Road foundation construction using lightweight tyre bales

Construction des assises de routes à l'aide de balles de pneus légères

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ABSTRACT: Road construction over soft ground presents considerable technical challenges. Such roads often serve remote communities and carry low levels of traffic; construction and maintenance must be achieved within very limited budgets. There are two main approaches to such construction: above ground (floating) and below ground (buried) construction. Floating construction is generally used where a relatively stiff material, such as fibrous peat, overlies a less competent material, such as amorphous peat. Buried construction is generally used in more competent materials, or in soft materials of shallower depth such that removal is viable. In both cases lightweight construction materials are desirable but can be costly. This paper describes tyre bales as a lightweight construction material and specifically addresses issues in relation to their use as a foundation material for roads over soft ground.

RÉSUMÉ : La construction de routes sur sol meuble présente des défis techniques considérables. Ces routes desservent souvent des collectivités éloignées et connaissent de faibles niveaux de trafic ; leur construction et leur entretien doivent respecter des budgets très serrés. Il existe deux méthodes principales pour ce type de construction : au-dessus du sol (construction flottante) et en dessous du sol (construction enterrée). La construction flottante est généralement employée lorsqu'un matériau relativement rigide, comme la tourbe fibreuse, repose sur un matériau moins compétent, tel que la tourbe amorphe. La construction enterrée est généralement privilégiée en présence de matériaux plus compétents, ou de matériaux souples moins profonds dont l'élimination est viable. Dans les deux cas, il est utile d'employer des matériaux de construction légers, qui peuvent cependant s'avérer coûteux. Cet article décrit les balles de pneus comme matériau de construction léger et traite spécifiquement des problématiques liées à leur utilisation comme matériau d'assise des routes sur sol meuble.

KEYWORDS: Sustainability, reuse, recycling, foundations, tyres, bales.

1 INTRODUCTION

The construction of roads over soft ground, such as peat, presents considerable technical challenges. Many such roads serve remote communities, carry only low levels of traffic, and must be constructed and maintained within limited budgets.

Where the depth of soft soil is significant, the approach to construction generally involves 'floating' the road on the existing subsoil. This may also involve the use of temporary surcharging and/or reinforcement at the base of the construction to help spread the load. If the depth of peat or other soft material is shallow then removal may be an option. The excavated material is then replaced by more competent materials. However, this does leave the issues of disposing of the excavated material and of preventing the adjacent material from flowing into the excavation. The resolution of either or both of these issues can prove costly, and such costs will increase rapidly with the depth of material excavated.

In both cases, the use of lightweight construction materials is desirable. This paper introduces lightweight tyre bales focusing upon their potential use as a road foundation material and draws on the author's experience in the UK and the USA. Relative to conventional lightweight foundation materials such as expanded polystyrene, the cost of tyre bale construction is relatively low.

2 TYRE BALES

Around 48M tyres (480,000 tonnes) are scrapped in the UK each year. However, the issue of scrap tyres is by no means unique to the UK and Europe. In the USA it has been estimated that over two billion used tyres are stockpiled, and that 285M are added each year (Winter et al. 2006). In the recent past the bulk of waste tyres in the UK was stockpiled, disposed of in landfill or illegally, or sent for energy recovery (Hird et al. 2001) or processed as waste-to-energy. In Europe the Landfill Directive outlawed the disposal of tyres in landfill, with UK exceptions being made for engineered works. In the USA a number of fires in waste dumps comprising whole tyres, and concerns regarding the potential flammability of tyre shreds and chips, led the drive towards alternative solutions.

The majority of R&D activity has addressed tyre shred, chip and crumb for use in construction works. An alternative is the baling of whole tyres to produce rectilinear, lightweight/low density, permeable, porous bales of high bale-to-bale friction.

2.1 *Composition, properties and behaviour*

Tyre bales comprise 100 to 115 car/light goods vehicle tyres compressed into a lightweight block of mass around 800kg and density *circa* 0.5Mg/m^3. The bales measure approximately 1.3m by 1.55m by 0.8m and are secured by five galvanized steel tie-wires running around the length and depth of the bale (Figure 1). They have considerable potential for use in construction particularly where their low density and ease of handling places them at a premium. A porosity of around 62% and permeability of approximately 0.02m/s through the length and 0.2m/s through the depth (Simm et al. 2005) makes them ideal for drainage applications. The bale-to-bale friction angle is around 35^o in dry conditions and stiffness in the vertical direction of Figure 1 is up to around 1GPa (Frielich & Zornberg, 2009; Winter et al. 2006). Furthermore, the process of tyre bale manufacture consumes around 1/16 of the energy required to shred a similar mass of tyres (Winter et al. 2006).

Substances that could potentially leach from tyres are already present in groundwater in developed areas. Studies suggest that leachate levels generally fall well below allowable regulatory limits and have negligible impact on water quality in close proximity to tyres (Hylands & Shulman, 2003) and that rates of release decrease with time (Collins et al. 2002). Similarly there is no evidence of significant deterioration of tyres buried in the ground for decades (Zornberg et al. 2004).

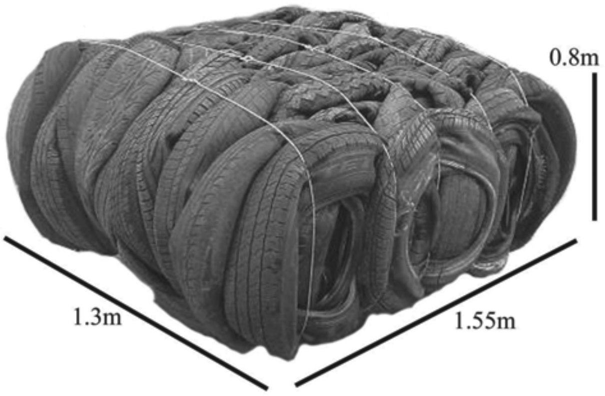

Figure 1. A typical tyre bale with dimensions.

Spontaneous fires in whole tyre dumps are not known to the author. In the USA, while combustion due to sparks from agricultural machinery and lightning have been reported, most observers suspect some form of arson in almost all cases. Baling whole uncompressed tyres reduces the volume by a factor of four to five, greatly reducing the available oxygen as well as the exposed rubber surface area as tyre-to-tyre contacts are formed, without exposing any steel reinforcing in the tyres. The exothermic oxidation reaction potential is significantly lower than for whole tyres and the risk of spontaneous combustion from tyre bales is viewed as extremely low. A modelled storage condition for a 17.5m by 6.0m by 3.0m volume of bales needed to reach and maintain a temperature of 188^{o}C for 39 days before spontaneous combustion became possible (Simm et al. 2005). In contrast reports have been made of internal heating of tyre shred and of apparently spontaneously combusted fires in large volumes in the USA (Sonti et al. 2000). Further details of tyre bale properties and behaviours are available (Anon. 2007).

Tyre bale use reflects positively on the sustainable use of materials and energy and other factors. In the last decade the application level has moved from domestic works/river bank erosion projects to slope failure repairs adjacent to a major Interstate Highway in the USA (Winter et al. 2009) and the construction of a lightweight embankment as part of the A421 A1-M1 link road construction which won the British Geotechnical Association's prestigious Fleming Award.

An adequate supply of tyres, and the resources to turn them into bales must be secured prior to the commencement of a project. As bales are around ¼ to ⅕ the volume of whole tyres it can be particularly difficult to gauge the volume of bales that will result from a stockpile of tyres. A series of nomograms was developed by Winter et al. (2006) and further refined (Anon. 2007) to rapidly describe the number of bales required to fill a given volume, the number of tyres likely to be used in their manufacture, and the number of eight hour (two man) shifts required to manufacture those tyre bales.

Tyre bales costs are similar to those of other road foundation materials (e.g. UK Type 1 Sub-Base). However, the main advantages of tyre bales are the much reduced plant and labour costs resulting from their rapid placement (Winter et al. 2006).

2.2 *British Standard*

The tyre baling industry in the UK reached a level of maturity with the production of a British Standard Publicly Available Specification (PAS) for tyre bales (Anon. 2007). It assists manufacturers to produce high quality, consistent and traceable products for use in construction by responsible and competent organizations, and demonstrate high and consistent quality via a Factory Production Control process. It covers activities and aspects of tyre bale manufacture, storage and use in construction, including: receipt, inspection and cleaning of tyres; handling and storage of tyres; production of bales (including a system for measuring and labelling bales to ensure traceability); handling and storage of the bales; transport, storage on site and placement of the bales; and factory production control.

Guidance is given to construction professionals in formulating preliminary design and construction proposals. Not all aspects of design are covered but information not available from other engineering documents is given. This includes: the measurement of properties; engineering properties and behaviours associated with tyre bale use in construction; example applications; and end of service life options.

3 METHODS OF CONSTRUCTION

There are two main approaches to road construction over soft ground: above ground (floating); and below ground (buried). Both use large volumes of granular fill.

It is important to decide whether or not a crust in, for example, peat may be breached or whether it must remain intact. Figure 2 illustrates advantages and disadvantages of floating and buried construction. The crust in peat will often be formed from fibrous vegetation. Similarly, many normally consolidated lowland clays in parts of Scotland and many Scandinavian 'quick clays' will have a stiffer crust. In general terms it is inadvisable to breach the crust of these materials and thus floating construction is preferred to buried construction.

3.1 *Floating construction*

In areas of deep soft soil, replacement techniques are unattractive as large volumes of material must be excavated, transported and disposed at both monetary and environmental cost. The surrounding soft material may create difficulties related to excavation support, basal heave and other factors, making the works uneconomic. Where the natural surface 'crust' is stiffer than the lower layers due to the presence of vegetation, desiccation, compaction and other factors, the surface may form the subgrade. Care is needed to ensure that the crust is not compromised during construction and that as the road is built the imposed loads are spread over a wide area.

In the past construction often utilised bundles of twigs (fascines), usually two layers orientated at 90^{o}, at subgrade level to resist differential movement. For greater loads logs were used on the fascines, working best for materials with stiff crusts (e.g. fibrous peat overlying softer amorphous, or humified, peat). The modern equivalent is a geosynthetic material; the use of tyre bales or other lightweight fill on the geosynthetic/sand layer lessens the applied load. The success of temporary surcharging is often limited in very soft soils such as peat due to the potential for long-term secondary and/or tertiary consolidation and the potential to breach any overlying stiffer layer.

3.2 *Buried construction*

The removal and replacement of in-situ materials with new, lightweight, fill is a costly option and may involve excavation below the water table. However, sidewall lateral restraint adds durable construction stiffness. The key to construction is to ensure that the fill adds minimal load.

Buried construction may be preferred in more competent materials, or in thinner layers of less competent materials for which removal is an option. Such materials include normally consolidated silts and clays, and soft predominately mineral soils (albeit with exceptions). A geotextile helps to spread the foundation load. Often the repair or reconstruction of an existing road over soft ground is required as a result of differential settlement which leaves an uneven surface with poor ride quality and an increased risk of flooding. The placement of material to raise and regulate the pavement surface increases the formation load causing further differential settlement; replacement of the existing material is thus necessary.

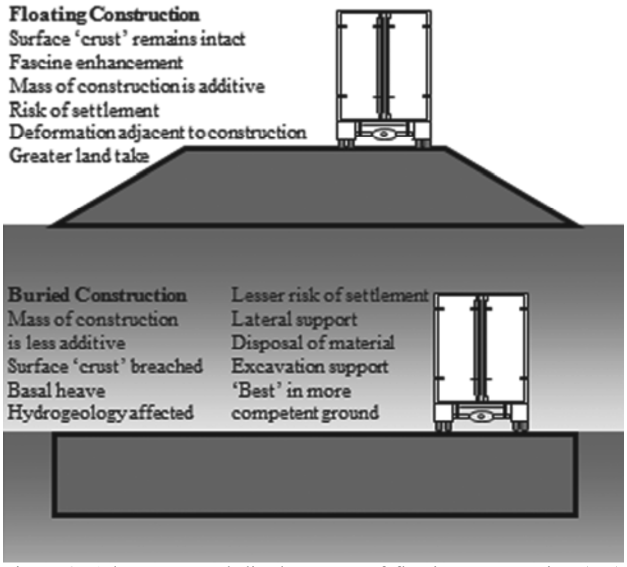

Figure 2. Advantages and disadvantages of floating construction (top) and buried construction (bottom).

4 CONSTRUCTION APPROACHES

The construction and rehabilitation of low-volume roads over soft ground is an ideal application for tyre bales. While there is currently little information to prove their use with higher traffic levels (in excess of a few hundred vehicles/day AADT) there are no pressing reasons why such uses should not be successful.

Low-volume tyre bale roads have been successfully constructed both above and below ground. A geotextile separator is used between the in-situ soil and the tyre bales, usually with a regulating layer of sand. The geotextile helps to prevent differential movement of the bales during and after construction. The decision as to whether the construction should be above or below ground is an important determinant of the approach to the design and construction.

Analytical input for low-volume road design on soft ground is often limited. The strength and stiffness properties of the soil involved are usually at or close to the lower limit of measurement, rendering input parameters subject to large errors. The sampling process may also disrupt the soil structure leading to values lower than the field condition. Accordingly many roads are designed on an empirical, specification-led basis.

The following sections summarises the main construction steps and issues and offer guidance based upon experience of successful projects and established good practice in constructing low-volume roads over soft ground using tyre bales. Further details are given by Winter et al. (2006) and Anon. (2007).

4.1 *Excavation and preparation*

For buried construction, excavation is the first construction activity. Low ground-pressure, tracked plant is preferred as is working in drier weather when the moisture content of the soil is minimised and strength and stiffness are maximised.

A suitable geotextile should be installed either at ground surface level or in the excavation followed by a regulating layer of sand if required. All geotextile-to-geotextile interfaces should have an overlap of 1m. The use of a geotextile has a number of advantages including aiding working conditions in soft soils, strengthening the structure by tying together the assembly of bales, and providing separation between the bales and the subsoil and thus preventing the ingress of fines. Randomly orientated, bonded, non-woven geotextiles have been found to be effective. Their main function is separation, with strength and resistance to clogging the most important properties. Geotextile design procedures should reflect local standards. The geotextile should be placed in the base of the excavation, or on the cleared ground. Sufficient excess should be allowed at either side to allow the bale assembly to be completely wrapped in the geotextile with a 1m overlap.

Rapid cellular construction minimises excavation size, exposure of the soil to weather and the likelihood of side slope failure. Bale sizes mean that excavations are unlikely to exceed 1m, but an assessment of the possibility of sidewall collapse and the associated risks to workers and others during the execution of such operations is essential.

4.2 *Placement and alignment*

Tyre bale handling must incur the minimum risk of damage to the steel tie-wires. The most successful means of handling tyre bales has been found to be a 'loggers'-clam', which can be attached to a variety of hydraulic equipment and provides an appropriate lift-and-place methodology while allowing the bale to be rotated to the correct alignment. Alternative forms of handling bales include brick-grabs and forklifts (Anon. 2007).

The manufacturing process renders tyre bales inherently heterogeneous. Information on the relative stiffness in each of the three directions is not currently available. Tyre bales exhibit a high stiffness when loads are applied vertically to the 1.3m by 1.55m plane (Figure 1); accordingly they are usually installed as illustrated in Figure 1 for applications that attract high vertical loads such as road foundations. The 1.55m by 0.8m plane is perpendicular to the load applied during manufacture and it is recommended that it is aligned perpendicular to the longitudinal confining stresses (i.e. with the tie-wires in line with the road.

While there are different layout options for the two-dimensional placement of tyre bales (i.e. in a single layer) a straightforward 'chessboard' pattern, as viewed in plan, is generally the easiest to construct and is recommended.

A regulating layer of sand is normally required between the top of the tyre bales and the geotextile wrapped over the top of the layer to help eliminate small variations in level.

The foregoing assumes that a single layer of bales is to support the road. If two or more layers are required then the second layer should be placed on top of the first, stepped in at either side to provide around half a bale width of overlap.

4.3 *Filling of voids*

The sub-rectangular shape of tyre bales means that voids remain at the corners of each bale even when they are butted up against one other. The design generally requires the stiffness and stability of the structure to be maximized and thus the voids should generally be filled (Figure 3). Coarse sand has been used successfully as have single-sized aggregate pellets. Crushed glass may be less likely to clog or arch than sand when wet, but is expensive. The most effective method of ensuring that the voids are filled has been found to be to bulldoze a 150mm to 300mm layer on top of the bale layer and then to apply a vibrating roller to the layer to vibrate the fill into the voids (Figure 3).

The fill material affects the density of the structure, with the voids taking up an estimated 4% to 8% (Anon. 2007) of the nominal rectangular bale volume, and must be allowed for in design calculations. The effects of regulating layer(s) above or below the tyre bale layer must also be taken into account.

Once the fill operation for a cell has been completed for a section of road, the geotextile should be wrapped around the bale-fill composite with an overlap of around 1m. A crushed rock sub-base should be placed and compacted on top of the completed section. A thickness of 150mm is likely to be sufficient to provide a construction platform for the works to continue without damaging the geotextile. The final thickness of sub-base must be assessed to ensure sufficient capacity during normal use and should be the subject of site-specific design. After these operations are completed the construction may proceed to the next cell, repeating the process described above until the road has been completed.

Figure 3. Bulldozing sand to fill voids, County Road 342 (CR342), 2000 (left); vibrating sand into inter-bale voids, CR647, 1999. (Courtesy Ken Smith, Chautauqua Co Dept of Public Facilities, NY.)

4.4 *Pavement construction and drainage*

Pavement construction is beyond the scope of this paper but further guidance is given by Winter et al. (2006) as is more detail on drainage considerations. The design should reflect local standards and climatic conditions.

5 SUCCESSFUL APPLICATIONS

Successful applications involving the construction of tyre bale road foundations have been achieved in both the USA (New York State) and the UK (Winter et al. 2005).

Chautauqua County Department of Public Facilities completed five projects using tyre bales as a lightweight subgrade replacement for roads over soft ground (Figure 4). The tyres result from the clean-up of a tyre dump and from a tyre amnesty programme. The geology of the County is characterised by sands and gravels in the river valleys with glacially deposited fine silty clays elsewhere, primarily on the hilltops which are often depressed forming high level swamps. These materials are stable if dry but are sensitive to moisture and to the freeze thaw cycle which can turn them into a material like 'pottery slip'. Conventional unpaved roads constructed on them can turn into impassable quagmires. Tyre bale road construction was targeted on these roads.

Figure 4. Completed CR342 2004 after four years in service (left); B871 in Highland, UK (right, Courtesy G Smith, Highland Council.).

To date with the roads having been in service for up to nine years no major signs of distress have been observed that could be attributed to the presence of tyre bales. In the case of CR342 the traffic levels have been greatly increased (up to around 1,500 to 2,000 vehicles per day AADT) due to a new residential development in the vicinity.

A public road was constructed by Highland Council (UK) in late-2002 (Anon. 2003); performance has been satisfactory despite extreme loadings imposed by a very high proportion of heavy logging trucks using the route (Figure 4).

6 CONCLUSIONS

The use of lightweight tyre bales in the construction of road foundations over soft ground has the potential to satisfy the demand for low cost materials exhibiting such a beneficial property. Such uses also help to address society's broader problem in respect of the large volumes of waste tyres which, in Europe at least, may no longer be sent to landfill for disposal; clearly such beneficial uses for waste tyres are required.

Supply and production issues are addressed and material costs shown to be comparable with conventional materials such as Type 1 sub-base. However, the key strength of tyre bales is their modular nature which leads to potential savings in plant and labour and the associated time savings. In some cases the low cost of tyre bales relative to other lightweight materials, such as expanded polystyrene, may allow the economic construction or rehabilitation of infrastructure in remote areas that would otherwise not be viable. An approach to the construction of low-volume road foundations on soft ground using tyre bales has been developed and is summarized herein.

Tyre bales offer a useful tool for the engineer across a wide range of construction applications that variously exploit their beneficial properties: namely low density, high permeability, high porosity and high bale-to-bale friction.

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