is no conflict of interests.

Notations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CBR	Californian bearing ratio
HDPE	High-density Polyethylene
MDD	Maximum dry density
OMC	Optimum moisture content
SWOT	Strength, Weakness, Opportunity, and Threat
UCS	Unconfined Compressive Strength

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