THE BRITISH STANDARD PUBLICLY AVAILABLE SPECIFICATION FOR TYRE BALES

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Abstract: The disposal of used tyres is a problem of international significance. In the European Community nations sending whole tyres and shredded tyres to landfill were banned in 2003 and 2006 respectively. A range of sustainable solutions that allow the reuse and recycling of used tyres is urgently required. One such solution is the manufacture of tyre bales which comprise approximately 100 whole tyres compressed into a rectilinear block. The bales are lightweight/low density, high permeability, high porosity and high friction and thus ideally suited to many construction applications. This paper describes the recently published British Standard Publicly Available Specification (PAS) 108 for the production of tyre bales for use in construction. Issues in respect of input materials (tyres), the production of tyre bales and issues in respect of the use of tyre bales are covered. The properties and behaviours of tyre bales are described in PAS 108 as are suggested methods of measurement. General construction considerations and specific applications for tyre bales are highlighted along with end of service life options. Tyre bales may be viewed as a new form of three-dimensional geosynthetic with dimensional similarities to constructed geocells.

Keywords: Cellular system, construction, design, waste, properties, economics.

INTRODUCTION

The European Union Landfill Directive (1999/31/EC) (Anon 1999) is an important driver for used tyre recycling as it bans the disposal of tyres to landfill. Whole tyres were banned as of July 2003 and shredded tyres from July 2006. The ban applies to almost all tyres including car, commercial, motorcycle, aircraft, and industrial (including solid tyres) although exemptions, on a case by case basis, are allowed for the use of tyres in landfill engineering.

The disposal of used tyres in the United Kingdom (UK) is a significant problem; every day over 100,000 worn tyres are taken off cars vans and trucks accounting for a total of around 48 million tyres (480,000 tonnes) per year. Of this figure, about 41 million tyres (293,000 tonnes) are from cars and four wheel drives, with truck and van tyres making up the remainder (Slater 2006).

The compression of whole tyres into bales (Figure 1) offers one means of putting post-consumer tyres to good use, at the same time reducing the use of primary materials (typically aggregates). Conversion of post-consumer tyres into tyre bales is currently a process which is managed under the Waste Management Licensing Regulations 1994 (as amended) (Anon 1994). The process of baling is a regulated activity, but Regulators in England and Wales are not actively pursuing licensing applications for tyre baling. In Scotland, subject to limits on the amounts involved, the baling of waste tyres is an exempt activity. Separately, the transport of whole tyres and tyre bales requires a Waste Transfer Note as specified by the Environmental Protection (Duty of Care) Regulations 1991 (as amended).

The specific use of bales (once manufactured) in construction is generally accepted by the waste regulators in the UK as a low risk activity. Regulators in England and Wales are not actively pursuing licensing applications for use of bales in construction; future amendments to regulations may introduce exemptions to cover this use. In Scotland the use of tyre bales in certain specified works is now an exempt activity and the Department of the Environment for Northern Ireland (DOENI) are currently considering their classification. Studies to date have indicated that fire risks are acceptably small and that leachates are well within regulatory limits and will thus have negligible impact on the quality of water in close proximity to tyres (Hylands & Shulman 2003) and that their rates of release decrease with time (Collins *et al*. 2002). Tyre bales offer significant advantages in construction projects due to their permeability (saturated hydraulic conductivity) and low bulk density, whilst still providing high inter-bale friction and stiffness. They represent one of a number of recycled materials and products that engineers are starting to consider seriously in practical applications such as in road engineering and in river and coastal engineering (Simm *et al*. 2004).

The British Standard Publicly Available Specification (PAS) 108 (Anon 2007a) is intended to assist manufacturers of bales of post-consumer tyres to produce a high quality, consistent and traceable product for use in construction by responsible and competent organizations. It is also intended to assist balers in demonstrating that their product is of a high and consistent quality via their Factory Production Control processes. In addition, the PAS provides guidance on general construction considerations and specific applications for tyre bales as well as end of service life options.

KEY ELEMENTS OF PAS 108

The PAS 108 (Anon 2007a) specification encompasses the following activities and aspects of tyre bale manufacture, storage and use in construction:

- Receipt, inspection and cleaning of tyres.
- Handling and storage of tyres.
- Production of reference bales and both larger and smaller sizes of bale, including a system for labelling bales manufactured in accordance with PAS 108.
- Handling and storage of the bales.

- Transport, storage on site and placement of the bales.
- Factory production control.

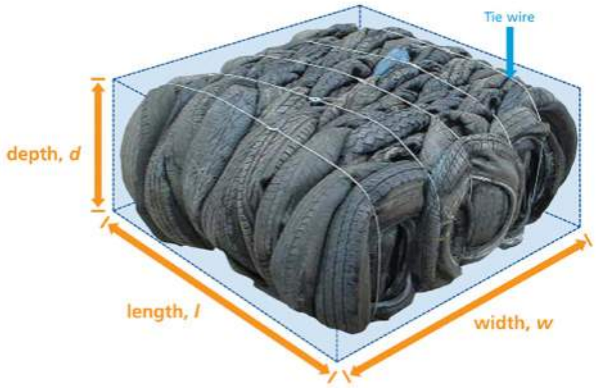

Figure 1. Reference sketch of tyre bale.

Requirements for Tyres

The PAS requires tyres received for baling to be inspected prior to incorporation into bales (rejecting any tyres that are oversized, damaged, burnt, deteriorated or chemically contaminated) and the cleaning of any tyres whose surface is physically contaminated. Tyres are then to be baled as soon as practical.

Production of Bales

The baling process commences with stacking tyres in the baling machine. For the 'reference' bales (see Figure 1) this machine has a rectilinear cavity measuring 2.0m (±0.1m) in the direction of compression (length of bale, l, is approximately 1.30m), 1.55m (±0.05m) in width (w) and 0.75m (± 0.05m) in depth (d).

'Capping tyres' are placed flat to form the top and bottom of the stack of tyres. These capping tyres help to ensure that the bale tie wires are less likely to penetrate into the tyre material on the edges of the bales and that the resulting bale is of a more rectilinear form (Figure 2). The tyres are inserted in a herring-bone arrangement until the baling machine is full (Figure 3).

Figure 2. Filling a typical tyre baler using (left) capping tyres to form the bale base; (right) a herring-bone pattern for the body of the bale.

The stack of tyres is then compressed, secured, further tyres added and the process repeated until the requisite number of tyres has been incorporated and the required compressed bale length has been achieved. Several stages are normally required due to the degree of compression required (volume compression ratios are typically 4 or 5 to 1). The number of tyres eventually required for each bale is likely to depend on the range and proportions of vehicle types from which the tyres originated. Such variations may be significant on a regional basis. The standard 'reference' bales will typically comprise between 100 and 115 tyres.

High tensile steel wires of a minimum diameter of 3.8mm are provided to act as tie wires around the bale and installed when it is under maximum compression. The wires are pre-looped at their ends and electro-galvanised to a thickness of at least 3μm or hot dip galvanised to a thickness of at least 6μm. When the tie wires are fitted around the bale (see Figure 3) they are evenly spaced and aligned approximately parallel to each other.

The resulting bale, when removed from the baling machine (see Figure 4), can be expected to have a mass density varying between 430kg/m^{3}and 570kg/m^3. In terms of dimensions, measurements on 50 reference bales produced from two different machines gave the dimensional ranges in Table 1.

Table 1. Engineering properties of reference tyre bales.

Property	Value(s)
Length (of reference bale)	1.33m (+0.08m/–0.06m)
Width (of reference bale)	1.55m (±0.07m)
Depth (of reference bale)	0.83m (± 0.04m)
Volume (of enclosing cuboid of reference bale – see Figure 1)	1.70m^3 (+0.24m^3/–0.15m^3)
Mass (of reference bale)	810kg (±35kg)

Note that because of relaxation as the load used to compress the tyres is removed, the depth of the bale is generally slightly greater than the depth of the chamber. The depth of the bales is dependent on the mix of tyres used.

For some applications, bales of sizes different from the reference bale may be more appropriate to the end use but a consistent size of bale should be used for a particular project or application. The PAS allows for reduced length bales down to about 0.6m. In addition, but only with alternative baling machines, which (to the authors' knowledge) are not yet commercially available, bales could also be produced with widths of either about 1.15m or about 1.95m. The width adjustment is possible by effectively adding or removing a 'column' of tyres in the bale.

Figure 3. Connecting the ends of the tie wires together (main picture) and after connection (inset to top-left).

Figure 4. Completed tyre bales.

The requirement of PAS 108 to attach a legible, durable and weatherproof label to each bale with the date of manufacture and description of the bale (including dimensions) permits proper rotation of stock and can be used to trace bales and to ensure that they are used appropriately and as intended.

PAS 108 has been based on current UK tyre baling and construction practice and covers a specific range of bale sizes (including the reference bale). However, alternative and satisfactory rectilinear shapes and/or forms of tying/wrapping may yet be developed and thereby permit manufacture of bales that are also useful for construction purposes. The properties of these yet-to-be-developed bales can be tested using the methods set out in PAS 108. For acceptable use in construction, the densities of the new bales (and hence their porosities and permeabilities) should be similar to those indicated in Table 2. Care will also be needed over the pattern adopted when placing the tyres in the baler to ensure satisfactory structural properties for the bale. Evidence of satisfactory performance derived from such testing will help to make the case for revising PAS 108 to include any new bale types.

ENGINEERING PROPERTIES

The values in Tables 1 and 2 are based on a combination of a limited number of laboratory and field tests, but can be taken to be indicative of the order of magnitude of the relevant property. Clearly the basic dimensional and mass properties ore important for design and construction; **density** is also important when assessing the stability of structures for example against sliding and overturning, and for the estimation of settlement of soft ground.

Table 2. Engineering properties of all PAS 108 tyre bales.

Property	**Value(s)**	**Comments**
Nominal mass density	470kg/m^3 (±50kg/m^3)	Mass density of the cuboid enclosing the tyre bale (see Figure 1)
True mass density	500kg/m^3 (±70kg/m^3)	Mass density of bale only
Porosity	62% (±5%)	
Shear strength: angle of inter-bale friction, ϕ'	35° to 36°	Tests performed on dry bales. Cohesion is small and can be ignored in design.
Stiffness (expressed as Young's Modulus), *M*	800MPa to 1000MPa	Values increase within range with increasing degree of confinement. Values based on a preliminary interpretation of USA data for arrangements of two and three bales with no joint filling.
Total Creep (35 months)	Up to 1.1%	Based on measurements of a bale stack in a beach at Pevensey. Measurements indicate creep process now substantially slower and long term creep not expected to exceed 1.5%.
Permeability through depth (see Figure 1)	0.1m/s to 0.2m/s	Comparable to the permeability of gravels
Permeability through length (see Figure 1)	0.02m/s to 0.04m/s	Comparable to the permeability of coarse sands and gravels

Porosity is useful for assessing the volume of water that can be stored within a stack of bales. Should fill be included within the tyre bale stack then the difference between the volume of the tyre bale itself and its enclosing cuboid (estimated as being between 4% and 8% for reference bales) must be known. This is important both for estimating the amount of fill required and the resultant overall mass density and porosity of the resultant bale/fill mix.

The approach to measurement of the **true volume** and hence the porosity and density of a tyre bale, given its uneven external shape, makes use of Archimedes' principle (when a body is wholly or partially immersed in a fluid it experiences an upthrust equal to the mass of liquid displaced). To measure the volume involves excluding water from the bales before measuring its weight when submerged. Subsequently the wrapping is removed and the volume of voids in the bale is determined with the assistance of a further weighing of the unsealed bale in water.

Permeability is important when bales are being used for drainage, determining the rate at which water is able to pass through and escape from the layer. It also affects stability under hydraulic loading, determining the rate at which pore water pressures within the bale mass are able to dissipate. For example, bales do not float in steady state conditions, because the density of the tyre material (1,300±40kg/m^3) is greater than that of water. However, under wave action, the bales appear to 'float' because their permeability is too low for the water to penetrate pore spaces within a typical wave period (<10 seconds). The permeability of a tyre bale is calculated using Darcy's law from the measured flow rate and head loss when a bale is installed in a flume and water is passed through it (Simm *et al*. 2005).

One of the key determinants of the stability of a structure is the **shear strength** of the material(s) from which it is formed. Investigations (Zornberg 2004) have indicated that the value of any cohesion intercept, c', is sufficiently small that it should be discounted for design purposes. This allows the frictional constant, μ (= tan φ'), to be estimated from the horizontal force required to move one bale over others divided by the normal force exerted by the mass of the upper bale on the lower bales. Tests are carried out in dry conditions to ensure repeatability and reproducibility.

The **stiffness** or stress-strain response of the tyre bales is an important serviceability parameter, determining the way the bale structures deform under load. Ideally stiffness tests should be conducted in confined conditions representing those in most construction works. However, as full confinement is difficult to achieve in the laboratory, PAS 108 recommends simple unconfined tests with two bales stacked vertically which will (conservatively) underestimate the stiffness. An analysis (Winter *et al.* 2006) of work carried out in the USA (Zornberg 2004) suggests that the underestimate is only of the order of 5% to 15% and should not be critical for most engineering applications.

Assessing **creep** of tyre bales under constant (compressive) stress and environmental conditions inevitably requires measurements over a long period of time. Whilst the strain immediately following the application of stress may be significant, continued observation yields a very slow decline in the rate of strain to zero over a period of days, weeks, months or even years depending upon the material.

Only rarely is it practical to conduct such long-term tests in advance of construction. Accordingly such tests are most often carried out in the field and upon specific structural arrangements. Field tests, such as those referenced in Table 2, must be seen as confirming the behaviour within expected limits and acknowledge the fact that ambient environmental conditions, such as temperature, will vary to some extent.

Engineering behaviours, including durability, contamination potential and fire resistance, are discussed elsewhere (Anon 2007a; Simm *et al*. 2005; Winter *et al*. 2006). None of these behaviours presents major/insurmountable obstacles to tyre bale use in appropriate construction applications.

CONSTRUCTION ISSUES

Handling and Storage

A range of items of plant, including forklift trucks, can be effective tools for lifting and handling tyre bales. However, it is also useful to be able to rotate the bales and thus orientate the tie wires (see below and Figures 5 and 6). For this purpose, experience indicates that either a ‘loggers’-clam’ (Figure 5) or a brick, or pallet, grab (Figure 6) are the most effective tools. Damage to the tie wires of the completed bale must be avoided in order to maintain bale integrity and PAS 108 therefore requires that bales shall never be lifted using these wires.

PAS 108 describes how the tyre bales should be arranged at the production, storage or construction site to ensure stability of bale stacks and to minimize degradation due to UV-exposure. Bales shall be stored at approved storage locations, not normally for more than 12 months and subject always to any statutory or licensing restrictions.

Figure 5. Placing tyre bales using a ‘loggers-clam’ (Courtesy, K Smith, Chautauqua Co. Dept. Public Facilities, NY).

Figure 6. Placing tyre bales (using a pallet grab) within a wrapping of geosynthetic (© Environment Agency).

Supply and Production

The availability and costs of tyres and bales need to be considered prior to deciding to use them in construction. This is a practical decision but is also important for assessing the extent to which the proximity principle (waste materials should be reused, recycled or disposed as close as possible to their point of arising) can be maintained.

Figure 7 allows the approximate number of tyres required to form bales to fill a given size of void to be determined. A related figure (included in PAS 108: Anon 2007a) may be used to determine the number of tyre bales required to fill a given volume.

The manufacturing cost is a function of material, plant and labour at the point of production. Plant costs are specific to the baler(s) being used. An initial assessment of labour costs can be made using a design chart similar to Figure 7, also included in PAS 108, which allows the labour resources required to fill a given volume to be estimated.

Transport and construction costs need to be added to the production costs. The former are minimized by locating the point of tyre collection and bale production as close to the site as possible. However this may not always be practicable so alternative modes of transport should be considered to minimize the carbon footprint. Unit construction costs are generally found to be low due to the simplicity of placing the bales.

Alignment and Layout (Patterns of Placing)

Alignment

Tyre bales have different properties in different directions and so orientating them correctly in the works is important. Bales have their highest stiffness through their depth and therefore should be installed such that this direction is in line with the maximum load. In most applications, this will mean that the bales will be installed “flat” (depth dimension vertical).

Bales should also be placed such that the direction of original compression (through the length – also the direction of the tie wires) is aligned with the direction of maximum confinement in the structure. Hence, the tie wires should always lie in line with the direction of the longer axis of the structure: i.e. in line with the direction of the chainage for a road or a flood defence embankment, for example. Bursting of the galvanised tie wires should not occur if construction follows best practice, but should the tie wires fail at some point in the future due to corrosion the tyres will then remain confined within the structure.

Friction between the bales is maximized by ensuring that the tyre bales are tightly abutted to one another on completion of placement.

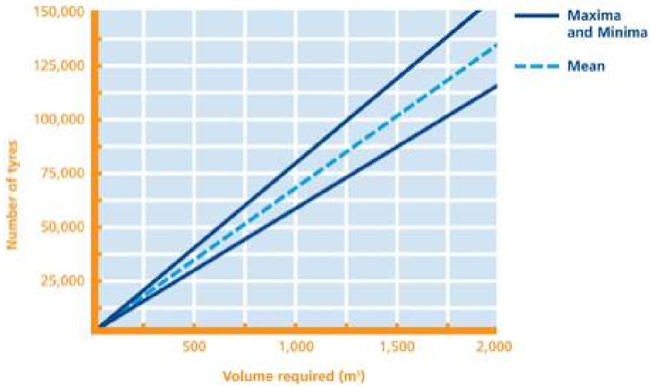

Figure 7. Number of tyres required in the manufacture of reference bales to fill a given volume. Maximum, mean and minimum values are allow for variations in bale dimensions, and thus volume, as well as the number of tyres.

Layout within a layer of tyre bales

There are various options for laying out tyre bales within a given layer. However, as the main threat to the integrity of layer of bales is from differential vertical, rather than lateral, movement a simple chessboard pattern is recommended as providing a compromise between interlock and simplicity of construction. It is however recognised that there may be specific construction reasons for requiring a stagger of the bale joints in one or the other direction.

Layer to layer layout

Figure 8 illustrates a typical arrangement for a repair to a slope failure, in this case a cutting slope. PAS 108 requires that subsequent layers of bales are stacked in a stretcher bond pattern in the longitudinal direction of the course (Figure 8a). Additionally, the form of construction may or may not require a stagger in the bales and/or the joints between the bales in the transverse direction. In most applications such as embankments and slope repairs, some degree of stagger of the bale joints will also occur almost by default in section (see Figure 8b).

Filling Between Bales

Bales have been placed successfully with, and without, fill between the bales. Whether fill should be introduced depends on the application and the design criteria.

Omitting filling between bales can be advantageous when structural rigidity is not critical with the advantages of:

- Maximizing the permeability of the tyre bale layer which can be useful in layers with a drainage function.
- Minimizing the load imposed on the underlying ground which can be important when total settlement of the embankment is critical. For example when flood defence embankments are constructed on soft ground the value of limiting gross settlement may outweigh the disadvantage of any increased differential settlement.

However, if the gaps between the bales are not filled then the entire bale structure should be encapsulated within a geosynthetic of suitable form to prevent the ingress of the surrounding soil into the bale mass. This approach was adopted on a project on the River Witham (see Figure 6), as reported by Simm *et al*. (2005) and Bo & Yarde (2006).

Filling between bales has several advantages which are important when total and differential settlement is to be minimised (including that under vertical loading):

- Maximising the friction between the bales by minimising the effect of the joint gaps between the bales caused by the slight curvature at the edges and corners of the bales. This has the dual benefits of maximising the internal stability of the bale mass and helping to reduce differential settlement between adjacent bales.
- Minimising the potential for the surrounding soil to be washed into these same gaps.
- Reducing any long term creep settlement of the bale stack.

For these reasons filling between the bales is particularly important for structural applications in which the friction and interlock between the bales must be optimised (usually maximised), for example in transport infrastructure embankments. It is estimated that gaps between bales take up between 4% and 8% of the volume of a mass of bales.

The material used to fill the gaps must be a compromise in terms of its properties between being able to flow freely into the gaps, exhibiting frictional strength and being able to drain freely. Coarse sand and fine gravel have been found to be good materials for this use. The addition of water to greater than the optimum moisture content is sometimes useful to promote the free flow of the material into the gaps, provided that suitable drainage exists for excess water to escape. Placement of fill between layers of tyre bales should be avoided, except for occasional regulating layers (see below). This avoids the potential to create a preferential slip plane between the layers of bales and also minimises the amount of fill required.

Depending on the form of structure, the key design considerations, and the grading of both the fill and the adjacent soil, the entire bale structure may need to be encapsulated within a geosynthetic of suitable form to prevent the ingress of the surrounding soil into the bale mass and to further limit differential settlement.

Regulating layers, comprising granular material, take up the cumulative minor irregularities which develop in the surface of the tyre bale layer when a significant number of bale layers are involved. It is therefore suggested that if filling between bales within layers is acceptable, an additional regulating layer of 200mm to 400mm depth should be placed between each "lift" of 3 or 4 tyre bale layers.

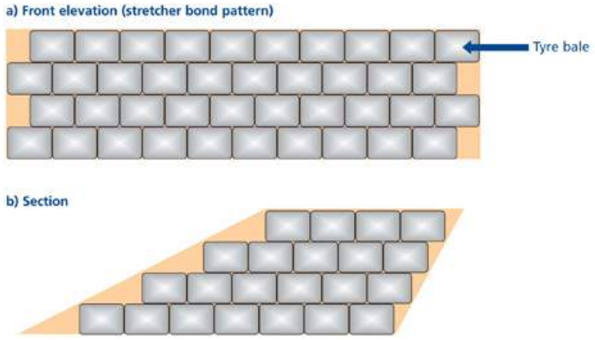

Figure 8. A typical tyre bale repair to a failure in a cutting slope (prior to placement of cover). The tyre bales are shown in grey and all other areas comprise fill.

Covering of Bales (Depth and Stability of Cover)

PAS 108 requires that tyre bales are covered at the end of the construction period in order to avoid degradation due to exposure to ultra-violet light (irrespective of whether or not it is desired to cover the tyre bales for aesthetic reasons). A minimum cover depth of 0.5m of inert fill and/or topsoil is recommended. Fine-grained material may be used to help reduce the ingress of water.

Where the slope is steep, erosion can be a particular problem, albeit that the stepped nature of an uncovered tyre bale slope aids stability of the cover, limiting the likelihood of large areas failing and biosynthetics can aid the longer term stability. The range of such materials is considerable and independent advice should be sought in terms of making such a selection. Hessian mats in conjunction with seed mulch have been successfully used on slopes of up to 1:2. The successful use of such materials on slopes much steeper than this may require the use of sacrificial staples to pin the Hessian mat to the topsoil. Such systems are unlikely to be effective for slopes in which the soil is placed at angles much greater than that of repose. Where greater angles are required systems comprising a steel mesh incorporating a seeded biosynthetic in order to promote vegetation growth may offer a solution and the vertical dimension of the steel mesh can be specified to match the dimensions of tyre bales making construction simpler.

Construction Breaks

When placing bales without filling of the gaps between them, it may be appropriate to consider the placement of short breaks, formed using frictional fill, in the longitudinal bale courses. The fill should be placed with each course in such a way as to maintain the stretcher bond pattern and typically will be of longitudinal dimension half to one times the length of a tyre bale. The reasons for considering this break are partly to correct unevenness in the stretcher bond pattern that may have developed over a length of, say, 100m. They can also provide reassurance to those concerned about the potential for arson during construction as they will provide a natural fire break.

CONSTRUCTION APPLICATIONS

Guidance on six potential tyre bale applications is given in PAS 108 (Anon 2007a), namely road foundations over soft ground, slope failure repairs, lightweight embankment fill, free-draining layers behind retaining walls, drainage layers (including landfill engineering applications), sustainable urban drainage systems.

Further guidance on these and other applications is given in related publications (Prikryl *et al*. 2005; Simm *et al*. 2005; Winter *et al*. 2005a, 2005b; 2006, 2007a, 2007b, In Press; Bo & Yarde, 2006). Most tyre bale applications in construction are best achieved in tandem with the use of a conventional planar geosynthetic to aid separation, reinforcement and/or filtration.

OTHER ISSUES

An Annex specifying a **f**actory production control system for tyre bales is included in PAS 108 (Anon 2007a) to ensure that they conform to the requirements of the standard.

The issue of what happens to tyre bales at the end of service life of the structure of which they form a part is as important as for any other material. Clearly any disposal at a later date will be determined by prevailing legislation, regulation and interpretation thereof at that time. The presence of tyre bales should be noted in the Health and Safety file (Anon 2007b). Further guidance on this important subject and the durability of tyre bales is given in PAS 108 (Anon 2007a).

CONCLUSIONS

The UK produces around 48 million post-consumer tyres per annum and their disposal to landfill has been effectively banned by the EU Landfill Directive. The compression of tyres to form tyre bales produces a low density, high permeability block with a range of beneficial engineering properties that render it suitable for engineering applications.

The British Standard Publicly Available Specification 108 (PAS 108) is designed both to aid the tyre baling industry in producing a consistent product suitable for use in construction, and to aid the construction industry in understanding the nature and potential applications of tyre bales in construction. It is also hoped that the publication of PAS 108 will help in increasing the use of tyre bales in construction across a variety of applications.

This paper describes PAS 108, in particular the specification for the manufacture of tyre bales and associated activities, details of tyre bale properties and descriptions of their behaviours, and construction issues.

It is concluded that tyre bales are a useful option for some construction applications and that their use has the added benefit of assisting society in dealing with the problems associated with tyre disposal.

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