

Sustainable Use of Recycled Plastic in Embankment Construction: Implications for Hydraulic Performance and Construction Material Supply Chains

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ABSTRACT

The present study is concerned with the construction of hydraulic dams and seeks to give an in-depth account of how leaks can be controlled. The impact of leaks in dams is directly proportional to the amount of water entering them. This implies that whenever leaks are beyond a certain level, it affects the stability of hydraulic dams. It was therefore crucial to find ways of mitigating this negative impact. The ways in which this can be achieved include improving the geotechnical properties of the fill material. To do this, our research sought to include recycled polypropylene sheets. For this purpose, different sizes of PP plastic flakes were used and mixed with silty sand. The effects of these flakes on various parameters of hydraulic dams, such as seepage velocity, permeability, critical head, and piping resistance, were studied. Constant head tests and piping tests were conducted. The best combination of PP and silty sand was then used in constructing small-scale embankment dam models with and without horizontal drains. In our study on hydraulically operated dams, we conducted an evaluation of their performance in relation to the incorporation of property-enhancing materials. In our evaluation using 2% recycled polypropylene film, 10 x 10 cm in dimension, it was evident that there was a reduction in the permeability of the silted sand. This reduction in permeability was highly favorable because it led to an increase of 38% in the conservation properties of the silt sand. This effect of the incorporation of recycled plastic films in hydraulically operated dams did not only have a positive effect on the properties of the silt sand; it also had a positive effect on the groundwater level and erosion resistance. In a bid to validate our positive results and to provide them with a practical example, we used SEEP/W software in our study. This study had a significant impact in two key areas: environmental conservation through recycling of plastics and promotion of environmental-friendly approaches in hydraulically operated dams.

Keywords: Seepage, recycled plastics, polypropylene flakes, reinforced soil, piping resistance, embankment stability.

INTRODUCTION

Piping is one form of internal erosion that is commonly experienced by earthen embankments (Wang et al., 2024). Internal erosion by seepage can be described as the movement of the soil resulting from the movement of the soil particles through the pores of the soil (Jiang et al., 2023). This is driven by the hydraulic gradient. This can be experienced widely by hydraulic embankments. For example, piping can be experienced by levees, check dams, canal diversion structures, among other hydraulic structures (Abubakar Tadda et al., 2020). In order to prevent piping failure, the materials used must be able to withstand internal erosion. However, the amount of water that can be retained by the facility is usually large, and the engineers may be

forced to use the materials that are locally available since they are cheaper. Mixing the materials is a very environmentally friendly practice (Naran et al., 2022).

Hydraulic embankments play a major role in the management of water flow, mitigation of flood risks, and the facilitation of irrigation (Iqbal & Riaz, 2024). Embankments can come in many forms, including dikes, levees, earthen dams, and canal diversion structures (Devipriya et al., 2022). Embankments are important tools in the management of watersheds and floodplains (El Hourani & Broll, 2021). One challenge that is commonly experienced by earthen embankments is seepage, which can happen either through the embankment or at the base (El-Molla & Kilit, 2025). Although seepage is expected to happen to a certain extent, uncontrolled seepage is a major concern since it can lead to the slow erosion of the soil particles (Xiang et al., 2024). This can cause failure at the base of the embankment, resulting in the creation of subsurface passages. This kind of failure is known as piping. Piping can lead to the creation of permanent passages that can cause the failure of the embankment (Nan et al., 2023). Embankment failure is very dangerous since it can lead to flooding, structural failure, environmental degradation, and even loss of life (Irmawan et al., 2024).

Soil stabilization is the improvement of the geotechnical properties of the soil by using additives that increase the shear strength, reduce the permeability, and increase the durability. This is particularly important in areas where the indigenous soils exhibit certain unfavorable properties such as compressibility, low bearing capacity, and erosion. Research on the fiber-reinforced soil system was carried out to assess the viability of using the technique to combat the effects of piping. For example, Xu et al. (2021) carried out an experiment on the use of discrete fibers on silty sand material containing 20% fines content. The experiment resulted in increased resistance to piping. Another example is the research carried out by Asfaw et al. (2022), where the stability analysis of the Didese dam slope was done using the Morgenstern-Price method. This was followed by the analysis using the SLIDE V6.0 software. This example shows the importance of seepage control in the stability analysis of slopes.

Devipriya et al. (2022) developed an experiment aimed at determining the seepage velocity, the critical hydraulic heads, and the resistance to piping on silty sand materials containing different percentages (0.5%, 0.75%, 1.0%, and 1.25%) of polypropylene (PP) flakelike fibers. The experiment resulted in increased resistance to internal erosion by randomly aligned PP fibers. The viability of the fiber-reinforced soil system was further demonstrated by Langroudi et al. (2021), where the increase in the content of the fiber resulted in the reduction of the permeability and the increase in the critical hydraulic heads. This was particularly demonstrated on dense soils. The simulation of the seepage on heterogeneous earth dams using SEEP/W was done by Haghdoost et al. (2023), where the analysis was done both with and without the use of the cut-off walls.

The above-mentioned studies have extended their research to measure the impact of polypropylene fibers in clayey soils. Taha et al. (2020) proved that the use of polypropylene fibers improves the consolidation and shear strength of clays with different values of plasticity index. Following the same concept, Develioglu and Pulat (2021) observed changes in the values of cohesion and angle of internal friction with the introduction of polypropylene fibers at 1%, 1.5%, and 2% in saturated fields, resulting in an increase in strength up to 250%.

Recent developments have emphasized the use of plastic waste in a manner that is environmentally friendly. Gayar (2020) studied mixed plastic as reinforcement materials in embankments and canal linings and proved it effective in reducing seepage. Faeq et al. (2024) studied how carbon and glass fibers can be mixed to increase the collapsibility indices of

gypseous soil, while [Ramadhan et al. \(2024\)](#) used sugarcane bagasse fiber and polypropylene fiber in gypseous soil and proved that these fibers improved hydraulic properties to a great degree at low additive percentages (0.8% - 0.2%).

Later research by [Nagappa et al. \(2022\)](#) investigated Legemera earth dam seepage behavior using GeoStudio 2012, finally concluding that foundation depth and homogeneity of materials are paramount factors that control seepage flow. In an associated study, [Suad and Al-Hadidi \(2025\)](#) established an extensive numerical model of Al-Hilla Canal, validating hydraulic efficiencies of its works by means of two-dimensional simulations supported by GeoStudio software.

This research initiative attempts to investigate the hydraulic behavior of silty sand soil with added recycled polypropylene flakes with reference to previous scholarly works. The goal of this study is to assess the effectiveness of randomly distributed plastic in improving both piping and seepage resistance, to find optimal dosage and size of the flakes to bring about maximum effectiveness, and to establish broader applicability of this technique to sustainable embankment construction. The study is specifically concentrated in terms of comparing changes in seepage velocity, permeability, critical head, and piping resistance, as investigated by laboratory and numerical analysis, with perspectives toward establishment of an effective technique in using plastic wastes in embankment construction.

MATERIALS AND METHODOLOGY

In the present research, the use of polypropylene flakes as a reinforcement agent to improve the geotechnical characteristics of the soil was investigated. The PP flakes are obtained from the first stage of plastic recycling plants in Ramadi city. In these plants, plastic wastes collected from four different points of the city are shredded into pieces of irregular shapes, each measuring less than 3 x 3 cm. Generally, shredded plastic wastes are transferred to second-stage recycling plants. However, due to the high cost and power consumption of the second recycling stage, the present research adopted the use of raw PP flakes in their natural state, which provides a cost-effective and eco-friendly way of improving the geotechnical characteristics of the soil ([Figure 1](#)) ([Gaber et al., 2025](#)).



Figure 1: PP Flakes shape

The substrate of the present research was identified as silty sand, which was selected as the original soil due to its prevalence and engineering importance in hydraulic engineering. Soil samples were collected from an area 10 km east of Ramadi city. In order to maintain the original state of the subsoil, the uppermost 20 cm of the surface soil was removed to allow the collection of the samples at a deeper level. The collected samples were immediately stored in plastic bags to maintain the original state of their moisture and composition (Figure 2).



Figure 2: Silty sand soil

The soil samples, as listed in Table 1, were sealed in plastic bags immediately after collection. The immediate sealing of the samples in plastic bags was done to ensure that there is no loss of moisture from the samples and that they remain in their original condition for further testing. A thorough set of tests for various properties of the soil was carried out. These tests include the Grain Size Distribution Test, Standard Proctor Compaction Test, Direct Shear Test, Specific Gravity Test, and Porosity Test. To find out the particle size distribution of the given sample of soil, a sieve analysis of the sample was carried out according to ASTM Standard C136. The sieve analysis results have been used to plot a graph for the grain size distribution curve (Figure 3).

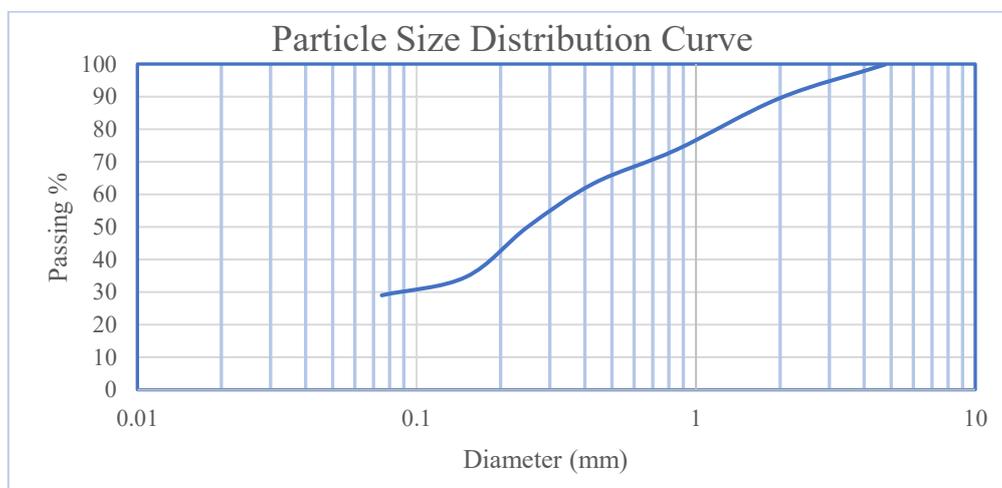


Figure 3: Size distribution curve for sand

Table 1: Physical and mechanical properties of the original silty sand

Property	Value
Specific gravity (SG)	2.54
Particle size distribution (PSD)	
(G)Gravel (%)	0
(S)Sand (%)	71
(Si)Silt (%)	24
(C)Clay (%)	5
(EPS)Effective particle size D_{10} (mm)	.075
(APS)Average particle size D_{50} (mm)	0.25
(CU)Coefficient of uniformity c_u	5.13
(CU)Coefficient of curvature c_c	0.0015
Classification (USCS)	SM
Max. dry weight (KN/m^3)	18.42
(OMC)Optimum moisture content (%)	12.3
Shear strength parameter	
Cohesion	17.4
Angel of internal friction ($^\circ$)	32.5

EXPERIMENTAL PROCEDURE

This test employs a direct measurement of permeability utilizing Darcy's Law (Kaboudan et al., 2021). It is appropriate for cohesionless soils with permeability. A standard configuration of the constant-head permeability test is illustrated in (Figure 4). In this laboratory configuration, the water supply at the intake is regulated to maintain a consistent differential head between the inlet and outflow during the testing duration. Following the establishment of a constant flow rate, water is gathered in a graduated flask for a specified duration.

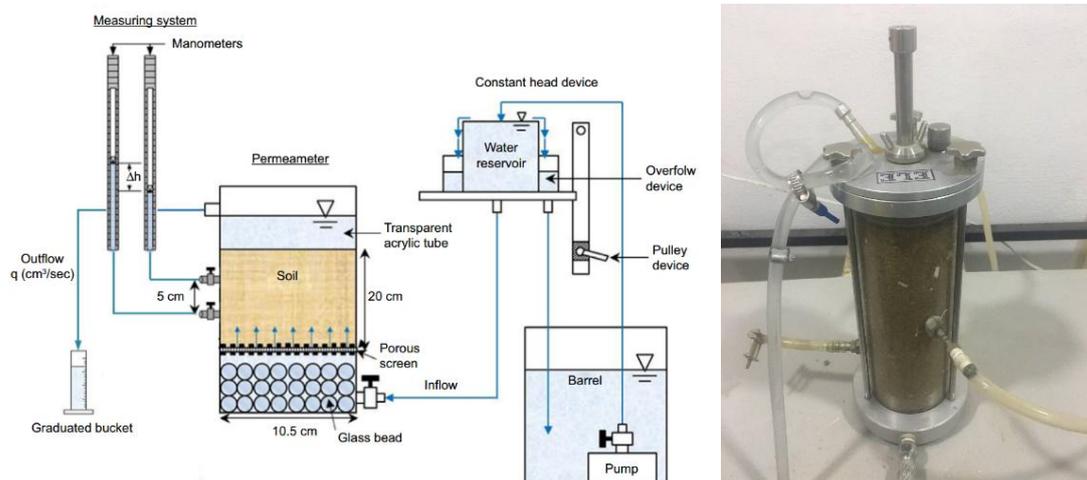


Figure 4: Constant head test system

The flow of water at the tip or the apex of the specimen was then measured and then channeled into the designated barrel. In order to determine the discharge velocity, denoted by v , at a specified hydraulic gradient, it was necessary to divide the total volume of water that was discharged over a specified period of time by the cross-sectional area of the soil specimen. In the apparatus, the permeameter cylinder was carefully drilled or punctured at two specified distances from the bottom of the specimen, i.e., at 7 cm and at 12 cm, and then connected to

two graduated manometers. The setup allowed for the precise quantification of the hydraulic head differential, i.e., the head loss, between two specified points on the path of the water flow at a specified location. Using the results obtained in the different phases of the test, it is possible to calculate the hydraulic gradient i by making use of the following equation:

$$i = \Delta h/L \quad (1)$$

Where Δh is the head difference between the two manometers, and $L = 7.5$ cm is the distance between the two measuring valves that are connected to the manometers. The piping test was conducted by gradually increasing the hydraulic head of the water in the reservoir by intervals of 2 cm. At the same time, the water level above the sample was kept constant at 50 mm (see [Figure 1](#) for reference). The increase in the head of the water was maintained for 10 minutes, during which time the discharge water coming out of the sample was collected and measured when the rate of discharge was stable.

The sample's discharge velocity was determined using Darcy's law. The seepage velocity (v_s) of water within the soil sample is:

$$v_s = \frac{v}{n} \quad (2)$$

where n represents the porosity of the soil sample, and v denotes the discharge velocity, defined as:

$$v = ki \quad (3)$$

where i represents the hydraulic gradient, and k is the hydraulic conductivity of the soil sample, defined as:

$$k = \frac{QL}{hAt} \quad (4)$$

In this particular discussion, h stands for the hydraulic head. Q represents the discharge volume measured at a specific time t . L stands for the length of the soil sample column, and A stands for the cross-sectional area of the soil sample column. The porosity of the soil sample was determined by calculating the void ratio. To obtain the void ratio for the reinforced and unreinforced soil samples, the dry density of the soil sample and specific gravity were utilized.

$$n = \frac{V_v}{v} \quad (5)$$

As the water flows through the soil, a force is acting on the soil particles, called the seepage force. In this problem, the seepage force is acting in the direction of the flow of the water, which is upward. The piping resistance of the soil is acting in the opposite direction of the seepage force. When the amount of the seepage force is equal and opposite to the piping resistance of the soil, the soil particles start moving upward along with the flow of the water. The amount of the seepage force at the critical hydraulic gradient, denoted by the letter "P," is calculated by the following formula:

$$P = \gamma_w h_c A \quad (6)$$

Where γ_w is the unit weight of water, and hc represents the critical hydraulic head. Seepage force or water pressure propagates fractures in most earth dam structures, leading to hydraulic fracturing. The result of the original sand is shown in [Table 2](#).

Table 2: Hydraulic parameters of the original soils

Soil type	Hydraulic properties			
	Critical hydraulic Head (m)	Seepage Velocity (m/s)	Piping Resistance (KN)	Permeability (m/s)
Silty sand	0.19	4.427×10^{-4}	8.23×10^{-3}	5.33×10^{-5}

Piping tests were performed on samples of soil that were randomly mixed with recycled flakes of various sizes, ranging from 5x5, 10x10, 15x15, and 20x20 millimeters. The samples also contained a constant amount of 0.5% of the dry weight of the soil. The objective of this test was to evaluate the effect of the size of the recycled plastic flakes on the improvement of the hydraulic properties of the soil. The results of the experiment are shown in [Table 3](#).

Table 3: Hydraulic parameters of the Silty sand reinforcement with PP flakes of 0.5%

Size mm	Hydraulic properties			
	Critical hydraulic Head (m)	Seepage Velocity (m/s)	Piping Resistance (KN)	Permeability (m/s)
(5x5)	0.22	3.84×10^{-4}	9.529×10^{-3}	4.63×10^{-5}
(10x10)	0.27	3.73×10^{-4}	0.01169	4.5×10^{-5}
(15x15)	0.26	3.87×10^{-4}	0.01126	4.66×10^{-5}
(20x20)	0.25	3.90×10^{-4}	0.01082	4.7×10^{-5}

[Siddique et al. \(2024\)](#) reported comparable findings. They examined soil incorporated with plastic chips measuring 15 mm by 15 mm and discovered that lightweight plastic chips occupied the voids within the soil sample.

A series of one-dimensional pipe experiments were performed on both a plain soil sample and a soil mixture including plastic flakes in different doses (0.5%, 1.5%, 2.0%, and 2.5%) [Figure 5](#) to estimate the optimum dosage of PP flakes that can enhance the hydraulic properties of soil.



Figure 5: Soil mixed with PP flakes

The correlation of velocity and hydraulic gradient, as observed after the pipe starts, revealed a distinct and pronounced gradient in the second segment. The critical hydraulic gradient value was determined by finding the point of intersection where the tangents of the two linear sections of the curve intersect. [Fakhri et al. \(2024\)](#); [Maass-Morales et al. \(2024\)](#) employed analogous methodologies to delineate the crucial hydraulic gradient. Different variations of parameters depend on the dosage of recycled PP plastic mixed with soil. [Table 4](#) shows the results of the dosage test.

Table 4: Hydraulic parameters of the reinforcement Silty sand and with PP flakes with the size of (10x10) mm for sand soil

Dosage	Hydraulic properties			
	Critical hydraulic Head (m)	Seepage Velocity (m/s)	Piping Resistance (KN)	Permeability (m/s)
1%	0.37	3.44×10^{-4}	0.0160	4.15×10^{-5}
1.5%	Silty sand	0.41	3.04×10^{-4}	0.0177
2%	0.46	2.74×10^{-4}	0.0199	3.3×10^{-5}
2.5%	0.43	2.87×10^{-4}	00.0186	3.46×10^{-5}

Mixing the soil with PP flakes with the size of (10x10) mm of 2% of soil dry weight can effectively reduce the hydraulic conductivity by 38% for silty sand.

PHYSICAL MODEL

Four Models of small dams with a laboratory scale were constructed to investigate the impact of using plastic on hydraulic performance (seepage and position of the phreatic line through the dam) [Table 5](#). The model's height is 0.55 m, the base length of the model is 2.77 m, and the crest width is 0.3 m. The side slopes of the dam are 2.5:1 for the upstream slope and 2:1 for the downstream slope. The drain used in models is a medium horizontal drain representing the average of the max and min length of the drain. The physical models of the homogeneous sections were as follows:

1. Dam constructed with original soil (H).
2. Dam constructed with original soil with horizontal drain (H+D)
3. Dam constructed with soil mixed with PP flakes (H+PP).
4. Dam constructed with soil mixed with PP flakes and horizontal drain (H+PP+D)

Table 5: Physical models sections

Model details	Homogeneous			
	H	H+D	H+P	H+P+D
Height (m)	0.55	0.55	0.55	0.55
Crest w (m)	0.3	0.3	0.3	0.3
FB (m)	0.1	0.1	0.1	0.1
U/S slope	2.5:1	2.5:1	2.5:1	2.5:1
D/S slope	2:1	2:1	2:1	2:1
Dam material	Silty sand			
Drain type	-	horizontal	-	horizontal

To construct the Laboratory Scale embankment Physical Model, and then observe the seepage and phreatic line, the following instruments are provided and used for this purpose: Experimental flume, Water Pressure Sensor, Water flow sensor, Data logger, High processor

laptop, and Piezometers. The water pressure sensor used in this study is WNK811, with precision (0.5-1) %, thread size G1/4, and wire length 4 m. The power supply voltage is 5 V, and the measurement range is 10 kPa [Figure 6](#).



Figure 6: Water pressure sensor with Pc

After 12 hours of construction of the physical model [Figure 7](#), the reservoir was filled gradually, for two hours. The model reaches a steady state condition after about 65 hours. The seepage rate and position of the phreatic line were measured using both flow and pressure sensors.

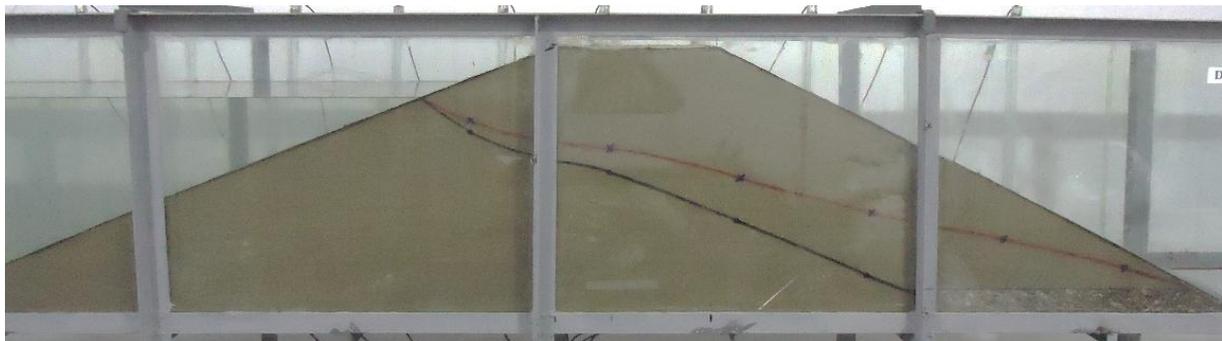


Figure 7: The section of the homogeneous dam with drain

NUMERICAL MODEL

Finite Element Method is one of the instrumental analysis tools for various science and engineering courses of study. In this regard, since seepage analysis is an integral part of this process, various software packages have been developed for seepage analysis, including Geo Studio 2024.1.0. For example, Geo Studio version 24.1.0.1406 has seepage analysis tools such as seep/w and slope/w, considering recent developments in this regard. For example, software packages such as Ansys have been developed for analyzing seepage conditions and water flow through soils using finite element methods. Therefore, there has been careful examination of the application of the finite element program SEEP2D for analyzing homogeneous and non-homogeneous (zoned) earth dams ([Kheiry & Kalateh, 2024](#)). The differential equation for seepage analysis can be written in its general form as follows:

$$\frac{\partial}{\partial x} \left(Kx \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial x} \left(Ky \frac{\partial H}{\partial x} \right) + Q = \frac{\partial \theta}{\partial t} \quad (7)$$

Where:

Q = The applied boundary flux

K_x = x direction of the hydraulic conductivity

K_y = y-direction of the hydraulic conductivity in

H = Total head

θ = The volumetric water content, and T = Time

Four Numerical models were constructed using the same data as the four physical models including geometry, hydraulic conductivity, and boundary conditions [Figure 8](#).

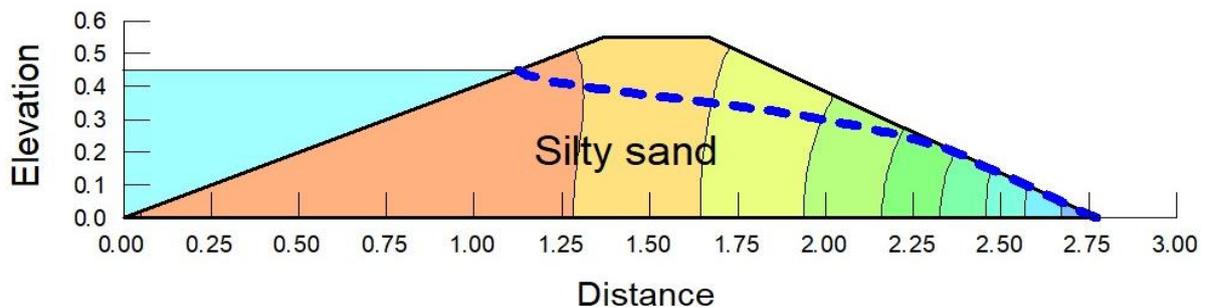


Figure 8: Water total head of the original soil

RESULTS AND DISCUSSION

The following section presents a detailed interpretation of the experimental and numerical studies on the hydraulic and geotechnical properties of silty sand reinforced using recycled PP flakes. The purpose is to reveal the influence of the size, dosage, and drainage pattern on hydraulic conductivity, seepage, and stability, as well as the discovery of new patterns of performance applicable to embankments.

Effect of PP Flake Size on Hydraulic Performance

The results of the test ([Figure 9](#) and [Table 6](#)) have shown that the relationship between the size of the flakes and the permeability (K) is non-linear. A significant reduction in hydraulic conductivity was observed for an increase in the size of the flakes from 5×5 mm to 10×10 mm, reaching the minimum K value of 4.50×10^{-5} m/s at 10×10 mm. This indicates that the water flow is being effectively obstructed by the presence of the flakes of this size.

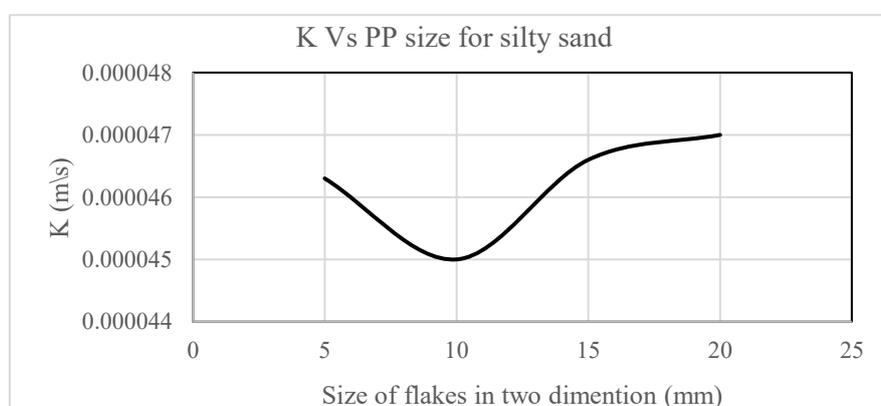


Figure 9: Hydraulic conductivity (K) of silty sand reinforced with various sizes of PP flakes

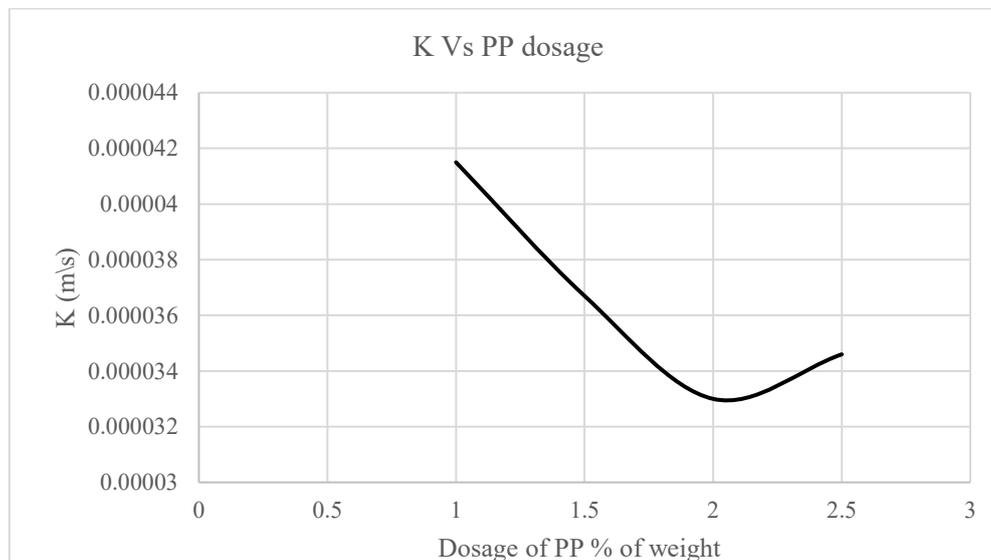
Table 6: Effect of PP Flake Size on Hydraulic Parameters (0.5% dosage)

Flake Size (mm)	Critical Head (m)	Seepage Velocity (m/s)	Piping Resistance (kN)	Permeability (m/s)
5×5	0.22	3.84×10^{-4}	9.529×10^{-3}	4.63×10^{-5}
10×10	0.27	3.73×10^{-4}	0.01169	4.50×10^{-5}
15×15	0.26	3.87×10^{-4}	0.01126	4.66×10^{-5}
20×20	0.25	3.90×10^{-4}	0.01082	4.70×10^{-5}

However, an increase in permeability was observed for the 15×15 mm and 20×20 mm flakes. It is apparent that the large flakes have resulted in the formation of voids in the soil-plastic mixture due to poor integration and packing. This critical knowledge is in line with the research conducted by [Shafea et al. \(2023\)](#), who observed the optimal dimensions of the fibers where the longer lengths of the fibers resulted in a compromised density of the matrix. The research has quantitatively determined the optimal dimensions of the flakes for the effective control of seepage in silty sand, making it unique in the sense that the research has focused on the dimensions of the flakes, unlike the dosage.

Effect of PP Dosage on Soil Hydraulic Behavior

As depicted in [Figure 10](#) and [Table 7](#), the optimum percentage of PP flake reinforcement was determined to be 2%, which reduced the permeability by 38.08%. This percentage of reinforcement resulted in the highest percentage of contact between the PP flake and the soil, minimizing the presence of macro voids.

**Figure 10: Variation of hydraulic conductivity with PP flake dosage****Table 7: Effect of PP Dosage (10×10 mm) on Hydraulic Parameters**

Dosage (%)	Critical Head (m)	Seepage Velocity (m/s)	Piping Resistance (kN)	Permeability (m/s)
1.0	0.37	3.44×10^{-4}	0.01600	4.15×10^{-5}
1.5	0.41	3.04×10^{-4}	0.01770	—
2.0	0.46	2.74×10^{-4}	0.01990	3.30×10^{-5}
2.5	0.43	2.87×10^{-4}	0.01860	3.46×10^{-5}

From a microstructural point of view, the inclusion of plastic affects the skeleton of the soil by increasing the friction between the particles. This, in turn, causes an interlock that resists the flow of water. This assertion is supported by the works of He et al. (2022), which indicate that the inclusion of plastic causes a shift from the suppression of permeability to the enhancement of permeability.

What this Research Contributes to Existing Literature: This research provides a clear indication of the percentage of inclusion of the PP flake that would result in the highest hydraulic benefits.

Seepage Behavior in Laboratory Dam Models

Four different configurations of the embankment were subjected to tests under controlled conditions. Table 8 shows the seepage rate per unit width. H+P (PP reinforcement only) resulted in a reduction of 22.11% compared to the unreinforced model. On the other hand, the model using horizontal drainage (H+D) experienced 44.5% more seepage, thus verifying that the presence of drainage facilitates the flow of water without hindering the permeability of the soil.

Table 8: Seepage Rate of Physical Homogeneous Models

Model	Seepage Rate (m ³ /s/m)	Relative Change vs. H
H	3.685×10^{-6}	—
H+D	6.652×10^{-6}	+44.5%
H+P	2.870×10^{-6}	-22.11%
H+P+D	3.892×10^{-6}	+5.6%

The use of recycled polypropylene waste flakes is a low-cost technique that contributes to the formation of a barrier similar to a geological membrane, thus supporting the rerouting of internal groundwater seepage. This environmentally friendly application enhances dam stability through the necessary reinforcement to lower the groundwater level, as clearly illustrated in Figure 11.

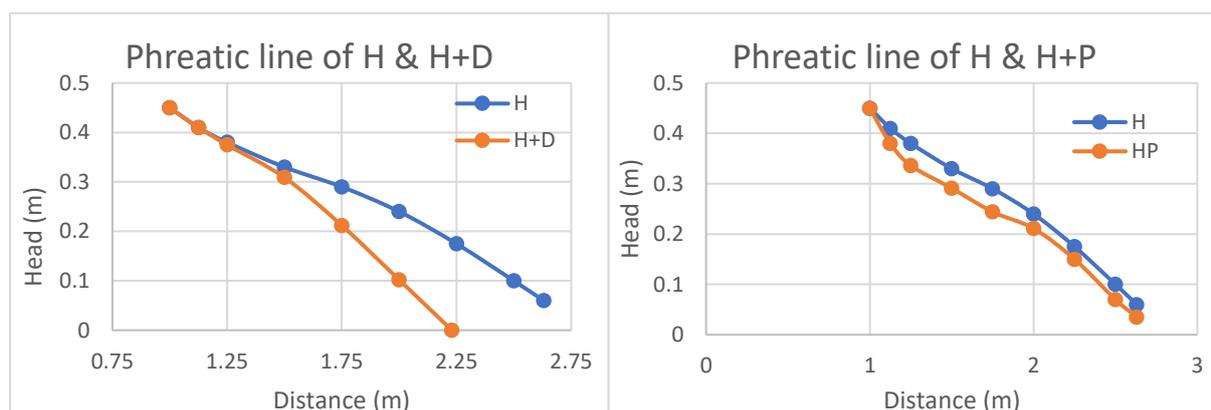


Figure 11: Phreatic line of the models (H, H+D, and H+P)

Numerical Validation and Predictive Modeling

The SEEP/W numerical model was able to replicate the conditions of the physical model, with the same properties of the soil and boundary conditions applied. As presented in Tables 9 and 10, the variation between the numerical and physical seepage rates was within the acceptable

limits of 6.7-13.5%. The profile of the phreatic line was similar, as presented in Figure 12 and 13, with <1% variation. This supports the validity of the finite element modeling approach for simulating seepage conditions, especially where new materials are involved, such as recycled plastics. This paper presents the successful simulation of the behavior of soil reinforced with plastics using FEM tools, where the accuracy of the model was confirmed by the results of the experiments.

Table 9: Seepage Rate from Numerical Models

Model	Numerical Seepage Rate (m ³ /s/m)
H	3.95×10 ⁻⁶
H+D	7.50×10 ⁻⁶
H+P	2.50×10 ⁻⁶
H+P+D	4.50×10 ⁻⁶

Table 10: Comparison Between Physical and Numerical Results

Model	Physical (m ³ /s/m)	Numerical (m ³ /s/m)	% Difference
H	3.685×10 ⁻⁶	3.95×10 ⁻⁶	6.7%
H+D	6.652×10 ⁻⁶	7.50×10 ⁻⁶	11.3%
H+P	2.870×10 ⁻⁶	2.50×10 ⁻⁶	12.8%
H+P+D	3.892×10 ⁻⁶	4.50×10 ⁻⁶	13.5%

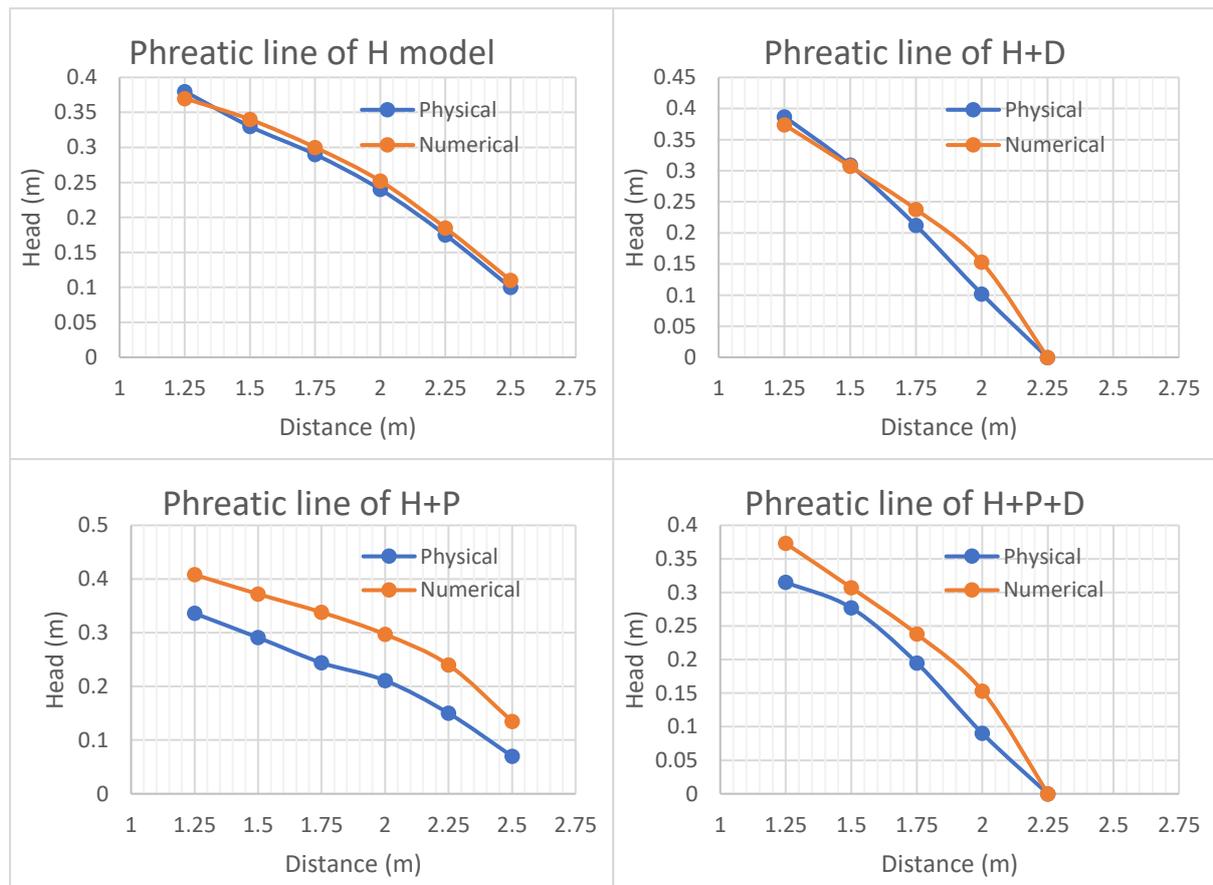


Figure 12: Phreatic line comparison between physical and numerical models

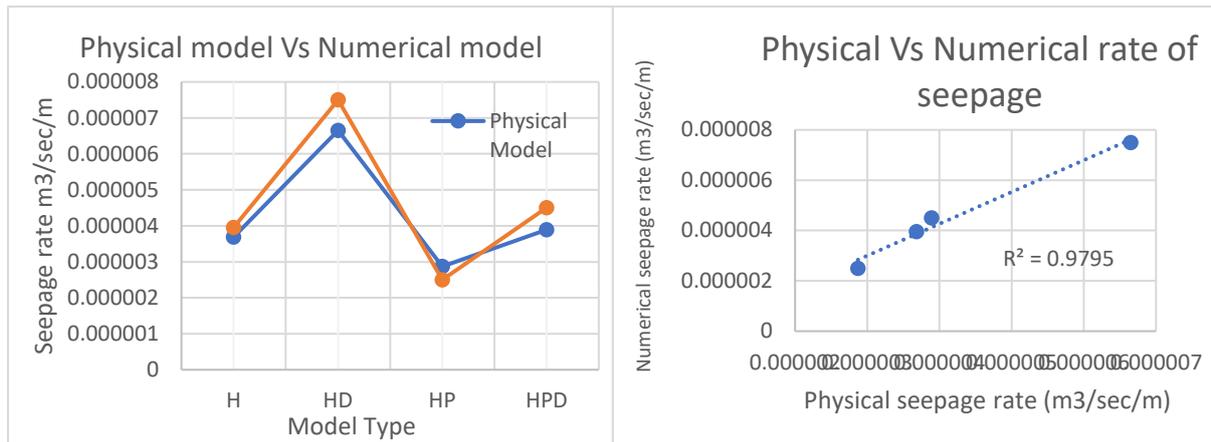


Figure 13: Seepage rate of physical and numerical models

Slope Stability Enhancement

Figure 14 and Figure 15 present the results of stability analysis using GeoStudio's SLOPE/W module. The safety factor increased by **12.56%** in the H+P model, indicating enhanced **inter-particle friction** and **cohesion** due to the inclusion of PP flakes. A horizontal drain also improved stability by **8.88%** by lowering the phreatic line, thus reducing pore water pressure near the downstream slope. These findings align with studies by Wang et al. (2025), which reported that plastic elements improve **shear strength** and **slope resistance** under seepage conditions.

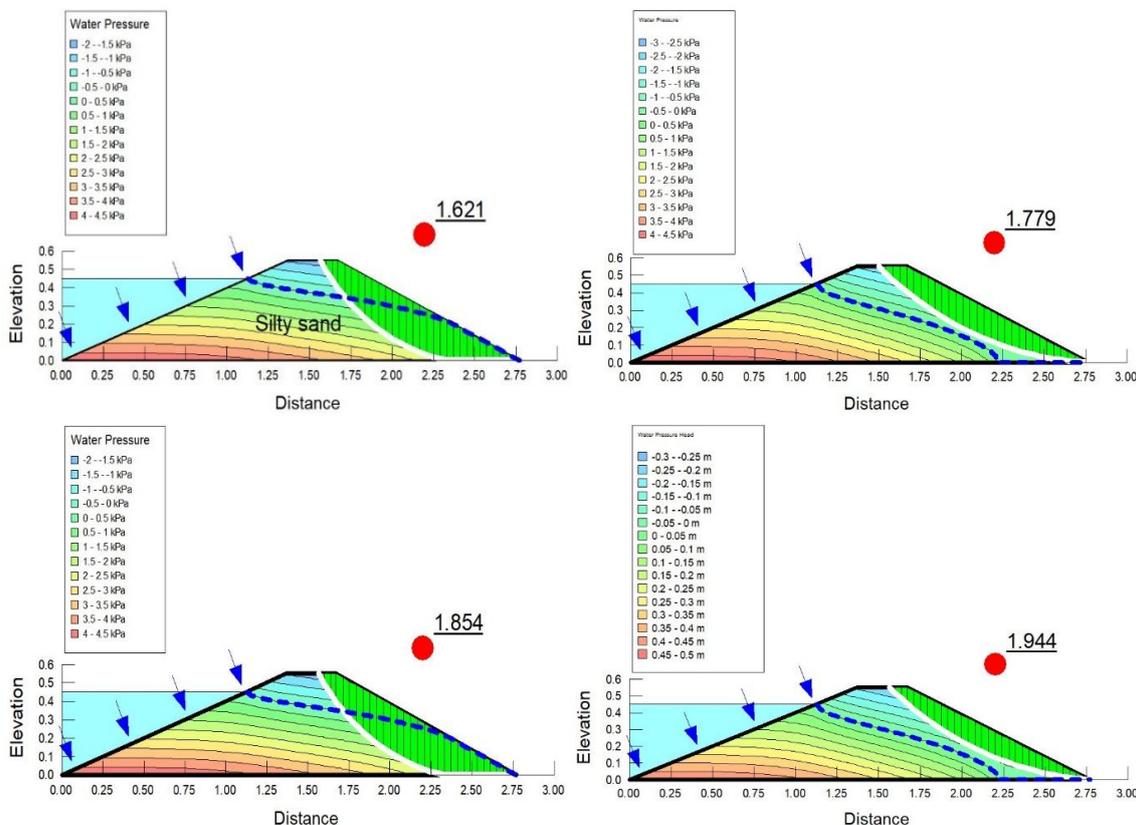


Figure 14: Safety factors of models (H, H+D, H+P, H+P+D)

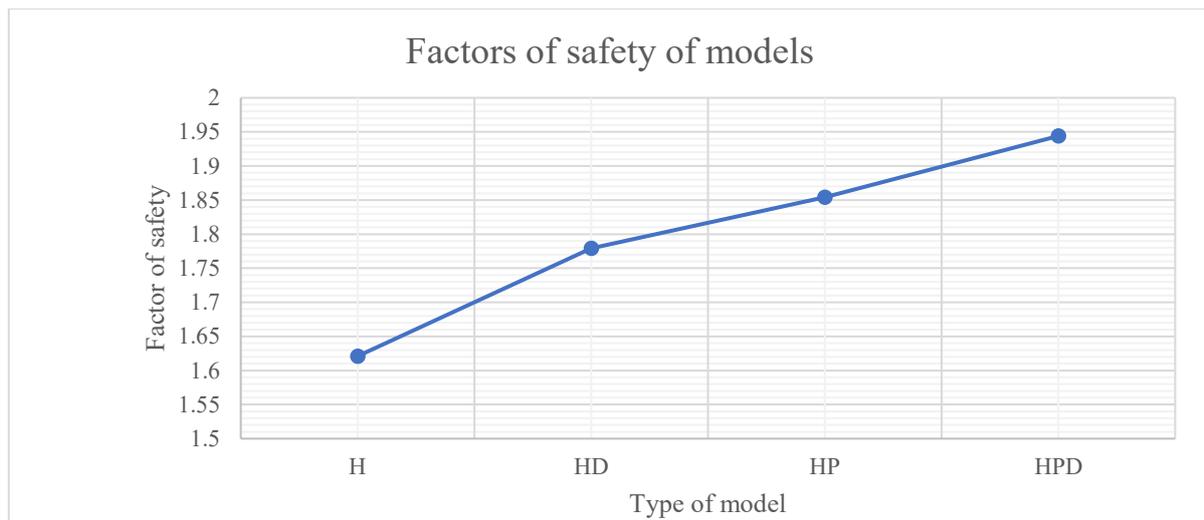


Figure 15: Comparative increase in safety factor due to PP flakes and horizontal drain

STUDY LIMITATIONS

The findings of this study provide important insights on the potential of using recycled PP flakes as reinforcing materials for soil reinforcement. Nevertheless, it is important to note the following limitations of this study:

1. **Scale of Testing:** The study was carried out on a laboratory scale. The results may not represent real-world scenarios.
2. **Soil Type:** The study was carried out on a single type of soil. The potential of using PP flakes on other types of soils, such as clay or gravel, was not considered.
3. **Short-Term Evaluation:** The study was based on a short-term evaluation. The potential effects of using PP flakes on the soil after a long period of time was not considered.
4. **Modeling Assumptions:** The numerical modeling was based on assumptions of homogeneous soils. The real-world scenario may differ.

CONCLUSION

At the conclusion of this study, some important novel contributions and implications can be identified for the first time. Firstly, this study offers a quantified solution for the first time for the optimum size and dosage of recycled polypropylene flakes for improving hydraulic and geotechnical characteristics of embankment soils, which are 10x10mm and 2% by weight of dry soil, respectively. Secondly, this study proves for the first time that unprocessed plastic flakes collected directly from first-stage plastic recycling units are effective for disrupting seepage paths and improving piping resistances, which can be used as a sustainable and cost-free solution for traditional soil stabilization methods. Thirdly, plastic flakes have a two-fold function for improving hydraulic and geotechnical characteristics of embankment soils, which are reducing hydraulic conductivity and improving stability by increasing cohesion and friction between soil particles. Finally, this study proves for the first time that finite element models validated by SEEP/W and SLOPE/W software are effective for simulating complex soil-plastic systems, which can be used for designing embankments and other geotechnical applications.

On the basis of a broad range of results that have been obtained by using the combination of laboratory experimentation and physical as well as numerical model testing, some important

findings can be determined regarding the application of the recycled material known as PP flake, particularly regarding the improvement of the hydraulic as well as the geotechnical characteristics of the silty sandy soils that are utilized in the process of embankment construction. The application of the PP flakes was determined to be highly effective in the reduction of the hydraulic conductivity, whereby the optimal size was determined to be 10x10mm, while the optimal dosage was determined to be 2% of the dry weight. With the specifications that have been provided, the permeability of the silty sandy soils was reduced by 38.08%, thus indicating the highly promising ability of the soil to counter the seepage forces that are experienced on the slopes. Improvement was at the same time experienced on the level of the mechanical properties of the soil, whereby there was a notable increase by up to 12.56% of the safety factor of the stability of the slope, from 1.621 to 1.854, owing to the increased level of interaction between the particles. These improvements were validated through numerical simulation, where it was found that the results were almost identical to those found in the physical model, confirming that finite element modeling is a reliable method of predicting seepage and stability in reinforced soils. Moreover, it was found that a horizontal medium drain had a lowering effect on the phreatic line, resulting in an increase in safety factor of 8.88%, while it also increased the seepage rate by 44.5%. The study also found that it is not always beneficial to add more fibers, as excessive amounts of fibers added to the soil matrix actually decrease its efficiency, either through macro-voids in the soil matrix or insufficient reinforcement. This study has proven that recycled PP flakes can effectively, sustainably, and inexpensively improve hydraulic sealing and stability in soils, providing a solution to regions that are facing many problems in terms of available resources and environmental sustainability.

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