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Review paper

Waste tyre bales in road engineering: an overview of applications

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Abstract: Waste tyres are among the largest and most problematic sources of waste today, due to the large volume produced and their long-lasting decomposition and resistance to water and extreme temperatures. Since 2000 in Europe the EU Landfill Directive has forbidden the disposal of waste tyres in a landfill. Since then waste tyre derived products (TDP), including whole tyres, tyre bales, shreds, chips, and crumb rubber, have been widely used also in civil engineering applications. The baling is nowadays the best way for the product recycling of waste tyres. Waste tyre bales have considerable potential for use in road applications, particularly where their low density, permeability and ease of handling give them an advantage. Road applications include but are not limited to: embankments construction, slope stabilization and repair (landslides), road foundations over soft ground, backfill material for retaining walls and gravity retaining structures (gabion-type). Several case studies, showing the opportunities to use waste tyre bales in road construction, are presented and illustrated in the paper preceded by providing the engineering properties of waste tyre bales, used within the road structures constructed worldwide. The article also describes the first world application of abutment backfill from the tyre bales in a road bridge, realized in Poland.

Keywords: waste tyre, tyre bale, embankment, slope stabilization, lightweight backfill, retaining structure

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1. Introduction

Waste tyres are among the largest and most problematic sources of waste today, due to the large volume produced and their long-lasting decomposition and resistance to water and extreme temperatures. Landfills of waste tyres are a large health and safety risk, mainly due to approx. 45–50 % content of rubber in tyres. Waste tyre landfill fires burn for years and they are very hard to extinguish. Moreover, the smoke includes toxic chemicals. Therefore the waste tyre landfills constitute a significant burden for the natural environment. The same characteristics which make tyres a waste problem also make them one of the most re-used waste materials. Rubber is a very dependable material, strong, elastic, flexible, durable, waterproof and easy to recycle. However, the forms of tyre recycling constitute an additional and environmentally heavy burden related to pollution (combustion) or the need to use large amounts of energy (material and energy recycling). Therefore the product recycling of waste tyres may be the preferred solution to this problem.

Since 2000 in Europe the EU Landfill Directive has forbidden the disposal of waste tyres in a landfill. Since then waste tyre derived products (TDP), including whole tyres, tyre bales, shreds, chips, and crumb rubber, have been widely also in civil engineering applications. The majority of these applications has addressed tyre derived aggregate (TDA), i.e. shreds, chips and crumb rubber, for use in road engineering [1–4]. An alternative is the baling of whole waste tyres to produce cuboidal, lightweight, permeable bales [5, 6]. The baling is nowadays the best way for the product recycling of waste tyres. It enables the re-use of the whole tyres with the possible use of low-energy processing. Typical waste tyre bale comprises 100 to 115 car tyres compressed into a block and secured by galvanized steel tie wires running around the length and depth of the bale. Compressing tyres into bales has been already standardized in a detailed specification [7]. The benefits resulting from the reduction of the production and transport costs of waste tyre bales create new opportunities for their economically effective re-use in construction.

Waste tyre bales have considerable potential for use in road applications, particularly where their low density, permeability and ease of handling give them an advantage. The use of lightweight bales in the construction of a lightweight embankment or road foundation over soft ground, the slope stabilisation or landslide repairs and the backfilling of retaining structures has the potential to satisfy the demand for low-cost materials exhibiting such a beneficial property. This paper comprises the review of up-to-date tyre bales applications in road engineering, prepared by the authors to encourage and accelerate the implementation of waste tyre bales in road and bridge construction in Poland.

2. Engineering properties of waste tyre bales

Geometrical dimensions and engineering properties of waste tyre bales are needed when designing and building structures comprising bales. Apart from basic dimensional and mass properties, the practical need to know the density and porosity of tyre bales are also important, for example when assessing the stability of structures against sliding and overturning. Permeability is a key parameter when bales are being used for drainage, as it determines the rate at which water can pass through the layer of bales. It is also significant regarding stability under hydraulic loading.

The stiffness of the tyre bales is important because it determines the way, in which the structures deform under loading. It is also most important when assessing serviceability limit state conditions.

One of the key determinants of the stability of a tyre baled structure is the shear strength of the material from which it is formed. In the case of porous materials, such as tyre bales, two parameters are often used to define a failure line. The parameters comprise a fixed element related to cohesion and a frictional element dependent upon the normal stress to which the material is subjected. The two parameters that define the shear strength are "c" and "φ". These parameters are respectively the intercept and slope angle of the failure line in the plane of the normal and shear stresses. Last but not least, creep response of a tyre bale or a baled structure describes its strain under constant load and environmental conditions. Therefore creep tests must almost always be carried out over a long time before tyre bales are introduced in road applications.

The dimensional and engineering values provided 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 [7].

Table 1. Geometrical dimensions and mass properties of reference tyre bales [7]

No.	Property	Value(s)
1	Length	1.33 m (+0.08 m / –0.06 m)
2	Width	1.55 m (± 0.07 m)
3	Depth	0.83 m (± 0.04 m)
4	Volume	1.70 m^3 (+0.24 m^3 / –0.15 m^3)
5	Mass	810 kg (± 35 kg)

Table 2. Engineering properties of reference tyre bales [7]

No.	Property	Value(s)
1	Nominal mass density	470 kg/m^3 (± 50 kg/m^3)
2	True mass density	500 kg/m^3 (± 70 kg/m^3)
3	Porosity	62 % (± 5%)
4	Shear strength: the angle of inter-bale friction, φ’	35° to 36°
5	Stiffness: expressed as Young’s modulus, M	800 kPa to 1.100 kPa
6	Total creep (35 months)	Up to 1.1%
7	Permeability through depth	0.1 m/s to 0.2 m/s
8	Permeability through length	0.02 m/s to 0.04 m/s

Assessment of environmental risk from using waste tyre bales concerning the potential impacts of waste tyre materials on human health and the environment indicates that they are neither hazardous nor dangerous [8–11]. It applies particularly to the use of tyre bales regarding the risk of fire, the potential leaching of chemicals and compounds into local watercourses and human health and safety issues. Tyre bales do not appear on any official list of hazardous materials. Therefore waste tyres and related materials do not pose a threat to the environment or human health so long as normal precautions are followed for treatment, processing, storage and use.

3. Application of tyre bales in road engineering

The application of waste tyre bales in road construction is beneficial due to their unique properties, such as three times lower volumetric weight than traditional soils, good drainage properties, high frictional resistance and favourable vibration-damping properties. Since the bales weigh less than conventional filling materials, they will induce less settlement of subsoils and lower lateral pressure on structures such as retaining walls or bridge abutments. The lightweight of tyre bales allows them to serve as a filling while reducing the dead weight and stabilizing a slope, similar to a stabilizing effect provided by thick gravel layers or geosynthetic reinforcements. Because of their relatively high permeability, they allow for good drainage as for gravel. The lightweight backfill made of tyre bales acts as a self-supporting block and high frictional resistance along the tyre bale – soil interfaces allows for earth pressure reduction. Finally, good damping properties reduce the harmful influence of road construction on the surroundings.

In addition to the above-mentioned engineering advantages, the tyre bales are easily handled enabling the use of small equipment for placement. The elimination of conventional filling requirements for compaction and moisture control makes construction with tyre bales easy and relatively fast. Therefore the cost of using tyre bales in road engineering applications is less than that of conventional filling materials. Last but not least, the environmental benefits of using these waste materials rather than landfill storage of them is indisputable. In short, tyre bales offer both environmental and economic benefits, thus enhancing the sustainability of road engineering.

Waste tyre bales were first used in civil engineering in the late 1990s in the USA [12]. Since then, several dozen projects have been implemented in road construction, mainly in the USA, Canada and Great Britain. Road applications of waste tyre bales include, but are not limited to embankments construction, slope stabilization and repair (landslides), road foundations over soft ground, gravity retaining structures (gabion-type) and backfill material for retaining walls. The most common applications of waste tyre bales in road engineering are shown schematically in Fig. 1. In the following chapter several case studies, showing the opportunities to use waste tyre bales in road construction, are presented and illustrated within the structures constructed worldwide.

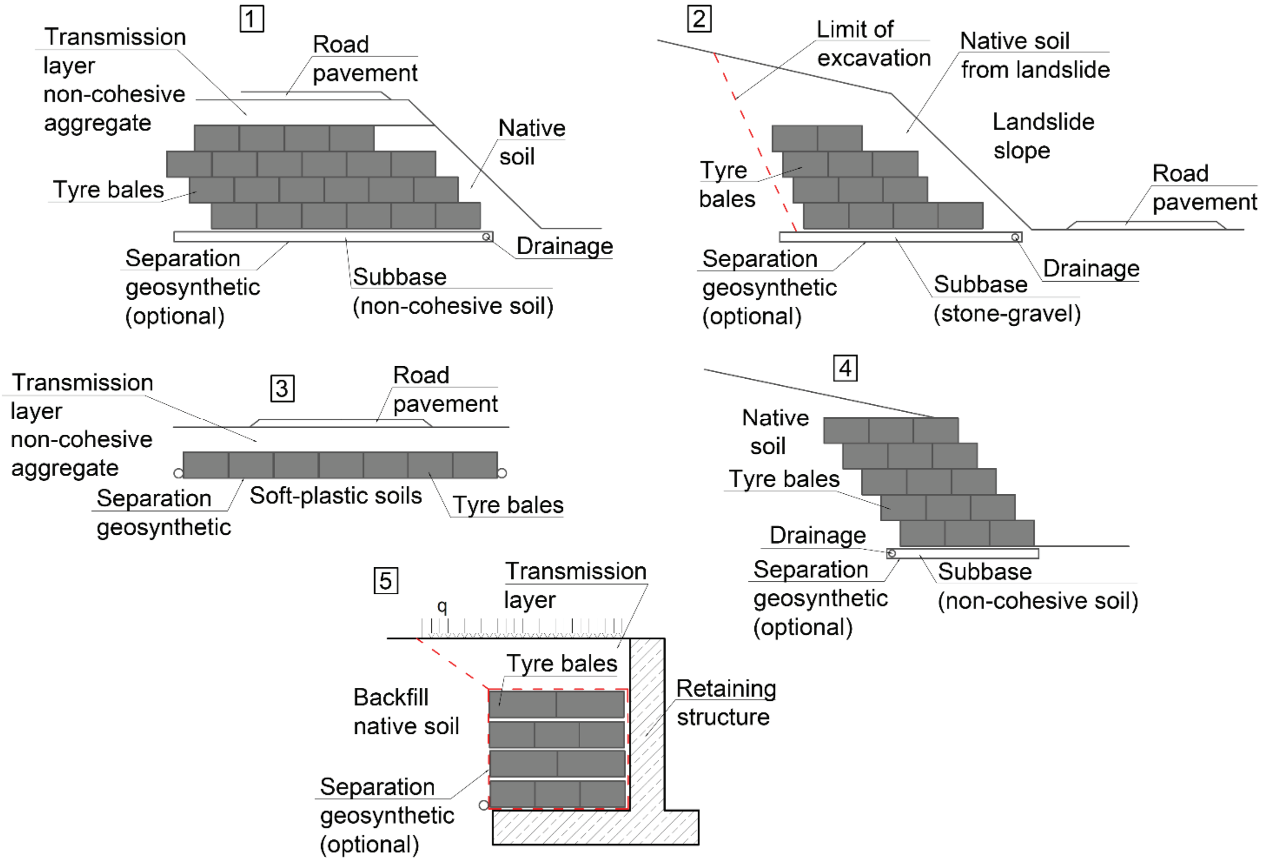

Fig. 1. Road applications of waste tyre bales

4. Case studies

4.1. Embankment construction

Tyre bales are considerably lighter than conventional fill used in road embankments, thus they can be used for road construction in soft ground conditions. They are long-lasting, non-polluting and require less compaction than conventional fills. Moreover, they are much cheaper than special lightweight materials typically used in such cases.

The most spectacular example of the waste tyre bales' use in the embankment structure is the section of the A-421 motorway in near Bedford in England [13]. The A-421 improvement scheme required the construction of the new dual carriageway and a realigned side road over two former borrow pits that have been partially infilled with up to 20 m of soft clay. The side road was constructed using lightweight fill comprising lightweight expanded clay aggregate (Maxit) and waste tyre bales manufactured under a standard [7]. The solution was chosen after consideration of various options against many constraints. The contractor decided to use lightweight infill instead of strengthening the subsoil with dozens of at least 29 m long piles.

Maxit was first used to form a level platform, on top of which a layer of tyre bales was laid down along the 240 m stretch. After one layer of bales had been laid, Maxit was used as fill for voids between the tyres and was vibrated down. Geotextile was then laid on top of the bales to prevent migration of fill and another tyre bale layer was added. The bulk of the embankment was formed from three layers of waste tyre bales with alternate thin levelling layers of Maxit. Once completed, the bales were finished with 1.0 m of fill on top. A surcharge load was then added to induce settlement. Extensive drainage laid beneath the tyre bales helped to accelerate settlement so the surcharge was only needed for six months. Once the surcharge period had been complete, conventional clay was placed on top, followed by traditional asphalt pavement construction.

The use of waste tyre bales on this project provided many environmental benefits as well as practical benefits including cost and ease of storage, handling and placing. Approximately 4,500 tyre bales were needed for the embankment, equating to about 500,000 tyres, and 11,000 m^3 of Maxit were utilized to construct the embankment (Fig. 2).

Tyre bales were also used as lightweight fill in an embankment ramp for the high traffic volume Tampere Western Ring Road project in Tampere, Finland [14]. The tyre bale section was about 130 m in length. The subsoil consists of weak clay extending down to about 10 m. The bottom layer of the road embankment consists of one layer of tyre bales surrounded by filter cloth and covered by a steel wire net. The road section includes 1.0 m of crushed stone aggregate under the pavement.

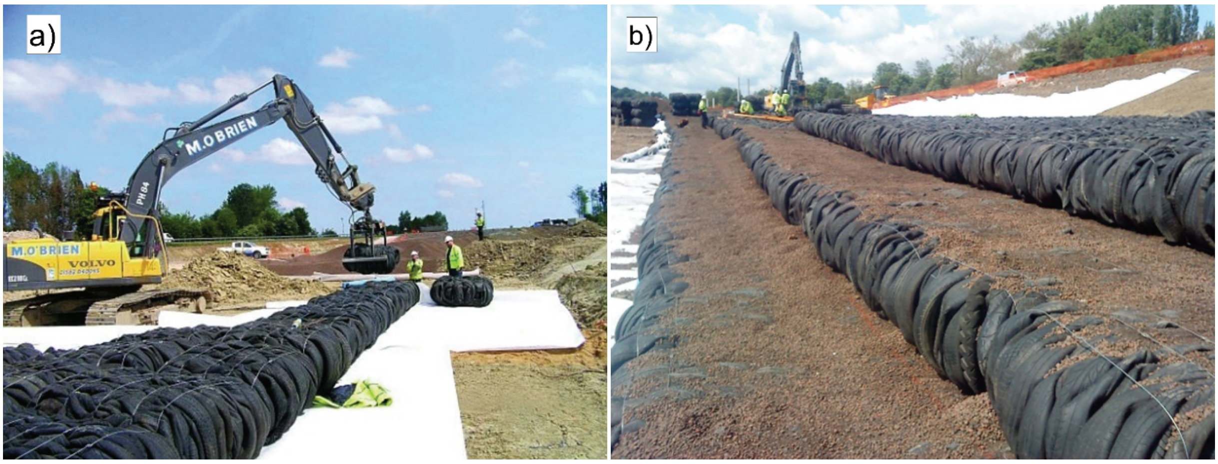

Fig. 2. Construction of lightweight embankment of the A-421 motorway, England: a) tyre bales placed on geotextile; b) tyre bales filled with Maxit [13]

4.2. Slope stabilization and repair

Tyre bales can be utilized to strengthen slopes at risk of sliding (landslides) or to repair failed slopes. A small gabion-type wall can be formed from bales at the toe of the slope. However, because of their lightness, they can be used only as wide “dowels” at the toe of the slope, rather than acting as a gravity wall or providing toe loading effect. Most landslides are less than 1.5 m deep, especially towards the toe, therefore many tyre bale “dowels” crossing the failure surface would have a major stabilizing effect [15]. Placing a mattress of half-buried tyre bales on the lower part of the slope can provide the slope stability, especially if the bales can help the slope drainage.

In the USA the remediation of soil cut slope instability has conventionally been achieved using existing or imported soils, with or without modification by hydraulic binders and often in conjunction with an H-beam wall, to minimise costs and construction time. However, in 2002 waste tyre bales were used for the first time for repairing several embankment failures. The most notable example of such remediation repair was the failed slope repair, which took place at Interstate Highway 30 (I-30) in Fort Worth, USA [16]. The length of the failed slope was approximately 46 m, the slope height reached 6.1m at a constant 1:3. The project was carried out in several phases using a total of 360 tyre bales containing on average 100 waste tyres per bale (Fig. 3a). Once the failed slope was excavated, tyre bales were laid in the base of the excavation and pushed together to ensure contact between adjacent bales and to fill the entire area of the excavation. This first layer of bales was covered with 0.20 m to 0.30 m of soil from the excavation and the second layer of bales was placed. The third layer of tyre bales was placed similarly. However, after the placement of just one row of bales, the economically viable supply of tyres for the bales was stopped due to external factors, leaving three layers only partially complete. The resulting voids were filled with material excavated from the failure area. Only limited compaction was applied. The soil was placed on the face of the slope without compaction to ensure a depth of cover of 0.90 m to the tyre bales, smoothly graded to restore slope geometry and then seeded to help reduce erosion (Fig. 3b). Since these operations were completed vegetation has been established.

Project monitoring indicated that the repaired slope had remained stable and porosity increased since the tyre bales allow water to flow through the slope. Initial assessment showed that this method improved the slope factor of safety by 2–3 times, compared to the original soil slope [16]. A potentially considerable improvement in the long-term repaired slope stability is thus possible where tyre bales are substituted for conventional soil backfill in areas where high plasticity clays predominate.

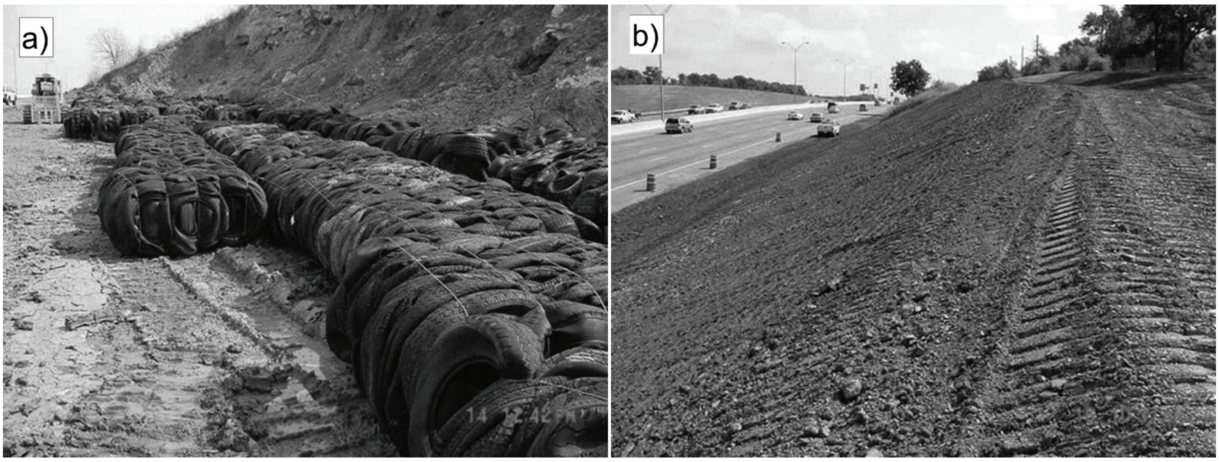

Fig. 3. Embankment slope repair at I-30 highway in Fort Worth, USA: a) tyre bales placed at the toe of the slope; b) tyre bales covered with soil and shaped to match the surrounding slope [16]

4.3. Road foundations over sorf ground

Due to their beneficial characteristics, tyre bales are often used as a road foundation over soft ground. Tyre bales are considerably lighter and require less compaction, as well as are very much cheaper than conventional or special lightweight materials, which could be utilized for lightweight road foundations. The first examples of using this technique took place between 1999 and 2002 in the Chautauqua County, NY, USA, where a total of five projects were carried out involving the use of lightweight tyre bales as a subgrade replacement for roads over soft ground [17]. In each project, subgrade material in the existing road was excavated. It was fine silty clay, which is generally stable if kept dry, but are very sensitive to moisture and even more so to the freeze-thaw cycle. The separation geosynthetic fabric was laid down, a single layer of tyre bales about 0.75 m thick was placed over the fabric as subgrade and gravel was used to fill voids (Fig. 4a). The final road surface consisted of 0.45 m of compacted gravel, covering the bales (Fig. 4b). The County found the following benefits of using tyre bales as lightweight fill over soft soils: road strengthening, thermal insulation and frost penetration, better drainage, lower cost than conventional fill, less installation labour since the bales were already compacted, and less settling over time.

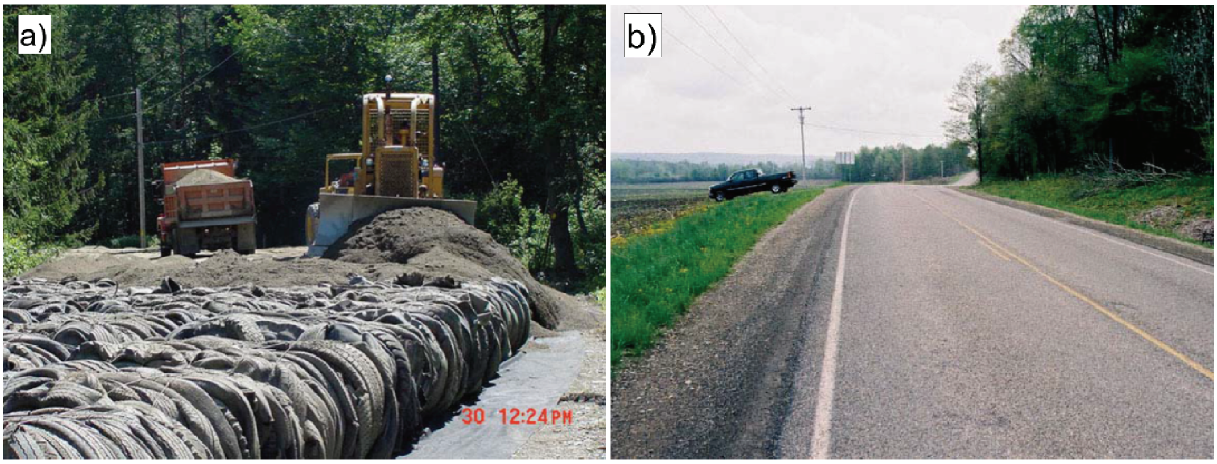

Fig. 4. Tyre bales road foundation in Chautauqua County, USA: a) placement of gravel layer on tyre bales; b) the finished road [17]

Another example of the use of tyre bales as a road foundation on soft soil is the section of the B-871 road in Sutherland, Scotland [18]. Although it is a road with low traffic, the peat in the subgrade was the reason for significant settlement, causing road deformation. Ultimately, the road load significantly increased due to heavy traffic with timber transport from nearby forest areas, which required to strengthen the existing road. On the critical section of the road (about 50 m in length) the soft soil subgrade was strengthened with 350 tyre bales. The tyre bales in the roadbed were arranged in two layers: the bottom layer with 6 bales, top layer with 5 bales. The substructure of the tyre bales was separated from the base subsoil using a separation geosynthetic fabric. The voids between the tyre bales were filled with lightweight expanded clay aggregate (LECA). The stone pavement of the road with a total thickness of 0.45 m consisted of three layers of stone, gravel and sand mix soils.

The road strengthening works progressed efficiently and methodically as follows. The forward excavator dug to formation level, approximately 1.5 m below the existing road, over a bay length of 5 m. As the material was removed, a strip of geotextile across the cross-section was placed, leaving a surplus for wrapping over the bales (Fig. 5a). Grab machine at rear placed a lower row of tyre bales in place, with assistance as required from forwarding machine to push them tightly into place. Lightweight fill was dumped over bales and allowed to percolate the voids (Fig. 5b). The second (upper) layer of bales was put in place and dressed off with lightweight fill before workers gathered loose geotextile to complete wrapping of bale group, with overlap on top. The rear excavator spread a 3 m wide layer of fine rockfill over the geotextile, to provide a working platform for moving forward to the next bay.

Fig. 5. Tyre bales in the B-871 road foundation, Scotland: a) placing tyre bales on geotextile across the cross-section; b) filling of tyre bales with lightweight aggregate [18]

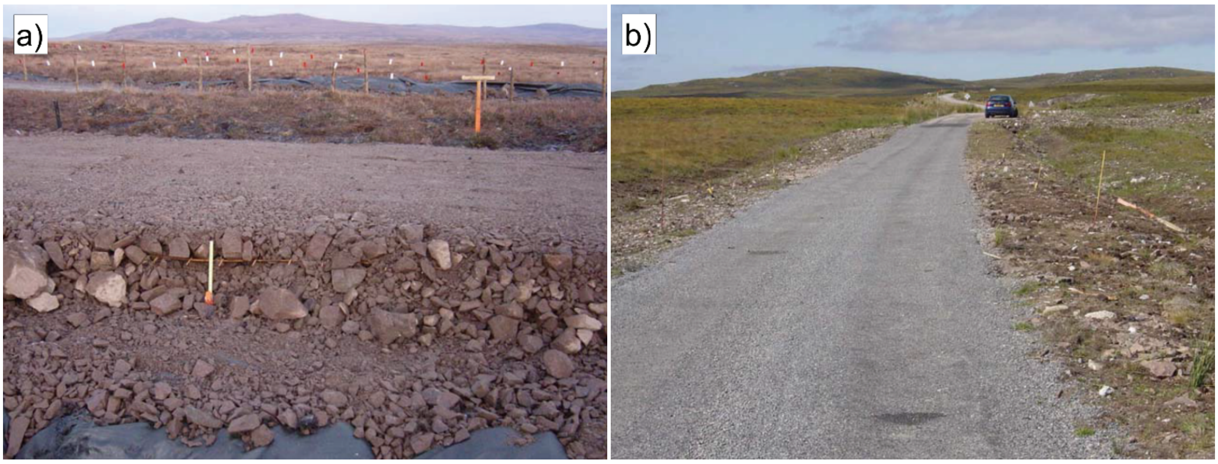

Fig. 6. Tyre bales in the B-871 road foundation, Scotland: a) rockfill layer topped over tyre bales; steel reinforcement installed in the subgrade; b) the B-871 road after completion of pavement [18]

As soon as the bale road foundation was installed, the rockfill layer was topped up to 0.25 m deep and dressed off to level. A welded steel reinforcing mesh (8 mm bars at 200 mm centres) was included in this layer (Fig. 6a). It was considered that this mesh would provide some additional strength to the capping layer, helping to tie it together during the significant bedding in movements that could be expected. This technique has been also used in Finland in similar soft subsoil situations [14]. An excavator then spread a 100 mm layer of sub-base on top of the rockfill to provide a finished surface. This enabled the road to be reopened to public traffic (Fig. 6b).

4.4. Gravity retaining walls (gabion – type walls)

Tyre bales are fairly regular in size and shape and can be used as modular blocks to build gravity retaining walls thus can replace conventional rock-filled gabions. Thanks to the use of tyre bales, the dimensions of the retaining structure and the pressure transmitted to the ground can be reduced. They are very much cheaper than conventional rock-filled gabions even when accounting for the rock material used to face the tyre gabions. The visible face of tyre bales are unattractive and are likely to be top soiled where necessary. Bales can be tied-back to the soil behind them using for example a geotextile to produce a form of reinforced soil construction.

Two projects using tyre bales in the form of gravity retaining wall were carried out in Winston and Hillsboro, New Mexico, USA, in the vicinity of two state roads [19]. At the first location, an arroyo runs almost parallel to the south side of the road and significant erosion of the arroyo banks arose after heavy floods, endangering the road due to undermining. In the second case, the east bank of an arroyo runs almost perpendicular to the road, and two culverts under the road were silt-blocked causing flooding on road and considerable erosion of the arroyo bank at this location. Both tyre bale projects were carried out to stabilize arroyo banks at these locations. Tyre bales were used in these projects as an alternative to rock gabions.

Similar materials and construction procedures were used to build the gravity retaining walls of the Winston and Hillsboro projects. These walls were built of multiple layers of tyre bales (Fig. 7). Construction started by placing two rows of tyre bales below the flow line of the channel. To serve as anchors, a series of steel bars (3 m long with L-shape cross-section) were driven in between the tyre bales with a spacing of about 6 m, starting and ending at both ends of the wall. The bars were driven to depths of 1.5 m to 2.4 m, depending on soil conditions. To firmly secure the first layer of bales, a 9.5 mm steel cable was run along the top of the bales and through the L-shaped bars. For this purpose, a 13 mm hole was predrilled in the upper end of each bar. Cable clamps were used to tightly secure the steel cable to the angle irons at both ends of the embankment. Once the cable was installed, the first tyre bale layer was encased in hexagonal gabion wire. The second layer of bales was formed by one single row of bales placed in the centre of the first layer. This second layer was also encased in gabion wire and fastened to the bottom layer using wire. The third and final layer was installed similarly. Each layer was offset back approximately half the tyre bale width for stability. In Fig. 8, only the upper two layers of bales are visible. The bales were initially covered with soil but are currently exposed after rain events. The Hillsboro bank was repaired using 160 tyre bales and about 610 tyre bales were placed along 396 m of the south bank of the arroyo that runs parallel to the state road in Winston.

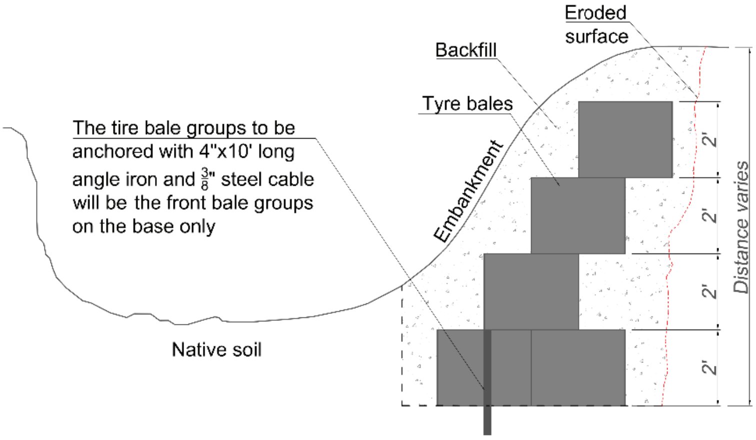

Fig. 7. Typical cross-section of the tyre bale gravity walls constructed in New Mexico

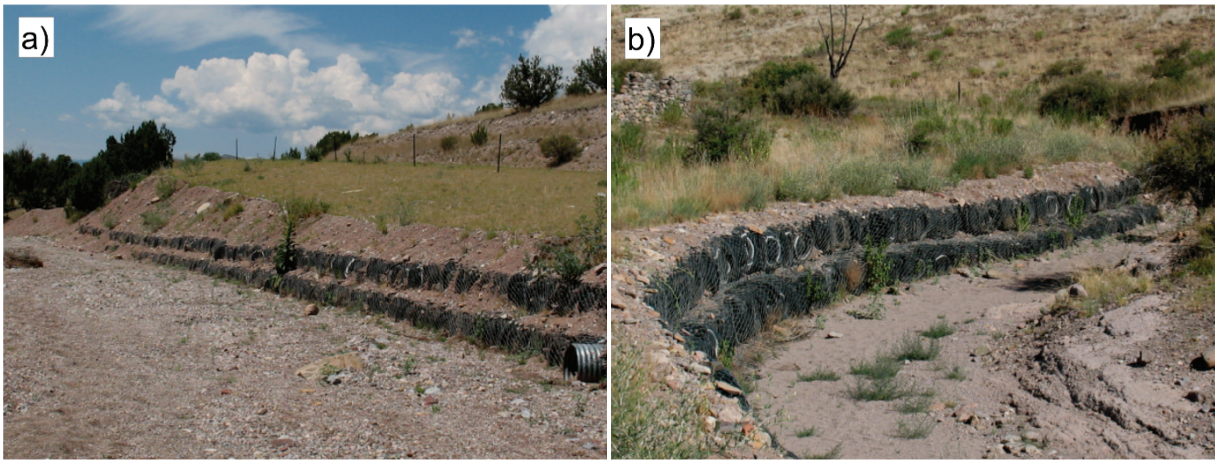

Fig. 8. Tyre bale gravity walls constructed in a) Winston and b) Hillsboro, New Mexico, USA [19]

4.5. Backfill to conventional retaining walls

By replacing some of the soil backfills immediately behind the rigid retaining wall with lightweight tyre bales, which are largely self-supporting, the considerable reduction of the overturning force to the wall can be obtained, allowing a comparatively lightweight wall design. Since the overturning force acting on the backwall is very dependent on the properties of the soil being retained, the lightweight tyre baled backfill can considerably reduce the earth pressure. Moreover, the permeable bales can provide a good drainage path against the back wall thus they can replace a drainage layer used conventionally to minimise hydrostatic forces acting on the wall. However, in the case of bridge abutment care is required to ensure that vertical load does not cause excessive compression, where the bales are immediately under the road structure. Typically the approaching slab supported on the abutment's backwall can reduce this load.

The advantage of using tyre bales as backfill is even more obvious in integral bridges, where the abutments are structurally connected to a continuous deck. In such cases, the temperature expansion of the deck can be taken up in elastic stress absorbing layer between the backwall and the fill material. Without such layer, high-quality backfill induces the high passive pressure developing on the backwall of the abutment. One means to avoid these high lateral stresses on the abutment is to use a compressible elastic cushioning layer with low stiffness. Tyre bales provide passive pressure much lower than conventional granular backfill. Lateral pressure induced on integral abutment by tyre bales can be as low as that on non-integral abutments, significantly reducing the cost of the integral abutment. The properties of the tyre bales seem to be appropriate as stress absorbing material.

The use of tyre bales as a backfill to conventional retaining walls was the main subject of the research project carried out by the authors at Rzeszow University of Technology [20, 21]. The laboratory tests included measurement and evaluation of full-scale tyre bales to determine basic values for the geometry and unit weight, compressibility characteristics of tyre bales, including Young's modulus and Poisson ratio, shear strength along the tyre – tyre and tyre – soil surfaces, creep and stiffness degradation under cyclic load. Brief outlines of the conclusions drawn from these tests are presented below, providing the resultant values along with the qualitative comparison with the relevant literature [5, 6, 23].

To manufacture the apprioprate tyre bales for testing approximately 135 car tyres were compressed in a baling machine and restrained with tie-wires. The process produced a cuboid bale of approximate dimensions 2.05×1.30×0.75 m, a mass of around 1030 kg, the average volume of around 2.0 m^3 and the unit weight defined using the average volume of approximately 0.515 Mg/m^3. This unit weight was found to be slightly lower than the values reported in the literature. A compression testing setup was used to measure the deformations of a tyre bale due to normal compressive loading. The approximate Young's modulus for the tyre bale was 826 kPa and is close to the values reported in the literature. The horizontal deformation measurements indicated a relatively low Poison's ratio on the order of 0.11, while these values reported in literature ranged from 0.08 to 0.24. The results from the dry tyre – tyre interface testing could be combined and modelled with a linear failure envelope with the cohesion of 0.03 kPa and friction angle of 46.0°, showing moderate variability between different bales within the range of 0.11% to 21.53%. The corresponding results from the wet tyre – soil interface testing indicated that for medium sand a linear failure envelope could be estimated with a small cohesion 0.77 kPa and a friction angle of 29.6° with the small variability of test results not more than 12%. Both results match well values provided in the literature.

The results from the tyre - soil interface testing compared with medium sand strength determined in the direct shear testing provided evidence that the tyre – soil interface strength is about 15% weaker than the soil only strength. However, up to 20% reduction was revealed in the literature. Creep deformation due to sustained normal compressive load for up to five days of loading constituted 6.1% of the average height of the bale. A significant portion of the creep deformation (approximately 95 %) occurred in the first day and the maximum deformation appeared within three days. The 1-year creep coefficient was estimated as 0.0039 and this value is very similar to those obtained in the literature. The cyclic load test results obtained as a resilient value (the difference between maximum and minimum deformations) were almost constant within about 400 minutes of loading, revealing no stiffness degradation of tyre bales under cyclic load. No similar tests were performed elsewhere up to date.

In addition to the tests described above, the authors conducted a series of experimental and numerical tests on waste tyre bales used as backfill for integral bridges. The experiment was prepared and conducted utilizing a special full-scale trial built to simulate actual bridge abutment conditions. The experiment revealed that the pressure (both active and at-rest) on the abutment back wall was significantly lower in the case of the waste tyre backfill when compared to a common, medium sand backfill [21].

Positive results of laboratory and field tests allowed us for the first known implementation of tyre bales in the backfill of the abutment of a three-span continuous bridge, located at Sielnica in south-east part of Poland [22]. Due to the complex stress state caused by the anchoring of the spans in both abutments, the tyre bales placed in the backfill were used to relieve the direct foundations and significantly reduce the earth pressure on the backwall. Thirty tyre bales in four layers were built into the backfill of each abutment. The number of tyre bales in each layer was 4, 9, 8, and 9 from the top, respectively, so that there were overlaps between the individual tyre bales in each layer (Fig. 9).

The medium-sized sand was applied to fill the voids and to cover each bales layer with the 10÷15 cm thick interlayer (Fig. 10a). The tyre bales including interlayers were enclosed in a geosynthetic fabric, separating the conventional backfill from the bales. To avoid the excessive compression of tyre bales due to the vertical load, the transition slab was used under the pavement structure. Moreover, to minimize the deformation (settlement) of the innovative backfill, before the transition slabs were cast, the temporary surcharge of tyre bales for 7 days has been applied in the form of precast road slabs with a total weight of 40 metric tons. (Fig. 10b). One year after the opening of the bridge for traffic, the monitoring of approach pavement and the abutments showed no deformations.

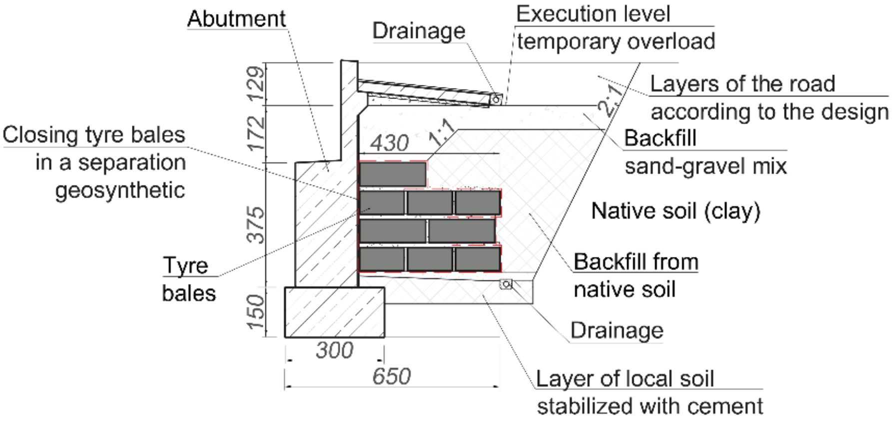

Fig. 9. The abutment backfill of Sielnica bridge, Poland: layers of tyre bales

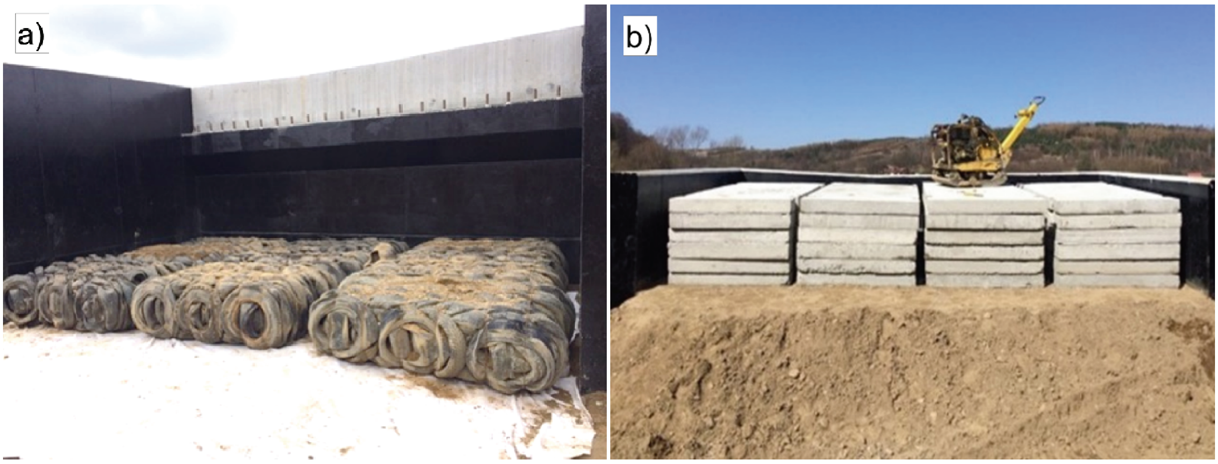

Fig. 10. The abutment backfill of Sielnica bridge, Poland: a) the first layer of tyre bales placed behind the backwall; b) surcharge of tyre bales (A. Duda)

5. Summary and conclusions

Today, a lot of waste is perceived as a valuable source of raw material. The waste treatment market is expanding into new areas. Waste tyres are an extremely burdensome waste because they are not biodegradable and constitute a serious fire hazard. They cannot be disposed of in landfills due to the possibility of spontaneous combustion. Energy or fuel derived from tyres seems to be a good solution to this problem, but in reality, it is far from being efficient waste management. When a tyre is burned in a cement kiln it is lost forever, producing large amounts of greenhouse gases. Tyres that are reprocessed to produce higher-value products or to replicate materials give a second, third or even fourth life of a raw material that can still be used as fuel in its final use phase.

The material from the recycling of waste tyres in the form of tyre bales is characterized by unique strength, mechanical, vibro-isolating, drainage and insulating properties and may soon be widely used in road and bridge construction or maintenance. However, the lack of standards and the fear of soil and water contamination from the bales have historically limited the number of road engineering projects that used waste tyre bales in most countries of Europe. The presented case studies revealed that using of waste tyre bales as fill material in embankments or backfills and road foundation or slope stabilisation projects did not represent a potential environmental risk from the leaching of either inorganic or organic chemicals. Furthermore, there are further potential areas of the application of waste tyre bales in road engineering, for example, crash cushion for bridge piers or bridge abutments, scour protection for river bridges and noise fences or screens. No one application from this group has been implemented for 20 years of using the bales in civil engineering. This review paper aims to encourage and accelerate the implementation of waste tyre bales in road and bridge construction in Poland.

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Pakiety ze zużytych opon samochodowych w budownictwie drogowym: przegląd zastosowań

Słowa kluczowe: zużyte opony, pakiety sprasowanych opon, nasyp, stabilizacja zboczy, lekka zasypka, konstrukcja oporowa

Streszczenie:

Zużyte opony samochodowe są współcześnie jednym z najbardziej problematycznych odpadów ze względu na ich dużą objętość, długotrwały rozkład w środowisku oraz odporność na wodę i temperaturę. Od roku 2000 dyrektywy unijne wprowadzone w Europie zabraniają składowania zużytych opon samochodowych na wysypiskach odpadów. Od tego czasu produkty z recyklingu opon, w tym: całe opony, opony sprasowane w pakiety, strzępy, chipsy oraz granulat gumowy, są szeroko stosowane w budownictwie oraz w inżynierii lądowej. Powtórne wbudowanie opon sprasowanych w pakiety to obecnie najefektywniejszy sposób na recycling zużytych opon. Pakiety z opon mają znaczny potencjał w zastosowaniach drogowych, szczególnie tam, gdzie ich niska gęstość, odpowiednia przepuszczalność i łatwość w wbudowaniu dają im przewagę w stosunku do materiałów tradycyjnych. Zastosowania drogowe pakietów z opon obejmują m.in.: budowę nasypów, stabilizację i naprawę zboczy (osuwisk), podbudowę dróg na podłożu o niskiej wytrzymałości na ścinanie, materiał zasypowy konstrukcji oporowych i grawitacyjne konstrukcje oporowe (typu gabionowego). W artykule przedstawiono i zilustrowano kilka przykładów wykorzystania pakietów z opon w budownictwie drogowym, poprzedzonych przedstawieniem właściwości materiałowych i parametrów inżynierskich pakietów, stosowanych w konstrukcjach drogowych budowanych na całym świecie. Artykuł opisuje również pierwsze światowe zastosowanie pakietów z opon w zasypce przyczółka mostowego, zrealizowane w Polsce. Ta pierwsza aplikacja została poprzedzona serią badań doświadczalnych, zarówno w laboratorium, jak również *in-situ*. Wybrane wyniki tych badań, potwierdzające odpowiednie parametry pakietów, również przedstawiono w artykule w porównaniu do wyników nielicznych badań obcych.

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