Sustainable Utilization of Scrap Tire Derived Geomaterials for Geotechnical Applications

Article · September 2017

DOI: 10.1007/s40098-017-0273-3

S. Bali Reddy
Madanapalle Institute of Technology & Science

A. Murali Krishna
Indian Institute of Technology Guwahati

Indian Geotech J
DOI 10.1007/s40098-017-0273-3

ORIGINAL PAPER

Sustainable Utilization of Scrap Tire Derived Geomaterials for Geotechnical Applications

S. Bali Reddy[1] · A. Murali Krishna[2] · Krishna R. Reddy[3]

Received: 10 March 2017 / Accepted: 13 September 2017

Abstract Use of scrap tire derived (STD) geomaterials in geotechnical engineering applications has received growing interest to prevent creation of wastes and conserve natural resources towards achieving sustainability. STD geomaterials and their mixtures with soils are being used in highway embankments, retaining walls, landfills and other applications as lightweight fill, backfill, compressible inclusion, vibration absorber, and drainage material. The use of STD geomaterials in these applications has been affirmed by characterization of the engineering properties based on laboratory tests and performance assessment based on physical model studies. This paper provides a review of engineering properties of STD geomaterials and their mixtures with soil (predominantly sand) based on published studies. Further, laboratory model and field studies on typical applications of STD geomaterials/mixtures such as retaining walls, foundations, embankments, and landfills are discussed. Overall, STD geomaterial alone or sand mixed with optimal STD content of 30–40% by weight has been shown to be effective for geoengineering applications.

Keywords Scrap tire derived (STD) geomaterials · Retaining wall · Foundation · Embankment · Drainage layer

Introduction

Different industrial waste by-products, such as waste tires, plastic bottles, flyash, cement kiln dust, stone dust, and rice ash husk, are being generated each year and their quantities have been increasing annually due to an increasing world population and consumption. Safe and efficient disposal of these waste materials has been a daunting challenge to waste management or environmental professionals. Among these waste materials, disposal of waste tires has become a major concern in worldwide. It was reported that the annual rate of scrap tire generation is 200–300 million in the United States [1–3], 104 million in Japan [4, 5], 112 million in India [6], and 20 million in Korea [7]. Scrap tire stockpiles can pose health hazard and fire hazard, thus alternative approaches to utilize large amounts of scrap tires has received attention of engineering community. Reuse of scrap tires prevents wastes that require disposal in landfills and preserve the natural resources towards attaining sustainability.

Scrap tires have been used in various applications [2] as shown in Table 1. The largest volume of waste tires has been used as tire derived fuel (TDF) in cement kilns, power plants, and paper mills for higher energy. TDF mainly produces the auxiliary fuel, pyrolysis oil, flammable gas, and char. In general, pyrolysis process can be expensive and can also cause air pollution problems [8]. Compared to

✉ S. Bali Reddy
balireddys@mits.ac.in; sodom@iitg.ernet.in

A. Murali Krishna
amurali@iitg.ernet.in

Krishna R. Reddy
kreddy@uic.edu

1 Department of Civil Engineering, Madanapalle Institute of Technology and Science, Madanapalle, Andhra Pradesh 517325, India

2 Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, India

3 Department of Civil and Materials Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, IL 60607, USA

Table 1 Utilization of waste tires [2]

Years	Thousands of tons in various fields								
	Tire-derived fuel	Ground rubber	Civil engineering	Reclamation projects	Exported	Punched/stamped	Agricultural	Baled tires/market	Electric arc furnace
2005	2144.64	552.51	639.99	0	111.99	100.51	47.59	0	18.88
2007	2484.36	789.09	561.56	132.58	102.08	1.85	7.13	0	27.14
2009	2084.75	1354.17	284.92	130	102.1	1.9	7.1	27.76	27.1
2011	1427.03	1093.5	294.99	54.29	302.48	1.9	7.1	1.92	65.55
2013	2120.29	975	172	49.17	245.84	1.9	7.1	30	65.56
2015	1922.67	1020.75	274.92	52.54	102.07	41.2	7.1	9.19	26

other applications, civil engineering applications hold great promise to consume large quantities of scrap tires.

Scrap tires can be used in geotechnical engineering applications in lieu of soils as lightweight fill material, high vibration absorption capacity, high elastic compressibility, insulation layer material, and drainage material. Prior to field application, it is critical to characterize the engineering properties and evaluate the performance based on the laboratory model tests and field pilot studies. Instead of whole tires, scrap tires are shredded and used alone or used after mixing with soil. The particle size and distribution of shredded tires can differ; these materials are called scrap tire derived (STD) geomaterials, which was reported by Hazarika and Yasuhara [9]. ASTM D6270 [10] classifies the scrap tire shredded materials based on the particle sizes: granulated rubber (maximum size of 12 mm), tire chips (generally between 12 and 50 mm) and tire shreds (generally between 50 and 305 mm) as depicted in Fig. 1. This paper provides a review of the reported studies on engineering properties of STD geomaterials and its mixtures with soil, model and field studies to investigate their performance in geotechnical applications such as retaining walls, foundations, embankments, and landfills.

Engineering Properties of Scrap Tire Derived (STD) Geomaterials

STD geomaterials have been used in various geoengineering applications due to various beneficial properties in the form of granulated rubber, tire chips, tire shreds and their mixtures with soil/sand. In general, STD geomaterials have lightweight, high vibration-absorption, high elastic compressibility, high hydraulic conductivity, and temperature-isolation properties, leading to wide range of geotechnical engineering applications.

Several investigators [11–18] have studied engineering properties of STD geomaterials. A summary of these properties for different size STD geomaterials was reported by Reddy et al. [17]. The range of specific gravity values for shredded tire chips was reported to be 1.02–1.24 [10, 11, 17–26] which shows the STD geomaterials are lighter. They possess high hydraulic conductivity, but it decreases with increase in overburden stress [27], hence provide better drainage characteristics. Friction angle values in the range of 15°–38° and cohesion values up to approximately 20 kPa were reported. Based on the published studies, a summary of range for major properties of STD geomaterials is provided in Tables 2, 3 and 4. The low unit weight [9, 11, 19] and higher shear strength [28, 29] make them ideal backfill material to enhance the stability of retaining structures. The shear strength of tire-derived geomaterials determined using triaxial and direct shear tests was reported by several investigators [13, 19, 24, 30]. Pando and Garcia [15] also summarized the shear strengths of STD geomaterials of various sizes under various confining pressures obtained by previous researchers. Moreover, based on their study, they reported the ranges of effective cohesion (0–14 kPa) and effective friction angle (9.2°–14.9°) for STD geomaterials (maximum size of 4.5 mm).

Engineering Properties of STD Geomaterials Mixed with Soil

In order to improve the mechanical properties of STD geomaterial, it can be mixed with soil, mostly sand. The mechanical properties of sand mixed with STD geomaterials (of different particle sizes) have been widely studied [19, 22, 23, 28, 37–49].

Ahmed [19] presented the first comprehensive study of the properties of sand mixed with tire chips using triaxial apparatus. It was observed that the confining pressure and gravimetric proportions of the tire chips mainly govern the shear strength behaviour of the sand–tire chips mixtures. The shear strength was improved after tire chips were added, while maximum improvement occurred when the

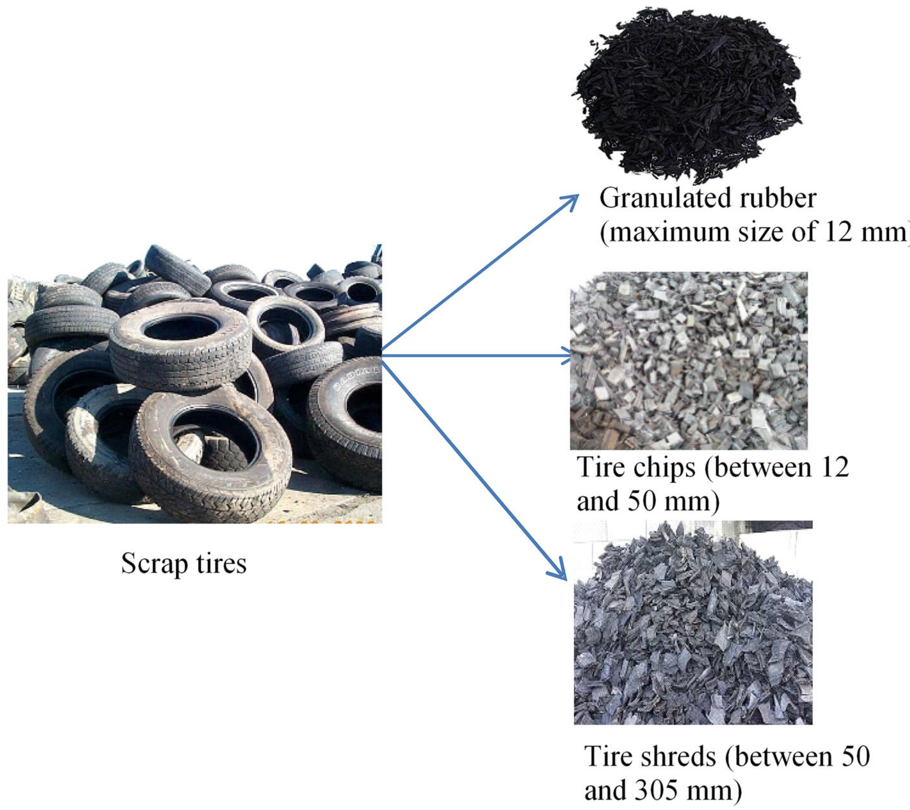


Fig. 1 Scrap tire derived geomaterials (Modified after Hazarika and Yasuhara [9])

Table 2 Dry unit weight of STD geomaterials

References	Tire derived material size (cm)	Dry unit weight (kN/m^3)	Compaction type
Humphrey et al. [13]	0.2–7.6	6.13	60% Standard
	0.2–5.1	6.29	60% Standard
	0.2–2.5	2.4	60% Standard
Ahmed [19]	1.3–2.5	4.90	ASTM D 4253
	1.3–5.1	6.07	50% Standard
	2.3	6.26	Standard
	1.27–5.1	6.56	Modified
	1.3–2.5	6.71	Modified
Reddy and Saichek [27]	1.27–13.97	4.16	No
Tweedie et al. [31]	3.8	6.96	Full scale field test
	7.6	6.78	Full scale field test
Hazarika et al. [32]	2.0	6.75	Compaction
Reddy et al. [21]	2.5	6.45	Compaction

voids between the tire chips were filled with sand. The maximum improvement occurred for the mixture with gravimetric proportion of 30% tire chips. It was also reported that the compaction effort had almost no effect on the shear strength and on load-deformation response of the sand-tire chips mixtures.

The investigations on compaction of clay and clayey soil mixed with tire shreds were performed by Cetina et al. [50]. The reported Proctor curves indicate that the maximum densities are higher for clayey soil alone and decrease as the percentage of tire shreds increases, both for fine and coarse tire shreds soil mixtures. Oikonomoun and Mavridou [30] conducted compaction tests on sand-tire shred mixture and reported that dry density decreases as the percentage of rubber increases regardless of the rubber size. Thus, the values of reduced maximum densities show

Table 3 Hydraulic conductivity of STD geomaterials

References	Tire derived material size (cm)	Hydraulic Conductivity (cm/s)	Void ratio (e)
Humphrey and Manion [12] and Humphrey et al. [13]	1–5.1	7.7	0.925
	0.1–5.1	2.1	0.488
	1.9–7.6	15.4	1.114
	1.9–7.6	4.8	0.583
	1–3.8	6.9	0.833
	1–3.8	1.5	0.414
Lawrence et al. [33]	1.3–3.8	7.6	0.693
	1.3–3.8	1.5	0.328
Reddy and Saichek [16]	1.25–14	0.65	–

Table 4 Shear strength properties of STD geomaterials

References	STD size (cm)	c (kN/m^{2})	φ (°)	Remarks
Humphrey et al. [14]	<3.8	8.6	25	Normal stress: 19.2–71.8 (kN/m^2)
	<5.1	4.3–7.7	21–26	
	<7.6	11.5	19	
Edil and Bosscher [28]	5–7.5	–	85	Compacted condition
Bernal et al. [34]	5.1	0	17–35	17° at 5% strain 35° at 20% strain
Masad et al. [35]	0.46	70.0	6	10% strain
		71.0	11	20% strain
		82	15	30% strain
Xiao et al. [36]	0.05–10	8.87	38	–
Reddy et al. [37]	2.5	18.3	26.7	10% strain

that the tire shreds or tire shred soil mixtures have high potential for lightweight fill materials. Porosity of the different sand–STD geomaterial mixtures were presented by Kim and Santamarina [43], as shown in Fig. 2. And it was reported that the sand skeleton controls the behaviour for volume fraction of rubber up to 30%.

Attom [38], Zornberg et al. [26], Ghazavi and Sakhi [41], Balunaini et al. [20, 39], Ghazavi et al. [42], Mashiri et al. [45] and Reddy et al. [37], were also discussed about the characterization of sand-tire chips mixtures. Figure 3 shows the void ratio of different ratio of sand tire chips (different size of tire chips) mixtures. From the figure it is

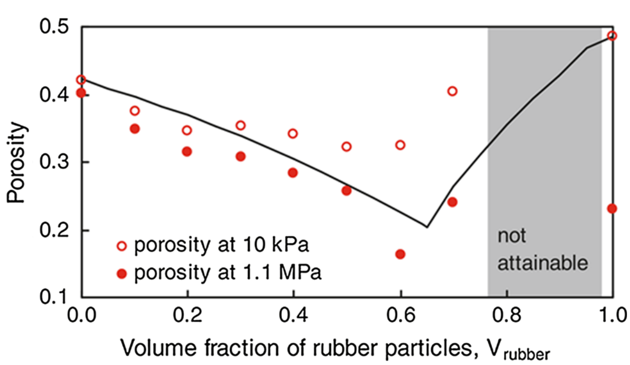


Fig. 2 Porosity of sand–rubber particles (After Kim and Santamarina [43])

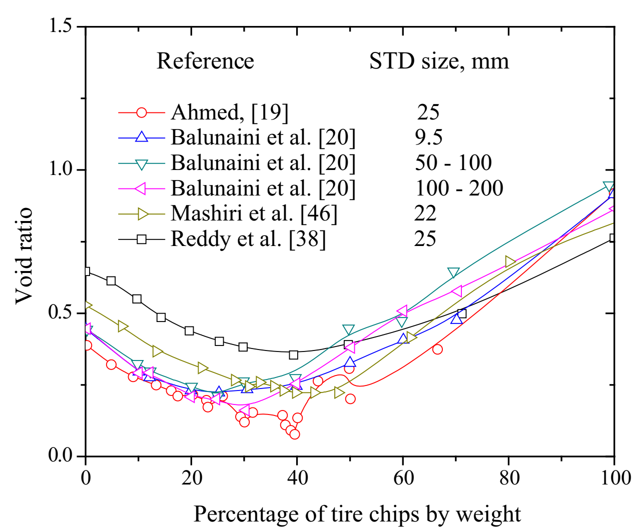


Fig. 3 Void ratio of different sand tire chips mixtures

observed that the void ratio is decreased with increasing tire chips contents up to 30–40% after that it is increased. It is to be noted that, though the void ratios for different size of tire chips matrix are different, the lowest void ratios are observed for 30–40% tire chips.

Figure 3 indicates that 30–40% tire chips is optimum mixture wherein, most of the voids between the tires chips are filled with sand particles. Maximum shear strength occurs approximately at minimum void ratio that is with closer packing. Larger air voids may cause settlement problems due to compaction under loads.

Edil and Bosscher [28] characterized tire shred–sand mixtures with varying tire shred contents using large-scale direct shear tests and concluded that tire shred inclusions improve the shear strength, especially for low and intermediate confining pressures. Lee et al. [51, 52] performed triaxial tests using pure tire shreds and tire shred–sand mixtures to investigate the effect of varying confining pressures on shear strength. The shear strength of tire shreds-Ottawa sand mixtures was determined by Masad et al. [35] using triaxial tests by varying sizes and concentration of tire shreds in the composite. It was concluded that the mixtures are suitable fill materials for the construction of highway embankments over soft compressible soils. The shear strength characteristics were improved from 36° to 40° and 11.77 to 26.48 kPa in terms of friction angle and cohesion, respectively. Shear strength properties of tire chips mixed with sand/soil were collated from various literatures and the values are presented in Fig. 4. It is observed from the Fig. 4 that internal friction angle is high at 30% tire chips compared to other mixtures. Shear strength (friction angle) and deformability (void ratio) properties for different mixtures indicate that optimum percentage of tire chips in mixture would lie in the range of 28–30%. The interaction between tire chips mixed with sand and reinforcements has been also investigated by conducting pull-out tests [20, 22].

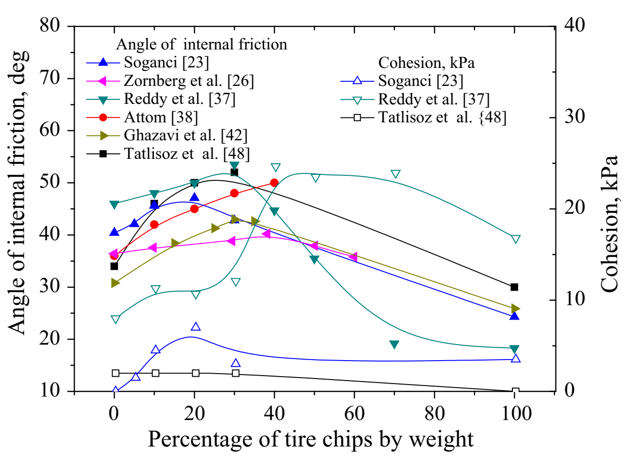


Fig. 4 Shear strength properties of sand tire chip mixtures

STD geomaterials are very free draining materials with hydraulic conductivity greater than 1 cm/s [29]. With the high permeability, STD geomaterials can be used as drainage layer or to allow effective drainage in applications such as landfills, roads, and retaining walls. Reddy and Marella [27] and Reddy and Saichek [16] were evaluated the variation in the hydraulic conductivity of tire shreds with their size. Tire shreds of larger size possessed a high enough hydraulic conductivity to serve as effective drainage material in landfill cover and liner systems [17, 53].

Geotechnical Applications of STD Geomaterials and STD-Soil Mixtures

Due to the lower unit weight, low void ratio and high shear strength of sand tire chips mixtures together with their widespread availability, they have been used as lightweight fill for geotechnical applications such as backfill behind retaining wall, bridge abutments, foundations, and embankments. Due to the higher void ratio of tire chips alone, they have been used as drainage layers in numerous highway embankments and landfill applications projects, and behind bridge abutments/retaining walls. The following sections discuss the studies investigating the applicability of STD geomaterials in various geoengineering applications.

Retaining Wall Backfill

STD geomaterials are lightweight and high shear strength materials (Table 2) so they produce low horizontal pressure on the backside of the retaining walls. Moreover, they are free draining materials [54], thus providing effective drainage and do not allow build-up of any excess pore water pressures behind the wall. Cecich et al. [11] used tire chips alone as retaining wall backfill and achieved higher factors of safety against sliding and overturning as compared to that using sand as backfill. Tweedie et al. [55, 56] were constructed retaining wall models of height 4.88 m and used concrete blocks to apply surcharge of 36 kPa. Granular soil and tire shreds were considered as backfill materials. Longitudinal cross section of retaining wall is shown in Fig. 5. Lateral pressures were measured with load cells at-rest and active conditions. It was reported that, horizontal pressures with tire shreds were about 45% less in at-rest condition and 35% less in active condition compared to those with granular soil.

Lee and Roh [57] proved that the dynamic earth pressures behind a retaining wall were reduced by using a backfill material having lesser elastic modulus and higher

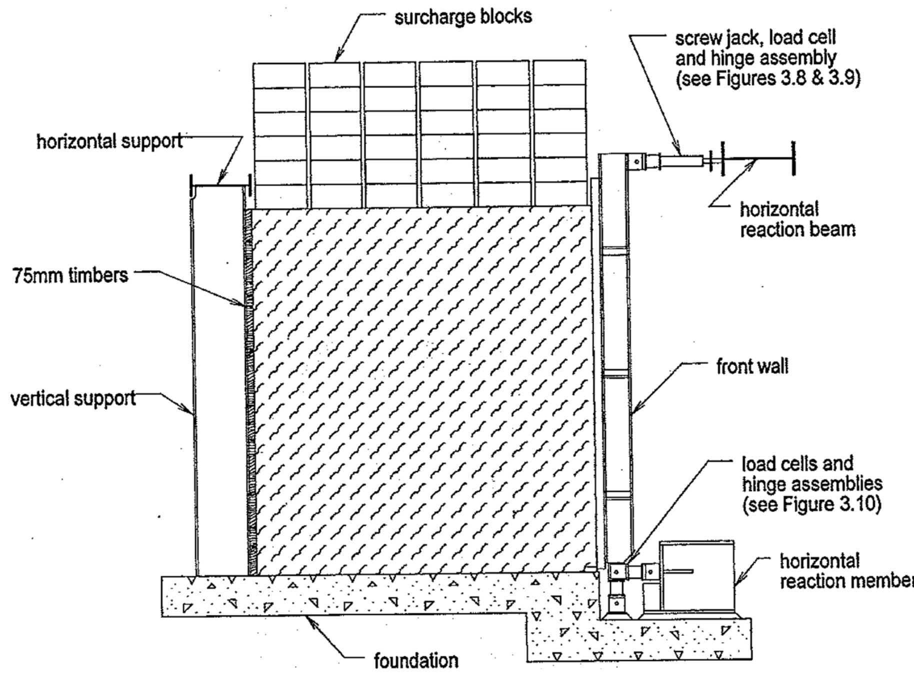


Fig. 5 Longitudinal cross section of retaining wall at University of Maine (after Tweedie et al. [56])

damping ratio and demonstrated that tire chips possesses these reliable properties. Numerical analysis on retaining walls backfilled with pure tire chips and pure sand carried out by Ravichandran and Huggins [46] and Shrestha et al. [22] showed that the bending moments, shear forces and the displacements of the walls backfilled with tire chips were reduced significantly than that wall backfilled with sand.

Humphrey et al. [13] constucted an abutment of 300-m long (Fig. 6), using STD geomaterials for a Bridge in Topsham. Four types of instruments were installed to monitor lateral earth pressure against the abutment wall, settlements, and heating. It was obeserved that the tire shred fill compressed about 370 mm during the placement of the overlying soil cover. Tire sherds used as lightweight fill to improve the slope stability for two highway projects constructed on weak marine clay.

Xiao et al. [36] studied seismic responses of geosynthetic reinforced walls with two types of backfills using shaking table tests. The wall was constructed in four layers of 400 mm each and using geogrid as reinforcement. The backfills were STD geomaterial and poorly graded sand, respectively. A section of reduced-scale MSE wall (1.6 m high, 1.5 m deep, and 1.5 m long) was built in a box that was placed on a shake table to apply earthquake excitations obtained from actual field recordings. The wall was instrumented with accelerometers, linear variable differential transformers, linear potentiometers, and dynamic soil stress gauges to record the accelerations, wall vertical deformations, horizontal deflections of the wall face, and transient effective stresses during the shaking, respectively. The accelerometers were placed at 40 cm to the face of the wall in each layer, and one accelerometer was attached to the box. Tables 5 and 6 presents the maximum values of lateral displacements and maximum accelerations of the four layers of the MSE walls with TDA and sand backfills. The study revealed that, 29% reduction in top displacements and 24% reduction in backfill accelerations.

Sand–STD geomaterial mixture showed that void ratio is low at the optimum mixture (Fig. 3) and higher shear strength (Fig. 4) compared to sand alone. This implies that optimum sand tire chip mixture can help to reduce the lateral earth pressures due to higher shear strength and lower unit weight, and reduce vertical settlements due to low void ratio. Hazarika et al. [5, 58] and other researchers [4, 18, 22, 25, 26, 38, 49, 51, 59–61] wee explained the use of sand–STD geomaterial mixtures to improve the backfill material of retaining walls and caisson quay walls. Here, some of these experimental test results are discussed.

Hazarika et al. [58] initiated the model studies using tire chips–sand mixtures as backfill material of retaining walls to investigate the influence of sand and sand mixed with tire chips on the seismic behaviour of caisson walls (Fig. 7). It was concluded from the study that, by using sand mixed with tire chips prevent the liquefaction related damages. Since liquefaction tends to increase the earth pressures against the wall, prevention of liquefaction reduced the incremental dynamic earth pressures on soil structures by about 60% as depicted in Fig. 8.

Reddy et al. [21], Reddy and Krishna [29], and Dammala et al. [62] were investigated the static and seismic behaviour of retaining wall models using different sand–

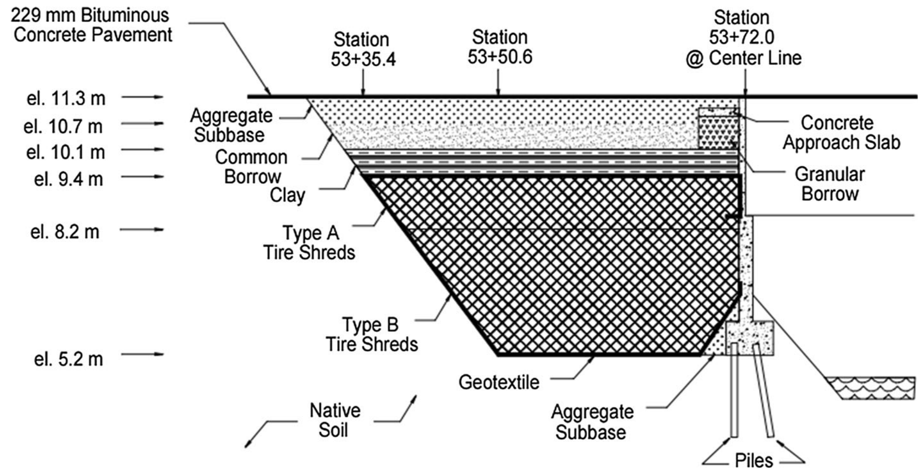


Fig. 6 North abutment of the 300 m long Merrymeeting Bridge (after Humphrey et al. [13])

Table 5 Maximum lateral displacements of the MSE walls with TDA and sand backfills (after Xiao et al. [36])

Locations—elevation	TDA backfill, relative to table movement (cm)	Sand backfill, relative to table movement (cm)	TDA backfill, relative to underlying layer (cm)	Sand backfill, relative to underlying layer (cm)
Layer 4 (top)—1400 mm	29.5	41.5	9.7	12.5
Layer 3—1000 mm	23	34.6	5.0	8.0
Layer 2–600 mm	20.6	34.6	5.0	9.0
Layer 1 (bottom)—200 mm	15.7	25.2	15.7	25.2

Table 6 Maximum accelerations measured in the TDA and Sand backfills (after Xiao et al. [36])

Locations—elevation	TDA backfill (g)	Sand backfill (g)
Layer 4 (top)—1400 mm	1.6	2.1
Layer 3—1000 mm	1.6	2.7
Layer 2–600 mm	2.1	3.9
Layer 1 (bottom)—200 mm	2.5	5.2

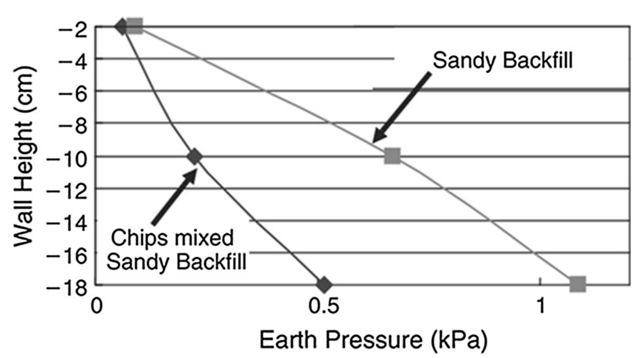


Fig. 8 Incremental seismic earth pressure (after Hazarika et al. [58])

STD geomaterial mixtures as backfill materials. Figure 9 shows the schematic diagrams of retaining wall models with instrumentation under static and seismic conditions. In the static case, surcharge pressures (Fig. 9a) were applied

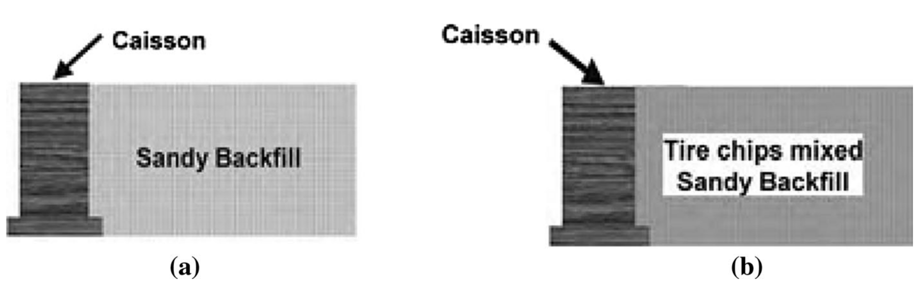


Fig. 7 Test conditions adopted by Hazarika et al. [58]

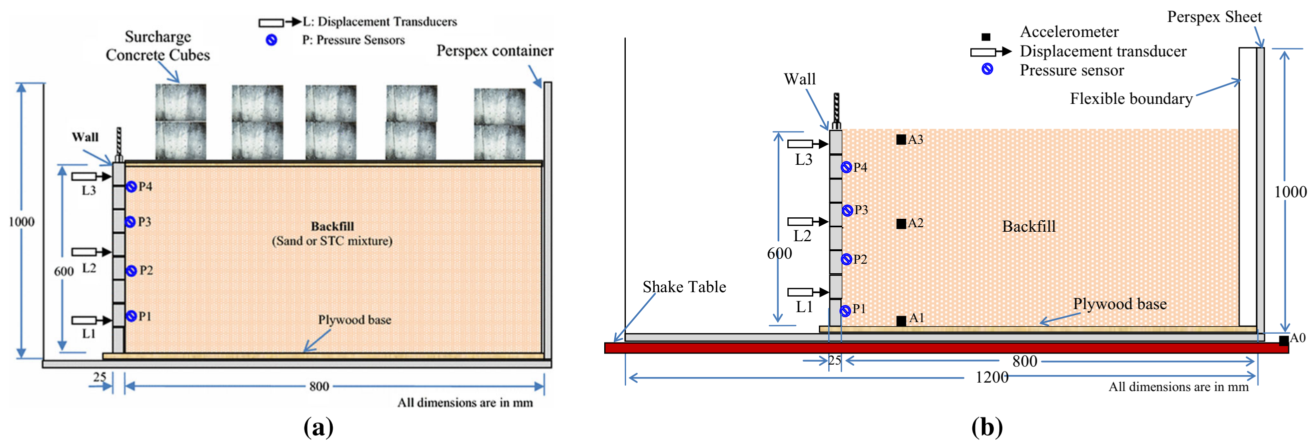


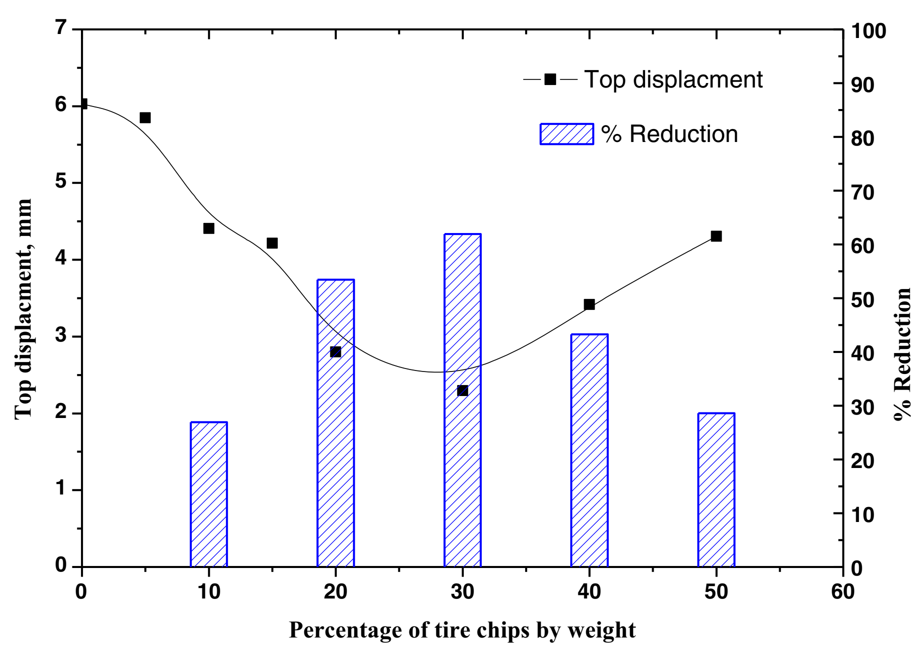
Fig. 9 Schematic diagaram of model wall; **a** static case (after Reddy and Krishna [29]); **b** seismic case (after Reddy et al. [21])

up to 10 kPa. In the seismic case different combinations of harmonic and irregular motions were used for excitations. Maximum displacements and its percentage reductions were shown in Fig. 10 under 10 kPa surcharge pressure. The figure reveals that displacements are decreased up to 30% tire chips. Different regular and irregular motions were used as input motions to observe the dynamic behaviour of retaining wall. Seismic tests, for South Napa earthquake input motion results are presented in terms of displacements, earth pressures, and acceleration amplifications in Fig. 11.

As seen from the Fig. 11, a significant reduction of earth pressures and displacements were observed with addition of tire chips contents. Further it is observed that the accelerations are amplified more on top of the wall in almost all the cases, the largest response acceleration of the model wall occurs in the case of sand and lower response acceleration of the model wall occurs in the case of 30% tire chips. Similar observations were also obtained for other earthquake motions. When tire chips are mixed with sand, attenuation of the acceleration is observed. Maximum reductions of displacements were observed at STC30 mixture for the earthquake excitations.

Reddy et al. [63] evaluated the financial benefits of the cantilever retaining walls with different heights using sand (STC0) and STC30 mixture as backfill materials. Comparison of retaining wall costs for 30 m long shown in Table 7. It was observed that the wall sizes and the corresponding reinforcement requirement have been significantly reduced for STC30 backfill wall in comparison to the sand backfill wall. Based on the analysis, it was indicated that STC30 mixtures have lower bending moment

Fig. 10 Top displacement and percentage of top displacement under 10 kPa surcharge (after Reddy and Krishna [29])



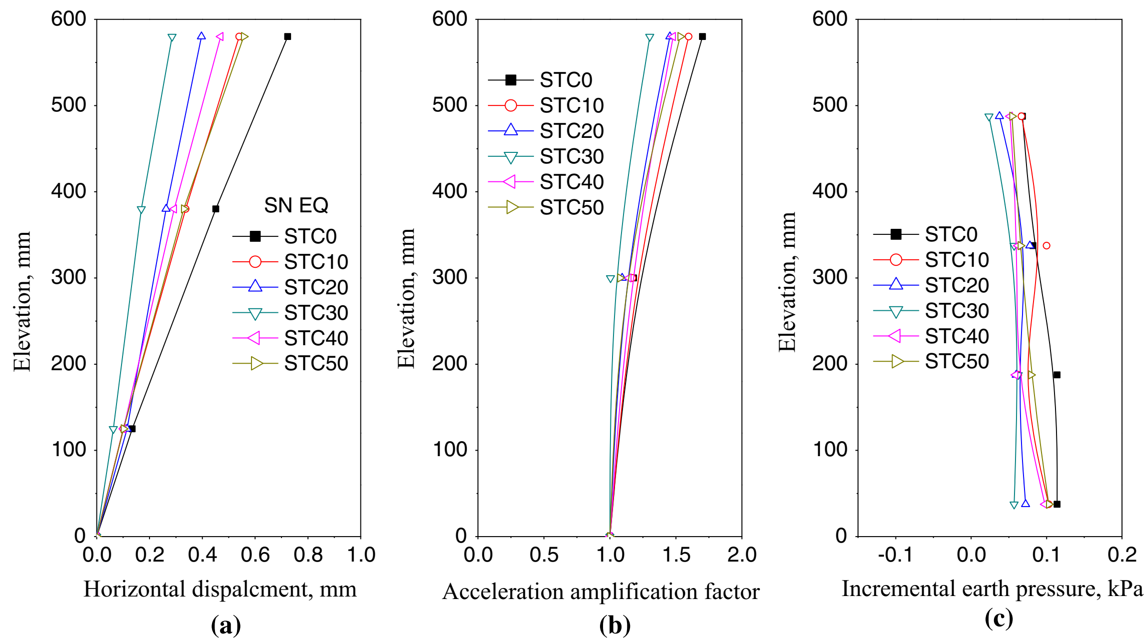


Fig. 11 Model response of SN EQ; **a** displacements, **b** incremental earth pressures and **c** acceleration amplification (after Reddy et al. [21])

Table 7 Comparison of costs for retaining walls (30 m long) [63]

Wall height (m)	Estimated backfill material cost (INR)		% Saving	Estimated total cost (INR)		% saving
	Sand	STC30		Sand	STC30	
3	316,316	202,362.9	36.02	498,237.6	363,634.6	27.01
6	1,350,998	927,297.1	31.36	1,866,434	1,333,351	28.56
9	3,039,746	2,104,095	30.78	4,367,339	3,050,002	30.16

and shear force on stem, heel and toe. Thus, the STC30 shows the better sustainable backfill material for retaining wall structures providing a financial benefit of about 30%.

Livingston and Ravichandran [44] presented the design of 6 m height retaining wall using different sand–tire chips mixtures under static and seismic conditions. Further cost analysis was done for 6 m retaining wall with different sand–tire chips mixtures. They found that, cost savings of concrete per unit length can range from 23 to 44% under static loading condition and 19 to 30% under dynamic loading condition when using shredded rubber–sand mixture, compared to the conventional granular soil backfill.

Compressible Inclusion (Cushion) Behind Retaining Wall

Most of the retaining walls and bridge abutments are designed to move very slightly outward to allow fully active conditions developed within the backfill, thereby reducing the horizontal pressures on the wall as compared to at-rest condition [18, 30]. However, sometimes the retaining walls or abutment walls may not move away from the backfill, thus leading to relatively high "at-rest" horizontal pressures. The concept of cushioning in dynamic application was first described and demonstrated by Hazarika and Okuzono [64] in which EPS was used. A cheaper and best alternative method would be to use STD geomaterials immediately behind the wall to allow creating active conditions within the backfill even if the wall does not move [19–21, 28]. STD geomaterials have high compressible behaviour [20, 28, 43] to allow the soil backfill to develop active state, and reducing lateral earth pressures.

Construction of a rigid frame structure using three-foot wide vertical strip of tire shreds in the backfill (Fig. 12) was reported by Humphrey et al. [28]. Pressure cells, soil strain meters, slope indicators, and temperature sensors were installed to monitor lateral earth pressures on the wall, as well as the temperature and movement within the tire shred zone. They observed that the pressures for the tire shred backfill were less than half of the pressures with the soil backfill. Large-scale underwater shaking table tests on gravity type caisson model with tire chips were

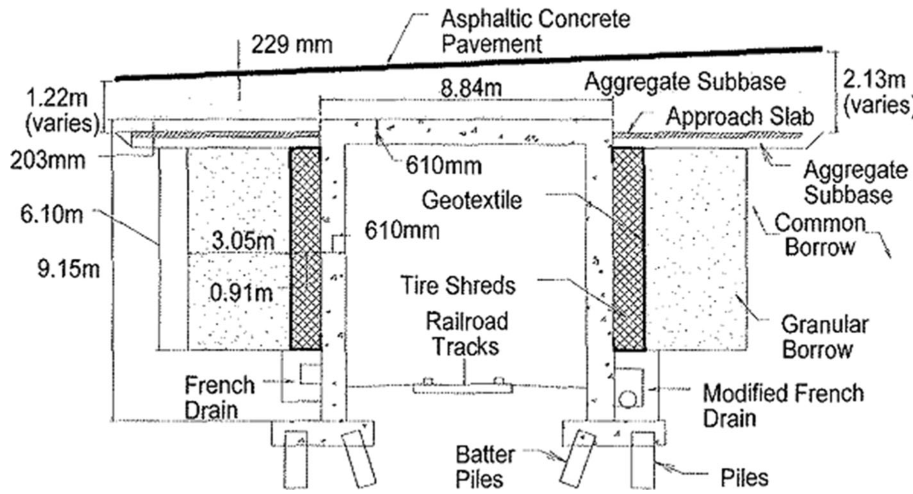


Fig. 12 Rigid frame structure with three-foot wide vertical strip of tire shreds (after Humphrey et al. [13])

conducted by Hazarika et al. [32]. The model caisson was made of 700 mm height with 300 mm thickness compressible layer using tire chips (average size of tire chips 20 mm). And installed with different instrumentations as in Fig. 13. The seismic performance of earthquake resistant techniques was evaluated by subjecting the system to three different earthquake loadings and analysed the measured responses. The results in terms of total seismic thrust and caisson top displacements (Fig. 14) demonstrated that the seismic load against the caisson quay wall and the earthquake-induced residual displacements were reduced using the tire chips cushion. Kaneda et al. [65] performed numerical investigation on retaining wall with using compressible inclusion (tire chips) behind of wall. It was reported that, lateral earth pressure was decreased by using compressible inclusion behind the wall. Reddy and Krishna [66] adopted similar cushioning technique for the application of retaining walls and carried out a series of shaking table tests on retaining wall models with tire chips as compressible inclusion. Schematic diagram of model wall with compressible inclusion and instrumentation is shown in Fig. 15. The results obtained from the study indicated significant reduction in displacements and earth pressures under different sinusoidal excitations as shown in Table 8. It is seen from the Table that up to 75% reduction in displacements and 80% reduction in incremental earth pressures, in the model walls with compressible inclusion, compared to that without compressible inclusion.

Whole scrap tires have been used for culverts, retaining walls, embankments. Hazarika and Yasuhara [9] and

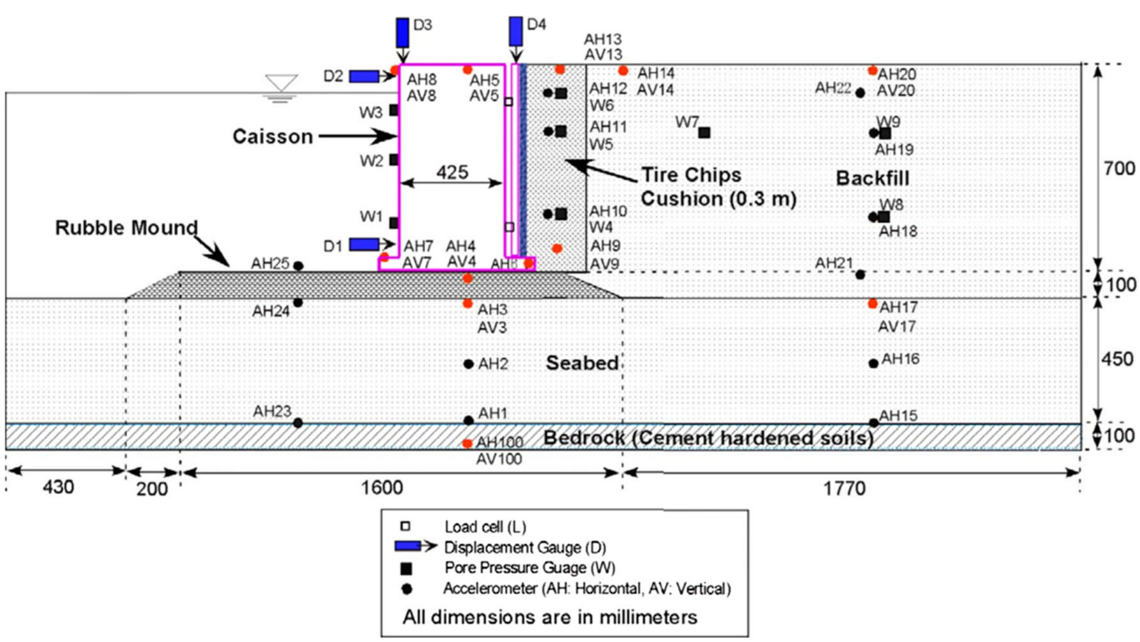


Fig. 13 Cross section of test caisson model (after Hazarika et al. [32])

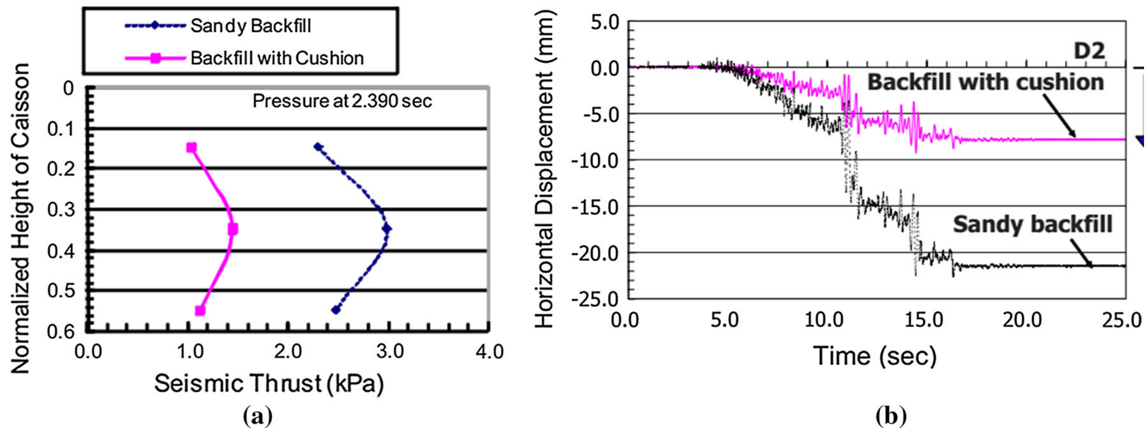


Fig. 14 Effect of cushion on caisson: **a** Total seismic thrust, **b** top (at 5 cm from the caisson top) (after Hazarika et al. [32])

Fig. 15 Schematic diagaram of model wall (after Reddy and Krishna [66])

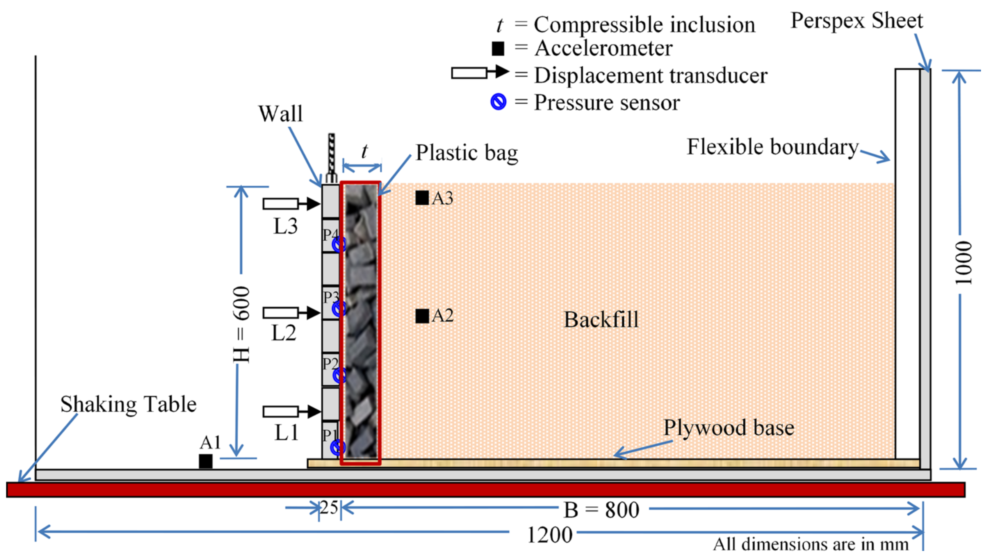


Table 8 Maximum displacements, earth pressures and its percentage reduction (after Reddy and Krishna [66])

Input motion	Top displacement (mm)			Percentage reduction	
	t/H = 0.0	t/H = 0.15	t/H = 0.30	t/H = 0.15	t/H = 0.30
0.1 *g*_3 Hz	0.61	0.32	0.195	47.54	68.03
0.2 *g*_3 Hz	3.22	1.76	1.11	45.34	65.53
0.3 *g*_3 Hz	4.32	2.53	1.70	41.43	60.65
0.3 *g*_5 Hz	3.05	1.64	0.73	46.23	76.06
Input motion	Bottom incremental earth pressure (kPa)			Percentage reduction	
	t/H = 0.0	t/H = 0.15	t/H = 0.30	t/H = 0.15	t/H = 0.30
0.1 *g*_3 Hz	0.379	0.211	0.119	44.33	68.60
0.2 *g*_3 Hz	0.745	0.389	0.167	47.78	77.58
0.3 *g*_3 Hz	0.996	0.379	0.181	61.95	81.83
0.3 *g*_5 Hz	0.58	0.24	0.097	58.62	83.27

Hazarika [60] were found that retaining wall (made of recycled tires) that miraculously survived after tsunami (2011) disaster in Okirai area, Iwate prefecture, Japan.

Highway/Embankment/Foundation Lightweight Fills

Construction of highways/embankments requires large volumes of construction materials; therefore, the use of waste materials has been of great interest. Properties of waste tires such as durability, strength, resiliency, and high frictional resistance are favourable for the use in highway embankments. The mixture of STD geomaterials with soil/sand for embankment construction provide alternative means of reusing tires to address economic and environmental concerns, and help to solve geotechnical problems associated with low shear strength [26]. Embankments constructed with soil–tire chip mixtures can potentially have steeper slopes because the backfill has higher shear strength and lower unit weight. Steeper side slopes decrease the volume of material needed.

Various studies were performed to assess the improvement of the bearing capacity of soil with STD geomaterials. Hataf and Rahimi [67] studied the bearing capacity with different mixtures of sand and tire shreds. The results of sand mixed with shredded tire showed that the bearing capacity ratio (ratio of bearing capacity of sand-tire shreds to sand alone) increased as tire shreds content increase. It was reported that optimum tire shreds content is about 40%.

Salgado et al. [3], Salgado and Prezzi [68] and Yoon et al. [18, 25] constructed the tire/soil embankment. The subgrade was prepared and a 150 mm thick layer of compacted aggregate base was placed and compacted. A layer of geotextile was laid on the compacted aggregate base as shown in Fig. 16. A 300 mm thick lift of premixed tire shred and soil mixture (Fig. 17) was placed on the filter fabric. Each layer of tire shred and soil fill was uniformly placed across the full width of the roadway cross section. It was observed that, maximum settlement was approximately 12 mm and the settlement stabilized after 200 days of traffic. Maximum lateral movement was observed about 5 mm. Observations from the study showed no signs of slope stability problems, cracking on the road or erosion.

Hazarika et al. [69] introduced Japanese experience in geotechnical related applications of geosynthetics that focus mainly on tire chips and tire shreds. STD geomaterials with sand mixtures have been investigated as base isolator for earthquake protection in seismic zone areas. Building foundation with different STD geomaterials with sand was modelled by Tsang [8] and Bandyopadhyay et al. [70]. Tsang [8] proposed a seismic isolation method particularly suitable for developing countries, which makes use of rubber–soil mixtures (Fig. 18) and series of numerical simulations were done to demonstrate the effectiveness and the robustness of the proposed method. Sand–STD mixture can reduce the horizontal and vertical ground accelerations by 60–70% and 80–90%, respectively. Bandyopadhyay et al. [70] conducted foundation tests using different STD geomaterial–sand mixtures by using rigid plexi-glass blocks (200 mm by 200 and 40 mm thick). The block was placed in the middle of a 1 m by 1 m tank filled with sand. The selected base isolator was placed between the block and the sand foundation. Accelerometers and LVDTs were used as instrumentations. The whole setup (Fig. 19) was mounted on a shake table and subjected to sinusoidal motions with varying amplitude and frequency. Sand was found to be effective only at very high amplitude (> 0.65 g) of motions. The net bearing capacity values were 173, 120, 1037 and 1235 kPa for sand, 20, 30, 50% tire chips by weight, respectively, indicating that the net bearing capacity increased significantly for 30 and 50% shredded tire mixture due to increase in cohesion.

Alqaissi [71] studied the influence of tire chips on the behaviour of strip footing on sandy soil. Different tire chips inclusions of 10, 20, and 30%, having a size of 5–9 mm and 10–20 mm were considered in the model tests. They

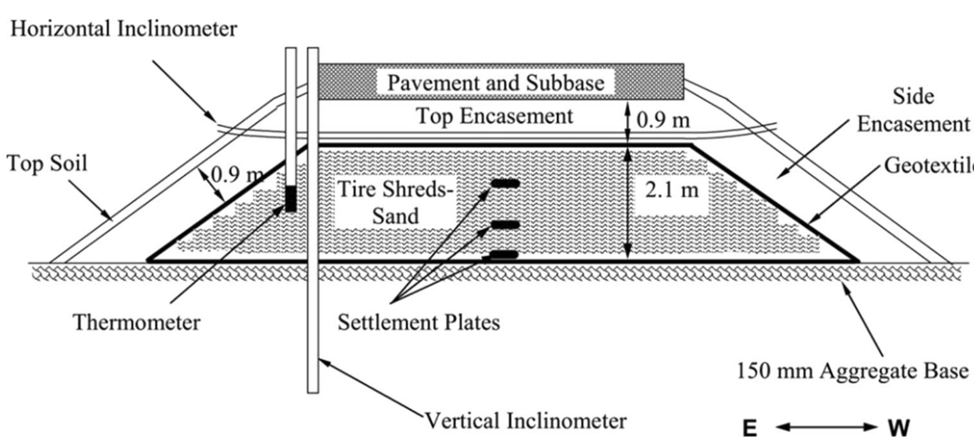


Fig. 16 Schematic diagram of tire shred and soil embankment (after Yoon et al. [18])

Fig. 17 Sand-tire chip mixture (75/25) (after Yoon et al. [18])

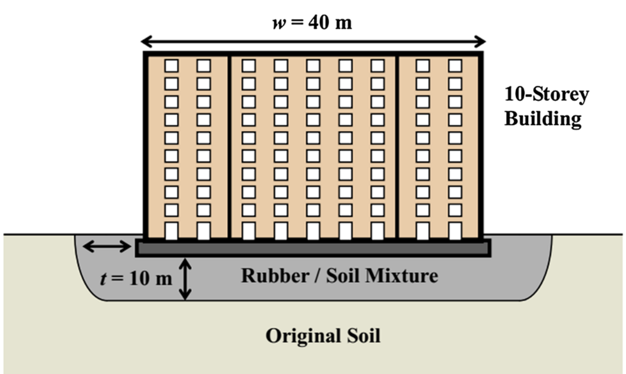


Fig. 18 Schematic drawing of the seismic isolation method using a layer of rubber–soil mixture (after Tsang [8])

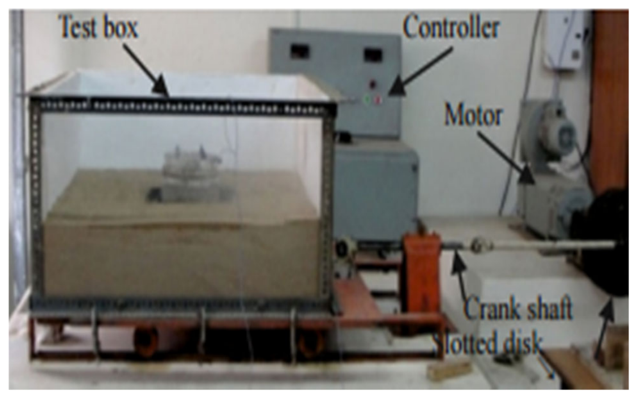


Fig. 19 Model setup adopted for foundation tests (after Bandyopadhyay et al. [70])

found that for strip footing on sand–tire chip mixture, settlement was reduced by 22% and the ultimate bearing capacity was increased up to two times, compared to that in the case of footing on pure sand.

Landfill Cover and Liner Systems

Tire chips, tire shreds, and rough shreds have potential to be used as drainage material [16, 17] in lieu of granular material in landfill cover and liner systems. Extensive laboratory and field studies were conducted by Reddy et al. [53, 54] to evaluate this application. Tire shreds were evaluated for hydraulic conductivity as a function of normal stress. Tire shred drainage layer in final cover is subjected to low vertical stress, so there is no concern with reduction of hydraulic conductivity. However, vertical stress due to overlying waste would be a concern if used as a drainage material in bottom liner system. It was shown that even under high normal stress conditions, tire shreds maintain high hydraulic conductivity to serve as an effective drainage layer. Model clogging and transmissivity tests also demonstrated that the tire shredded drainage layers possess excellent properties to serve as effective drainage media.

Tire shreds could contain steel wires, hence any potential damage to underlying geomembrane in cover or liner system is a major concern. This issue was investigated through field test plots as well as large-scale laboratory model tests [53] and found that a geotextile cushion is necessary to be placed between the geomembrane and tire shreds to protect the geomembrane. Reddy et al. [54] used tire shreds as drainage material in final cover at a landfill and monitored its performance and found that it performed excellent.

Concluding Remarks

Applications of STD geomaterials alone or mixed with sand as construction material in geotechnical engineering has shown great promise. The reuses of scrap tires prevent creation of wastes and conserve natural resources towards achieving sustainability. This paper provided a review of engineering properties of STD geomaterials and model/-field studies using STD geomaterials and their mixtures with sand. The following conclusions are drawn based on this review:

- Based on engineering properties and laboratory model studies concluded that optimum ratio of sand tire chips mixture was 30–40% by weight.
- STD geomaterials can be used as backfill material and compressible (cushion) material for retaining walls, fill materials for embankments, and drainage material in highway embankments, landfill cover and liner systems.
- STD geomaterial mixed with sand can be used as lightweight backfill material in retaining wall applications. Optimum sand–STD geomaterial mixture, shows the better sustainable backfill material for retaining wall structures providing a financial benefit of about 30%. Which may vary from place to place.
- These materials has high potential in highway embankment, as lightweight backfill and also as fill for foundations for improving static and seismic behaviour. Settlements of foundations with tire chip mixture would be reduced by 22% less than that without tire chips. Whole scrap tires can be used as culverts, retaining walls, and for slope stabilization.

The engineering properties reviewed and the studies on various Geoengineering application demonstrate the sustainable aspects of the use of STD geomaterials in various infrastructure projects. This is to be noted that with increasing use of such materials will also enhance the abundant availability of the materials, which further enhance the financial benefits. This paper concludes that the STD geomaterial possess the beneficial engineering properties which indicate the promising potential for the use in Geoengineering applications.

References

1. Ahn S II, Cheng L (2014) Tire derived aggregate for retaining wall backfill under earthquake loading. Constr Build Mater 57:105–116
2. RMA (2016) U.S. scrap tire management summary. Rubber manufacturersassociation. https://rma.org/sites/default/files/RMA_scraptire_summ_2015.pdf; www.rma.org
3. Salgado R, Yoon S, Siddiki NZ (2003) Construction of tire shreds test embankment. Publication FHWA/IN/JTRP-2002/35. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2003. doi:10.5703/1288284313165
4. Hazarika H, Yasuhara K, Karmokar AK, Kikuchi Y, Mitarai Y (2010) Multifaceted potentials of tire derived three dimensional geosynthetics in geotechnical application and their evaluation. Geotext Geomembr 28(3):303–315
5. Hazarika H, Kikuchi Y, Otani J (2012) Evaluation of tyre products as ground improving geomaterials. Ground Improv Inst Civ Eng 165(GI4):267–282
6. Rao GV, Dutta RK (2006) Compressibility and strength behaviour of sand–tyre chips mixtures. Geotech Geol Eng 24(3):711–724
7. Kim YT, Kang HS (2013) Effects of rubber and bottom ash inclusion on geotechnical characteristics of composite geomaterial. Mar Georesour Geotechnol 31(1):71–85
8. Tsang HH (2008) Seismic isolation by rubber-soil mixtures for developing countries. Earthq Eng Struct Dyn 37(2):283–303
9. Hazarika H, Yasuhara K (eds) (2007) Scrap tire derived geomaterials - Opportunities and challenges. Taylor & Francis Group, London
10. ASTM D6270 (2012) Standard practice for use of scrap tires in civil engineering applications. West Conshohocken, PA
11. Cecich V, Gonzales L, Hoisaeter A, Williams J, Reddy K (1996) Use of shredded tires as lightweight backfill material for retaining structures. Waste Manag Res 14(5):433–451
12. Humphery DN, Manion WP (1992) Properties of tire chips for lightweight fill. In: Proceedings of the conference on grouting, soil improvement, and geosynthetics, ASCE, New Orleans, Louisiana, vol 2, pp 1344–1355
13. Humphrey D, Cosgrove T, Whetten NL, Herbert R (1997) Tire chips reduce lateral earth pressure against the walls of a rigid frame bridge. In: Seminar on rehabilitation and upgrades in civil and environmental engineering, ASCE. https://rma.org/sites/default/files/CIV-044-Tire_Chips_Reduced_Lateral_Earth_Pressure_Against_The_Walls_Of_A_Rigid_Frame_Bridge.pdf
14. Humphrey DN, Whetten N, Weaver J, Recker K, Cosgrove TA (1998) Tire shreds as lightweight fill for embankments and retaining walls. In: Proceedings of the conference on recycled materials in geotechnical applications, ASCE, p 15
15. Pando M, Garcia M (2011) Tire derived aggregates as a sustainable backfill or inclusion for retaining walls and bridge abutments. Presentation at the sixth Geo3T2 Conf. and Expo, Raleigh, NC
16. Reddy KR, Saichek RE (1998) Assessment of damage to geomembrane liners by shredded scrap tires. Geotech Test J 21(4):307–316
17. Reddy KR, Marella A, Ala P (2002) Transmissivity behavior of shredded scrap tire drainage layer in landfill covers system. In: Proceedings of the 6th international symposium on environmental geotechnology and global sustainable development, Seoul, Korea, pp 277–285
18. Yoon S, Zhang J, Prezzi M, Koh T (2005). Construction and performance of a tire shred–sand demonstration embankment. In: Proceedings of the 20th international conference on solid waste technology and management, Philadelphia, PA, April, pp 237–246
19. Ahmed I (1993) Laboratory study on properties of rubber-soils, Ph.D. thesis, School of Civil Engineering, Purdue Univ., West Lafayette, I. N
20. Balunaini U, Yoon S, Prezzi M, Salgado R (2009) Tire shred backfill in mechanically stabilized earth wall applications. FHWA/IN/JTRP-2008/17. West Lafayette, Indiana

21. Reddy SB, Krishna AM, Dasaka SM (2016) Seismic resilience of retaining walls backfilled with sand–tire chips mixtures. Jpn Geotech Soc Spec Publ 3(2):20–23
22. Shrestha S, Ravichandran N, Raveendra M, Attenhofer JA (2016) Design and analysis of retaining wall backfilled with shredded tire and subjected to earthquake shaking. Soil Dyn Earthq Eng 90:227–239
23. Soganci AS (2015) Strength characteristics of tire-sand mixtures. Soil Mech Found Eng 51(6):306–309
24. Yang S, Lohnes RA, Kjartanson BH (2002) Mechanical properties of shredded tires. Geotech Test J 25(1):44–52
25. Yoon S, Prezzi M, Siddiki NZ, Kim B (2006) Construction of a test embankment using a sand–tire shred mixture as fill material. Waste Manag 26(9):1033–1044
26. Zornberg JG, Cabral AR, Viratjandra C (2004) Behaviour of tire shred–sand mixtures. Can Geotech J 41:227–241
27. Reddy KR, Marella A (2001) Properties of different size scrap tire shreds: implications on using as drainage material in landfill cover systems. In: Seventeenth international conference on solid waste technology and management, Philadelphia, PA, USA
28. Edil TB, Bosscher PJ (1994) Engineering properties of tire chips and soil mixtures. Geotech Test J 17(4):453–464
29. Reddy SB, Krishna AM (2015) Recycled tire chips mixed with sand as lightweight backfill material in retaining wall applications: an experimental investigation. Int J Geosynth Ground Eng. doi:10.1007/s40891-015-0036-0
30. Oikonomoun N, Mavridou S (2008) The use of waste tyre rubber in civil engineering works, chapter 9, sustainability of construction materials Edited by Jamal M. Khatib, CRC
31. Tweedie JJ, Humphrey DN, Sandford TC (1998b) Tire chips as lightweight backfill for retaining walls-phase 11, A Study for the New England Transportation Consortium, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine. http://www.uvm.edu/~transctr/pdf/netc/netcr08.pdf
32. Hazarika H, Kohama E, Sugano T (2008) Underwater shake table tests on waterfront structures protected with tire chips cushion. J Geotech Geoenviron Eng 134(12):1706–1719
33. Lawrence BK, Chen LH, Humphrey DN (1998) Use of tire chip/soil mixtures to limit frost heave and pavement damage of paved roads. Department of Civil and Environmental Engineering, University of Maine, Orono
34. Bernal A, Lovell CW, Salgado R (1996) Laboratory study on the use of tire shreds and rubber–sand in backfills and reinforced soil applications, FHWA/IN/JHRP-96/12. Purdue University, West Lafayette
35. Masad E, Taha R, Ho C, Papagiannakis T (1996) Engineering properties of tire/soil mixtures as a lightweight fill material. Geotech Test J 19:297–304
36. Xiao M, Bowmen J, Graham M, Larralde J (2012) Comparison of seismic responses of geosynthetically reinforced walls with tire-derived aggregates and granular backfills. J Mater Civ Eng 24:1368–1377
37. Reddy SB, Kumar DP, Krishna AM (2016) Evaluation of optimum mixing ratio of sand–tire chips mixture for geo-engineering applications. J Mater Civ Eng 28(2)
38. Attom MF (2006) The use of shredded waste tires to improve the geotechnical engineering properties of sands. Environ Geol 49(4):497–503
39. Balunaini U, Mohan VKD, Prezzi M, Salgado R (2014) Shear strength of tyre chip–sand and tyre shred–sand mixtures. Proc Inst Civ Eng Geotech Eng 167(6):585–595
40. Foose GJ, Benson CH, Bosscher PJ (1996) Sand with shredded waste tires. Geotech Test J GTJODJ 122(9):760–767
41. Ghazavi M, Sakhi MA (2005) Influence of optimized tire shreds on shear strength parameters of sand. Int J Geomech 5(1):58–65
42. Ghazavi M, Ghaffari J, Farshadfar A (2011) Experimental determination of waste tire chip-sand-geogrid interface parameters using large direct shear tests. In: 5th Symposium on advances in science and technology
43. Kim HK, Santamarina JC (2008) Sand–rubber mixtures (large rubber chips). J Can Geotech 45(10):1457–1466
44. Livingston B, Ravichandran N (2017) Properties of shredded roof membrane–sand mixture and its application as retaining wall backfill under static and earthquake loads. Recycling 2(2):1–14
45. Mashiri MS, Vinod JS, Sheikh MN, Tsang H (2015) Shear strength and dilatancy behaviour of sand–tyre chip mixtures. Soils Found 55(3):517–528
46. Ravichandran N, Huggins L (2014) Applicability of shredded tire chips as a lightweight retaining wall backfill in seismic regions. In: Proceedings of geo-congress (GSP 234), ASCE, Atlanta
47. Sheikh MN, Mashiri MS, Vinod JS, Tsang HH (2013) Shear and compressibility behavior of sand-tire crumb mixtures. J Mater Civ Eng 25(10):1366–1374
48. Tatlisoz N, Edil TB, Benson C (1998) Interaction between reinforcing geosynthetics and soil–tire chip mixtures. J Geotech Geoenviron Eng 124(11):1109–1119
49. Tsai WT (2015) The utilization of scrap tires as an energy source and its environmental benefit analysis in Taiwan. Energy Sour B 10(4):333–339. doi:10.1080/15567249.2010.551825
50. Cetina H, Fenerb M, Gunaydin M (2006) Geotechnical properties of tire-cohesive clayey soil mixtures as a fill material. Eng Geol 88:110–120
51. Lee JH, Salgado R, Bernal A, Lovell CW (1999) Shredded tires and rubber–sand as lightweight backfill. J Geotech Geoenviron Eng 125(2):132–141
52. Lee C, Truong QH, Lee JS, Lee W (2010) Characteristics of rubber–sand particle mixtures according to size ratio. J Mater Civ Eng 22(4):323–331
53. Reddy KR, Stark TD, Marella A (2008) Clogging potential of tire shred-drainage layer in landfill cover systems. Int J Geotech Eng 2(4):407–418
54. Reddy KR, Stark T, Marella A (2010) Beneficial use of shredded tires as drainage material in cover systems for abandoned landfills. Pract Period Hazard Toxic Radioact Waste Manag 14(1):47–60
55. Tweedie JJ, Humphrey DN, Sandford TC (1998) Tire shreds as retaining wall backfill, active conditions. J Geotech Geoenviron Eng 124(11):1061–1070
56. Tweedie JJ, Humphrey DN, Sandford TC (1998) Tire chips as lightweight backfill for retaining walls-phase 11, A Study for the New England Transportation Consortium, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine. http://www.uvm.edu/~transctr/pdf/netc/netcr08.pdf
57. Lee HJ, Roh HS (2006) The use of recycled tire chips to minimize dynamic earth pressure during compaction of backfill. Constr Build Mater 21(5):1016–1026
58. Hazarika H, Yasuhara K, Karmokar AK, Mitarai Y (2008) Shaking table test on liquefaction prevention using tire chips and sand mixture. In: Hazarika H, Yasuhara K (eds) Scrap tire derived geomaterials - opportunities and challenges. Taylor & Francis Group, London, pp 215–222
59. Hazarika H, Yasuhara K, Hyodo M (2009) Sustainable material recycling of scrap tires-few innovative applications in Japan—Proceedings of the international joint symposium on geodisaster prevention and geoenvironment in Asia (JS-Fukuoka 2009), Fukuoka, Japan, pp 179–184
60. Hazarika H (2013) Paradigm shift in earthquake Induced geohazards mitigation-emergence of nondilatant geomaterials. In: Keynote lecture, proceedings of the annual conference of Indian Geotechnical Society (IGC Roorkee), India, CD-ROM

61. Hazarika H, Yasuhara K (2015) Sustainable and smart materials in geotechnical constructions. Discovery 42(195):233–244 **(Paper no.A58)**
62. Dammala P, Reddy SB, Krishna AM (2015) Experimental investigation of applicability of sand tire chip mixtures as retaining wall backfill. IFCEE, ASCE Geotechnical special publication, pp 1420–1429. doi:10.1061/9780784479087.128
63. Reddy SB, Krishna AM, Arun ChB (2017b) Feasibility study of retaining walls backfilled with sand–tire chips mixtures. In: Sivakumar Babu GL et al. (eds) Geoenvironmental practices and sustainability, developments in geotechnical engineering. doi: 10.1007/978-981-10-4077-1_25
64. Hazarika H, Okuzono S (2004) Modeling the behavior of a hybrid interactive system involving soil, structure and EPS geofoam. Soils Found 44(5):149–162
65. Kaneda K, Hazarika H, Yamazaki H (2008) The numerical simulation of earth pressure reduction using tire chips in backfill. In: Hazarika H, Yasuhara K (eds) Scrap tire derived geomaterials—opportunities and challenges. Taylor & Francis Group, London, pp 245–251
66. Reddy SB, Krishna AM (2017) Tyre chips as compressible inclusions in earth retaining walls. Proc Inst Civ Eng Ground Improv. doi:10.1680/jgrim.16.00034
67. Hataf N, Rahimi MM (2006) Experimental investigation of bearing capacity of sand reinforced with randomly distributed tire shreds. Constr Build Mater 20:910–916
68. Salgado R, Prezzi M (2004) Construction of a tyre-shreds test embankment. Proc Inst Civ Eng Eng Sustain 157(2):65–66
69. Hazarika H, Kohama E, Suzuki H, Sugano T (2006) Enhancement of earthquake resistance of structures using tire chips as compressible inclusion. Technical Report of the Port and Airport Research Institute, Yokosuka, Japan 45(1):1–28
70. Bandyopadhyay S, Sengupta A, Reddy GR (2015) Performance of sand and shredded rubber tire mixture as a natural base isolator for earthquake protection. Earthq Eng Eng Vib 14(4):683–693
71. Alqaissi (2012) Behavior of strip footings resting on sand mixed with tire-chips. J Eng Dev 16 (4). ISSN: 1813–7822