FEASIBILITY OF USING SHREDDED TYRES AS A DRAINAGE MATERIAL IN GEOTECHNICAL APPLICATIONS

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ABSTRACT

Worldwide there are at least 1.6 billion scrap tyres produced each year. Of these Britain is responsible for 50 million, equating to an annual production of 700,000 tonnes of waste. Tyres have traditionally been disposed of in landfill sites and illegal dumping has caused problems. As a result many countries have implemented legislation and set objectives to reduce, and in some cases eliminate, the dumping and land-filling of waste tyres, EU legislation bans the disposal of whole tyres in landfill this month, and that of shredded tyres by 2006.

To meet these requirements alternative uses of scrap tyres must be developed. Currently the most common of these are re-treading, burning for electricity generation/incineration in cement kilns and for surfacing for sports arenas and play areas. In the construction industry the tyres are shredded and used as lightweight fill, landfill drainage layers and as an alternative to aggregate in concrete and road pavements. Another option is to use the shredded tyres as a drainage material.

Shredded tyres are a lightweight material which can be graded to suit requirements, are free-draining and very permeable. Under load the shredded tyres behave in an elastic manner and are highly compressible. Shear strength parameters are similar to those of a granular soil. Permeability reduces when loaded but remains higher than that of many other granular drainage materials. In light of these findings it is considered that shredded tyres could be used as a drainage material in many types of construction project and could in some circumstances be a viable alternative to aggregates or geotextiles. There are at present certain cases where traditional drainage materials are better to use but with further research to thoroughly establish the properties and behaviour of this new material, shredded tyres could be used with greater confidence in a widespread range of drainage applications.

Keywords: Drainage Materials, Recycled Materials, Tyres, Sustainability.

1 INTRODUCTION

Each year in Britain there are 50 million tyres discarded, in the past these tyres were simply sent to landfill sites or were dumped in vast tyre stockpiles. The practice of disposing of tyres to landfill sites will be banned when the EC Landfill Directive 1999/31/EC comes into force. It states that both whole and shredded tyres are to be classified as a banned waste which must no longer be land filled. These regulations take effect this month for whole tyres and July 2006 for shredded tyres. A major consequence of the new legislation is the pressure to find alternative uses for waste tyres, in order to prevent the previously land filled tyres being illegally dumped across the countryside or adding to the already large stockpiles.

At present tyres are re-treaded, incinerated to produce electricity and shredded to be used in athletic tracks and playground surfacing. More innovative, larger scale uses are also being developed such as use in coastal defence schemes, creation of artificial off-shore reefs, as aggregate/fill alternatives for geotechnical works, as an addition to concrete to produce a lighter weight material and in asphalt roads to reduce noise.

Using the tyre shreds as a drainage material is another possible option for tyre re-use that is being considered. Should laboratory testing and field trials find that the properties of the tyres make them a viable option for use as a drainage material then they can be compared to the alternative materials, aggregates and geotextiles on the basis of cost, availability, ease of construction etc.

This paper reviews the issues associated with tyre recycling in civil engineering applications, and investigates the feasibility of using shredded tyres as a drainage material in geotechnical projects. It discusses some potential uses for tyres that are being considered for such application and coupled with results of some laboratory tests on recycled tyre shreds compares the properties of tyre shreds with conventional graded drainage aggregate. It concludes there are many applications where shredded tyres could replace quarried selected aggregates if careful consideration of the properties of the material are considered.

2 THE NEED FOR TYRE REUSE

The 50 million scrap tyres produced annually in the UK equates to approximately 700,000 tonnes of waste [1]. This amount is likely to increase as car usage increases, the number of vehicles on the road rises and tread depth regulations become stricter [2]. Until recently it was common practice for tyres that were unsuitable for vehicle use to be sent to landfill or to be stored in stockpiles/unlicensed dumps [3]. These tyre dumps are an environmental problem as they are a breeding ground for bacteria, can be prone to self-combustion, and form a very obvious eyesore (Figure 1).

Figure 1 – Tyre stockpiles [1]

In 1991 the EC identified scrap tyres as one of the first projects under its “priority waste streams” initiative [4]. Numerous targets were set to be achieved by 2000 involving the disposal, recovery, re-use or extension of the life of tyres to reduce their disposal to landfill. Subsequently the Landfill Directive 1999/31/EC was introduced [5]. Its aim is to prevent or minimise the negative effects of land filling waste on the environment and hence human health [4]. The directive requires that certain wastes will be banned from landfill, including whole tyres (prohibited from July 2003) and shredded tyres by 2006. This legislation has prompted a significant change in the way in which used tyres are/can be disposed. The reported proportion for current end use of scrap tyres varies between different sources of information [1, 3, 4, 6] but generally the end use of tyres has been as shown in Figure 2.

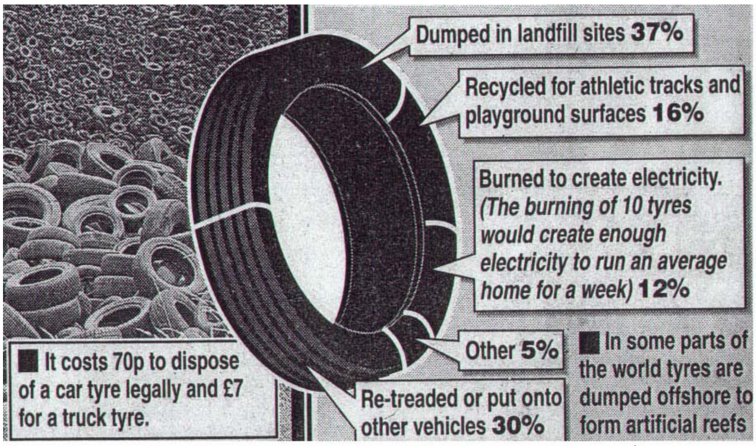


Figure 2 – Waste tyre disposal and re-use [1]

However, the re-use of scrap tyres must increase significantly as both the current and future environmental and waste management legislation has effect. Large quantities of tyres are currently incinerated to provide energy for electricity production, and burnt in kilns for cement manufacture [6], tyres are classified as a renewable energy resource [3], however careful treatment of the combustion products is required, and the sustainability and efficiency of this use is open to debate.

3 TYRES CONSTITUANTS AND SHREDDING

Tyres are made of vulcanised rubber that contains reinforcing fibre, high strength steel belts and a high strength steel reinforcing bead [4, 7]. There is also a large amount of chemicals in the tyre that are added to aid the manufacture and improve the properties of the rubber to make it better suited for use in tyres. Typical material proportions are vulcanised rubber (60%, usually Styrene Butadiene rubber (SBR)). Carbon black, (30%, added to strengthen and add abrasion resistance to the tyre), sulphur (3%, hardens the rubber to prevent high temperature deformation), extender oil, (5%, added to aid manufacture to make the rubber more workable), zinc oxide, (1%, aids the vulcanisation process and enhance the final physical properties of the rubber). Finally there are other chemicals (1%) that act as fillers, accelerators and processing aids in manufacture process [4, 7].

In the past ten years steel braced radial tyres have been produced with improved strength and durability. Although these tyres have benefits whilst on the vehicle they are vastly more difficult and more costly to shred for reuse than tyres made entirely from rubber or rubber with fibre reinforcing [3].

Tyres can be shredded to a number of sizes varying from ground rubber (425µm - 2mm) to rough shreds (50mm – 300mm) [8]. Shred size depends on the machinery used, the client's specifications and the intended end use. All the chips/granules/shreds produced are usually irregularly shaped and the larger, rougher shreds can contain remnants of steel and textile reinforcing fibres [8, 9, 10, 11]. Obviously energy and cost is associated with the shredding process and generally the smaller the particle generated the higher the cost of production [10].

4 TYRE SHRED PROPERTIES AND USES

Numerous authors report data on the testing of tyre shreds, in summary the results of past tests have shown that tyres are a lightweight material, are very compressible, exhibit elastic behaviour under load, have a degree of "conjectured cohesion" and have an angle of friction between 20° – 45°. They are found to be unaffected by water content, are very permeable and free draining, with permeability reducing only slightly when compacted. When used as part of a soil-tyre fill mix an increased percentage of tyre shreds was found to decrease the weight and CBR of the fill but increase the frost resistance. The effects of tyre shreds on the shear strength of fill were found to vary depending on the percentage of shreds, the orientation and size of the shreds and the soil making up the majority of the fill [8, 12, 13, 14, 15]. Hence they have a number of properties that are useful in the built environment.

Consequently scrap tyres are increasingly being re-used and recycled in a variety of built environment projects. An example of a smaller scale use of tyre shreds is their use in play area and sports arena surfacing [10]. However, the largest potential for tyre re-use exists in the heavy construction industry where shredded tyres can be, and have been, used as a lightweight fill in embankments and behind retaining walls [15], and as an aggregate alternative in concrete mixes, asphalt roads and filter drains [17] as well as a permeable draining layer in landfill sites.

Drainage of soil is a vital part in many construction and geotechnical projects as un-drained and poorly drained soils are often one of the main causes of earthwork failures [16]. Granular materials are often used as a drainage material to aid water flow from less permeable clays and silts. The characteristics of a drainage material will vary depending on the specific application but generally the material must be more permeable than the surrounding soil, be sized to resist clogging from fine silt/clay particles, be non-polluting and retain permeability both under load and throughout its design life, clearly shredded tyres possess these properties to some degree.

If shredded tyres are to be used as a drainage material to replace conventional materials in construction projects, in the short term, until wide experience of their use and suitability is gained they must comply with the relevant standards and specifications for existing materials and/or be proven to be suitable through laboratory testing or monitored trial sites [15]. The main criteria for materials used in drainage systems are the filtration and permeability requirements, these are usually derived based on the particle size of the material. Since tyres can be shredded, granulated or ground to produce sizes from 425μm to 150mm [10] obtaining a suitable grading that suits the permeability and filter design is possible. Tyre shreds could also be batched in the proportions required to make up gradings to match those of standard graded drainage materials (such as Type A, Type B or 6F material, as specified by the UK Highways Agency for drainage material/fill [17]), however, consideration of the strength and durability of any replacement material must also be made.

5 LABORATORY TESTING

To assess the suitability of tyres as drainage media a short series of laboratory tests were performed on graded tyre shreds to assess some basic properties of the tyre shreds such as compaction characteristics, shear strength, density and particle density. From the test results and in conjunction with published literature, outline consideration has been made of the suitability of tyre shreds for use as a replacement standard drainage fill material, and comparisons to traditional drainage media such as aggregates and geotextiles has been drawn. The planned tests were California Bearing Ratio (CBR), Particle Density, Proctor/Compaction tests (Figure 3) and Shear box testing (300mm) (Figures 4, 5 and 6). All tests were to be carried out to BS1377:1990 [18] and the tyre shreds for testing were provided by Charles Lawrence Recycling, Newark [10].

To allow the properties of tyre shreds to be compared to those of aggregates it was decided to make up 3 samples of tyre shreds to match standard UK drainage materials. Mix 1 and 2 were based on the Highways Specification, Series 500, Table 5/5 - Criteria for filter drain backfill Type A (Table 1). Replicating exactly the mix make-up of a Type A or Type B aggregate was not possible due to the lack of both very fine tyre shreds (less than 1.18mm) and larger tyre shreds (retained on a 37.5mm sieve). Therefore the mixes made up were a fine and coarse version of the Type A grading and a third mix of shreds that were larger than 10mm (Table 1).

Table 1 – Grading of Mixes Used in Tests

Sieve Size (mm)	HA Type A Aggregate	Fine Type A	Coarse Type A	14mm- 0mm
63				
37.5	100			
20	85 – 100		100	100
10	50 – 100	100	50	0
5	35 - 90	75	10	
1.18	15 - 50	0	0	
0.6	5 - 35			
0.15	0 - 5			

This final grading was used to investigate the characteristics of a single sized material of larger shreds, since it is cheaper to shred to only 14mm rather than to smaller sizes, and this could be a more economical option than the fine Type A mix and would therefore be preferable to use if it had suitable properties.

6 TEST RESULTS AND OBSERVATIONS

Tyre shreds were found to be a lightweight, highly compressible material which behaved elastically under load. The smaller tyre shreds (passing a 10mm sieve) were found to be regularly shaped, the larger material tended to be more irregular in shape with particles ranging from long, thin shreds to more angular chunks of rubber. Some of the larger shreds (>10mm) were observed to contain small remnants of steel reinforcing wires and fibre reinforcement, smaller shreds appeared to be pure rubber with no steel or fibres present.

Density was not found to be affected by water content, the compaction curves of the Proctor test (Figure 3) are observed to be reasonably flat, although this is comparable to many graded aggregates. Increased compactive effort did increase the density of the samples (Figure 3) but again the improvement was not as great as would be expected for soil. The highest compression and hence density of tyre shreds was obtained during the sustained application of a large (150kPa) normal stress in the shear box tests. In all cases even under load in the shear box (both when in loose and compacted states), the density of the tyre shreds and thus their unit weight was found to be at least half that of a typical soil (approximately 5KN/m^3 loose and 7kN/m^3 compacted).

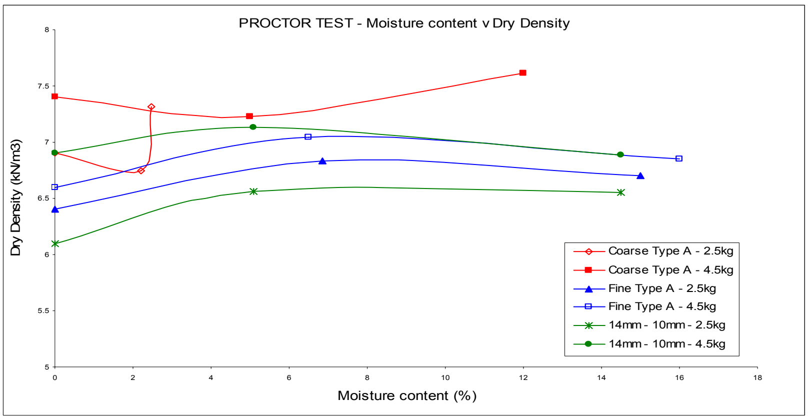
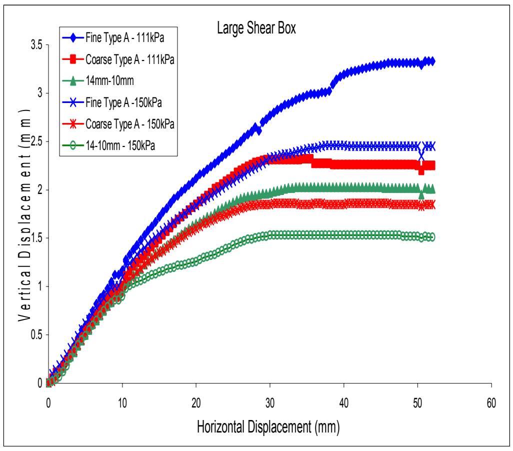


Figure 3 – Proctor Test Results

Under normal stress the samples compressed by 20%-25%, most of the compression was observed to be immediate. The voids ratio of the tyre mixes, (on average a value of 1 for the loose samples), reduced by 50% when a normal stress was applied [19]. There was no defined "peak" stress or dilatency observed in the shear box tests (Figures 4 and 5) and the samples rebounded when the normal stress was removed. The shear strength parameters of the tyre shreds were found to be φ' = 26° - 31° and the c' = 0kN/m^2 - 7kN/m^2 (Figure 6). The standard tests used on aggregates and soils, such as the CBR test and Proctor test, were not always suitable for testing tyre shreds, due to elasticity and rebound, consequently results from these tests would perhaps be less reliable. However a possible compression test using a CBR mould with a full mould width diameter plunder is an option. The properties requiring testing also differ so some standard tests may be unsuitable or irrelevant to tyres, as was demonstrated by the CBR test. New tests may have to be developed to carry out a more in-depth study of the critical tyre properties such as compressibility, effects of load on tyre shred properties (eg. permeability and shear strength) and environmental impacts (eg. water pollution and flammability).



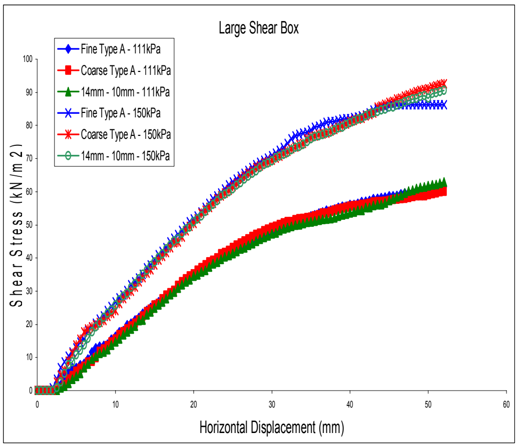


Figure 4 – Horizontal - vertical displacement (normal stress = 110kPa and 150kPa)

Figure 5–Stress - displacement graph (normal stress = 110kPa and 150kPa)

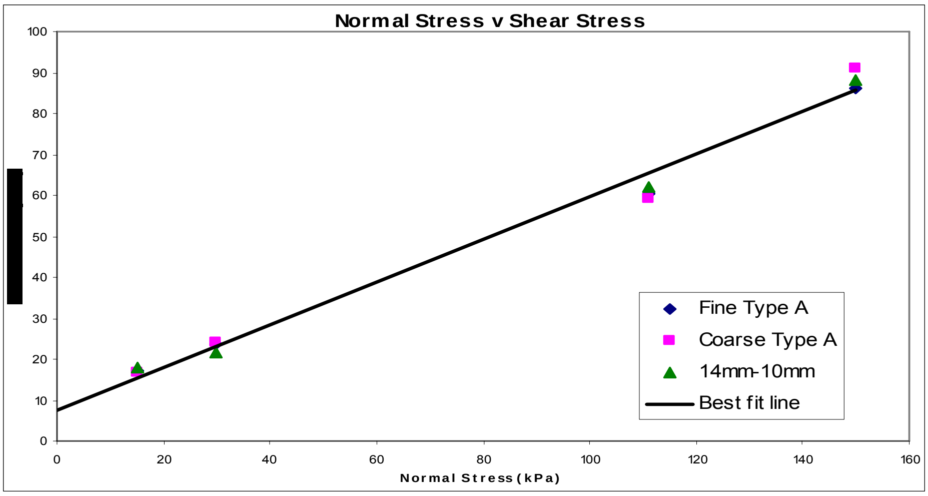


Figure 6 – Normal stress – shear stress results

The tyre shreds were found to have properties which would make them suitable for use as an alternative drainage material. They were free draining, showed no disintegration in water or under loading, and had an angle of shear resistance, φ, of approx. 31°. They differed from aggregates mainly in their compression and rebound behaviour and lighter weight. Between the samples there was very little variation in tested properties. Thus the cheaper, larger chips would be as suitable for use as the more expensive smaller chips. However, the larger chips were noted to contain a greater proportion of remaining steel/textile reinforcement which may raise environmental concerns and as such, affect their use.

7 ARE TYRES SUITABLE FOR A DRAINAGE (FILL) MATERIAL?

Although the tyre shred sizes may meet grading criteria for standard materials the larger tyre shreds have been observed to have a higher metal content which is reported to be a pollution concern[7, 10]. The large particles were noted to be irregular in shape which could lead to unpredictable characteristics, at the other extreme, the finest ground rubber is more expensive to produce so including it in a Type A fill may increase costs.

It has been found both in this project and in the literature that tyre shreds are a very compressible material and experience approx. 20%-25% settlement when loaded. Such high compressibility leads to potential for large and un-even settlements when load is applied. This may make tyre shreds unsuitable for use in cases where limited or uniform settlement is a key part of the design, for example under roads or supporting pipes in filter trenches. However, it is considered most settlement is immediate and long term settlements are almost negligible [8,19]. This means once a load was applied and the tyre fill had compressed little further deformation would be expected. When the load was removed from the tyre shreds it was noted that they underwent elastic recovery and rebounded by 10%[19]. Although this would not affect drainage layers onto which a permanent load was applied, such as embankments, it may be an undesirable characteristic in applications where repeated loading and unloading will occur such as in a drainage layer beneath a porous road pavement. The tyres would settle under a heavy vehicle load and, when it had passed, they would rebound, the resulting movements due to low stiffness could compromise the integrity of the pavement.

Another potential cause of instability, if tyres were used as drainage under porous pavements, is the swelling that occurs when tyres absorb gasoline or petrol [20]. Oil spills and petrol spills draining through from the road surface may cause volume change and the subsequent movements could damage the pavement.

Voids ratio decreases by 50% and porosity reduces by 30% when the tyre shreds are loaded to 111kPa and 150kPa [19]. This reduction in permeability under load must be considered if using tyres under embankments and other heavily loaded circumstances. It would also apply to their use in vertical drains where lateral loads from the surrounding soil could reduce permeability. In non- (live) load bearing cases, such as roadside drains, this aspect of tyre behaviour would not be such a significant concern if allowed for in design.

The shear strength parameters of the tyre shreds investigated in the laboratory testing [19] were found to be φ' = 26° - 31° with a c' value of between 0kN/m^2 and 7kN/m^2. These values are similar to those of granular soils and indicate that the tyre shreds would have sufficient shear strength when loaded. Therefore the inclusion of a tyre shred drainage layer in an earthwork would not threaten the overall stability as it would not create a weak zone.

The design life of tyre shreds in geotechnical projects is uncertain but a proven design life of 120 years is required for permeable backfill to retaining structures [17]. At present this means tyres would be unsuitable. However, the main constituent of the tyre, SBR vulcanised rubber, is an inert, corrosion resistant polymer so the material should be very durable if not subject to chemical ingress, future testing could demonstrate that a design life of 120 years is possible.

Standard materials frequently have a 10% fines value [17] specified to insure stability under load. Observations during the laboratory tests suggest tyre shreds would satisfy this criteria (although it is not perhaps directly applicable). In both the force – penetration tests and the shear box test [19] the tyre shreds were put under high loads which caused compression but no signs of crushing or disintegration. The stress applied in the 10% fines test is greater so there would be more compression but it is thought that the individual tyre shreds would remain intact.

Tyre shreds fit the criteria for backfill to earth retaining structures and in rigid walls their inclusion would benefit the design. As the layer of tyre shreds behind the wall is compressed by the mass earth backfill it mobilises the fill. This allows active pressures to be used in wall design rather than the larger at rest pressures and results in a lighter, more economical retaining wall design [15]. The criteria for landfill drainage [20] are also met by shredded tyres. They are available in the sizes required (75mm) and can be graded if necessary. Although compression occurs under load, permeability has been found to remain high, approx 0.1cm/s[13], and significant loading can be resisted (150kPa tested in shear box) [19]. Placing shredded tyres on a slope is possible since their angle of friction is approximately 30º.

8 ENVIRONMENTAL CONCERNS AND DURABILITY

The concerns regarding tyre shreds causing pollution to groundwater when used in construction projects is well documented and much research has been carried out [3, 7, 8, 12]. The potential for pollution depends largely on the pH of the water and soil surrounding the tyre shreds. When the surrounding conditions are acidic, metals (eg. lead, manganese and iron) are most likely to be leached whilst in basic conditions leaching of hydrocarbons is more common [8]. In these cases the levels of metals or hydrocarbons has been found to exceed recommended allowable limits for drinking water [3]. It may therefore be prudent not to use tyre shreds in acidic or basic conditions and limit their use to projects where free draining, unsaturated, neutral conditions exist. The recommendation that tyres are used in un-saturated zones and above the water table [8] could restrict their use in deep vertical drains extending below groundwater level.

A benefit of using tyre shreds in landfill drainage systems is their ability to absorb paraffin and other hydrocarbons [15, 20]. If these leachates are absorbed by the tyre layer there is a reduced threat of pollution to the surrounding area. Despite shredded tyres fitting the criteria for landfill drainage the EC directive may extend to banning tyres from landfill, even if used as an engineering material. However the long term and structural effects on the tyre shreds of chemical leachates oil spills and anti-freeze in surface run-off from roads should be considered. The leachate criteria specified by the HA [17] for drainage materials refers to sulphates, to prevent sulphate attack of concrete drainage pipes and reduce potential algae blooms at outfalls. Sulphates are not reported to be a leachate from tyre shreds, however consideration of leaching from the tyres must be made, especially iron oxides from remnants of steel reinforcement. A lack of knowledge of this is currently limiting the materials use due to concerns from the Environment Agency.

A major concern with using tyre shreds is the fire hazard they present. Previously cases of burning tyres occurred in fills that were greater than 3m thick, and as a result tyre fill must now not exceed 3m in thickness [8], drainage layers are usually <500mm in depth so comply with this regulation. The combustion temperature of tyres has been put at 322° [15], a level unlikely to be reached in most situations. However the potential for a road accident to lead to fire and this igniting the tyre drain must be considered, the hazard can be reduced by coating the tyre shreds with bitumen, as in the Safedrain material which has been trialed [13].

9 CONCLUSIONS

New legislation is being introduced which has led to research of options for scrap tyre re-use and recycling to avoid the soon to be banned practice of landfillling this material. At present tyres are re-used as fill and aggregate in construction, are burnt for energy production or are used as surfacing in sports arenas. A further use being considered is as a drainage material, replacing standard aggregate, granular soils or geotextiles.

The standard drainage materials presently in use are aggregates, granular soils, such as sands and gravels, and geotextiles, of which numerous specialist products are on the market. If shredded tyres are to be a feasible alternative to use as a drainage material they would have to demonstrate similar or better qualities than the materials already commonly used. The advantages and disadvantages are summarised in table 2.

Table 2 – Advantages and disadvantages of tyres as a drainage material (After Miller 2002[19]).

ADVANTAGES	DISADVANTAGES
• Lightweight, about half the weight of aggregate/granular soils • Adequate strength; φ'=31°, c'=5kN/m^2. • Re-use of a waste material. • Compaction characteristics not affected by moisture. • Resistant to frost penetration. • No crushing under load. • Behind retaining walls active earth pressures are mobilized. • Grading can be batched at plant to suit individual projects.	• Un-tested in comparison with aggregates so properties are not established. Less design certainty. • Rebound on load removal. • Pollution from metal/hydrocarbon leachates. • Fine granules more expensive to produce. • Very compressible – settlement problems. • Reduced permeability under load. • No standards exist for testing tyres or specifying sizes, properties etc. • Larger shreds are irregular shaped and have protruding metal fibres. • Fire risk.

This research has found that there are some situations where tyres would not be suitable as a drainage material and it would be preferable to use the traditional materials. However, for a large number of drainage applications it would be feasible to make use of shredded tyres due to their shear strength, permeability and lightweight nature.

The short series of laboratory testing demonstrated the tyre shreds to have lower unit weight (5-7kN/m^3) than aggregates, an angle of shear resistance of 31° comparable to an aggregate, no disintegration under load, although compressions of up to 25% were noted, and the availability in batches of specified gradings. The tyre chips were observed to be very free-draining throughout the tests.

Shredded tyres have been found to have properties and characteristics which show clear advantages for their use such as situations where weight is critical ie. construction over soft ground. The unit weight is half that of a granular fill so the overall weight of the structure could be reduced. The problem of stone scatter, common in aggregate roadside drains, and its resultant damage to cars is reduced if tyre chips are used whilst the permeability and durability of the drain is retained. Behind rigid retaining walls a compressible tyre shred drainage layer allows a more economical wall design. Finally the tyre shreds can be used in landfill drainage instead of freshly quarried aggregate.

Situations in which the properties of shredded tyres compare less favourably with the alternatives include locations where very fine particles are required in the grading i.e. sand size, sand is probably cheaper than reducing the tyres to such minute granules. If thickness has to be limited, geotextiles have the advantage over tyres. When aesthetics and a natural looking material are required, aggregates will provide a more natural appearance than black tyre shreds.

In summary it is considered that tyres are suitable for use as a drainage material in roadside drains, landfill drainage layers, behind retaining walls and drains/drainage layers in non-load bearing situations. Further research about permeability of tyre shreds when under loads will determine whether the material is suitable for drainage blankets in large embankments or as vertical drains. Cases where tyres would be unsuitable to replace aggregates or geotextiles are as a porous sub-base under porous road pavements, in large embankment dams, any application where the tyres would be below the groundwater table and situations where the groundwater or surrounding soils are especially acidic or basic.

Further research may demonstrate that tyre shreds could be used, with confidence, in a wider range of projects, it is considered this should further develop research to investigate:

- Rowe cell and triaxial permeability tests to investigate permeability of tyre shreds under load and when compressed
- Field tests at sites where tyre shreds are in use to assess the effectiveness of a tyre shred drainage layer
- Monitoring of long-term behaviour to assess durability, corrosion, disintegration etc.

Overall it is considered that tyre shreds are, at present, a feasible drainage material for many types of construction project. In the future as research work investigates more thoroughly the properties and behaviour of this new material, if necessary by the use of modified or alternative tests, shredded tyres will be able to be used with greater confidence as an alternative to traditional drainage materials in an increasingly widespread range of applications.

10 REFERENCES AND BIBLIOGRAPHY

1) Browne A. Tyre mountains pose toxic threat to the countryside. The Times, 27th June 2002. 2) Sibilia V. Tyre recycling in the year 2000: rubber, a valuable raw material. Wastes Management, July 1996.

2) Department of Trade and Industry, Tyre Recycling Factsheet, http://www.dti.gov.uk/sustainability/downloads/tyre.pdf

3) Ogilvie SM. Opportunities and barriers to scrap tyre recycling. AEA Technology, National Environmental Technology Centre, Report No. AEA/CS R1026/C, February 1995.

4) Waste Watch Wasteline. Waste Tyre Solutions. 2002. Available: www.wastewatch.org.uk

5) European Landfill Directive 1999/31/EC. 26th April 1999.

6) Dufton P. Scrap tire disposal into the 21st century. Waste Management Engineering, April 1996

7) O'Shaughnessy V and Garga VK. Tire reinforced earth fill. Part 3: Environmental assessment. Canadian Geotechnical Journal, Volume 37, No. 1, February 2000.

8) ASTM Designation D6270-98. Standard practice for use of scrap tyres in civil engineering applications. American Society for Testing and Materials, 1998.
9) CM Shredders. CM Shredder designed for simplicity and productivity. Waste Management Engineering, April 1996.

10) Charles Lawrence Recycling. Technical information (2002). Charles Lawrence Group, Newark Industrial Estate, 2002.

11) Granutech Saturn Systems. Technical information (2002). Granutech-Saturn Systems, Kingswinford, West Midlands, UK.

12) Bressette T. Used tyre material as an alternate permeable aggregate. Report No. FHWA/CA/TL-84/07, Office of Transportation Laboratory, California Department of Transportation, Sacramento, CA, 1984.

13) Carswell J and Jenkins EJ. Re-use of scrap tyres in highway drainage. TRL Report 200 (0968-4107), HMS0 1996.

14) Edil TB and Bosscher PJ. Engineering properties of tire chips and soil mixtures. Geotechnical testing journal, Vol 17, No. 4, December 1994.

15) Humphrey DN. Civil Engineering Applications of Tire Shreds, Tire Industry Conference, South Carolina, March 1999.

16) Craig R.F, Soil Mechanics, 5th Edition, Chapman and Hall 1992.

17) Department of Transport. Specification for highway works, Volume 1, May 2001.

18) British Standards, Methods of test of soils for civil engineering purposes. BS 1377:1990, BSI, London, 1990.

19)Miller CC. Feasibility of using shredded tyres as a drainage material in geotechnical projects, MSc Thesis, Nottingham Trent University 2002.

20) Al-Tabbaa A, Cogswell CA, Al-Tabbaa A. Geoenvironmental applications for permeable sand-shredded tyre mixtures. International symposium on physical modelling and testing in environmental geodetics, La Baule, France, 2000.