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Alternative Road Construction Technology Over Soft Yielding Ground using Lightweight Fill Materials: An Overview

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Abstract: The characteristic of existing soil at the construction site is not always totally suitable for supporting structures especially when deals with soft yielding ground. Some kind of special ground improvement is required to ensure the embankments constructed on them are stable and strong without risking excessive settlement and bearing failure. Innovative use of lightweight fill material can meet the geotechnical challenges posed by soft yielding ground because it offers an attractive solution to reduce settlement. Once the stress on the subsoil can be reduced, the settlement will also reduce or eliminate all together if the road embankment is constructed out of fill material lighter than that of soil. Alternative construction technology by lightweight fill material is not a new concept; it is well-established in construction sectors, since, 1990's to meet the challenges of yielding ground. This study is critically reviewed the alternative lightweight fills used in current road construction which may be promising low cost and effective soil improvement.

Key words: Ground improvement, road, soft yielding ground, lightweight fill material, construction, stress

INTRODUCTION

Ground improvement plays an important role in geotechnical engineering because it is the only way to stabilise and modify the properties of soil. This is because the characteristic of existing soil at the construction site is not always totally suitable for supporting structures. This is important, especially for the construction over soft yielding ground. Such soft yielding ground are geotechnically problematic which comprise of high compressibility, high moisture content (>200%), high compressibility, low bearing capacity (<8 kN/m^2) and low shear strength (<20 kPa) as reported by Zainorabidin and Wijeyesekera (2007) and Wijeyesekera *et al.* (2015) Infrastructure constructions on soft yielding ground have had many post construction problems in the past. The most critical geoenvironment challenges are associated with excessive settlement and differential settlement leading to hazard and discomfort in road usage. Nearly, 28.6% of the road user complaints received in 2011 referred to poor condition of road due to differential consolidation settlement. Hence, some kind of special ground improvement is required to ensure the embankments constructed are stable and strong without risking excessive settlement and bearing failure.

Within the Medium term National Infrastructure Development Plans there are proposals being mooted for the construction of the new East Coast Highway and Dual Track Rail Road extensions from Kluang to Seremban. Such projects will necessarily meet challenging peat ground conditions. Some authorities frequently consider construction of roads on peat to be a 'black art'. Consequently, many engineers opt for conservative but unsustainable construction technology such as excavation and replacement with alternative natural resources. Furthermore, this technology also leads to uneconomic designs because it will increase the cost of construction and delay the period to completion. Various alternative construction and stabilisation methods such

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as surface reinforcement, preloading, chemical stabilisation, sand or stone column, pre-fabricated vertical drains and piles have been suggested and adopted in the past to support structures over soft yielding ground (CREAM., 2015). However, these technologies are constrained by technical feasibility, space and time limitations and expensive process.

Innovative use of lightweight fill material can meet the geotechnical challenges posed by soft yielding ground because it offers an attractive solution to reduce settlement. The stress on the subsoil can be reduced, so that, the settlement is reduced or eliminated if the road embankment is constructed out of fill material lighter than that of soil. In this respect, various types of lightweight materials (sawdust, fly ash, slag, cinders, cellular concrete, lightweight aggregates, Expanded Polystyrene (EPS, Shredded tires and seashells) have been proposed for road embankment construction.

MATERIALS AND METHODS

Benefits of soil improvement by lightweight fill materials: The magnitude of the load from the embankment on the foundation can be reduced by using lightweight fill materials in place of undesirable soils. Lightweight fill material is not a new concept; it is well-established in construction sectors, since, 1990's to meet the challenges of yielding ground (Zornberg *et al.*, 2005). According to Kalla (2010), the main advantages provided from this technology are: unit weights of lightweight fills are less than conventional earth fill (average unit weight approximately 2000 kg/m^3). Reducing residual settlement of embankment built on soft ground and minimising differential settlement between approach embankment and structure. Due to logistical and technical reasons, the solution of applying a compensated load is often the only one which can be used: in most cases, in fact, surcharges are not required. In many cases, the uses of alternative lightweight materials make it unnecessary for time consuming.

Alternative technology using lightweight fill materials: Table 1 describes the physical and mechanical properties of various lightweight fill materials (EPS geofoam, shredded tires, foamed concrete, bamboo grid, expanded clay and shale, oyster and clams shells, fly ash, etc.) to make the road system lighter and the summary of construction problem associated with them.

Fig. 1: Road construction using EPS block

Expanded Polystyrene (EPS) geofoam: Since, the 1960s, blocks of expanded polystyrene have been used extensively as a geotechnical material (EPS Industry Alliance, retrieved on 2013). The first application of the EPS in Malaysia was in 1992 to remedy the settlements of a bridge abutment. Expanded Polystyrene (EPS block) is a closed-cell structure, comprised of approximately 98% air and 2% polystyrene. EPS block is normally the preferred block material for use as a lightweight fill. It is extremely adaptable, coming in a range of densities/strengths, block sizes and even block shapes. Fig. 1 shows the embankment was built up with reused EPS block.

EPS is a super lightweight material (extremely low density), unit weight of EPS which is at least 20-30 times lighter than other lightweight fill materials. This material is expected to minimise the settlement problem, reduce inertial forces and lateral loading on adjacent structures. Moreover, the very low density of EPS makes it economical in certain circumstances such as in certain aspect of transportation and human resources (Engstrom and Lamb, 1994). Highway constructed by EPS-block geofoam are easy to handle on site and can be placed or constructed in any weather.

EPS is prone to high buoyancy forces. It is often used when existing soil conditions are soft or loose and not capable of supporting required loads. However, the buoyancy forces should be concerned in the application of EPS for construction situated below the water level. Two failures associated with buoyancy forces and water fluctuations were reported by Horvath (1999) and Frydenlund and Aaboe (2001), respectively. The first failure reported by Horvath (1999) occurred in 1987 in Norway, the flotation of the mat structure due to extreme flood event. The second failure occurred in Thailand involved an unexpected high water level that caused a

Table 1: General properties of various lightweight materials and problem associated with them

Lightweight material	General density (kg/m^3)	Compression strength (kPa)	Young's modulus (kPa)	App.cost (RM/m^3)	Descriptions	Implementation problem (Dondi *et al*., 2003)
As a fill material						
EPS geofoam	11-32 (Zornberg *et al*., 2005)	40-690at 10% deformation (Dondi *et al*., 2003)	6.5×10^3 (Dondi *et al*., 2003)	107-200 Saboundjian, 2008	Ultra lightweight expandable synthetic resins	Floating Flammable Dissolve by chemical Kalla, 2010
Shredded tires	600-918 (Zornberg *et al*., 2005)	>815	0.43 (Dondi *et al*., 2003)	61-92 (Dondi *et al*., 2003)	Usually used above ground water level cover soil layer at least 0.9 m is required	Possible release of pollutants
Foamed concrete	335-775 (Saboundjian, 2008), 500-1200 (Suryani and Mohamad, 2012)	-	-	180-300 (Saboundjian, 2008)	Density adjustable self-hardening; and various application	Supposedly for wall flow able system
Bamboo grid frame	270-940 (Nor, 2012)	19.5×10^3-42.8×10^3 (Nor, 2012)	2.6×10^3 8.8×10^3 (Nor, 2012)	-	-	Decay with time
As additive to the soil fill						
Wood Chip	712-1020 (Elragi, 2006)	0.83×10^6 (Dondi *et al*., 2003)	0.83×10^6 Dondi *et al*., 2003)	36-62 (Balunaini, 2009)	Usually to be used below groundwater level	Spontaneous combustions Decomposition
Expanded clay and shale	712 approximate (Elragi, 2000)	1.2 (Dondi *et al*., 2003)	4×10^4 (Dondi *et al*., 2003)	130-182 (Graettinger *et al*., 2005)	Variable density and deformation characteristics to soil	Floating Differential Icing water absorption
Oyster and clams shells	1120 approximate (Elragi, 2000)	-	-	-	Sized 12-76 mm interlocking effects	
Fly Ash	1020-1530 (Elragi, 2000)	1.2×10^3 (Dondi *et al*., 2003)	$10\div11\times10^6$ (Dondi *et al*., 2003)	46-65 (Balunaini, 2009)	Granular material self-hardening	Wind erosion

Current cost may differ due to inflation, A price includes transportation cost, FOB (Free on Board) at the manufacturing

complete road fill to be washed away. Another failure caused by the fire was reported in Norway. Ordinary polystyrene is a combustible material and will burn when set on fire.

Furthermore, this material is relatively expensive compared to other lightweight fill materials in ranges from RM 107.00-200.00/m^3 (Balunaini *et al*., 2009). It is dependent on factors such as production density, percentage of EPS that is recycled and additives such as insecticides (Saboundjian, 2008). Even though expensive, EPS may be cost effective in term of construction cost. Kalla (2010) reported that EPS would dissolve when they react with certain chemicals, particularly petroleum like petrol and diesel. A 100-500 mm reinforced concrete slab is cast on top of EPS blocks in order to prevent possible damage by chemicals. Moreover, this material will absorb water when placed in the ground. The EPS blocks when submerged in water have resulted in densities of 76.89-102.52 kg/m^3 after 10 years while block placed above the water had densities of 30.22-51.2 kg/m^3 for the same period (Saboundjian, 2008).

Shredded tires and tire bale fills: Generally, rubber tire is made using thermosetting polymer that cannot be remelted or reformed into new objects and is a non-biodegradable material (Saboundjian, 2008). This material has improved properties such as permeability, thermal conductivity and they are relatively lightweight. Tire shreds are one of several materials that prove suitable as a lightweight fill material for road construction to replace a conventional fill material (Engstrom and Lamb, 1994). Minnesota began using shredded tires in 1985 on logging road throughout weak soils (Ho, 2014). General density of shredded tire ranges from 600-918 kg/m^3 but it is still considerably lighter than conventional fill soils. According to Prezzi (2009) the density of tire chips (tire shred) is very low when the ratio of tire chips is 100% but it is not good because they are elastic material and will give a high rebound on road surfaces. According to Balunaini (2009), mixing ratio that produces the maximum shear strength depends on the shape and size of the tire shreds which was also concurred by Ho (2014). Figure 2 shows an example, of tire shreds used as a lightweight fill material in "St. Stephen Embankment Reconstruction Project". The shredded tire fills display excellent porosity features (Engstrom and Lamb, 1994) it is important for groundwater flow. Shredded tires also serve as a form of insulation and offer vibratory damping, thus, providing

Fig. 2: Tire shreds into 50-300 mm in length

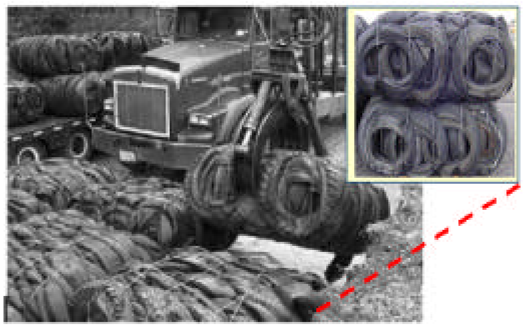

Fig. 3: Tire bales for lightweight embankment fill

protection with respect to permafrost foundation soils and damage from seismic activity (Saboundjian, 2008). However, they are inexpensive which is approximately RM61.00-92.00/m^3 (Balunaini, 2009).

Lately, a new alternative method of recycling tires (which is tire bales) as lightweight fill is in development to replace the application of tire shreds (Saboundjian, 2008). About 100 whole tires were tied together to form a 'bale' which is then placed in the embankment as blocks of lightweight fill (Fig. 3).Saboundjian (2008) claimed that tire bales hold considerable advantages over shredded tires. Embankment construction using this technology requires less skilled workers, less equipment and less processing reduce a critical expense (in term of time) (Zornberg *et al.*, 2005; Saboundjian, 2008).

Although, it is an effective method to improve ground strength there are some inherent problems with using this material. Waste tires are flammable, so, toxic fumes are produced when they prone to the fire and as a result, it will cause major health problem to the humans (Ho, 2014). Besides that, this material will release higher concentrations of metals such as barium, cadmium, chromium, lead, selenium and zinc when immersed in a highly acidic solution with a pH of 3.5 (Engstrom and Lamb, 1994; Saboundjian, 2008). The concentrations of the contaminants leached are not dangerously high but pose a possible environmental and health concerns. Therefore as a precaution, the tires must be cleaned before using or keeping the tire shred above the groundwater table. This is to ensure that they are free from oils and grease in order to avoid soil and groundwater contamination.

Foamed concrete (blocks/panels): Foamed concrete is mainly composed of water/cement ratio, fine sand and air pores with filler (such as PFA, sand etc.) without any course aggregates (Fig. 4). Foamed concrete is classified as having an air pore of more than 25% (Samsudin and Mohamad, 2012) where the air pores are formed by agitating air with a foaming agent (Saboundjian, 2008). Air entrainment of the concrete decreases the density and increases the buoyancy. In saturated areas, low density foamed concrete is susceptible to buoyancy forces like geofoam. A sufficient soil cap will protect the foamed concrete from uplift while also minimizing degradation of the foamed concrete (Saboundjian, 2008).

Foamed concrete had a density in the range 335-1200 kg/m^3 with the cost is about RM180.00-300.00. Foamed concrete has low density by its cellular microstructure (unit weight of normal concrete about 2400 kg/m^3), low cost, fast completion and easy application when compared to normal concrete. Hui (2010) stated that mechanical properties of foamed concrete are more related to the samples size and shape, method of pore formation, direction of loading, age of the samples, characteristic of the ingredients were used and method of curing.

Recently, lightweight-foamed concrete has been used widely in the field construction such as in road sub-base, bridge abutment, sidewalks, roof insulation, panel and partition wall system, floor construction, lightweight precast block and others (Hui, 2010).

Bamboo grid frame: Lately, "bamboo grid frame" technology has been successfully adopted in some embankments and building platforms over soft to very soft peat and/or clay of great depth in Malaysia. Bamboos are arranged in a grid frame on the ground before laying a geotextile. Immediately after the bamboo geotextile mattress, general earthworks can be carried out above the bamboo mattress system without any problem of machineries sinking due to very soft issues. Figure 5 shows an example, of construction using bamboo grid frame.

The density of bamboo varies depending on the seasons and weather in that area as well as their age (Nor, 2012). The average moisture content, density, compression strength and Young's modulus of the

(a) (b)

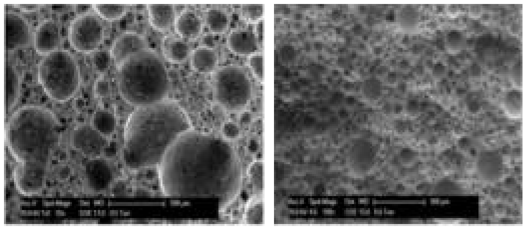

Fig. 4: SEM images of foamed concrete: a) for a density 500 kg/m^3 and b) for density 1000 kg/m^3

Fig. 5: Ground improvement using bamboo grid frame technology

bamboo are in the ranges of 30-118%, 0.27-0.94 g/cm^3, 19.5-42.8 and 2.6-8.8 MPa, respectively (Nor, 2012). The compression strength of bamboo is almost similar to the concrete but less than timber. However, bamboos have better Young's modulus when compared with concrete and timber where Young's modulus of concrete in ranges 10-17 kN/mm^2 whereas Young's modulus of timber is about 8-13 kN/mm^2 (Nor, 2012). Unfortunately, bamboos also have some disadvantages such as easy to be influenced by insect and fungi attack, easy to degrade and low shear resistance.

Other lightweight fill materials (mixed or added to the soils): Fill materials such as sawdust, wood chip, expanded clay or shale, oyster and clams shells are mixed with the soils which are considered as additive to embankment to make the embankment lighter. Additive such as Portland cement, lime and fly ash are added into the soils in order to increase the strength and stiffness but they are not lightweight material, it is more on soil stabilisation technique. For completeness a brief review of these methods are made here.

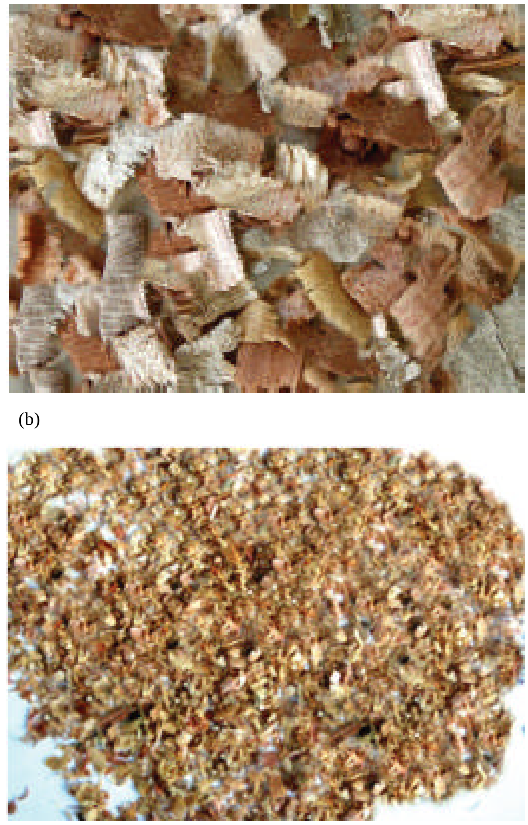

Fig. 6: a) Wood chip coarse fibre and b) Sawdust coarse fibre

Sawdust and wood chip: These technologies may be effective economically to consider as additive to embankment material compared to other lightweight materials. According to Balunaini (2009) their cost is in the range of RM36.00-62.00. Sawdust and wood chips are usually used below permanent groundwater level. If not completely submerged, this material tends to biodegrade over time (Engstrom and Lamb, 1994). Besides that, this material is also difficult to be compacted and therefore not sustainable as wood will degrade with time. Figure 6 shows an example, of wood chip and sawdust in coarse fibre.

Expanded clay and shale: Expanded shale is lightweight gravel that has small porous holes and is gray in color. Figure 7 shows an example of expanded shale used in construction. When added into the soil, it can help retain moisture, aerate and breakdown clay-based soil. This material possesses good engineering properties for use as additive in lightweight fill. The strength of these materials is based on the interlock between individual particles.

Fig. 7: Expended shale

Fig. 8: Clam shells

Moreover, this material will absorb some water after placement, if it continually submerged in water more water will be absorbed.

Oyster and clams shells: Commercially mined or dredged shells available mainly off Gulf and Atlantic coasts. General sizes are 12-75 mm (Ahmed and Lovell, 1993). Figure 8 shows an example of clam shell used in construction field. When loosely dumped, shells have a low density and high bearing capacity because of interlock.

Chemical additive for soil stabilisation: Chemical soil stabilisation involves a chemical reaction between chemical admixtures with soil particles to improve soil properties such as its stability, strength and stress-strain properties, permeability and durability (Safry *et al*., 2013). The strength of these stabilisation depends on many factors such as type and properties of soil, quantity and type of admixture, moisture content, mixing and compaction method, condition and curing time, temperature, soil minerals and used admixture (Rafizul and Alamgir, 2012).

Portland cement stabilisation is comprises of calcium-silicates and calcium-aluminates that hydrate to form cementitious product (Little and Nair, 2009). This is a common technique used to stabilise subgrade soils and road base material. It offers a longer pavement life. Cement is used to treat granular soils but is difficult with cohesive soils as serious cracking renders less durable. Fly ash is an inorganic residue of coal burning thermal power plants. Fly ash is used widely as stabilisation in sub-base courses, base courses and subgrade soils in rural road which can create long lasting and sustainable infrastructure. Fly ash can be divided into two categories, namely class C (self-cementing) and class F (non-self-cementing) they contain a substantial amount of lime. Little and Nair (2009) stated that the properties of fly ash can vary significantly depending on the source of the coal and the steps followed in the coal burning process. However, they can absorb water over time, resulting in an increase in unit weight and leach substance which may adversely affect adjacent structures and groundwater quality. In addition, the leaching of trace metals from fly ash also causes bad effect on the environment (Kalla, 2010).

Saboundjian (2008) reported that the lime is the best chemical to use with clayey soils. Lime (quick or hydrated) is used to improve strength, workability (reduce plasticity by reducing moisture content of soils) and durability of soils. However, carbonation, sulphate attack and environment impact are few advantages of lime (Little and Nair, 2009). Lately, researchers found that the Palm Oil Fuel Ash (POFA) as a pozzolanic material is useful to use as cement substitute due to its high silica content. POFA is a waste product from the process of burning palm oil fiber until it is in fly ash condition. In geotechnical engineering, POFA can be used to treat the soft soil. Moreover, the utilisation of the POFA (agro waste) in soil stabilisation techniques reduces the environmental problem related to the agricultural waste management.

RESULTS AND DISCUSSION

Critical design properties of feasible lightweight fill blocks used in embankment construction: EPS-block geofoam, tire bales and foam concrete as such fill material generally present in block form that consider as a rigid foundation. These technologies are more popular usage in the construction field due to reduced cost, lightness and easy to work in the field. Table 2 reports the comparison of typical physical and mechanical properties between EPS-block geofoam, tire bales and earth fill

Table 2: Comparison of typical properties of EPS geofoam, tire bales and earth fill materials (Modified from Zornberg *et al.*, 2005)

	EPS geofoam (ASTM D6817)		Tire bales*(No ASTM tests)		Earth fill (ASTM/AASHTO/ DOT tests)	
Properties	Reported values	Remarks	Reported values	Remarks	Reported values	Remarks
Approximate unit weight (kN/m^3)						
Dry	0.1-0.5	ASTM C578	5.2-6.3	Lab test	15-22	Lab test
Wet (Long-term)	1.0	(Zornberg *et al.*, 2005)	5.8-6.4			
Specific gravity	0.01-0.03	-	1.02-1.2	Not critical	2.5-2.7	Lab test
Permeability (cm/sec)	Relatively impermeable	Nonporous material	0.05-0.1	Lab test	10-6-10+2	
Water adsorption (%)	2-4	ASTM C272	2-9.5	Lab test	Varies	
Compression strength						
Ultimate strength (kPa)	40-690(at 10% strain)	Function of density, stress, strain, time and temperature	>815	Lab test. Function of fabrication	100-1000	Lab test
Elastic limit (kPa)	15-280	Value at 1% recommended for design	NA	Lab test: indicate strain hardening	Variable	Lab test
Elastic modulus				Lab test		
Initial tangent (kPa)	4-10 k		400 960	Unconfinedconfined-sand	5-200k	Lab test
Resilient Modulus (Mpa)	21	Based on CBR = 2 (Zornberg *et al.*,2005)	2152	Unconfined confined-sand	55-275	
Poisson's ratio	0.05-0.5 (Elragi, 2006)	At working stress	0.1-0.4	At working stress	0.15-0.45	
Shear strength (kPa)						
Internal: in material	Su = 36	Rare test (Zornberg *et al.*, 2005)	-	-	N = 25° -45°	Lab test
Internal interface (within embankment)	30°	Typical (Zornberg *et al.*, 2005)	δ>25° and adhesion, a = 2.4	Lab test (lower bound value)	NA	-
External Interface (embankment and adjacent material)	10-55°	Lab test-varies with material (Zornberg *et al.*, 2005)	As required by design	Bale on soil, geotextile or geomembrane test	NA	-
Leachability	NA	(Zornberg *et al.*, 2005)	Contaminant below regulated amount	-	NA	Expect for contaminated materials

NA = Not Applicable, *Tire bales: with 100 pieces of automobiles tires or 20 pieces of truck tires tied together

material (is classified as a flexible foundation). In Table 2, it clearly shows that EPS provides the lightest weight compared to tire bales and Earth fill material. However, the 60-70% weight reduction over soil provided by tire bales would be more adequate to provide embankment stability and/or reduce the settlement to tolerable levels (Zornberg *et al.,* 2005). Furthermore, they also claim that tire bales provide superior characteristics (such as permeability, compressive strength and resilient modulus) compared to EPS. These properties can be as good as or at least comparable to that of soil-only embankments.

CONCLUSION

A review of the use of lightweight fill materials and additive material, adding to the soil fills are effectively improving soil strength. However, in terms of density, EPS is extremely light in weight (with a density in the range 11-32 kg/m^3) compared to other lightweight fill. Nevertheless, the density of other lightweight fill materials that are <1500 kg/m^3 are still considered lighter than conventional earth fill (average density of 2000 kg/m^3). Due to their lightweight characteristic, any construction below the groundwater table must also carefully consider the buoyancy forces in the design especially for the density less than density of water (1000kg/m^3). In terms of cost, wood chip and fly ash (as additive to soil fill) are relatively low-cost compared to other lightweight fill alternatives. However, for the fill material categories, shredded tire and/or tire bales shows the low-cost compared to the EPS and foamed concrete. The benefits and implementation problems with the lightweight fill materials are also outlined. Lightweight fill materials or additive materials in a particle form (as flexible foundation) are still ineffective as they give rise to differential settlement. EPS-block geofoam, tire bales and foam concrete by virtue of the mat form (rigid foundation) not only effectual to reduce excessive settlement but they also can be overcome differential settlement presented by non-homogeneity behavior of soft yielding ground. Moreover, tire bales provide superior characteristics (such as permeability, compressive strength and resilient modulus) compared to EPS. These properties can be as good as or at least comparable to that of soil-only embankments.

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