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The use and application of two contrasting non-traditional embankment and pavement foundation materials

L'utilisation et l'application de deux matériaux non traditionnels contrastés en remblais et en fondations de chaussées

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ABSTRACT: The increased use of non-traditional materials is driven from multiple perspectives. These include societies' desire for a more sustainable future, reinforced by legislation, regulation and policy mechanisms to encourage the greater use of such materials. This paper discusses two contrasting materials. Tyre bales are free-draining and lightweight and have been used in road foundations and embankments over soft ground as well as in slope failure repair or slope stabilisation. Electric arc furnace steel slag has been used as a direct replacement for a road embankment and a base course layer, as well as in a rail track. Experience demonstrates that such uses become widespread only when a given environmentally friendly material has a cost advantage and/or a performance benefit, and the material and its use is included in an appropriate standard or specification. It is concluded that the lack of a Quality Protocol is likely to further impede their use.

RÉSUMÉ: Les progrès vers une utilisation accrue de matériaux non traditionnels sont motivés par un certain nombre de points de vue différents. Le premier d'entre eux est un enjeu de plus en plus important des sociétés pour un avenir plus durable; cela est souvent renforcé par des mécanismes législatifs, réglementaires et politiques de haut niveau visant à encourager une utilisation accrue de ces matériaux. Cet article traite de deux matériaux contrastés. Les balles de pneus sont drainantes et légères et ont été utilisées dans des fondations routières et dans des remblais sur les sols mous ainsi que lors des réparations et stabilisation de talus. Les scories d'aciérie de four à arc électrique ont été utilisées pour remplacer directement un remblai routier et une couche de base, ainsi que sur une voie ferrée. L'expérience montre que ces utilisations ne se généralisent que lorsqu'un matériau respectueux de l'environnement présente un avantage en termes de coûts et / ou un avantage en termes de performances, et que le matériau et son usage sont inclus dans une norme ou une spécification appropriée. Il est conclu que l'absence de protocole de qualité risque d'entraver leur utilisation.

Keywords: Embankment; pavement; foundation; recycled materials.

1 INTRODUCTION

Society demands a more sustainable approach to construction and in this paper two contrasting materials are considered. Tyre bales are free-draining and lightweight and have been used in road foundations and embankments over soft ground as well as in slope failure repair while steel slag has been used as a direct replacement for a road embankment and a base course layer as well as in a rail track.

The composition, properties and behaviours of each material are described. Costs are considered relative to those of conventional materials and the wide variety of successful applications that both materials have seen in recent years is detailed. The development of the relevant standards and specifications is set-out.

It is clear that the use of non-traditional (reused, recycled and recovered) materials can make a significant contribution to sustainability. However, sustainability is a broad concept and experience indicates that the use of such materials becomes widespread only when there is a cost advantage and/or a performance benefit, and the material and its use is included in an appropriate standard or specification as is the case for each of the materials considered in this paper (Gomes Correia 2015; Gomes Correia et al. 2016). However, it is concluded that the major requirement for the materials to become part of the mainstream is the development and implementation of a Quality Protocol. A Quality Protocol removes the materials from the waste stream at the point of production and thus allows their use in construction without the impediments associated with compliance with waste regulations.

2 MATERIALS

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

The majority of research and development has addressed the use of tyre shred, chip and crumb for construction works. An alternative is the processing of whole tyres to form rectilinear, lightweight/low density, permeable, porous bales of relatively high inter-bale friction.

In Portugal, there are two Iron/steel companies (ISC Maia and Seixal) and they currently operate electric arc furnaces. They produce about 1,500,000 tonnes of steel, resulting in 270,000 tonnes of black steel slag (Gomes Correia et al. 2012). After removing the metallic component for recycling, 250,000 tonnes of non-metallic components remain, for inert aggregate production. Based on ISC data, in the medium term about 400,000 tonnes of this black steel slag are expected to be produced annually.

The management of this large volume of material, in accordance with applicable regulations, represents a significant source of national and ISC concern. The reuse and recycling of such materials is beneficial to the producers, the end users and the nation. These materials could be used, for example, in the construction of transportation infrastructure and geotechnical works. In this context a research and development project was undertaken in Portugal (2005 to 2009), which was designed to study the reuse of processed steel slags, involving the National Laboratory of Civil Engineering (LNEC), the University of Minho (Uminho) and the Centre for Waste Valorisation (CVR). After this project these slags became known as Inert Steel Aggregate for Construction

(ISAC) (Gomes Correia et al. 2012; Reis Ferreira, 2010).

3 COMPOSITION, PROPERTIES AND BEHAVIOUR

Tyre bales comprise 100 to 115 car/light goods vehicle tyres compressed into a 800kg block having a density of about 0.5Mg/m^3. The bales are about 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 potential for use in construction particularly where their low density and ease of handling places them at a premium. A porosity of about 62% and permeability of about 0.02m/s (similar to sand) through the length and 0.2m/s (similar to gravel) through the depth (Simm et al. 2005) makes them ideal for drainage applications. The bale-to-bale friction angle is around 35° in dry conditions and stiffness in the vertical direction of Figure 1 is up to around 1GPa (Frielich & Zornberg, 2009; Winter et al. 2006).

Figure 1. A typical tyre bale with dimensions

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

Spontaneously combusted fires in whole tyre dumps are not known to the authors. In the USA, while combustion of whole tyre dumps due to sparks from agricultural machinery and lightning have been reported, most observers suspect arson.

Baling whole uncompressed tyres reduces their volume by a factor of four to five, greatly reducing the available oxygen as well as the exposed rubber surface area as tyre-to-tyre contacts are formed, without exposing any steel reinforcing in the tyres. The exothermic oxidation reaction potential is significantly lower than for whole tyres and the risk of spontaneous combustion from tyre bales is viewed as extremely low. A modelled storage condition for a 17.5m by 6.0m by 3.0m volume of bales needed to reach and maintain a temperature of 188°C for 39 days before spontaneous combustion became possible (Simm et al. 2005). In contrast reports have been made of internal heating and of apparently spontaneously combusted fires in large volumes of tyre shred in the USA (Sonti et al. 2000). Further details of tyre bale properties and behaviours are available (Anon. 2007).

Both sources of Inert Steel Aggregates for Construction (ISACs) have similar geotechnical index properties (Reis Ferreira, 2010). Based on the particle size distributions (Figure 2) they can be classified as well graded materials. Based on the Atterberg limits test results, the fines of both materials are non-plastic. They have similar Flakiness and Shape Indexes and good resistance to fragmentation and abrasion, with Los Angeles (LA) values of 25% and a micro-Deval (MDe) of 11%. The compaction test results have high values for the maximum dry density (2320 kg/m^3, for Seixal ISAC and 2430 kg/m^3 for Maia ISAC) and low values for the optimum water content (5.00%, for Seixal ISAC and 3.45% for Maia ISAC) for modified Proctor.

The very high values of dry density are a consequence of the very high particle density (around 3000 kg/m^3). The values found for the CBR (100%, for Seixal ISAC and 72% for Maia ISAC) are substantially higher than the values of some unbound granular materials. The swelling properties for Seixal ISAC indicates a 1.5% volume increase which is compliant with the requirements of UNE EN 1744-1 (1999) (results are not available for Maia ISAC). In terms of strength behavior these materials exhibit high values of friction angles (a critical state friction angle around 47º). These high values are consistent with those found in the literature (SAMARIS 2002/2005). They also present high stiffness values. Further details of mechanical properties and behaviours are presented by Gomes Correia et al. (2012).

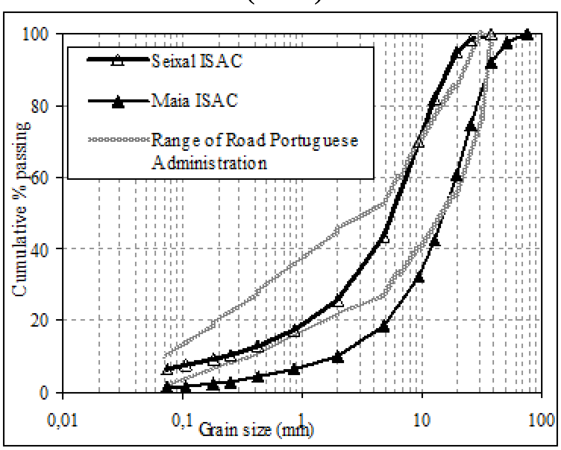

Figure 2. Particle size distributions of Maia and Seixal ISACs and their comparison with particle size distribution ranges specified by Portuguese Road Administration

4 SPECIFICATION AND STANDARDS

The tyre baling industry in the UK reached a level of maturity with the production of a British Standard Publicly Available Specification (PAS) for tyre bales (Anon. 2007). The PAS assists manufacturers in the production of a consistent and traceable product for use in construction and helps to demonstrate the consistency of quality, via a Factory Production Control process, to end users. The PAS 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. Furthermore, the PAS gives guidance to construction professionals on formulating preliminary design and construction proposals. This guidance does not cover detailed design but provides key design information that is not available from other engineering documents. This information includes: the measurement of relevant tyre bale properties; engineering properties and behaviour of tyre bales in construction; example applications for tyre bales in construction; and end of service life disposal options.

The particle size ranges of the ISAC materials are compared with those specified in the Specification of the Portuguese Roads Administration for crushed natural raw materials for pavement construction in Figure 2. The curves of the ISACs do not fit completely within the specified ranges. While correction of the grading would be feasible, embankment trials have shown good performance during compaction and good mechanical behaviour, for both source materials (Gomes Correia et al. 2012).

The CBR values are substantially higher than the values specified in the Specification of the Portuguese Road Administration for natural aggregates. The swelling properties, only available for Seixal ISAC, was 1.5% (volume) lower than the maximum value (5%) of class V5 specified in the European standard EN 13242 (2002). Furthermore, the other physical and mechanical properties have better performance values than the standard unbound granular materials for roads (Res Ferreira, 2010). The leachability data for Maia ISAC (data for Seixal

ISAC is not available) show that all elements present have lower values, sometimes significantly lower, than the leaching limit values required by the Portuguese legislation for waste admissible in inert waste landfills. The complete leaching values can be found in Roque et al. 2010. Therefore ISACs, from a leachability point of view, were waste admissible for inert waste landfills and have been approved by the Portuguese Environment Agency for recycling in civil engineering works.

5 COSTS

The total cost of any given construction work is determined by the unit prices 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 total cost.

The cost of tyre bales is broadly similar to other typical road foundation materials such as Type 1 Sub-Base (Anon., Undated) (Winter et al. 2006):

- 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).

The price for the transport of Type 1 may be somewhat less than for tyre bales due to the substantial network for the supply of the former (Winter 2002). The construction process for tyre bales is very different to that for conventional materials. Conventional materials are usually compacted in-situ require significant labour and plant time. Tyre bales are simply placed and the voids between them 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 (Zornberg et al. 2005) indicate that the cost of storing, protecting and handling tyre bales at site, including placement, is around US$0.80/m3 (around £0.53/m3). These estimates 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 above supports the view that the cost of tyre bale fill is around half that of conventional fill. Even when low cost fill is used, savings from the simple methods of constructing with tyre bales more than compensate. Other cost comparisons (Anon. 1998; 2001) report substantial cost savings with the use of tyre bales in the foundations of roads over soft ground. Higher costs for constructing a road with tyre bales over very soft ground have been reported (Anon. 2003). However, it was acknowledged that success using conventional construction was unlikely, and the project was unlikely to have gone ahead without the availability of tyre bales as the use of other lightweight materials would have been prohibitively costly.

In obtaining cost comparisons for tyre bales compared with conventional materials it is essential that all elements of cost (i.e. materials, plant and labour) are considered. In such circumstances it is probable that the cost of tyre bale construction will be much lower than 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. In addition, the process of tyre bale manufacture consumes around 1/16 of the energy required to shred a similar mass of tyres (Winter et al. 2006).

The material costs of ISACs in Portugal are similar to those for natural aggregates, and the total costs are conditioned by the transport costs (Gomes Correia et al., 2012). In a case study described by those authors the total costs of a cubic meter placed in situ of well graded aggregate, of a rejected aggregate mixture from a limestone quarry, and of ISAC were €11.28, €8.81 and €7.77, respectively. The differences were mainly due to the transport costs.

6 SUCCESSFUL APPLICATIONS

Successful applications for tyre bales include as road foundations in both the USA (New York State) and the UK (Winter et al. 2005) (Figure 3). Winter et al. (2006) include applications such as 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 bale applications is available (Simm et al. 2005; Anon. 2007; Winter et al. 2007) and a wide-ranging series of case studies has been described (Winter et al. 2005). Details of their use in slope failure repair are given by Prikryl et al. (2005) and Winter et al. (2009).

A methodological approach was taken to the promotion of the use of Portuguese electrical arc furnace steel slag. A large laboratory research programme was carried out which addressed four elements of geotechnical and geoenvironmental behaviour: ultimate strength under monotonic loading, resilient behaviour (stiffness), susceptibility to the increment build-up of permanent deformation due to repeated loading, and leachability. The use of these tests and their associated results represent a significant departure from the empirical tests detailed in the national specifications for embankments and structural layers of transport infrastructure. It was concluded that performance laboratory tests give a much better picture of material performance than do those from empirical tests (Los Angeles (LA) and micro-Deval (MDe)), as shown in Figure 4a and 4b. In addition, this material when compared with results of mechanical tests of natural unbound granular materials used in road construction demonstrates better mechanical performance (Figure 4c). Leaching test results show that this by-product is inert and the title "Inert Steel Aggregates for Construction (ISAC)" was adopted.

These laboratory conclusions were validated in a full-scale trial using end performance testing (devices which measure in-situ stiffness by spot tests and by continuous monitoring, as well as leaching values measured with lysimeters). This field trial (integrated into a Portuguese national road, at km 13+600 of National Highway EN 311) involved three different sections:

- GA+Soil: only natural materials were used (in the embankment, capping and base layers of the pavement).
- ISAC+ISAC: only ISAC was used (in the embankment, capping and base layers of the pavement).
- ISAC+Soil: granitic residual soil was used, in the embankment and the capping layers of the pavement, and ISAC was used in the base layer.

Figure 4 (d) shows relevant results of field tests obtained by FWD tests (Figure 5) with three different load levels: 20kN, 30kN and 47kN. It can be observed from the maximum deflections presented as a function of the applied load demonstrate that the sections with ISAC (ISAC+ISAC and ISAC+Soil) perform better than the section comprising only natural materials (granite aggregate and soil, GA+Soil). These sections were monitored for 28 months and demonstrated some improvement in stiffness throughout that period (Gomes Correia et al. 2012). After around ten years after construction the pavement demonstrates very good performance (Fortunato et al. 2018).

Successful applications of ISAC, include a road construction project carried out recently in Portugal, near Lisbon, named "EN10 - Nó Desnivelado da Quinta do Conde" in a competitive tender with a natural virgin aggregate for the sub-base layer (Gomes Correia et al. 2012). Two other applications were the construction of the embankment of the railway branch of REFER – Rede Ferroviária Nacional (Portuguese Railway Company) that connects the Seixal ISC to the national railway network,in Coina (South of Lisbon), and the construction of drainage layers at Bessa Século XXI Stadium, in Portugal, made by the Global Stadium-ACA contractor, using 10,000 tonnes of ISAC.

Figure 3. Completed construction: CR342, May 2004 after four years in service in New York State (left); B871 in Highland, UK, subject to heavy logging trucks (right, photograph courtesy Garry Smith, Highland Council)

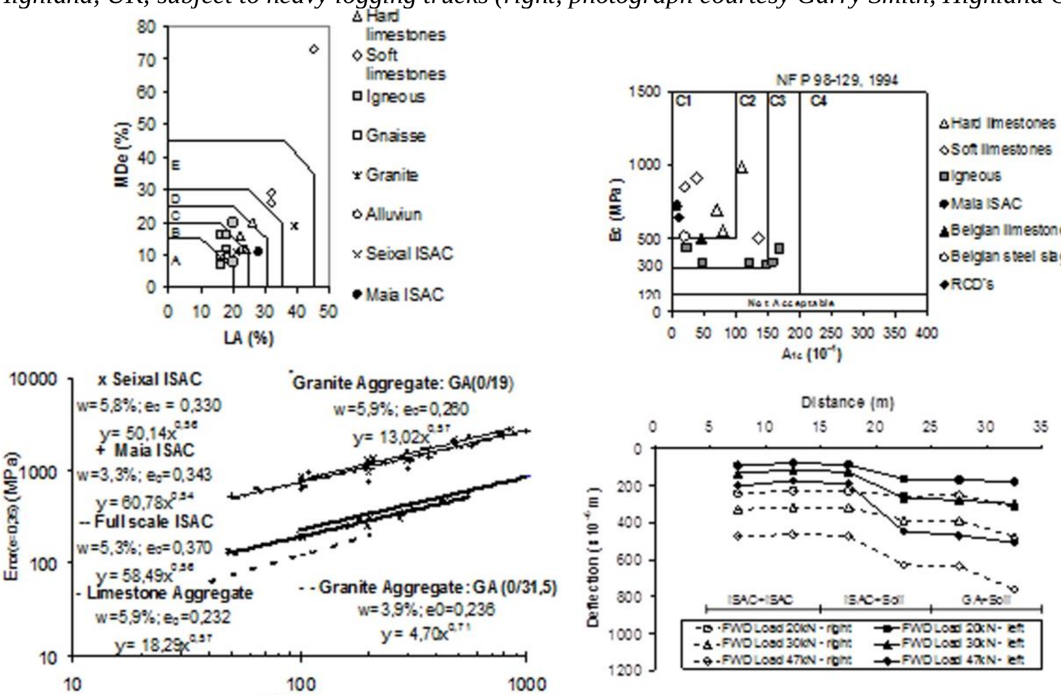

Figure 4. Comparisons of empirical tests (a, top left) versus performance based tests (b, top right) of laboratory test results; Comparison between ISAC and raw aggregates performance, in laboratory by precision triaxial tests (c, bottom left) and in the field by FWD tests (d, bottom right)

Figure 5. FWD tests: during operation (left); detail of the plate on ISAC base layer (right)

7 DEVELOPING SUSTAINABLE RECYCLING MARKETS AND BUSINESSES

Recycling businesses that form to exploit new products and systems manufactured from waste materials can often develop very slowly. Unlike the conventional alternatives there is often not an established manufacturing and distribution infrastructure. This is needed in order to develop the markets for the products, but the markets are needed to justify the investment in the infrastructure. Such businesses and market thus often develop in a highly incremental manner.

Typically, the introduction of a new material to the construction market follows the sequential stages set-out in Figure 6. First applications are often undertaken with little civil or geotechnical engineering input. However, where these are successful, and the beneficial properties and cost advantages of the materials are clear these will often lead to the involvement of professionals and to research, development and demonstration projects. Again, if these are successful, there may be an opportunity to develop standards and specifications that conform to national requirements. At this point large civil engineering contractors may begin to take an interest in the product. Indeed, this mirrors the first authors experience as Balfour Beatty opted to use tyre bales in the construction of a major English strategic road, the A421 that links the critical A1(M) and the M1 north-south corridors.

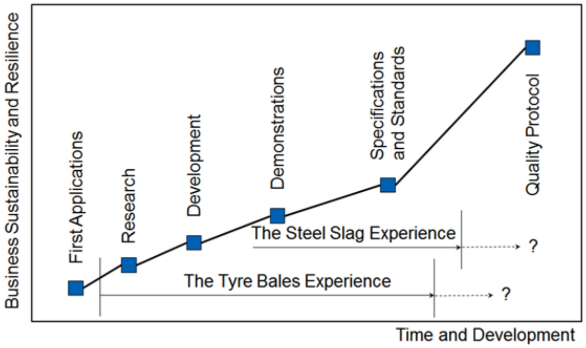

Figure 6. The development of business based on the production and sale of a new product based on re-used, recycled or recovered waste materials

During this period the interest in using the product can be significant, but the experience in the UK is that actual take-up is limited by the necessity of contractors operating within the framework of the waste management regulations. For those materials that have been removed from the waste stream at the point of production (e.g. recycled aggregates in the UK) by means of the application of a Quality Protocol the uptake in use has been significant as indicated in Figure 6. It is important to note that a Quality Protocol and the associated conformance is a rigorous regulatory process with a specification based upon a Factory

Production Protocol lying at its heart. Even though a standard or specification, such as PAS 108 (Anon., 2007) may also have a Factory Production Protocol at its heart a Quality Protocol is still needed in order to remove the product from the waste stream at the point of production.

As yet a Quality Protocol is not available for tyre bales in the UK or for ISACs in Portugal. It is clear that in both cases that this not only limits the use of the materials in appropriate and beneficial applications but that, at least in the case of tyre bales, it makes it difficult to regulate the nascent industry and to ensure a quality product. In this environment it is difficult for legitimate businesses to develop into sustainable entities that have a suitable degree of resilience.

8 SUMMARY AND CONCLUSIONS

One way in which the construction industry can make a positive contribution to society's legitimate demands for a more sustainable future is in the increased use of reused, recycled and recovered waste products. In this paper the technical benefits of tyre bales, which are both lightweight and relatively free-draining, and of Inert Steel Aggregate for Construction (ISAC), which confers high strength and stiffness, are discussed alongside the development of the markets for the products in the UK and Portugal, respectively. Each product has been demonstrated to be an effective addition to the available materials in the construction sector.

It seems clear that the development of such industries and their associated markets are relatively slow. Initial applications may lead to research, development and demonstration projects. These may, in turn, lead to sufficient interest being generated for the development of specifications and standards to be developed. While this development may lead to significant interest from major players in the construction business, experience suggests that this will be ultimately limited by the fact that the materials are still considered by environmental regulators to be a waste and are thus subject to the relevant regulations. These regulations can impose a significant cost and risk burden on constructors.

Where materials have been removed from the waste stream at the point of production by the introduction of a Quality Protocol underpinned by a Factory Production Protocol, as is the case for recycled aggregates in the UK, their use increases significantly. It is concluded that the lack of a Quality Protocol is likely to further impede their use.

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