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Use of Waste Tire Chips and PET Plastic Flakes in Backfill Behind Retaining Walls

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Abstract

The use of waste in the field of civil engineering is one of the solutions to reduce the harmful impact of waste on the environment on the one hand and preserve natural resources on the other. This study aims to investigate the effect of using waste materials such as plastic and tire chips that can be used as backfill in retaining walls. A numerical study has been carried out by using PLAXIS 2D software version 8.6 to model three types of rigid retaining walls, namely: scale wall test, cantilever wall, and gravity wall. In addition, the backfills of those retaining walls are composed of two mixtures. The first is a mixture of sand and tire chips (TC) with different percentages (10%, 30%, 50%, and 70%). The second is a mixture of sand and PET plastic flakes at different percentages (12.5%, 22.5%, and 32.5%). The results obtained from this study confirmed that the use of PET plastic waste and tire chips waste mixed with sand in the backfills of rigid retaining walls contributes effectively to the reduction of horizontal and vertical displacements as well as the earth pressures behind the retaining walls, therefore improving the stability of the retaining walls.

Keywords: tire chips (TC), PET plastic flakes, rigid retaining walls, backfill, PLAXIS 8.6

1 Introduction

Some soils, due to their poor geotechnical properties, can be considered problematic soils that cannot support heavy loads. Therefore, these soils require some improvement to increase their mechanical stabilities and enhance their performance. Conventional soil reinforcement techniques involve vertical or horizontal reinforcement elements in the soil [1]. Soil reinforcement consists of combining the soil with fibers to form a composite material. The recovery of waste in the field of civil engineering is an important sector where several types of waste have found applications under the condition that they are not subject to very rigorous quality criteria. Among the waste affecting the environment are waste tires and plastic bottles left in nature. According to [2], scrap tire derived (STD) in the form of tire chips, granulated rubber, and powdered rubber, and plastic bottles (PET, PP) in the form of flakes or granules have experienced an increase in their application in the geotechnical field [3].

Several researchers have conducted studies on the use of additives such as scrap tire-derived (STD) and plastic bottle waste in geotechnical applications. Recycled tires are usually shredded or crushed, and they can be used as substitute aggregates in backfill in road embankments, retaining walls, foundations, landfills, and other applications [4, 5]. Cecich et al. [6] investigated the effect of using tire chips as lightweight backfill for retaining structures. They found a more than 60% gain in total construction cost, and that the wall is more stable. Hataf and Rahimi [7] carried out a series of laboratory tests to investigate the use of tire chips mixed with sand to increase the bearing capacity of the foundation. Yoon et al. [8] studied the compression behavior and performance of tire-derived aggregate (TDA) used in the construction of road embankments in Canada.

Reddy and Krishna [9] made a scale model of a retaining wall in order to determine the effect of using a light fill composed of a mixture of sand and tire chips on the mechanical behavior in terms of displacement and earth pressure.

Reinforcement of poor-quality soils with fiber materials such as PET plastic waste has been conducted by several researchers to improve their bearing capacities and reduce lateral deformation and settlement [10, 11]. The standard PET plastic soil-waste composite is defined by [12] as a composite with discrete and randomly distributed elements of PET plastic flakes, which can improve the mechanical behavior of the composite. Soils reinforced with PET plastic flakes are seamlessly integrated into a floor matrix [13].

In this work, a numerical study has been carried out for three retaining walls, namely: a scale model wall, a cantilever wall, and a gravity wall whose backfill is placed behind it and is composed of two types of mixture. The first one is made up of a mixture of "sand and PET plastic flakes", whereas the second one is made up of a mixture of "sand and tire chips (STC)" with different percentages, thus forming a backfill material for retaining walls to improve the stability on one side and the recovery of plastic and rubber waste. In addition, it will protect the environment and preserve the deposits of sandy materials.

2 Scale Wall Test

This numerical study used two types of backfill behind the retaining walls. The first type of backfill is sand alone, and the second is a mixture of sand and tire chips (STC) in different percentages (10%, 20%, 30%, 40%, and 50%), according to the work reported by [9]. The characteristics of the embankments (sand and tire chips) (STC) as well as the properties of the retaining wall model used in the numerical analysis are presented below.

2.1 Wall Materials Test

2.1.1 Sand

For this study, it would be of interest to use fine to medium sand. The properties of sand are presented in Table 1 [9].

Table 1: Properties of sand

Parameter (unit)	**Value**
Specific gravity G_s (-)	2.66

Unit weight (kN /m^3)	17.4
Effective diameter D_{10} (mm)	0.175
Uniformity Coefficient C_u (-)	2.314
Coefficient of curvature C_c (-)	0.99
Modulus of elasticity Es (MPa)	58
Poisson's ratio v (-)	0.3
Internal friction angle φ (°)	33.5
Cohesion C (kPa)	9.3

2.1.2 Backfill of Sand and Tire Chips (STC)

Laboratory characterization tests were carried out by using scrap tire chips (TC) of 10 x 10 mm size and about 20 mm length in different STC mixtures (10%, 20%, 30%, 40%, and 50%). The properties of the mixture of sand and tire chips (STC) are presented in Table 2 [9].

Table 2: Properties of the different STC mixtures for the backfill of the scale model wall

STC Mixture (%)	γ_{sec} **(kN/m^3)**	φ **(°)**	E**(kPa)**	υ
STC 0	16.1	48	50 000	0.330
STC 10	14.62	51	45 101	0.325
STC 20	14.12	52	40 202	0.320
STC 30	13.17	56	35 303	0.315
STC 40	12.29	51	30 404	0.310
STC 50	10.42	44	25 505	0.305

2.1.3 Wall Test

The wall test is made of steel of 25 cm thickness and 60 cm height with a density equal to 70 kN/m^3. Reddy and Krishna [9] reported the characteristics of the scale wall test.

3 Numerical Study of the Scale Wall Test

The numerical study was performed with PLAXIS 8.6 software, using the Finite Element Method. The backfill soil is modeled based on the drained Mohr-Coulomb model [14]. The soil is modeled into 15-node triangular elements. The boundaries are fixed horizontally and vertically at the bottom and on one of the side boundaries of the model, as shown in Figure 1. The dimensions of the model are (8 x 0.6) m. Overloads varying between 0 and 10 kN/m^2 are applied on the free horizontal face of the embankment (to investigate the impact of raising the overload in relation to the percentages of the TC and determine the maximum vertical displacements).

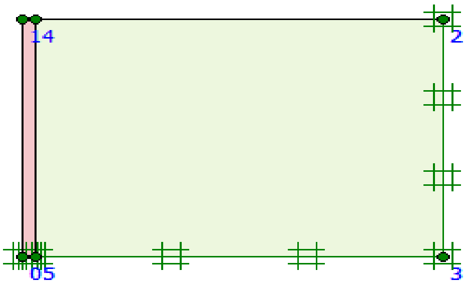

Figure 1: Modeling the test wall profile

A fine mesh is used for the model. The initial mesh of the test wall model is shown in Figure 2. The deformed mesh of the test wall model is shown in Figure 3.

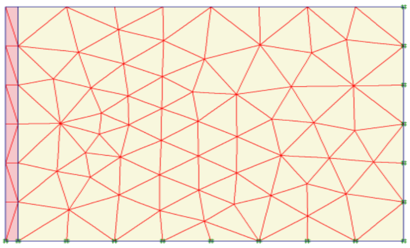

Figure 2: Initial mesh of test wall model

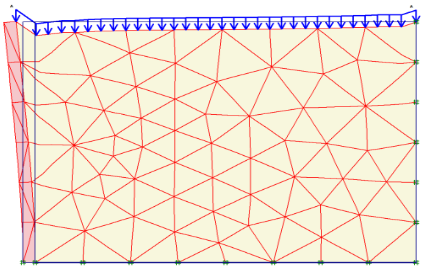

Figure 3: Deformed mesh of wall test model (STC 10%)

3.1 Results and Discussion

The backfill of the test wall is carried out with sand alone and with mixtures (sand and tire chips) with different percentages of tire chips, as presented in Tables 1 and 2. The response of the wall was determined after the application of surcharges that varied from (0 to 10) kN/m^2. It is worth discussing these interesting facts revealed by the results in terms of horizontal and vertical displacements along the height on the face of the wall (Figures 4 and 5), as well as the lateral earth pressures (Figure 6).

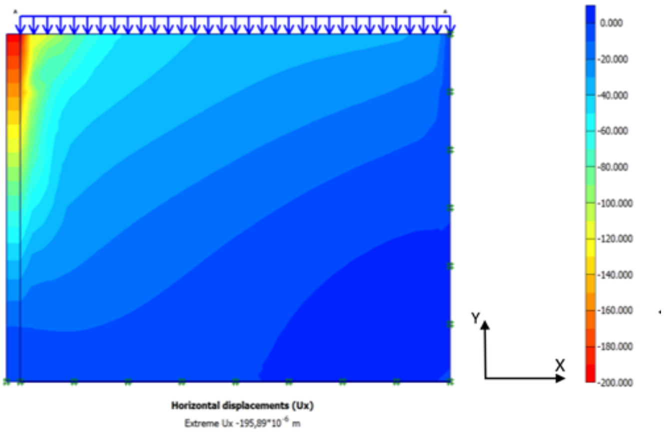

Figure 4: Horizontal displacements (U_X), the case STC 10 %

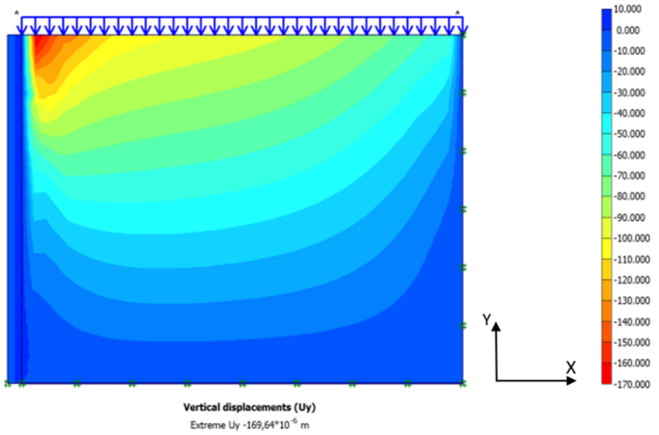

Figure 5: Vertical displacements (U_Y), the case STC10 %

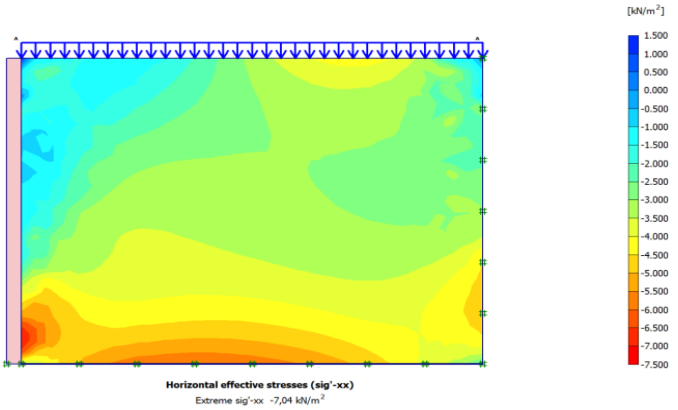

Figure 6: Horizontal restraints (σ_{xx}), case STC10 %

The most striking results emerge from the horizontal displacements computed behind the wall. It is apparent from Figure 7 that the Horizontal displacements decrease with the increase of the tire chips percentages (% TC) and minimum displacements are recorded at the 30 % level. For the STC 0 backfill and the surcharge (q = 10 kN/m^2), it is interesting to notice that the maximum displacement of the wall is about 0.22 mm.

The STC 30 backfill has the lowest displacements at the top of the wall (0.15 mm). However, the horizontal displacements showed an increase at the percentages of 40% and 50%. It has been observed that the vertical displacements showed a decrease for a percentage of 30% (Figure 9). From Figures 8 and 9, the horizontal and vertical displacements have increased with increasing the applied surcharge from (0 to 10) kN/m^2.

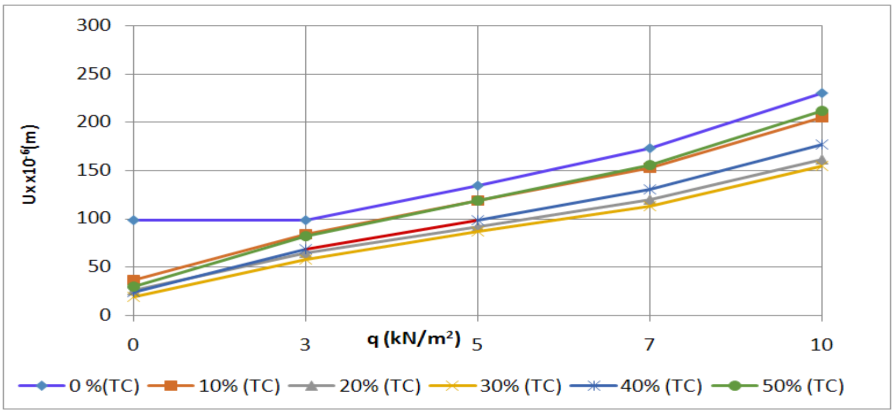

Figure 7: Horizontal displacements depending on the surcharge applied for different % (TC)

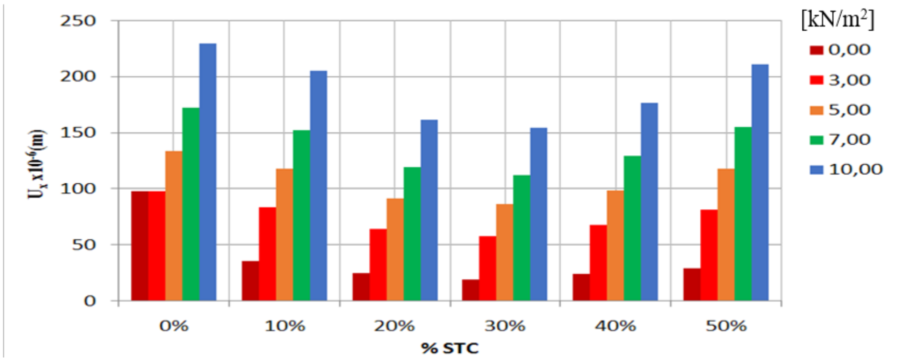

Figure 8: Horizontal displacements as a function of percentages (TC) for different applied surcharges

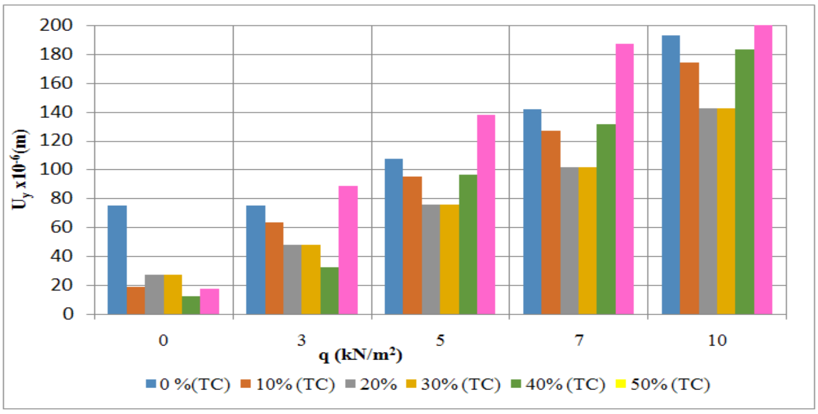

Figure 9: Vertical displacements as a function of percentages (TC) for different applied surcharges

The results obtained from the numerical study, which was performed on the wall test model, confirm that the percentage of 30% of tire chips is the ideal percentage that contributes to the reduction of horizontal and vertical displacements, whatever the surcharge applied. These results are in accordance with the experimental results reported by [9].

4 Numerical Study of Retaining Walls

To validate the results of the test wall on the rigid retaining walls in situ, a numerical Finite Element Analysis (FEM) is carried out by using the software PLAXIS 8.6. In addition, the effect of using sand PET-plastic mixtures and sand tire chips (STC) on the behavior of both retaining walls (cantilever wall and weight wall) has been studied.

4.1 Material Parameters of Retaining Wall Models

The materials used in this study are sand, PET plastic flakes, and tire chips (TC) as well as reinforced concrete retaining walls.

4.1.1 The Structure of Retaining Walls

Two types of retaining walls were used, namely, the gravity wall and the reinforced concrete cantilever wall, whose characteristics are illustrated in Table 3 [15].

Table 3: Properties of reinforced concrete retaining wall [15]

Model	**γ (kN/m^3)**	**E (MPa)**	**υ**
Elastic	25	34180	0.200

4.1.2 Sand-PET Plastic Mixture

PET Plastic flakes are used in percentages of 12.5%, 22.5%, and 32.5% of the dry weight of sand. The properties of the sand-PET plastic mixture are shown in Table 4 [16].

Table 4: The properties of the sand-PET plastic mixture

Parameter (unit)	**Sand-PET Plastic Mixture**		
	12.5%	**22.5%**	**32.5%**
Unit weight (kN/m^3)	16.3	15.47	14 .98
Modulus of elasticity $E_{p\text{-}s}$ (MPa)	394.50	663.7	932.9
Poisson's ratio v (-)	0.31	0.32	0.33
Angle of internal friction φ (°)	40.3	44.4	41.1
Cohesion C (kPa)	49.5	30.3	46.3

4.1.3 Tire Chip Sand Mixture (STC)

In this study, mixtures of sand and tire chips (STC) are considered lightweight backfill materials behind both cantilever retaining walls and weights for different percentages (STC 0, STC 10, STC 30, STC 50, STC 70) as shown in Table 5 [4].

Table 5: Tire chips sand mixture properties

STC %	γ (kN/m^3)	φ (°)	C (kPa)	E (kPa)	υ
STC 0	18.15	41	0	47888	0.300
STC 10	16.30	37.2	1	32700	0.300
STC 30	16.11	38	13.98	45145	0.306
STC 50	14.89	35	31.21	42155	0.309
STC 70	11.41	27	22.11	36037	0.314

4.1.4 In-situ Soil Tests

The in-situ soil properties are presented in Table 6 [17].

Table 6: In situ soil properties

Model	γ (kN/m^3)	φ (°)	C (kPa)	E (kPa)	υ
MC	18.0	28	5	50000	0.300

4.2 Numerical Analysis of Cantilever Wall

The soil is modeled into 15 node-triangular elements by using the drained Mohr-Coulomb model. The boundaries are fixed laterally on both sides and fixed horizontally and vertically at the lower boundary, as shown in Figure 10. The initial mesh is shown in Figure 11. The dimensions of the model are (80 m x 15 m). The cantilever wall is analyzed using both mixtures (STC) and PET plastic sand as lightweight backfill materials, whose characteristics are shown in Tables 4 and 5, respectively. The number of elements and nodes are respectively 162 and 1391 [16].

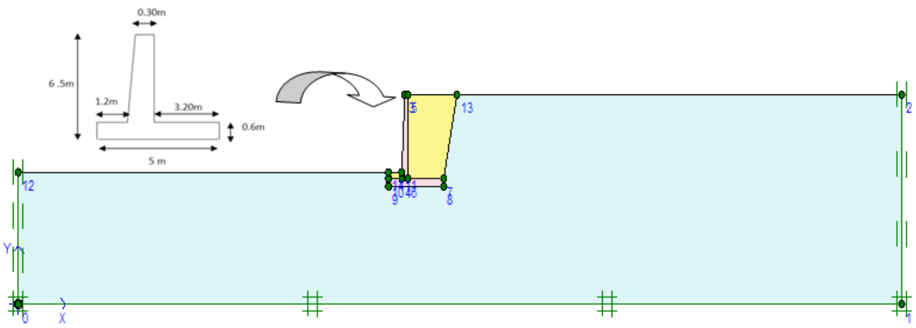

Figure 10: Cantilever retaining wall model

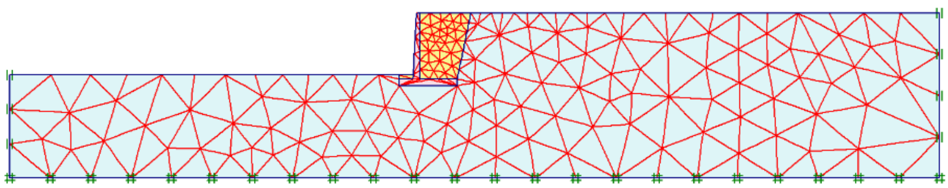

Figure 11: The initial mesh of the cantilever retaining wall model

4.2.1 Results and Discussion

Figures 12, 13, and 14 show the deformed mesh of the model, the vertical and horizontal displacements, the stresses, and the strains along X and Y respectively.

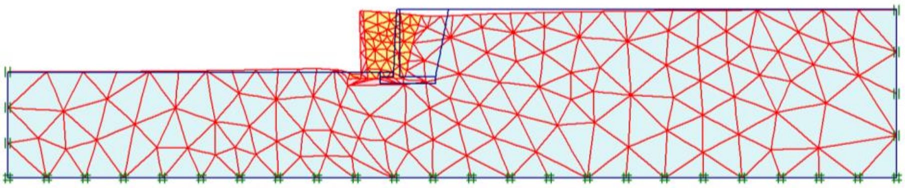

Figure 12: Deformed mesh of the cantilever retaining wall

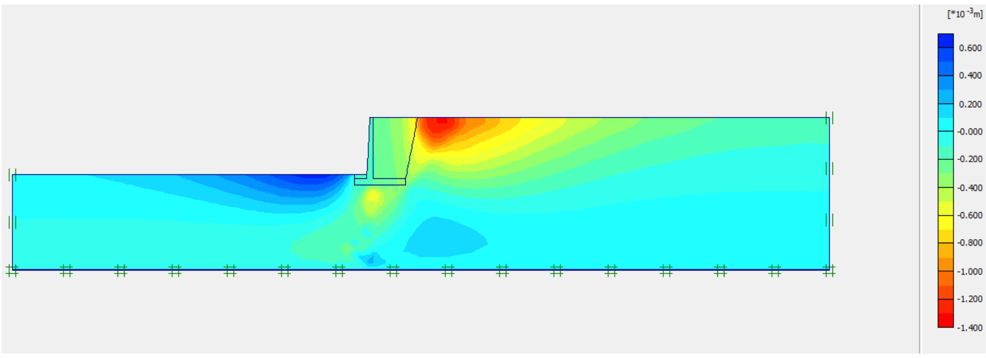

Figure 13: Vertical displacements (U_y) of the cantilever retaining wall

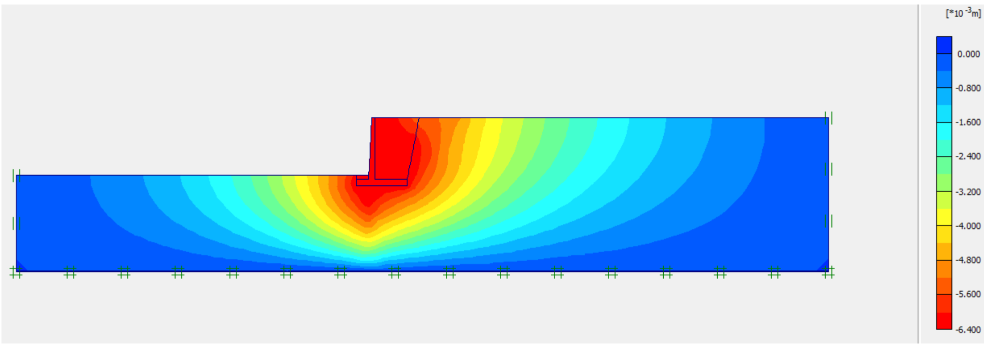

Figure 14: Horizontal displacements (U_x) of the cantilever retaining wall model

The main obtained results are shown in Tables 7 and 8.

Table 7: The main results for the case of cantilever wall with backfill (sand-plastic PET)

(%) PET	$U_{X(max)}$ **x10^{-3} (m)**	U_Y **x10^{-6} (m)**	σ_{xx} **(kN/m^2)**	F_s
0	7.52	1.35	29.31	1.993
12.5	6.35	1.32	44.20	2.079
22.5	6.32	1.28	31.18	2.082
32. 5	6.29	1.23	62.69	2.084

Table 8: The main results for the case of cantilever wall with backfill (STC)

(%) (TC)	$U_{X(max)}$ x10^{-3} (m)	U_Y x10^{-3} (m)	σ_{xx} (kN/m^2)	F_s
0	9.64	3.10	122.44	1.956
10	9.50	2.59	82.95	1.955
30	7.43	1.39	80.36	2.060
50	7.50	1.29	80.41	2.082
70	7.69	1.10	84.66	2.075

4.2 Numerical Study of the Gravity Wall

To study the effect of lightweight embankments on the stability of rigid walls, a gravity wall is modeled as a rigid element with the same elastic model as the cantilever wall whose geometry is presented in Figure 16, and with the same type of soil in situ. The wall is 4 m high and 1.5 m wide. Both backfills, STC and sand-PET plastic, are placed behind the gravity wall over a thickness of 0.50 m (Figure 15).

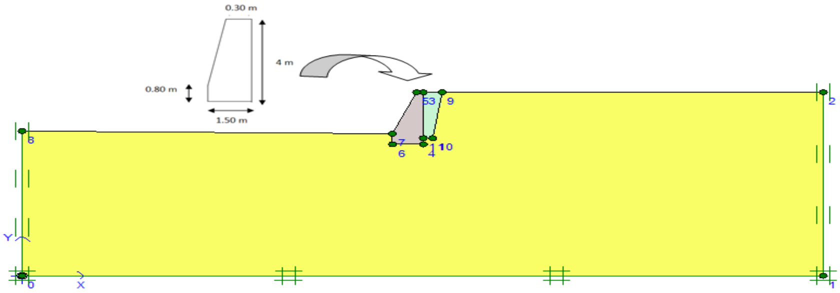

Figure 15: Gravity wall model

A refined mesh was chosen to obtain more reliable results. The number of elements and nodes are respectively 1132 and 9273. The generation of the mesh is given in Figure 16.

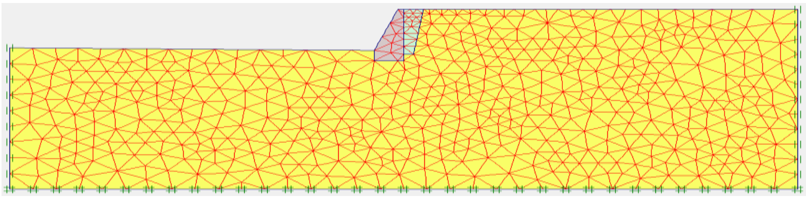

Figure 16: The initial mesh of the gravity wall

4.3.1 Results and Discussion

Figures 17, 18, and 19 show the deformed mesh of the model, the vertical and horizontal displacements, the stresses, and the strains along X and Y respectively.

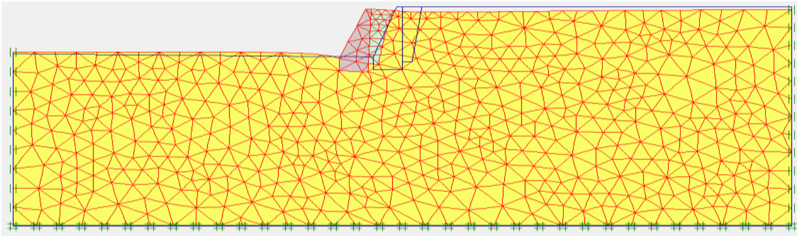

Figure 17: Deformed mesh of the gravity wall

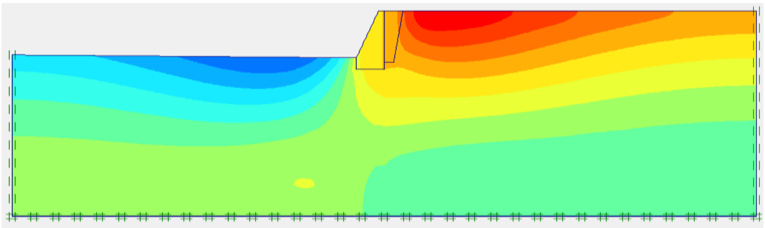

Figure 18: Vertical Displacements (*Uy*) of the gravity wall, case 22.5% PET Plastic

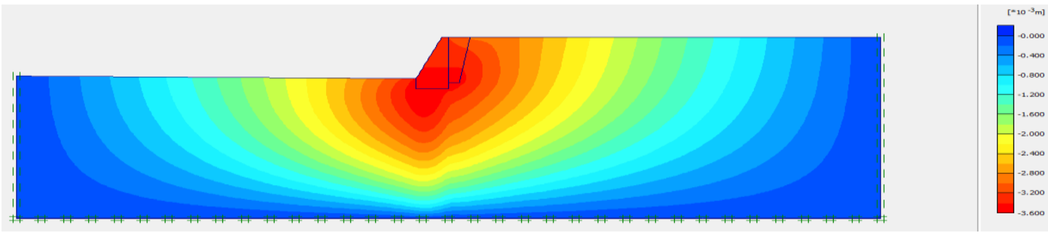

Figure 19: Horizontal displacements of the gravity wall (U_x), case 22.5% PET plastic

The results of the modeling of the gravity wall with both backfills, sand-plastic PET and STC, are shown in Tables 9 and 10.

Table 9: The main results of the gravity wall with sand-plastic PET backfill

PET plastic (%)	$U_{X(max)}$ **x10^{-3} (m)**	U_Y **x10^{-6} (m)**	σ_{xx} **(kN/m^3)**	F_s
0	3.61	685.61	36.77	1.834
12.5	3.59	683.97	30.99	1.976
22.5	3.58	675.34	26.58	1.988
32. 5	3.58	671.98	37.24	1.994

Table 10: The main results of gravity wall with STC backfill

TC (%)	$U_{x(max)}$ **x10^{-3} (m)**	U_Y **x10^{-6} (m)**	σ_{xx} **(kN/m^2)**	F_s
0	4.11	1.50	3282	1.356
10	3.78	888.57	2463	1.455
30	3.59	682.71	2811	2.670
50	3.58	672.59	1907	2.752
70	3.54	659.44	1702	2.545

As shown in Tables 7, 8, 9, and 10, the horizontal and vertical displacements decrease with increasing percentages of tire chips (TC) and PET plastic flakes. This decrease is observed for both the retaining walls (cantilever wall and weight wall). It has also been noticed that the earth pressures increased slightly with increasing percentages of recycled waste: PET plastic flakes and tire chips (TC) added to backfill behind retaining walls.

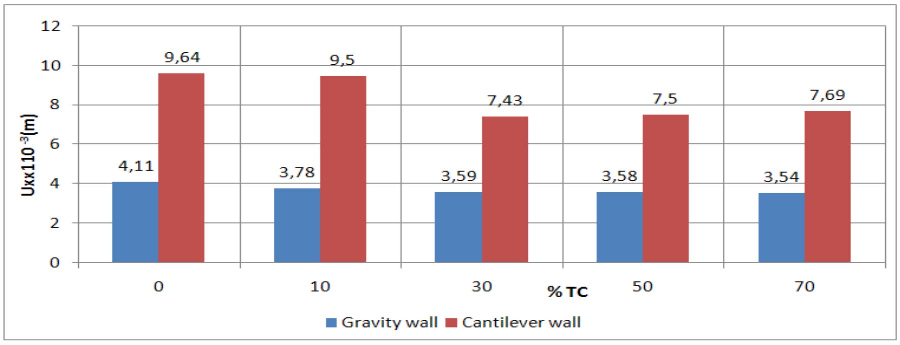

Figure 20: Comparison between cantilever wall and gravity wall displacements in the case of STC backfill

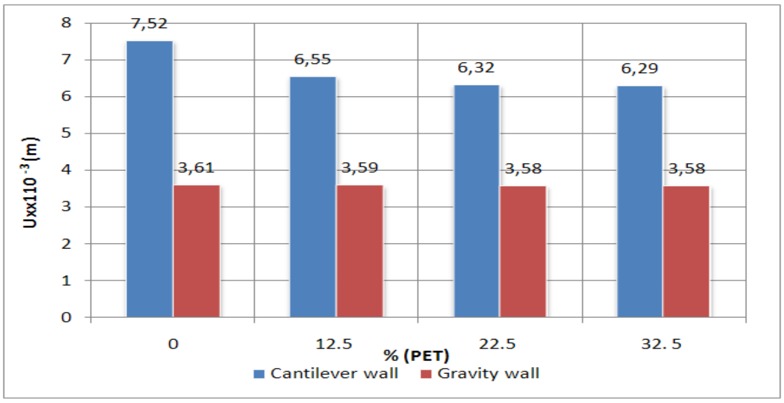

Figure 21: Comparison between the horizontal displacements of the cantilever wall and the gravity wall in the case of sand-plastic PET backfill

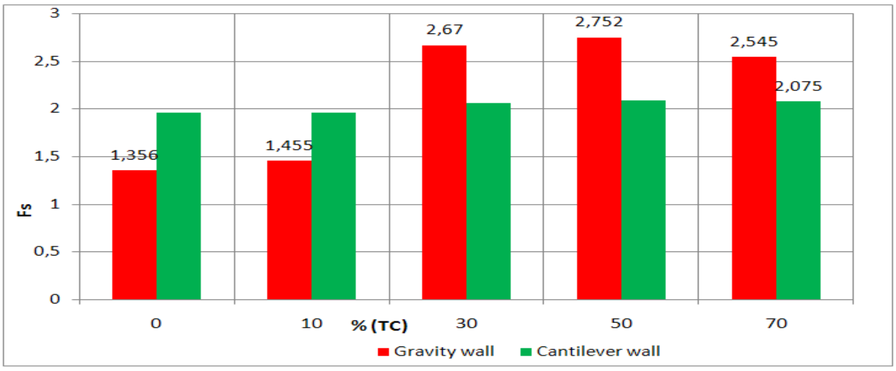

Figure 22: Comparison between safety factors of cantilever wall and weight wall in the case of STC backfill

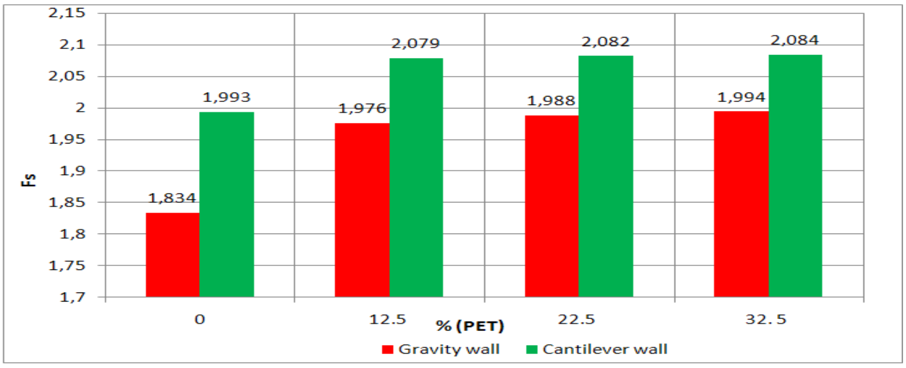

Figure 23: Comparison between safety factors of cantilever wall and weight wall reinforced in the case of sand-plastic PET backfill

Based on the results presented in Figures 20 and 21, the horizontal displacements developed behind the cantilever retaining wall are greater than those developed behind the gravity wall.
Referring to Figures 22 and 23, the safety factors showed an improvement with the increase in the percentages of both waste PET plastic flakes and tire shavings (TC).

5 Conclusion

To expand the field of use of inert waste materials such as used tires and plastic bottles in geotechnical structures, a numerical study using finite element software, PLAXIS 8.6, has been performed on a scale model retaining wall. The study was realized by considering a mixture of tire chips and sand as backfill for the retaining wall. The principal findings are derived from the horizontal displacements computed behind the scale model retaining wall.

- The minimal displacements are recorded at the 30% percent level, and the horizontal displacements decrease as the tire chips percentages (% TC) rise.
- It is significant to note that the maximum displacement of the wall for the STC 0 backfill and the surcharge (q = 10 kN/m^2) is around 0.22 mm.
- The lowest displacements at the top of the wall (0.15 mm) can be observed in the STC 30 backfill. However, at 40% and 50% of the percentage, there was an increase in the horizontal displacements.
- It has been stated that the vertical displacements decreased for the percentage of 30%.

In general, the numerical results are in accordance with those obtained from the experimental study, in which the percentage of 30% of tire chips is the ideal percentage that contributes to the reduction of horizontal and vertical displacements as well as active earth pressures, whatever the surcharge applied.
In order to apply these results to full-scale walls, a numerical study is carried out using PLAXIS software on rigid retaining walls. Two types of backfill are placed behind these walls, which are sand-tire chips (STC) and sand-PET plastic flakes mixtures.
The main finding of the mathematical study on rigid walls has a direct connection to their displacements and, as a result, their stability.

- The displacements, both horizontal and vertical, decrease as the percentage of tire chips (TC) and PET plastic flakes increases.
- This reduction has been observed for the weight wall and cantilever wall retaining walls.

- The percentage of 22.5% of PET plastic flakes and the percentages between 30% and 50% of tire chips (TC) reduce the horizontal and vertical displacements, which affect these structures, and contribute to the reduction of earth pressure behind the retaining walls.
- The safety factors showed an improvement with the increase in the percentages of both waste PET plastic flakes and tire chips (TC).
- The stability of retaining walls (cantilever and gravity walls) is improved by the efficient reduction of horizontal and vertical displacements achieved via the use of PET plastic waste and tire chips (TC) combined with sand as backfill behind rigid retaining structures.

In conclusion, this study suggests that the use of recycled waste mixed with sand with well-defined percentages is generally determined by laboratory tests.

Acknowledgments

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