ROAD FOUNDATION CONSTRUCTION USING TYRE BALES – A LOW-ENERGY ALTERNATIVE

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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 generally works best where a relatively stiff material, such as fibrous peat, overlies a less competent material, such as amorphous peat. Buried construction is generally preferable in more competent materials, or in poor materials of shallower depth such that removal is viable. In both cases lightweight construction materials are desirable but can be costly. This paper introduces a relatively new lightweight construction material in the form of tyre bales. Issues in relation to the use of tyre bales such as sustainability, waste management, costs and end of life are described in addition to describing their application to the construction of road foundations over soft ground. The British Standard for tyre bales is also described.

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 either case, the use of lightweight construction materials may be desirable. This paper introduces lightweight tyre bales focusing upon their potential use as a road foundation material and drawing 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. In the state of Texas alone 69M scrap tyres are estimated to be stockpiled and a further 24M added each year [1]. In the recent past the bulk of waste tyres in the UK has been stockpiled, disposed of in landfill or illegally, or sent for energy recovery [2]. In Europe the EC Landfill Directive outlawed the disposal of whole tyres in landfill in 2003 and that of shredded tyres in 2006, although exceptions have been made for use in engineered landfill works in the UK. 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.

While research activity on the reuse and recycling of used tyres has increased in recent years, the majority addressed tyre shred, chip and crumb for use in construction works. A relatively new process 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 between 100 and 115 car/light goods vehicle tyres compressed into a lightweight block of mass around 800kg and density *circa* 0.5Mg/m^3, indicating a truly lightweight material. 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 [3] 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 [4, 1]. Furthermore, the process of tyre bale manufacture consumes around 1/16 of the energy required to shred a similar mass of tyres [1].

Figure 1 – A typical tyre bale with dimensions.

Substances which 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 will have negligible impact on the water quality in close proximity to tyres [5] and that rates of release decrease with time [6].

Spontaneous fires in whole tyre dumps are not known to the authors. 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 piles of whole uncompressed tyres reduces the volume by a factor of four to five greatly reducing the available oxygen within the tyre mass 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 thus significantly reduced compared to whole tyres and the risk of spontaneous combustion from tyre bales is thus generally 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°C for 39 days before spontaneous combustion became possible [3]. In contrast reports have been made of internal heating of tyre shred and of apparently spontaneously combusted fires in large volumes in the USA [7]. Further details of tyre bale properties and behaviours are available [3, 4, 1, 8].

2.2. Sustainability

Tyre bale use reflects positively on all four of the oft-quoted pillars of sustainability.

- *Environment:* Precludes landfill and/or fly-tipping of used tyres; baling is a low energy process; mobile plant can deal with local sources, satisfying the proximity principle.
- *Resource use:* Tyre bales are usually used as a direct substitute for primary aggregate; no waste is generated from their production; high volumes of tyre arisings are used.
- *Economic:* Tyre baling has the potential to generate employment and wealth; relatively labour intensive; cost-effective use of high volumes of used tyres.
- *Social:* Other low density construction materials are expensive; some remote infrastructure may be uneconomic to construct and/or repair; impacting negatively on safety, access to employment and quality of life in remote communities. The low density/low cost of tyre balers can facilitate the rehabilitation of infrastructure that might otherwise have remained unrepaired or even have been closed.

2.3. Raising the utility of application

The work reported herein forms a small part of a programme to develop the use of tyre bales in construction by increasing the utility (Figure 2), value and scope of such works. At the outset tyre bales were being used predominantly in informal, low utility, civil engineering applications (e.g. small erosion protection projects) and in landfill construction where innovation is less constrained than in other sectors of the construction industry.

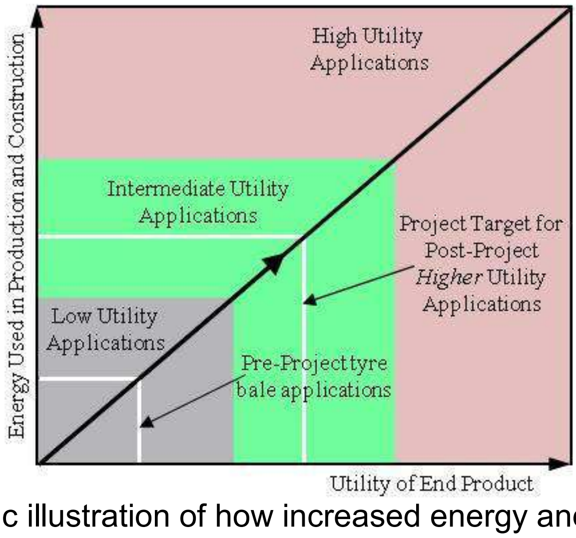

Figure 2 – Schematic illustration of how increased energy and expense during the recovery process results in products with a higher value or utility (after [9]).

Applications in other sectors of the civil engineering industry require more design and specification, and consideration of the design life of the completed construction. Without formal design procedures and specifications, designers will not use tyre bales in higher utility or value applications [10]. The concept of utility was developed [9, 11] to show how the same waste material can be used in different applications with different values and utilities, judged against both economic and environmental factors. Figure 2 shows how increasing the energy used in (and cost of) processing leads to a higher utility end product.

The project targeted the production of practical advice and guidance on design, construction and related issues in order to raise the utility/value of applications to the intermediate level. Thus, at the start of the work slope failure repairs included work on a slope adjacent to a residential driveway while latterly such applications included slope failure repairs adjacent to an Interstate Highway in the USA [12].

2.4. British Standard and Waste Management Licensing / Permitting

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 [8]. The PAS is intended to assist manufacturers to produce a high quality, consistent and traceable product for use in construction by responsible and competent organizations and to help to demonstrate the high and consistent quality via a Factory Production Control process. It encompasses a wide variety of 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.

In addition, guidance is given to assist construction professionals in formulating preliminary design and construction proposals. This guidance is not intended to cover all aspects of detailed design but to provide key information that could not be sourced from other engineering documents. This information includes: the measurement of relevant tyre bale properties; engineering properties and behaviours of tyre bales associated with their use in construction; example applications for tyre bales in construction; and end of service life disposal options for tyre bales.

In the UK the current regulatory implementation of the EU Waste Framework Directives and of the associated case law is such that tyre bales are regarded as a waste product until they are incorporated into the final construction. However, Exemptions are operated within the pertinent Regulations, meaning that neither a License nor a Permit is required for such size/time restricted uses. All bales that are used must be in accordance with the British Standard PAS 108 and work is ongoing to develop a Quality Protocol to remove such tyre bales from the waste stream.

2.5. Supply and production

It is important that an adequate supply of tyres, and the resources to turn them into bales, is secured prior to the commencement of a project. This is particularly pertinent when one considers the four to five times volume reduction achieved during the baling of whole tyres; making it particularly difficult to gauge the likely volume of bales that may be produced from a stockpile of whole tyres. Figure 3 gives an indication of 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. The calculations undertaken to develop the data presented were based upon a production rate of four bales per hour as advised by tyre balers. Figure 3 enables a rapid assessment of the approximate level of material, plant and labour resources required to generate the tyre bales required for a given project. For example, to fill a volume of 1,000m^3 around 69,000 tyres, in the form of approximately 600 tyre bales, are required. These are likely to require around 18, eight hour, two-man shifts to manufacture [1].

Such an evaluation of the number of tyres required can give a rapid indication of the sufficiency of the available resources.

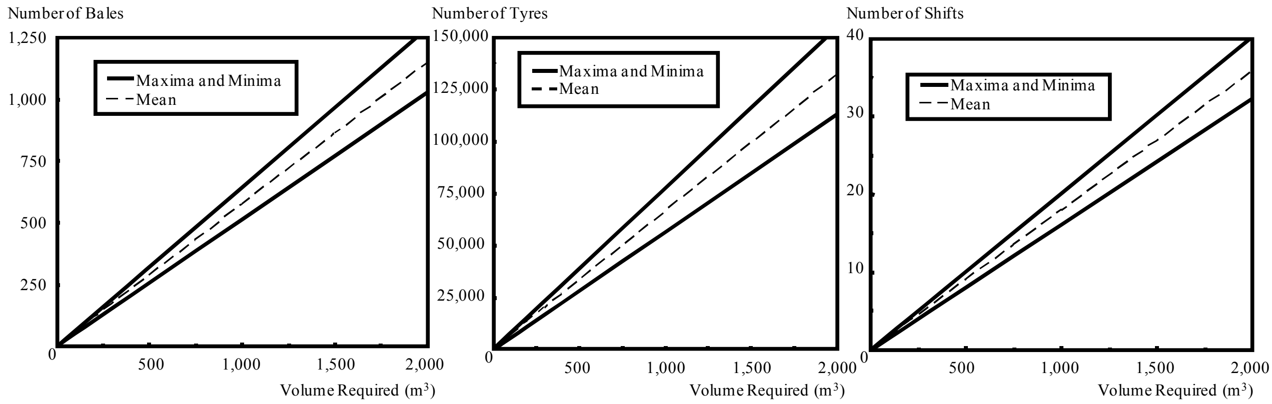

Figure 3 – Nomograms showing the number of bales required to fill a given volume (left); number of tyres required in the manufacture of bales to fill a given volume (centre); and Number of eight-hour shifts required to manufacture tyre bales to fill a given volume (right). Maximum, mean and minimum values are given to allow for variations in bale dimensions, and thus volume, as well as allowing for the variation in the number of tyres.

2.6. Costs

The total cost of any given construction activity is determined by those of the materials, plant and labour required. There is however a tendency to simply compare the unit costs of tyre bales to those of the materials that they are replacing, thus considering only one part of the potential savings.

Comparisons of the cost of tyre bales with a typical road foundation material in the form of Type 1 Sub-Base (UK Manual of Contract Documents for Highway Works, Volume 1: MCHW 1, http://www.standardsforhighways.co.uk/) indicate that the material costs are broadly similar [1]:

- Type 1: £7.20/m^2 to £12/m^2 (based upon a nominal 0.40m depth of sub-base and other granular foundation materials).
- Tyre bales: £7.40/m^2 to £9.80/m^2 (based upon a nominal 0.80m depth tyre bale layer including the material used to fill the voids).

Similar as they are these material costs do not take account of either transport or labour costs. However, it is also true to say that prices for the transport of Type 1 may be somewhat less than for tyre bales due to the substantial network for the supply of such materials and the consequently lower transport costs [9].

The construction process for tyre bales is very different to that for conventional materials. Conventional materials are usually compacted in-situ, consuming significant labour and plant time. Tyre bales are simply placed and the voids filled and compacted; a much quicker process. While cost savings are difficult to quantify other than on a project specific basis they are usually substantial. Estimates for an embankment construction in Colorado [13] indicate that the cost of storing, protecting and handling tyre bales at site, including placement, is around US\$0.80/m^3 (around £0.53/m^3). These estimates further suggest that the total cost of tyre bale fill was around half that of conventional imported fill and substantially less than the cost of most other lightweight materials such as expanded polystyrene, foamed concrete and shredded tyres.

The outline cost comparisons given above support the broad view that tyre bale fill is around half the cost of conventional fill. Even when lower cost fill is used, savings from the simplified method of construction when using tyre bales compensate. Other cost comparisons for tyre bales with conventional materials have also been found to be favourable, with reports [14, 15] of substantial cost savings for the use of tyre bales in the foundations of roads over soft ground. In contrast, higher construction costs for a road over very soft ground compared with conventional methods have been reported [16]. However, it was acknowledged that in many instances conventional construction would have been unlikely to be successful and that without the availability of tyre bales the project was unlikely to have gone ahead as other forms of lightweight construction were ruled out on the grounds of prohibitive cost.

In terms of obtaining valid cost comparisons for tyre bales compared with constructions utilizing conventional materials it is essential that all elements of cost (i.e. materials, plant and labour) are considered. In such circumstances it is highly likely that the cost of tyre bale construction will compare most favourably with more conventional approaches. In addition, the use of tyre bales confers other advantages such as increased speed of construction and the potential to construct and maintain infrastructure economically in locations that might not otherwise be viable.

2.7. End of life issues

End of the service life issues for structures incorporating tyre bales is as important as for those containing any other material. Disposal at a later date, due to demolition for example, will be determined by the prevailing legislation, regulation and interpretation thereof at that time. However, the appropriate management of such materials must seek to avoid disposal either by their subsequent reuse in other structures or by incorporating them into any reconstruction; the latter is the most attractive option. As with all construction components the presence of tyre bales should be noted in appropriate documentation. In the UK this is the Health and Safety File required by the Construction (Design and Management) Regulations 2007 and any anticipated approaches to reincorporation and/or removal should be noted therein. The management of any bales emerging at the end of service life must be appropriate, but clearly forms of recovery involving both engineering and non-engineering uses could be considered.

There is no evidence of significant deterioration of tyres buried in the ground, even after many years (e.g. [17]). However effective reuse will be more conveniently achieved if the bales are not contaminated with fine or clayey material. This is most readily achieved where the bale stacks or layers have been covered with a suitable geosynthetic fabric as part of the original construction. The bales can then be reused in other application, if the tie wires are intact. Should the tie wires not be intact then consideration could be given to re-baling the tyres on site, albeit that this will add to the overall cost of the operation.

End of life issues are described in detail for specific applications in the British Standard PAS for tyre bales [8].

3. METHODS OF CONSTRUCTION

There are essentially two broad construction approaches for roads over soft ground: above ground (floating); and below ground (buried). Both use large volumes of granular fill.

One of the most important considerations in deciding between floating and buried construction is whether or not a crust (Figure 4) in, for example, peat may be breached or whether it must remain intact. Figure 5 illustrates some of the advantages and disadvantages associated with floating and buried construction. The crust in peat will often be formed from fibrous vegetation. Similarly, many normally consolidated lowland clays around Paisley and Falkirk in Central Scotland and many Scandinavian ‘quick clays’ will have a stiffer crust. In general terms it is inadvisable to breach the crust in all of these materials and thus floating construction option is preferred to buried construction.

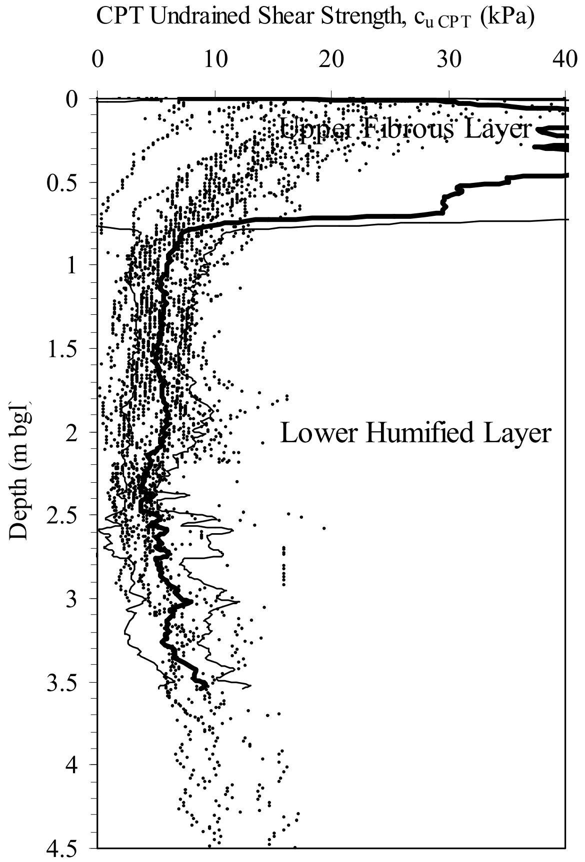

Figure 4 – Average CPT values illustrating the crust effect in peat (data and figure courtesy of Dr Paul Jennings, AGEC Ltd).

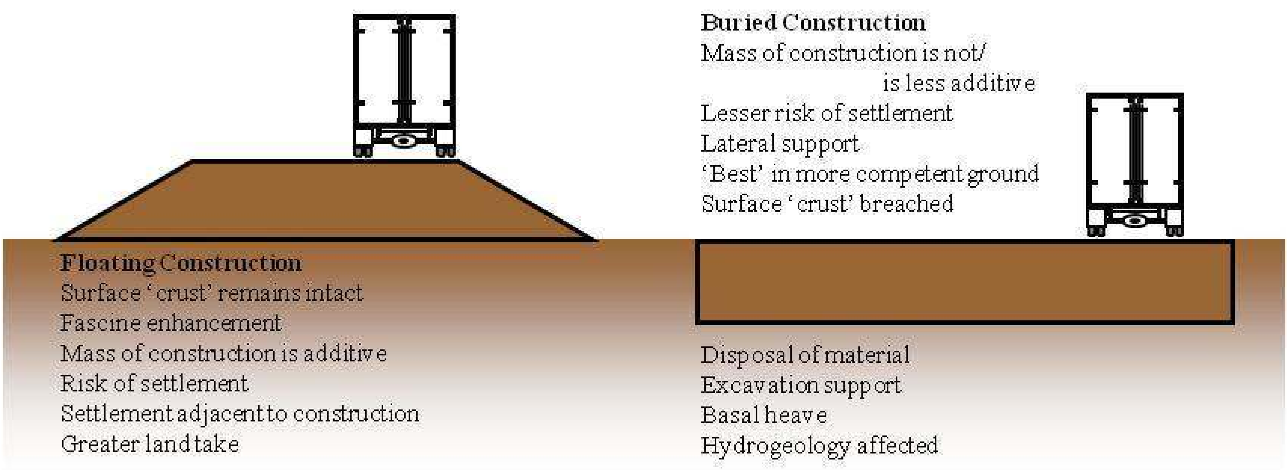

Figure 5 – Advantages and disadvantages of floating construction (left) and buried construction (right).

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 of with the consequential effects on costs and the environment. The surrounding soft material may create technical difficulties related to excavation support, basal heave and other factors, making the works difficult if not 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 be suitable for use as part of the road foundation. Care is needed to ensure that the crust is not broken or otherwise compromised during construction and that as the road is built the imposed loads are spread over as wide an area as practical.

Above ground construction often utilises bundles of twigs, or fascines, placed at subgrade level to provide resistance to differential movement. Often these were orientated at 90^{o} to one another in two layers. Where loads were greater, logs were used above the fascines. This generally worked best where a stiffer material, such as fibrous peat, overlay less competent material, such as amorphous, or humified, peat. The modern equivalent is a geosynthetic material often with a sand regulating layer. The use of tyre bales on top of the geosynthetic/sand layer further allows the applied load to be lessened.

Temporary surcharging of newly constructed roads has been employed in an attempt to consolidate and strengthen the subsoil in both Scandinavia and parts of Sutherland in Scotland. Typically two metres of fill material has been placed to surcharge the road for several weeks and after some consolidation of the subsoil, the fill is removed and the surface regulated and repaved. Such an approach to floating the construction is often employed where the depth of soft material is sufficiently thick to preclude complete removal. However, its success is often limited in very soft soils such as peat due to the likelihood of long-term secondary and/or tertiary consolidation and the potential to compromise, or even breach, any overlying stiffer layer.

3.2. Buried construction

The removal and replacement of in-situ materials with new, preferably lightweight, fill is undoubtedly a more expensive option. However, due to the lateral restraint provided by the excavation boundaries a durable construction is likely. As with floating construction, the key to construction lies in ensuring that the new material adds as little load as possible.

Buried construction may be preferred in more competent materials, or in thinner layers of less competent materials for which removal is an option. More competent materials may include normally consolidated silts and clays, and soft predominately mineral soils for example (but see Section 3.1, above, for 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. The road materials will have settled giving an uneven surface, poor ride quality and an increased risk of flooding. The placement of additional material to raise and regulate the pavement surface is simple but will increase the loading on the formation and almost certainly cause additional differential settlement. The replacement of the existing material is thus a necessity.

4. CONSTRUCTION APPROACH

The construction and rehabilitation of low-volume roads over soft ground represents one of the most promising applications for tyre bales. There is currently relatively little information to justify their use with higher traffic levels (in excess of a few hundred vehicles per day AADT). When more information and greater experience are available it may be possible to incorporate tyre bales in foundations for higher traffic flows. One tyre bale road foundation construction, designed for just a few hundred vehicles per day, has been subjected to around 1,500 to 2,000 vehicles per day due to a new residential development in the vicinity.

Having been retrofitted with a high quality pavement surface performance appears to have been unaffected to date (see Section 5).

Low-volume tyre bale roads have been successfully constructed both above and below ground. A geotextile separator has been used between the in-situ soil and the tyre bales, often with a regulating layer of sand. The geotextile is particularly important to prevent differential movement of the bales during and after construction. The decision as to whether the construction should be above ground (floating) or below ground (buried) is clearly an important determinant of the approach to both the design and construction. The former exploits any stiffer layer that may exist close to the surface, while the latter exploits the lateral support available from the in-situ materials and has the potential to limit the additional loads placed on the subgrade. Thus the designer needs to consider which approach is most suitable for the given circumstances.

Analytical input for low-volume road design on soft ground is usually limited. Setting aside economic factors, this is because the strength and stiffness properties of the soil involved are usually at or close to the lower limit of what can be measured, rendering the analytical input parameters subject to wide error ranges. In addition the sampling process tends to disrupt the soil structure leading to lower values than might exist in the field situation. Accordingly many such roads are designed on the basis of experience and on a specification-led basis.

The following sections describe the main construction steps and offer guidance based upon experience of successful projects and emerging good practice in constructing low-volume roads over soft ground using tyre bales.

4.1. Excavation and preparation

If the construction is to be buried then 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 at a minimum and strength and stiffness are maximised. The plant should be driven carefully to the start of the excavation to ensure that the surrounding soil formation is not unnecessarily damaged.

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 in the case of floating construction, perpendicular to the line of the road. 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.

The foregoing is largely predicated upon buried construction being the preferred approach. However, the basic principles set out are similar for floating construction. The key difference is to prevent damage to the in-situ soil formation (see Section 3.1) as a result of the construction works. The installation of the geotextile is relatively straightforward as it does not need to be fitted into an excavation.

4.2. Placement and alignment

Tyre bale handling must incur the minimum risk of damage to the steel tie-wires. Approaches that have been tried include webbing straps wrapped around the bale and lifting ropes formed as part of the bale. However, the most successful means of handling tyre bales has been found to be a 'loggers'-clam' (Figure 6). The clam 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 [8].

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 perpendicular to the horizontal plane illustrated in Figure 1 (1.3m by 1.55m); 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, see Figure 6).

Figure 6 – Use of a 'loggers'-clam' to handle tyre bales. (Photograph courtesy of Ken Smith, Chautauqua County Department of Public Facilities, New York State).

Three different options for the two-dimensional placement of tyre bales (i.e. in a single layer) are illustrated in Figure 7, each has advantages and disadvantages.

The chessboard layout (Figure 7a) is simple to construct and has been used successfully. It does not however provide mechanical interlock to resist differential lateral movement. Such resistance must come from friction and passive resistance between adjacent bales and the inter-bale fill material. However, the main threat to the integrity of a two-dimensional tyre bale layout is from differential vertical, rather than lateral, movement. The stretcher bond layout (Figure 7b) affords improved resistance to lateral movement. However, it also uses more tyre bales (10% in Figure 7b) for a given, usable, plan area and the castellations create additional resource needs and construction and operational difficulties. The comments made for the stretcher bond layout also apply to the staggered layout (Figure 7c). However, the castellations are more problematic being formed at either end of the construction over which traffic will pass. The chessboard pattern (tie-wires in line with the road; shortest dimension vertical) is recommended. Generally, the bales should be placed as close together as possible to minimise potential deformation under load and the amount of inter-bale fill needed.

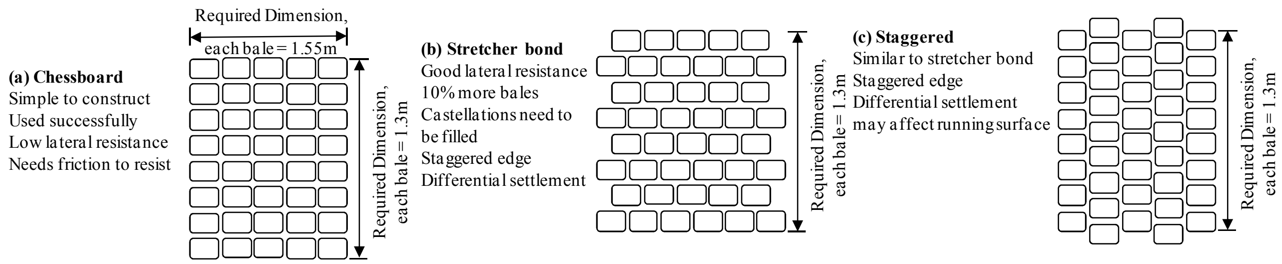

Figure 7 – Two-dimensional layouts: (a) chessboard; (b) stretcher bond; (c) staggered.

The width of the foundation should be at least two bales wider than the completed road surface to maximize load spreading. Other considerations (land availability, cost, soil strength, etc) may encourage greater or lesser widths based on engineering judgement. Six bales yield a 9m nominal width, while seven bales yield a nominal width of 10.5m. It is customary in many parts of the world to construct unbound roads wider than normal.

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 (see Section 4.1). This helps to eliminate small variations in level in the base of the excavation, if the construction is buried, or in the existing ground surface if floating construction is planned. Similarly, the omission of a regulating layer or the provision of one with minimal depth above the geotextile will provide maximum economy and minimum weight. Practical plant operating requirements may be the deciding factor especially if a load spreading or protective layer is needed.

Rows of bales should be placed across the width of the road; when they are about 1m from the far edge of the geotextile; a second geotextile sheet should be overlapped with the first. Further rows of bales may then be added so that they rest on the second sheet.

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. Filing 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 (Figure 8). In practice small gaps are usually left between adjacent bales. The design generally requires the stiffness and stability of the structure to be maximized and thus the voids should generally be filled (Figure 9). Coarse sand has been used successfully as have single-sized aggregate pellets. Crushed glass of a suitable grading may be less likely to clog or arch than sand when wet, but cost considerations, in the UK at least, may render the use of such a material impracticable.

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 9).

If the fill becomes wet or clogs the voids applying water using a bowser may unclog such areas. Note that both very dry and very wet sand will generally flow effectively, but that it is generally easier to add than remove water, at least in a temperate climate. The fill material will affect the density of the structure. The voids have been estimated to take up 4% to 8% [8] of the nominal rectangular bale volume. This must be allowed for in calculations of, for example, bearing capacity. The effects of regulating layer(s) above or below the tyre bale layer must also be taken into account.

Figure 8 – Construction in which the bales have not been placed as close together as possible and in which the voids between the bales have not been well filled. (Photograph courtesy of Dennis Scott, Northern Tyre Recycling.)

Figure 9 – Construction: bulldozing sand to fill voids, County Road 342 (CR342) in 2000 (left); vibrating sand into inter-bale voids, CR647 in 1999. (Photographs courtesy of Ken Smith, Chautauqua County Department of Public Facilities, New York State.)

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.

4.4. Pavement construction

Pavement thicknesses should be determined from traffic flows and type, foundation conditions and the material used to form the pavement layers. Experience in the USA is of tyre bale roads with AADT 2-way flows of between 200 and 1,600 vehicles per day. Local methods of determining pavement thickness are likely to prove most suitable.

Total pavement thicknesses between 250mm and 450mm have been employed. The 250mm thick pavement employed an A252 welded reinforcing mesh (8mm bars at 200mm centres) to help stiffen and strengthen the pavement.

In the USA three 150mm layers of crushed gravel sub-base type material have been used to form the pavement and bituminous layers added on top if required. If an unbound road surface is required then a suitable rock surfacing layer must also be incorporated. Similarly, if a bituminous pavement surfacing is required then the requisite layers must be added. The precise type of pavement will depend on local standards and requirements.

The low traffic flows associated with such pavements yield an excellent opportunity to maximise the use of reused and recycled, and/or marginal materials, whilst allowing for potentially greater traffic levels in the future.

If an unbound pavement surface is used then re-grading after any initial differential settlement is a relatively inexpensive operation compared to the equivalent operation for a bound surface. However, it should be pointed out that the use of unbound construction for public roads, in the UK and much of Europe, is at best unusual and likely to be considered only for those roads with very low traffic flows.

Bituminous layers, where required, are usually added at a later date after initial differential settlement of the unbound layers under traffic has occurred and suitable adjustments have been made to the profile. This presents a lower risk to the bituminous materials by lessening the risk of excessive deformation which would be costly to correct.

4.5. Drainage

Cross falls and drainage should conform to local standards and be appropriate for local climatic conditions. Cross falls in particular are critical to the efficient shedding of water and to preventing water ingress to an unbound construction. Experience in the northeast USA indicates that cross falls between 1 in 24 and 1 in 16 have been found to be effective. This is however no guarantee that they will be effective elsewhere. Although cross falls of 1 in 32 have been reportedly used with a degree of success, it is considered that cross falls shallower than 1 in 24 are unlikely to be effective on unbound surfaces.

Drainage provision should take account of both current needs and emerging needs in terms of climate change. In Scotland, for example, the current 1 in 100 year design return period for rainfall events has been raised to a 1 in 200 year return period.

Additionally, the high porosity and permeability of tyre bales means that edge drainage is critical and should form an integral part of a design incorporating tyre bales in a road foundation, especially at bends and even more so at banked bends. Care is needed, especially for roads founded in or on peat, that the drainage is of the road and not of the surrounding wetlands which may be damaged if drained excessively.

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 [18].

Chautauqua County Department of Public Facilities completed five projects using tyre bales as a lightweight subgrade replacement for roads over soft ground (Figure 10). The tyres result from the clean-up of a tyre dump and from a tyre amnesty programme. Future projects of this nature will depend upon the now limited availability of tyres [14, 15].

Figure 10 – Completed construction: CR342, May 2004 after four years in service (left); B871 in Highland, UK (right, photograph courtesy of Garry Smith, Highland Council).

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' (used to manufacture clay utensils). Conventional roads constructed on them can turn into impassable quagmires. Tyre bale road construction was targeted on these roads.

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 1,600 vehicles per day AADT) since construction due to local development.

A public road has been constructed by Highland Council in the far north of the UK [16]. It was completed in late-2002 and performance to date has been broadly satisfactory despite extreme loadings imposed by a very high proportion of heavy logging trucks using the route (Figure 10).

This paper focuses on the construction of road foundations using tyre bales. However, research in the UK and USA has developed design and construction methods for a wide range of tyre bale applications. Other applications [1] include: slope failure remediation; lightweight embankment fill; gravity retaining walls; drainage layers/ paths; storm water management systems and rainwater soakaways; and environmental barriers.

Further information on tyre bales applications is available [3, 8, 19] and a wide-ranging series of case studies has been described [18]. The remediation of a slope failure using tyre bales has been described in detail [20] and used, with other information, to develop design and construction advice for such works [12]. One of the largest recent applications involved the construction of a lightweight embankment over an in-filled lake (Figure 11). The construction involved the use of over 6,000 bales (0.6 to 0.7M tyres) and forms part of the A421 trunk road scheme promoted by the Highways Agency in southern England. Monitoring of the embankment indicates that it is performing entirely as expected approximately 18 months after construction. This project was the recipient of the British Geotechnical Association's prestigious Fleming Award for 2010.

Monitoring of the embankment, by the author and colleagues, indicates that its behaviour is well within the expected limits. The monitoring data is also being used as part of ongoing work to better understand the in-situ creep and stiffness responses of tyre bale structures.

Figure 11 – Construction of the A421 embankment.

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 described. The construction stages considered are: excavation and preparation; placement and alignment of bales; void filling; pavement construction and drainage. Particular attention has been paid to the stages that deviate most from conventional construction; placement and alignment of bales; and void filling.

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 exhibiting high bale-to-bale friction. The implementation of a British Standard and the potential for a Quality Protocol, the latter removing the tyre bales from the waste stream, eliminates the main obstacles to their potential use in construction and appears to be unique. Although the Texas Department of Transportation have developed construction specifications [21] the UK experience bears repetition elsewhere.

ACKNOWLEDGEMENTS

effort has been made to ensure that the matter presented in this report is relevant, accurate and up-to-date at the time of publication, TRL Limited cannot accept any liability for any error or omission, nor for the results of any use to which the information may be put.

Funding was via a Veolia Environmental Trust Landfill Tax Credits Scheme grant additionally supported by Inverness & Nairn Enterprise and Transport Scotland. The Royal Academy of Engineering part-funded (International Travel Award No. 04-301) the first of two study visits by the author to the USA.

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