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

1Tuan Noor Hasanah Tuan Ismail, 2Devapriya Chitra Wijeyesekera, 2Alvin John Lim Meng Siang, 3Siti Aimi Nadia Mohd Yusoff
1Department of Civil Engineering Technology, Faculty of Engineering Technology, 2Department of Infrastructure and Geomatic Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia 3School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia

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 fill 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/m²) 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
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 Kalle (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/m³). 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 Aabor (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

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

<table>
<thead>
<tr>
<th>Lightweight material</th>
<th>General density (kg/m³)</th>
<th>Compression strength (kPa)</th>
<th>Young’s modulus (kPa)</th>
<th>App. cost (RM/m³)</th>
<th>Descriptions</th>
<th>Implementation problem (Dondi et al., 2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>As a fill material</strong></td>
<td></td>
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</tr>
<tr>
<td>EPS geofoam</td>
<td>11-32 (Zornberg et al., 2005)</td>
<td>40-69% (10% deformation)</td>
<td>6.5 x 10⁶ (Dondi et al., 2003)</td>
<td>107-209</td>
<td>Ultra lightweight expandable synthetic resins</td>
<td>Floating</td>
</tr>
<tr>
<td>Shredded tires</td>
<td>600-918 (Zornberg et al., 2005)</td>
<td>&gt;815</td>
<td>0.43 (Dondi et al., 2003)</td>
<td>61-92 (Dondi et al., 2003)</td>
<td>Usually used above ground water level cover soil layer at least 0.9 m is required</td>
<td>Flammable Dissolve by chemical Kalla, 2010 Possible release of pollutants</td>
</tr>
<tr>
<td><strong>As additive to the soil fill</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foamed concrete</td>
<td>355-775 (Saboundjian, 2008), 500-1200 (Suryani and Mohammad, 2012)</td>
<td>-</td>
<td>-</td>
<td>180-300 (Saboundjian, 2008)</td>
<td>Density adjustable self-hardening, and various applications</td>
<td>Supposedly for wall flow able system</td>
</tr>
<tr>
<td>Bamboo grid frame</td>
<td>270-940 (Nor, 2012)</td>
<td>19.5 x 10⁵-42.8 x 10⁵ (Nor, 2012)</td>
<td>2.6 x 10⁻²-8.8 x 10⁻¹ (Nor, 2012)</td>
<td>-</td>
<td>-</td>
<td>Decay with time</td>
</tr>
</tbody>
</table>

Wood Chips

Expanded clay and shale

Oyster and clams shells

Fly Ash

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

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/m³ (Baluniami 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/m³ after 10 years while block placed above the water had densities of 30.22-51.2 kg/m³ 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/m³ 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 Baluniami (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
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 coarse 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 entrapment of the concrete decreases the density and increases the buoyancy. In saturated areas, low density foamed concrete is susceptible to buoyancy force 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/m³ 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/m³), 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
bamboo are in the ranges of 30-118%, 0.27-0.94 g/cm³, 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/mm² whereas Young’s modulus of timber is about 8-13 kN/mm² (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.

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.
Portland cement stabilisation is comprised 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)

<table>
<thead>
<tr>
<th>Properties</th>
<th>EPS geofoam (ASTM D6817)</th>
<th>Tire bales (No ASTM tests)</th>
<th>Earth fill (ASTM/AAHSTO/DOT tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate unit weight (kN/m³)</td>
<td>0.1-0.5</td>
<td>5.2-6.3</td>
<td>15.22</td>
</tr>
<tr>
<td>Dry</td>
<td>0.1-0.5</td>
<td>5.2-6.3</td>
<td>Lab test</td>
</tr>
<tr>
<td>Wet (Long-term)</td>
<td>1.0</td>
<td>5.8-6.4</td>
<td>Lab test</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.03-0.03</td>
<td>1.0-2.12</td>
<td>2.5-2.7</td>
</tr>
<tr>
<td>Permeability (cm/sec)</td>
<td>Relatively impermeable</td>
<td>Lab test</td>
<td>Lab test</td>
</tr>
<tr>
<td>Water adsorption (%)</td>
<td>2-4</td>
<td>0.05-0.1</td>
<td>10-60+20</td>
</tr>
<tr>
<td>Compression strength</td>
<td>ASTM C272</td>
<td>2-0.5</td>
<td>Varies</td>
</tr>
<tr>
<td>Ultimate strength (kPa)</td>
<td>40-600 at 10% strain</td>
<td>&gt;815</td>
<td>Lab test. Function of fabrication</td>
</tr>
<tr>
<td>Elastic limit (kPa)</td>
<td>15-280</td>
<td>Value at 1% recommended for design</td>
<td>Lab test: indicate strain hardening</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial tangent (kPa)</td>
<td>4-10 k</td>
<td>400-960</td>
<td>Lab test</td>
</tr>
<tr>
<td>Resilient Modulus (Mpa)</td>
<td>21</td>
<td>2152</td>
<td>Unconfined confined-sand</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.05-0.5</td>
<td>At working stress</td>
<td>Unconfined confined-sand</td>
</tr>
<tr>
<td>Shear strength (kPa)</td>
<td></td>
<td>0.1-0.4</td>
<td>At working stress</td>
</tr>
<tr>
<td>Internal interface</td>
<td></td>
<td></td>
<td>0.15-0.45</td>
</tr>
<tr>
<td>(within embankment)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Interface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(embankment and adjacent material)</td>
<td>10-55°</td>
<td>Lab test-varies with material</td>
<td></td>
</tr>
<tr>
<td>Leachability</td>
<td>NA</td>
<td>Contaminant below regulated amount</td>
<td>Lab test for contaminated materials</td>
</tr>
</tbody>
</table>

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/m³) compared to other lightweight fill. Nevertheless, the density of other lightweight fill materials that are <1500 kg/m³ are still considered lighter than conventional earth fill (average density of 2000 kg/m³). 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/m³). 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.

ACKNOWLEDGEMENT

The researchers would like to acknowledge Universiti Tun Hussein Onn Malaysia (UTHM) for the financial
support for this study under the research grant TIER 1 VOT. H221 and Research Management Center (RMC).

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