Geomechanics and Engineering, *Vol. 30, No. 6 (2022) 517-524*
https://doi.org/10.12989/gae.2022.30.6.517

The effects of half-section waste tire reinforcement on pipe deformation behavior

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(*Received August 12, 2020, Revised August 17, 2022, Accepted August 23, 2022*)

Abstract. Every year, millions of waste tires are discarded across the world. Storage of waste tires presents many problems such as fire threats, epidemics, and non-economic factors. Furthermore, the disintegration process of waste tires is not economical or practical due to its time-consuming, and disposal requirements. In this study, half-section waste tires (HSWTs) were integrated with high-density polyethylene (HDPE) pipes under different relative density conditions. The main aim of the study was to reduce the deformation values of embedded HDPE pipes in sandy soil and to evaluate the soil–pipe interaction. In comprehensive laboratory tests, half-section waste tires were integrated in two different ways: in the middle of the pipeline and along the pipeline. Accordingly, it was concluded that the effectiveness of waste tires reduces the deformation and bending moment values in the critical regions of pipes. As a result of reinforcement in the mid-point of the pipe defined as the most critical region, 52% and 36% less deformation was observed in the crown and springlines of the pipe, respectively. In addition, the bending moment values for the same critical section were determined to be 40% less in the crown and 28% less in the springline regions of the pipe.

Keywords: deformation behavior, HDPE pipe, reinforcement, silica sand, waste tire

1. Introduction

In the pipe industry, polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polybutylene (PB), acrylonitrile butadiene styrene (ABS), and glass fiber reinforced polyester (GFRP) are among the best known plastic products. In the piping sector, PE and PVC are preferred primarily due to cost, time, and functional factors (Makris *et al*. 2020, Plastics Europe 2019, Heathcote 2009).

The use of HDPE pipes in water, gas, and sewerage networks, slurry transfer lines, electricity and communication lines, rainwater and drainage pipe applications are increasing day by day. High-density polyethylene pipes are widely used around the world as a flexible pipe type used for fluid or gas transfer due to their many advantages. Advantages such as high flexibility and tensile strength, low production cost, easy installation, suffering minimal impact from underground movements, with a high cracking and impact resistance play an important role in the preferential use of HDPE pipe. Other advantages of HDPE pipes are given below and feature the following:

- Low internal surface roughness. This characteristic provides great advantages when choosing a diameter during the project phase,
- Are resistant to ultraviolet (UV) rays and chemicals,
- Do not alter the taste and smell of the transported materials,
- Are not affected by harmful substances that have a corrosive effect in the soil,
- Their service life is a minimum of 50 years at nominal operating pressures (Erenson 2020).

Over the years, many applications have been developed to increase the service life and protect the pipeline. The use of waste tire-based materials is one of them. Because this is preferred because the tires are energy-absorbing due to their engineering properties and to prevent waste storage. There are many civil engineering applications to eliminate waste tire storage that create many problems in terms of the environment. Waste tires are used in many ways according to the purpose they are used for, such as being formed into granules, strips, pieces, half sections, or as complete or mixtures of components. However, due to the wire bundles and cord fabric in the vehicle tire structure, dismantling the tire is difficult, time-consuming, and costly. Facilities, factories, and storage areas come into service every year to recycle millions of tons of waste tires. The costs and spending on established recycling plants are quite high. For this reason, the use of complete waste tires or large sections eliminates the negative consequences of shredding costs and recycling processes. In this study, an innovative geo-environmental approach was suggested to use waste vehicle tires in specific engineering applications and thereby decrease the expected negative impact on the environment and natural habitat. For this purpose, waste tires were used as a protective layer by only dividing them into two parts in this study.

On the other hand, with the increased use of vehicles comes a large rise in the number of waste tires. Other

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ISSN: 2005-307X (Print), 2092-6219 (Online)

handicaps of waste tire storage operations are that they cause fires and potentially fatal epidemics. When the rubber burns, which is the raw material of the tire, many harmful components are spread into the atmosphere due to the chemical content of rubber. Also, carbon black, volatile particles, polycyclic hydrocarbons, oils, sulphur dioxide, nitrogen oxides, nitrosamines, carbon oxides, arsenic, cadmium, iron, lead, zinc, and many other harmful materials are scattered into the environment and into the atmosphere due to the burning of tires. Cheng *et al*. (2014) emphasized the disadvantages of the waste tire disintegration process. Tire rubber crumbs include a wide variety of organic pollutants and heavy metals that can pass into vapour and into the air, and percolate into the rainwater. The other problem is epidemic diseases. Due to the characteristic structure of the tires, the temperature in the tires is lower than the exterior temperature. For this reason, insects and rodents nest in waste tire storage areas. As a result of rainfall, harmful residues and pollution are spread into the environment. Therefore, it is important to create new usage areas for waste tires to eliminate these harmful effects.

In the context of published literature, it has been frequently observed that rubber-based layers or tire-containing reinforcement materials are preferred to ensure pipeline stability. Numerous applications have been carried out in the strengthening of pipelines until today. In the last decades, many researchers have preferred to create a protective layer or to use reinforcement material on the pipeline to deliver long-term service lives for buried pipes. In the studies carried out within this scope, geocells using (Teja 2018, Khalaj *et al*. 2017, Nirmala and Rajkumar 2016, Hedge *et al*. 2015), geogrids (Hedge *et al*. 2014, Fattah *et al*. 2016, Armaghani *et al*. 2015), geosynthetics (Cui *et al*. 2018), geofoams (Mane *et al*. 2017), waste materials (Trentin *et al*. 2016, Terzi *et al*. 2015, Tafreshi and Norouzi 2015), and other filler materials have been used as reinforcing elements (Rajendran *et al*. 2018, Lee *et al*. 2014). As a result, these reinforcing elements have contributed significantly to these studies, which aim to reduce pipe deformations and even out pressure distributions on the pipe. However, new products and applications lead to higher costs. For this reason, it is economically important to select recyclable materials as reinforcement elements. In their study, Frangopol and Liu (2007) emphasized that cost-competent maintenance and management of civil infrastructure requires a balanced consideration of both the structural performance and the total cost accrued over the entire life-cycle. Ensuring long service life in infrastructure applications is crucial in terms of maintenance, repair, and time criteria. For these reasons, reinforcement materials have gained an important place in areas of project and design. Also, the use of waste or discarded materials in this infrastructure provides an economic advantage. Among recyclable materials, the use of waste tires as lightweight fills, backfill materials, highway embankments, soil reinforcement elements, and soil-retaining walls is increasing day by day in geotechnical engineering (Mehrjardi *et al*. 2012).

In the literature, studies in which the characteristics of tires such as energy absorption and elasticity are evaluated to maintain the stability of the pipelines and improve the system draw attention. For instance, Meguid and Youssef (2018) indicated that the addition of tire-derived aggregate (TDA) around buried pipelines will decrease the earth pressure on the pipes. Rezaei *et al*. (2012) installed the TDA layer between soil layers to show the positive effects of TDA efficiency on the pressure distribution in the pipelines. Arefnia *et al*. (2020) stated in their study that the TDA applications increase the elasticity behavior of the backfill. Mahgoub *et al*. (2019) investigated the deformation behavior of steel pipelines with TDA layer and granular layer in field conditions. The researchers suggested that the TDA layer significantly reduces the stress and load values transferred to the pipe. Also, Oikonomou and Mavridou (2009) emphasized that waste tire applications could be used to protect the pipeline.

Pipelines are subject to forces at critical cross-sections due to changes in loading combinations or natural factors. Changing the pipe diameter, wall thickness or material quality of the whole pipeline project creates large-scale costs compared to strengthening critical cross-sectional areas. For this reason, the implementation of improvements only in critical regions provides optimum benefits in terms of both economy and safety. In this context, applications with no reinforcement, HSWT reinforcement only in the middle region of the pipeline (Formation I), and HSWT reinforcement throughout the pipeline (Formation II) were tested under different relative density conditions to demonstrate the effectiveness of HSWT reinforcement.

Consequently, this study presents an innovative solution to the storage problems of waste tires while strengthening HDPE pipelines with HSWTs. Also, this study, in which HSWTs were used as a protective layer on the pipeline, showed successful results in eliminating the negative factors in the storage and fragmentation process of the tires, reducing the deformations in the pipe, and ensuring stability.

2. Materials

The properties and usage details of materials used in conducting laboratory tests are as follows:

2.1 Silica sand

In the laboratory experiments, silica sand was used as a backfill material that had no additives and was uniformly compressible. To achieve precise results, homogeneous soil was formed in each region of the test box. For this purpose, silica sand, which has a low coefficient of uniformity, was used. Backfill material was compressed into the rigid test box in layers of 10 centimeters. Primarily, the silica sand was filled in a rigid test box using a screw conveyor to provide uniformity. The layers were compacted by the free-falling of the 10 kg plate every 10 centimeters. While no compaction was applied for 45% relative density value, 5 and 10 drops were applied for 60% and 75% relative density values, respectively. In this study, relative density

Table 1 The engineering parameters of silica sand

R_D*	45%	60%	75%
Weight per unit volume (γ) (kN/m^3)	14.6	15.8	16.4
Angle of internal friction (ϕ)	34^o	36^o	38^o
Elasticity modulus (E) (MPa)	32	52	63
Specific Gravity (G_s)	2.65		
Soil Class (USCS)**	poorly graded sands (SP)		

*Relative density
**Unified Soil Classification System (ASTM D-18 2017)

Table 2 The engineering and chemical properties of HDPE pipe

Elasticity modulus (E)	900 MPa
Density (γ)	0.945-0.965 g/cm^3
Poisson ratio (v)	0.42
Production temperature	>100°
Crystal structure ratio	90%
Transparency ratio	90%-95%
Melting point	135°
Rupture stress at 23°C	>21 MPa

values were calculated and checked according to ASTM D4254-16 (2016). Density checks were performed according to the index properties calculation of the weighed specimens. Engineering parameters of the backfill material used in the experiments carried out in three different density conditions are shown in Table 1.

Silica sand used in the experiments was obtained from Şile, in the İstanbul region. Washing, enrichment, classification, and dewatering processes were carried out on the backfill materials. The sand produced by the supplier was untouched by human hands with a maximum AFS (American Foundry Society 2015) clay of 0.5‰, a maximum humidity of 7‰, and a degree of homogeneity of 70‰ or above. As a result of the sieve analysis, the C_c, C_u, D_{10}, and D_{50} values were found to be 1.04, 3, 0.13, and 0.31, respectively.

2.2 HDPE pipe

In the experiments, pipes were tested under quality and conformity criteria such as pipe diameter, pipe curvature, wall thickness, and polyethylene content. Engineering properties and chemical properties obtained from the R&D tests on the pipes are shown in Table 2.

Extensive laboratory tests were conducted on HDPE100 pipes. The pipe had an outside diameter of 400 mm and a wall thickness of 9.8 mm. The length of the HDPE pipe specimen selected was 1500 mm.

2.3 Waste tires

Waste vehicle tires were obtained from the scrapyards and storage facilities in the Aksaray province in the middle of Turkey. Waste tires were selected from 15 and 16-inch car tires with a 400 mm internal diameter. Tires were divided into two parts using a cutter and positioned on the pipeline. Then, the backfill material was filled into spaces between the pipe and half-section tire to form a composite structure. Layers, wires, fibers, and other elements in the tire section are shown in Fig. 1, the disintegration step is shown in Fig. 2, and tire formations are shown in Fig. 3 and Figs. 4(a)-(b)-(c). Also, small-scale waste tires can be used for compatibility in small-diameter pipe applications. On the other hand, heavy vehicle waste tires can be preferred as reinforcement material where larger diameter pipes are used.

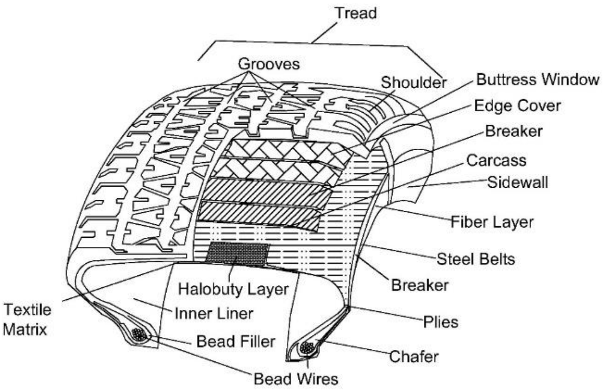

Fig. 1 Tire section

Fig. 2 Waste tire disintegration process

3. Testing procedure

Full-scale tests were carried out in a 1500 x 1500 x 1250 mm rigid test box at the geotechnical laboratory of Aksaray University. In this study, AASHTO (1996) and ASTM D2321 (2020) standards were taken into consideration to reflect real field conditions while sizing the test box.

To represent the true plane strain condition, the lateral deflection of sidewalls should be controlled to be small enough (Brachman *et al*. 2000). Therefore, the rigidity properties of the test tank were guaranteed using reinforcement bars around the sidewalls. The supports were

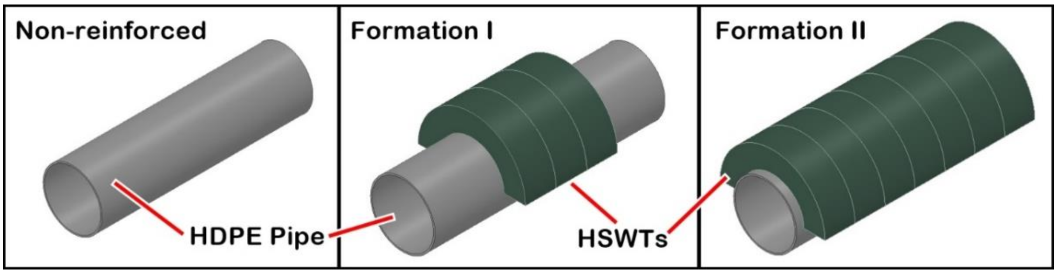

Fig. 3 Waste tire formation on the HDPE pipe

(a) non-reinforced (b) formation 1 (c) formation 2

Fig. 4 HSWT installations

Table 3 Minimum trench width values according to the standards

Inner diameter (mm)	External diameter (mm)	AASHTO (1996) (mm)	ASTM D2321 (2020) (mm)
100	120	480	530
150	177	570	580
200	233	650	640
250	287	742	690
300	356	840	760
375	450	980	870
380	400	1500×1500 ✓	
450	536	1110	970
525	622	1240	1080
600	699	1350	1180

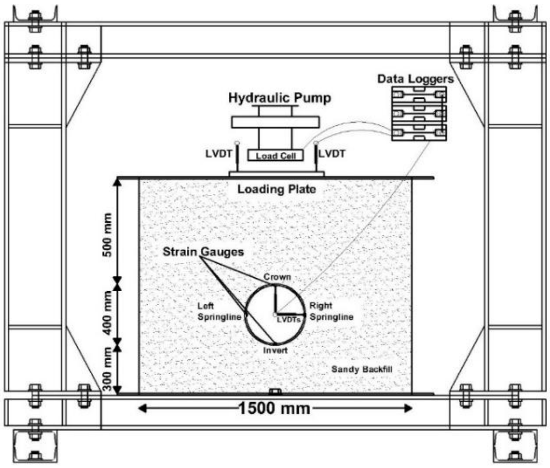

Fig. 5 Test box and equipment

welded to both test box walls to prevent displacements resulting from this lateral pressure. Also, the K_0 conditions were successfully provided. According to the standards, the minimum width values of the test box in which the backfill is used are given in Table 3.

The box was located on a frame system with an integrated loading mechanism, and the load was transferred to the loading plate by a hydraulic jack. The load cell located between the hydraulic pump and the loading plate transferred the data to the data logger.

A steel loading plate of 650 mm in length and width, and 20 mm in wall thickness was used to provide loading. The loading plate was centered on the backfill material. Loading steps were carried out every 90 seconds. At each step, 10 kN increments were applied and the tests carried on up to 100 kN.

Initially, a 300 mm bedding layer was spread inside the test box and the HDPE pipe was placed on this bedding surface. Then a 500 mm backfill layer was placed on the pipeline under controlled density conditions. Then, interpretations of the deformation behavior of the pipe were suggested by the deformation and bending moment values measured from the pipe. Vertical and lateral displacements were measured by LVDTs (linear variable differential transformers) at the midpoint ($L/2$=750 mm) and the quarter-point ($L/4$=375 mm) of the pipeline. In addition, settlement values were obtained by LVDTs on the loading plate.

For both sections of the pipe, strain gauges were placed on the crowns, springlines (left and right), and base regions so that the bending moment values could be calculated. In addition, soil pressure at the base of the box was measured by means of soil pressure meters located under the pipe. Thus, the efficiency of waste tires was evaluated as a correlation between transferred stress and soil pressure.

As a result, waste vehicle tires were positioned in two different formations which are “along the pipeline” and “in

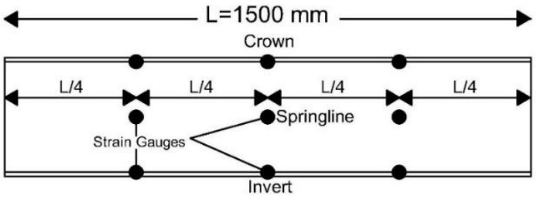

Fig. 6 Strain gauge configuration

the middle of the pipeline”. Then, all data were compared and interpreted with reference experiments without reinforcement. The test frame and testing equipment in the system are given in Fig. 5.

In the preliminary tests, microcontroller-based pad-type pressure meters were installed on the sidewalls of the box to check that no stress reached the walls during the control of the experimental setup and measuring instruments. Throughout the experiments, it was observed that the load was transferred to the bottom of the box via the backfill and no stress difference occurred on the box sidewalls. In this respect, it was obvious that real field conditions were reflected. For this reason, friction treatment was not applied at boundaries. On the contrary, it was emphasized in the literature that geosynthetic treatments were applied to reduce the boundary effects in the conditions caused by frictions mobilized at sidewalls (Tognon *et al.* 1999). For instance, in such cases where the interface angle needs to be reduced, friction treatments for different geotechnical studies have been successfully used in pipelines (Ni *et al.* 2018), landfill liners (Joshi *et al.* 2017), and stormwater collection structures (Brachman and LeBlanc 2017).

4. Measurement assembly

All devices and equipment were calibrated according to the manuals and the precise results were obtained in accordance with reference tests.

LVDTs, strain gauges, a soil pressure meter, and load cells transmitted signals to the data logger. The data acquisition system designed for high measurement performance converted the signals from the sensors to digital data, and the final results were transferred to a computer.

4.1 LVDTs

Displacement data collected from the crown and springline regions of the HDPE pipe were transferred directly to the software in the data logger via LVDTs with 10±0.01 cm capacity. As a result of load-deformation correlations, it was observed that half-section waste tires significantly reduced deformations.

4.2 Strain gauges

BF-120-10AA type strain gauges with 120±0.1 Ω capacity were integrated into two different sections along the pipeline to the crown, left springline, right springline, and bottom areas of the pipe. Strain values were calculated according to the formulas in the manuals of the company who supplied the data logger and strain gauges. Then, bending moment values were obtained as a result of the strain values gathered according to millivolt changes. Thus, enforced zones of the buried pipe were detected under load. The positioning of strain gauges on the pipe section is shown in Fig. 6.

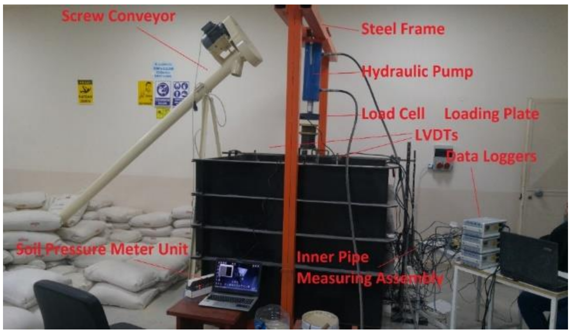

Fig. 7 Experimental setup

The stiffness of the HDPE pipe material is very close to the stiffness of the adhesive for strain gauges. Also, the stiffness of the gauge is similar to that of the PE, resulting in a local imperfection in the strain field undersurface of the gauge (Brachman 1999). In the published literature, it was emphasized that corrections should be made regarding the temperature factor, modification factor, and bridge correlations (Cholewa *et al.* 2009, Ni *et al.* 2018). Within the scope of this study, as a result of material tests, the instructions of the company supplying the product, and displacement-based tensile tests, the strain values were verified and the values were processed accurately.

4.3 Soil pressure meter

The soil pressure meter with 1000±0.1 kN/m^2 capacity located at the base of the rigid test box was installed under the embedded pipe. In this study, soil pressure values were taken from a load cell connected to a microcontroller and the data collected was sent to the data logger.

Stress values from the box base were close to similar relative density conditions. This inferred that the load on the pipe was transferred directly to the box base for all relative density conditions. As a result, since the waste tire application reduced the deformation in the vertical direction, the applied load was transferred to the box base through the half-section tires.

4.4 Load cell

The load cell is a kind of transducer that carries out the function of transforming a force into an electric output that can be measured. A calibrated load cell with a capacity of 500±0.01 kN integrated with the hydraulic jack sends signals to the data loggers at the moment of contact with the loading plate. As a result of the transferred load values and displacement data, the deformation behavior of the buried pipe was interpreted.

Finally, the final test setup is shown in Fig. 7 after all installations were completed.

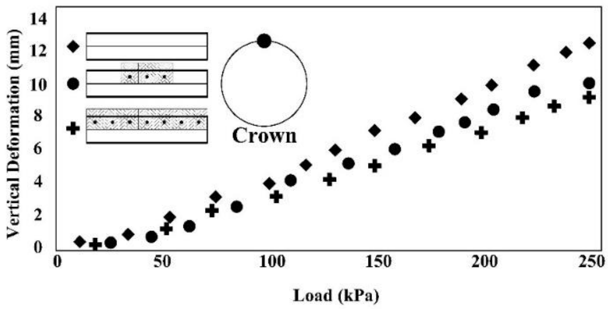

Fig. 8 Vertical deformation at 75% relative density

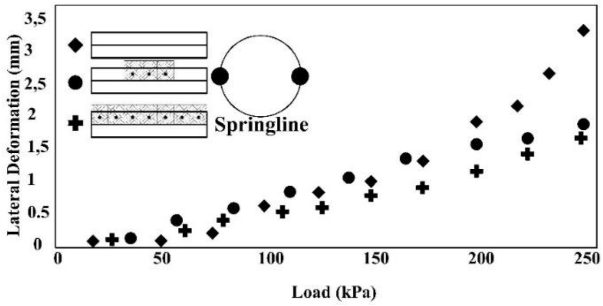

Fig. 9 Lateral deformation at 75% relative density

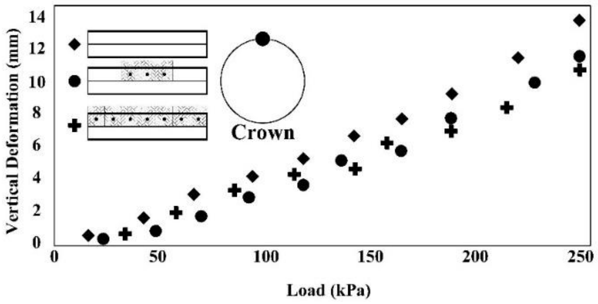

Fig. 10 Vertical deformation at 60% relative density

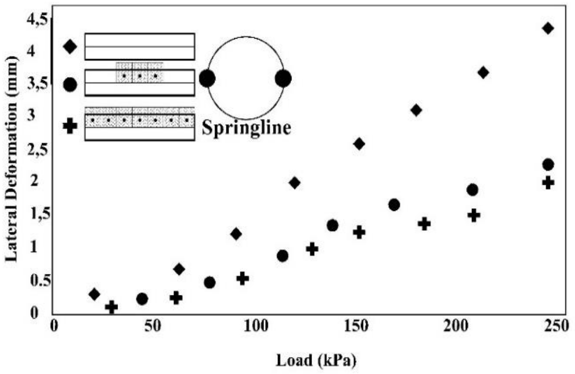

Fig. 11 Lateral deformation at 60% relative density

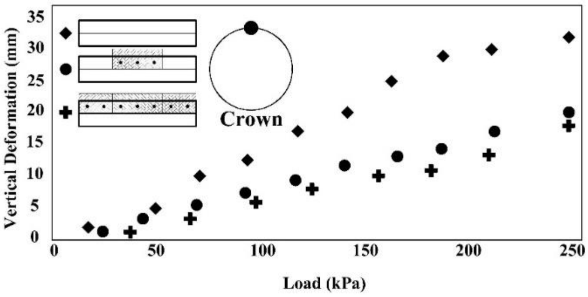

Fig. 12 Vertical deformation at 45% relative density

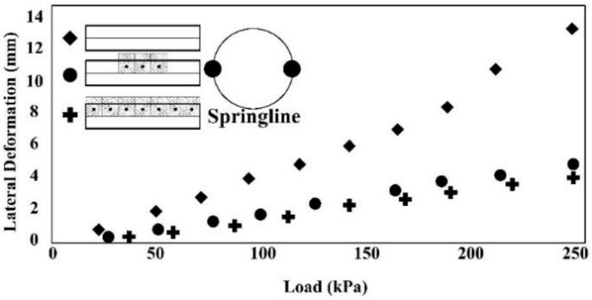

Fig. 13 Lateral deformation at 45% relative density

5. Experimental results

A series of full-scale laboratory tests were conducted to investigate the positive impacts of installing half-section waste tire covers over buried flexible HDPE pipes backfilled with silica sand. In this context, the research showed the results of an experimental investigation conducted to determine the deformation behavior of HDPE pipes.

Vertical and horizontal displacement values occurring under the effect of a vertical load for 75%, 60% and 45% relative density conditions are given in Fig. 8, Fig. 9, Fig. 10, Fig. 11, Fig. 12 and Fig. 13, respectively.

Bending moment values obtained for both sections of pipe samples are presented in Table 4. Bending moment values decreased significantly in pipe sections where the half-section waste tires (HSWTs) were applied compared to the sections where they were not applied. In the experiments carried out in this study, bending moment values that occurred on the pipeline under the effect of

Table 4 Bending moment values on the pipe section

Relative density (D_r)		75%		60%		45%	
Location		*L*/2	*L*/4	*L*/2	*L*/4	*L*/2	*L*/4
Non-reinforced	Crown (kNm/m)	0.0732	0.0022	0.0911	0.0035	0.0943	0.0038
	Springline (kNm/m)	0.0347	0.0011	0.0872	0.0028	0.0910	0.0037
Formation 1	Crown (kNm/m)	0.0383	0.0022	0.0402	0.0024	0.0407	0.0036
	Springline (kNm/m)	0.0294	0.0019	0.0322	0.0013	0.0442	0.0036
Formation 2	Crown (kNm/m)	0.0376	0.0020	0.0408	0.0017	0.0411	0.0033
	Springline (kNm/m)	0.0312	0.0010	0.0354	0.0013	0.0398	0.0332

vertical loading are given in Table 4.

In this experimental study, the deformation behavior of flexible HDPE pipes reinforced with HSWTs buried in sandy backfill was investigated. As a result of the findings, the study showed that HSWTs play an important role in reducing deflections and stresses observed in the critical sections of the pipes.

6. Conclusions

According to the test results and associated inferences, the significant efficiency of HSWTs is clearly observed. HSWTs can be used along the pipeline to provide stability for the whole pipeline. Furthermore, in order to reduce the deformation values in critical sections, stability can be ensured only by strengthening the critical regions.

The significant effects of HSWT in reducing the deformations determined in the pipe section are listed as follows:

- For all relative density conditions, HSWT reinforcement in each section of the pipe reduced both vertical and lateral deformations,
- In all of the experiments performed without HSWT reinforcement and HSWT application along the pipeline (Formation II), the deformation and bending moment values in the *L*/4 sections were lower than in the *L*/2 sections,
- For all relative density conditions, the deformation and bending moment values in the *L*/2 section were significantly reduced in experiments where HSWT was applied only the middle of the pipeline. Thus, the high deformation values in the critical section were reduced to equal or less to the deformation values in the *L*/4 section,
- For 75%, 60% and 45% relative density conditions, the vertical deformation values at the crown were observed to be reduced by 50%, 49% and 45%, respectively, in the tests where the HSWTs were installed along the pipeline. For the same relative density conditions 58%, 57% and 31% less lateral deformation values were observed at the springlines,
- As observed with the deformation values, bending moments on the pipeline showed approximate equivalent results under the same conditions.

Finally, results were obtained within the scope of aims in this study, which were carried out and shown to significantly reduce pipe deformations and to open new areas of use for waste tires. In this regard, an innovative approach has been presented for pipelines and waste management.

Acknowledgments

This research was partially supported by a Scientific Research Project of Aksaray University under the project numbers BAP-2015-086 and BAP-2018-051. We would also like to show our appreciation to the Kuzeyboru Company for the HDPE pipe supply, R&D cooperation and sharing their technical information with us during this research.

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