Sustainable Re-use of Tyres in Port, Coastal and River Engineering

Guidance for planning, implementation and maintenance

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Cover picture: Reconstruction of the flood defence embankment on Branston Island on the River Witham near Lincoln. (Courtesy of the Environment Agency)

Summary

Sustainable Re-use of Tyres in Port, Coastal and River Engineering

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December 2004

HR Wallingford led this study on the potential re-use of tyres in coastal and river engineering which was funded by DTI/EA and a range of other funders. Work was prompted by a European-wide ban, in the summer of 2003, on the disposal of whole tyres to landfill sites and builds on earlier work at Southampton University and at TRL-VIRIDIS. Research identified a wide range of potential uses, especially when tyres are compressed and bound in bales of about 100.

A key aspect of the study was to address the full range of issues arising from the potential use of tyres in engineering works and in the water environment. Pilot schemes in coastal and river sites were used to demonstrate the suitability of tyres to different applications, and sites were monitored for physical movement, stability and chemical leaching.

Research has culminated in this guidance manual to inform civil engineers about the appropriate use of tyres (particularly tyre bales) in river and coastal engineering. The manual gives engineering reasons as to why tyres might be used compared to other materials, along with economic, social and environmental benefits of doing so. An introduction to tyre properties, reprocessing and re-use is given as well as the specific properties, production and use of tyre bales as established through the work of this project. Case examples are provided of the use of whole tyres, tyre bales and tyre treads in port, coastal and river engineering applications. The durability, monitoring and maintenance of structures utilising tyres is also discussed and an environmental impact and risk assessment provided.

The results of pilot studies have been complemented by laboratory testing of bales at both prototype and model scale and by collation of information from industry and environmental protection and waste management.

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This manual was prepared by HR Wallingford (HR) and was published on behalf of the Department of Trade and Industry (DTI) and the Environment Agency. The views and information presented in the guide are those of HR Wallingford and while they reflect the views of the advisory committee they are not necessarily those of the funding organisations. The project was managed by Jonathan Simm of HR Wallingford.

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HR Wallingford carries out advanced research, consultancy and software development relating to civil engineering hydraulics and the water environment. Established in 1947 as a Government research centre, it is now an independent not-for-profit company employing over 200 engineers, scientists, mathematicians and support staff. HR Wallingford is concerned with all aspects of water management and engineering in catchments, rivers, estuaries, coasts and offshore. It carries out predictive physical and computational model studies, desk studies and field data collection backed by large-scale laboratory research and the development of advanced computer simulation technology.

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Glossary

Aggregate	Granular material used in construction. Aggregate may be natural, manufactured or recycled.
Alternative materials	Materials, such as recycled and secondary aggregates, that are not normally considered as traditional construction materials.
Aquifer	A deposit or rock containing water that can be used to supply wells.
Armour	Outer protective layer of a sea or river defence usually made of ‘armour units’.
Armour stone	Large quarried stone used as primary protection against wave attack.
Armour units	Large quarried stone or specially shaped concrete blocks used as primary protection against wave action.
Bale (tyre)	Tyres which are compressed and secured.
Beach recharge (or renourishment)	Supplementing the natural volume of sediment on a beach, using imported material (also referred to as beach nourishment/feeding).
Bead	The part of a tyre that is made of high tensile steel wires wrapped in woven textile which are held to the plies, anchoring the part of the tyre which is shaped to fit the rim.
Benzothiazole	an organic compound containing sulphur produced from accelerators used in the manufacture of tyres. For more information see: http://www.osha.gov/dts/chemicalsampling/data/CH_220335.html
Breakwater	A massive wall built out into the sea to protect a shore or harbour from the force of the waves.
Chips	Mechanically fragmented, ripped or torn post-consumer tyres resulting in irregularly shaped post-consumer tyre pieces of approximately 10mm to 50mm in size.
Civil engineering applications	the use of whole, shredded or granulated tyres in construction projects, e.g. porous asphalt.
Cladoceran	a tiny freshwater crustacean.
Clay	A grain whose diameter is less than 4μm.
Controlled waters	Virtually all fresh and saline natural waters out to the offshore territorial limit, including: rivers and streams, canals, relevant lakes and ponds, certain reservoirs, estuaries and coastal waters, and groundwaters.
Copepod	tiny marine or freshwater crustacean that lives among plankton and is an important food source for many fish.
Core	Material within the defence structure protected by the outer armour or cover layer.
D_{50}	Particle size corresponding to 50% of the material.
Dead Weight Tonnage	A measure of carrying capacity or size of a vessel equal to the weight of cargo and supplies that can be supported. Measured in tons of 2,240 pounds.

Glossary continued

Density	Mass per unit volume of a substance, usually expressed in units of g/cm^3.
Dewatering	The removal of water from the ground or excavations with pumps, wellpoints, or drainage systems to lower the water table.
Dioxin	A particularly toxic class of halogenated aromatic hydrocarbons, the by-product of the bleaching process used in the manufacture of white paper and the manufacture of other chemicals such as the herbicide 'Agent Orange' and from the incomplete incineration of wastes containing chlorine.
Durability	The ability of a material to resist degradation and retain its physical and mechanical properties.
Ecosystem	The plants, animals and micro-organisms that live in a defined space and the physical environment in which they live.
Elastomer	Any material able to resume its original shape when a deforming force is removed.
Embankment	Earth structure, often built for flood protection.
End-of-life tyre	A tyre which has been permanently removed from a vehicle without the possibility of being remounted for further road-use.
Energy recovery	the incineration of tyres (e.g. in cement kilns) principally to extract the fuel or energy value from whole or processed tyres.
Environment	Surroundings in which an organism operates, including air, water, land, natural resources, flora, fauna, humans and their interrelation.
Embodied energy	The quantity of energy required by all of the activities associated with a production process including the acquisition of primary material, transportation, manufacturing and handling.
Epibiota	Organisms that live, usually parasitically, both on the surface and within the body of a host.
Estuary	A semi-enclosed body of water in which seawater is substantially diluted with freshwater entering from land drainage.
Extender	Substance added to glues and resins to dilute them or modify their viscosity.
Gabion	A rectangular (generally) box or mattress made of wire mesh and filled with stone.
Geotextile	A synthetic fabric used as a filter or a separation layer (can be woven or unwoven).
Granulation/ crumbing	the mechanical shearing of rubber to reduce it in size into finely dispersed pieces of under 25mm in any dimension.
Greenhouse gas	Atmospheric gases that absorb UV energy and the radiate it as heat.
Groyne	A structure, generally perpendicular to the shoreline or riverbank, built to control the movement of beach material or arrest erosion.
Fluvial	Occurring in or of a river.

Glossary continued

Flume	A narrow channel through which water flows.
Groundwater	That part of the subsurface water that is in the soil or flows through and around terrestrial crustal rocks.
Heavy metal	Metals whose atomic weights exceed 20 amu.
Hydrocarbons	Organic compounds composed entirely of carbon and hydrogen atoms.
Inert	Unreactive.
Landfill	Low-lying sites or tips being filled up with alternate layers of rubbish and earth.
LC_{50}	The lethal concentration at which a chemical causes the mortality of 50 percent of the test organisms during a specified period of exposure.
Leachate	The liquid generated after a solid is subjected to a leachant.
Lysimeter	packed bed of earth or similar solid material through which water is percolated.
Manufactured aggregate	Aggregate of mineral origin resulting from an industrial process involving thermal or other modification.
Marine pollutant	Any substance introduced into the ocean by humans that alters any natural feature of the marine environment.
Mud	A sedimentary deposit composed of 70 percent or more by mass clay-sized grains.
Municipal	Relating to a town, city, or borough or its local government.
Permeability	The ease with which water will pass into and through the pores in rock, soil, sand or gravel.
Phenol	Any organic compound whose molecules contain one or more hydroxyl groups bound directly to a carbon atom in an aromatic ring.
pH	The negative log of the hydrogen ion activity. Solutions with pH greater than 7 are acidic and those with pH less than 7 are alkaline. A solution is neutral if its pH equals 7.
Photochemical smog	An atmospheric (normally low level) fog caused by the reaction of certain gases such as VOCs, nitrogen oxides and unburnt hydrocarbons in sunlight.
Pollution	The introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems, damage to structures or amenity, or interference with legitimate uses of the environment.
Polynuclear aromatic hydrocarbon	A natural component of petroleum and very potent carcinogen with greatly elevated environmental concentrations because of oil spills, burning of fossil fuels and the use of tars and wood preservatives.
Porosity	Ratio of voids of a material to its total volume.

Glossary continued

Portland Cement	A type of cement (not a brand name) that hardens under water; made by heating clay and crushed chalk or limestone in a kiln and pulverising the result.
Post-consumer tyre	A tyre which has been permanently removed from a vehicle without the possibility of being remounted for further road-use.
Primary Aggregate	Construction aggregates produced from crushed rock, and sand and gravel (land and marine won). These aggregates are subject to the Aggregates Levy.
Primary Materials	Materials extracted from virgin natural reserves.
Pulverised fuel ash	The fine powder removed from the exhaust gases of power stations that burn pulverised coal.
Pyrolysis	Decomposition of rubber by heat in an oxygen free atmosphere into oil, gas, steel and carbon, char.
Recycled Aggregate	Aggregate resulting from the processing of inorganic material previously used in construction.
Resource	A concentration of materials from which extraction of a commodity may be possible.
Reuse	The employment of an article or item once again for its original purpose, or for a different purpose, without prior processing to change its physical or chemical characteristics.
Revetment	One or more layers of stone, concrete or other material used to protect the sloping surface of an embankment, natural coast or shoreline against erosion.
Rip-rap	Widely graded rock armour.
Risk	The chance of an adverse event actually occurring.
Road runoff	The transport of water, solutes, and particles from roads and highways to waterways and the ocean.
Rubberised asphalt	An open-textured asphalt mixture with a very high void percentage made possible by the addition of rubberised bitumen as a binder
Rubble-mound structure	A mound of randomly shaped and randomly placed stone.
Salinity	The grams of inorganic ionic solutes that are present in 1000g of seawater.
Salmonid waters	Waters in which game fish (such as salmon, trout, grayling and whitefish) are found.
Scalpings	Small stones used for drainage in excavations, and as hardcore.
Scour	Erosion of bed or beach material close to a structure due to wave or river action.

Glossary continued

Secondary Aggregates	Construction aggregates produced from by-products of industrial processes (manufactured aggregates) such as metallurgical slags, Pulverised Fuel Ash (PFA,) and Incinerator Bottom Ash (IBA), plus aggregates produced as by-products from other mineral extraction processes such that they do not incur the Aggregates Levy, such as china clay sand, and slate aggregates.
Shingle	Defined as a sediment with particle sizes in the range 2-200mm. Shingle structures may take the form either of spits, barrier islands or cuspate forelands.
Shredding	Any mechanical process by which tyres are fragmented, ripped or torn into irregular pieces of greater than 25mm and less than 300mm in any dimension.
Sidewall	The outermost rubber to which the tread is vulcanised.
Site of Special Scientific Interest (SSSI)	An area of land or water notified under the Wildlife and Countryside Act 1981 (as amended) as being of geological or nature conservation importance, in the opinion of the Countryside Council for Wales, English Nature or Scottish Natural Heritage.
Special Area of Conservation (SAC)	Established under the EC Habitats Directive (92/43/EEC), implemented in the UK by The Conservation (Natural Habitats etc) Regulations 1994 and The Conservation (Natural Habitats etc) (Northern Ireland) Regulations 1995. The sites are significant in habitat type and species, and are considered in greatest need of conservation at a European Level. All UK SACs are based on SSSIs, but may cover several separate but related sites.
Special Protection Area (SPA)	The Directive on Conservation of Wild Birds (79/409/EEC) allows for the designation of areas specifically for bird species to prevent deliberative capture, killing and disturbance of certain endangered species as well as the destruction or damage to eggs and nests. (Designated sites are also subject to the provisions of the Conservation (Natural Habitats etc) Regulations 1994).
Spoil	Soil or rock or other material arising from excavation, dredging, or other ground engineering work.
Substrate	The base upon which an organism lives and grows.
Toe	The lowest part of a coastal or river defence structure or river bank.
Tyre recycling	Any process by which post-consumer tyres or materials derived from post-consumer tyres are converted into useable material.
Under-layer	Granular layer beneath armour or cover layer which may serve as a filter and/or as a separating layer. May be replaced or augmented by a geotextile.
UV, ultraviolet radiation	The form of electromagnetic radiation having wavelengths ranging from 1 to 400nm.
UK waters	These include territorial waters, whose limits extend to 12 nautical miles offshore, and waters to 200 nautical miles offshore within which the UK exercises certain rights and jurisdictions.

Glossary continued

Viscosity	A measure of the ability of fluid to flow.
Volatile Organic Compounds	Low-molecular-weight molecules used as industrial solvents and dry cleaning fluids, refrigerants, flame retardants and aerosol propellants. Most VOCs are carcinogenic.
Vulcanise	To treat rubber with sulphur under heat and pressure to improve elasticity and strength.
Weir	A low dam built across a river to raise the water level, divert the water or control its flow.
Waste	Waste is something that 'the producer or holder discards or intends to or is required to discard' (Waste Management Licensing Regulations 1994). In order for a substance or object to be waste it must fall into one of the categories set out in Part II of Schedule 4 to the Regulations; and • Be discarded or disposed of by the holder; or • Be intended to be discarded or disposed of by the holder; or • Be required to be discarded or disposed of by the holder. (from DoE Circular 11/94).
Whole tyre	An untreated tyre of which the principle parts are the casing, the cord, the bead and the tread which consists of elastomers, carbon black and silica, metal and fabric.
Whole tyre applications	Use of whole tyres without physical or chemical transformation to create such projects as artificial reefs, sound barriers, temporary roads, stabilisation, etc.
Young's Modulus	The ratio of stress to strain, also called modulus of elasticity.

Abbreviations

AAS	Atomic Absorption Spetrometry
AONB	Area of Outstanding Natural Beauty
BAP	Biodiversity Action Plan
BCA	Benefit Cost Analysis
BMAPA	British Marine Aggregate Producers Association
BPEO	Best Practicable Environmental Option
BRE	Building Research Establishment
BS	British Standard
BSI	British Standard Institute
BVSF	British Vehicle Salvage Federation
CADW	Welsh Historic Monuments
CCW	Countryside Council for Wales
CEN	European Standards Committee
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CIRIA	Construction Industry Research and Information Association
COMAH	Control of Major Accidents and Hazards (Regulations)
COPA	Control of Pollution Act
COTC	Certificate of Technical Competence (WAMITAB)
CROW	Countryside and Rights of Way Act
CWA	CEN Workshop Agreement
Defra	Department for Environment, Food and Rural Affairs
DoE	Department of the Environment
DETR	Department of the Environment Transport and the Regions
DTI	Department of Trade and Industry
DWT	Dead weight tonnage
D_{50}	Particle size for which 50% of the material is finer
EA	Environment Agency
EC	European Community
EDTA	Ethylenediaminetetraacetate
EMS	Environmental Management System
EN	English Nature
EPA	Environmental Protection Act
EQS	Environmental Quality Standard
EU	European Union
FEPA	Food and Environmental Protection Act
FRS	Fire Research Station
GTR	Ground Tyre Rubber
HMSO	Her Majesty's Stationary Office
HSE	Health and Safety Executive
Hs	Significant Wave Height
ISO	International Organisation for Standardisation
Loa	Length overall
MCA	Multi Criteria Analysis
MVDA	Motor Vehicle Dismantlers Association
NMED	New Mexico Environment Department
NTDA	National Tyre Distributors Association
NTFSL	National Tidal Facility for Sea Level
ODPM	Office of the Deputy Prime Minister
PAH	Polynuclear aromatic Hydrocarbon
PCDL	Pevensey Coastal Defence Limited
PFA	Pulverised fuel ash

Abbreviations continued

PG	Planning Guidance
PPG	Pollution Prevention Guidance
pH	Acidity/alkalinity
ppt	Parts per thousand
PVC	Polyvinyl chloride
REAS	Rubberised Emulsion Aggregate Slurry
RTT	Reykjavik Truck Tire (fender system)
SAC	Special Area of Conservation
SBR	Styrene-butadiene copolymer
SEPA	Scottish Environmental Protection Agency
SHW	Specification for Highway Works
SNH	Scottish Natural Heritage
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
TRL	Transport Research Laboratory
UK	United Kingdom
USA	United States of America
U.S. EPA	United States Environmental Protection Agency
UTWG	Used Tyre Working Group
UV	Ultra Violet (light)
VOC	Volatile Organic Compound
WAMITAB	Waste Management Industry Training and Advisory Board
WFD	Water Framework Directive
WML	Waste Management Licence
WRAP	Waste and Resources Action Programme

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Appendices

1. Background and use of the manual

1.1 BACKGROUND

The use of whole tyres in port, coastal and river structures has occurred for many years now. There are numerous case studies from around the world, including Australia, the United States and Israel illustrating a wide range of uses and designs such as boat and quayside fenders, floating breakwaters, revetment work and as artificial reefs. As well as developments using whole tyres, technology now exists to produce tyre bales (typically containing approximately 100 tyres with dimensions of 1.5m x 1.25m x 0.75m and weighing around a tonne). These blocks can be built into sea defences and bank protection, potentially opening up new structural applications, although until now relatively little was known about the engineering properties of these tyre bales. This manual presents useful information for many interesting applications of tyres in various forms, derived from the results of laboratory, prototype and scale model tests, and experiences from field trials and case studies.

1.1.1 Construction materials and waste

Construction is the largest consumer of natural resources in the UK. More than 90 percent of the non-energy minerals that are extracted in the UK supply the construction industry. This represents, on average, nearly 300 million tonnes a year (mt/a) of primary materials (Smith, Kersey and Griffiths, 2002), the majority of which (some 214 mt/a) is in the form of aggregates. By 2012 this could mean that an extra 20 mt of aggregates will be needed annually if demand rises by only 1 percent per annum. There is increasing concern about the environmental consequences and the long-term sustainability of utilising aggregate resources on this scale.

The introduction of the Aggregates Levy in April 2002 by the UK Government is an environmental tax on the commercial exploitation of aggregates. Currently, at £1.60 per tonne, the main objectives are to reduce the demand for primary aggregates and encourage the use of alternatives.

In addition to being a major consumer of natural resources, the construction industry is also one of the largest generators of waste in the UK, producing approximately 150 million tonnes of waste per year (Smith, Kersey and Griffiths, 2002). The limited amount of remaining landfill space for disposal together with the implementation of the EU Landfill Directive, prompted the UK Government to introduce the Landfill Tax and a waste strategy in an attempt to secure behavioural changes and meet new waste targets. It is this tax, rather than the aggregates levy, which has largely encouraged the use of alternative materials in construction.

1.1.2 Post consumer tyre waste

With the implementation of the Landfill Directive and the End of Life Vehicle Directive the Tyre Industry faces the challenge of dealing with post-consumer tyres economically and in a sustainable manner. The risk is that with the implementation of the Landfill Directive lack of provision of sufficient reprocessing capacity will cause the rapid increase of illegal dumping and stockpiling of post-consumer tyres.

In 1998, 41% of the post-consumer tyre arisings were not reprocessed but disposed of in landfill, stockpiled or illegally dumped. The high cost of responsible disposal of post-consumer tyres is contributing towards the growth of unregulated tyre disposal (Hird et. al, 2002).

Concentrating on solutions for post-consumer tyres is vital now because of the immediate challenge of the Landfill Directive which banned the disposal of whole tyres to landfill in July 2003 and will also prohibit shredded tyres by July 2006 (though some landfill sites will not have to comply until July 2007). The EU Directive on End of Life Vehicles also specifies targets for increasing reuse and recovery within this waste stream.

During the implementation of the Landfill Directive it is likely that post-consumer tyre arisings will exceed national capacity by 127 - 140kt per annum. By 2006 this amounts to over 500kt of post-consumer tyres (Hird et.al, 2002).

While the UK has had a good record for the recovery of materials and energy from post-consumer tyres, the level of recovery declined from over 70% in 1999 to 63% in 2000. Existing recovery systems have not been adequately supported and new facilities have not been developed swiftly enough.

There are several established markets which will have to absorb those tyres that would have gone to landfill before the new legislation was introduced. If arisings of used tyres do not fall then these markets will either have to expand their consumption or new markets will have to be developed. Table 1.1 gives an indication of the variety of existing applications within the markets in the built environment to which whole tyres or derivatives can be put.

Table 1.1 Representative civil engineering applications of tyres (Shulman, V., ETRA)

Civil engineering (road/non road)	Roads and infrastructure	Sport and safety surfaces
Artificial reefs	Asphalt additives	Equestrian tracks
Bridge abutments	Asphalt rubber	Hockey/soccer pitches
Concrete construction additives	Coatings	Indoor safety flooring
Construction bales	Expansion joints	Playground surfaces
Culvert drainage beds	Road furniture	
Embankments	Sealants	
Insulation	Surfacing	
Landfill drainage layer	Trains and tram rail beds	
Landfill engineering	Wearing course	
Slope stabilisation		
Temporary roads		
Thermal insulation		
Collision barriers		
Light weight fill		
Noise barriers		

1.1.3 Use of tyres in coastal and river engineering

Each year in the UK, Coastal and river engineering schemes consume about 1 million tonnes of amour-stone and about 2 million tonnes of largely sea-won aggregates, worth well in excess of £100 million. This consists almost entirely of primary materials such as marine dredged sand and gravel for beach recharge schemes and high quality rock predominantly from coastal quarries.

With increased occurrence of severe river flooding and the predicted acceleration of sea level rise it is expected that the increase in the demand for materials will be proportionately greater in this sector of civil engineering than for general construction. It is therefore important that coastal and river engineers address their resource usage and reduce this consumption wherever possible.

In the form of tyre bales it may be possible to utilise around an estimated 2 million tyres per annum over the next 5-10 years in port, coastal and river engineering schemes - around a fifth of the total diversion from landfill required.

Although there is continuing demand for large quantities of primary aggregates, the costs are rising due to measures such as the aggregate tax, and, ultimately, the supply of economically accessible primary aggregate is limited. This is increasingly encouraging the consideration of alternative and secondary materials such as used tyres.

Many applications in civil engineering require easily accessible, environmentally sound, inexpensive, lightweight materials that are readily available in large quantities. This is especially true of particular coastal and river schemes, for instance beach replenishment and flood embankment construction. Many materials however, generally only meet three of these four requirements at any one time. Post-consumer tyres can meet all of them concurrently.

1.1.4 This manual

The objective of this project was to explore methods for the reuse of used tyres in port, coastal and river engineering without adverse affect on the environment. The approach was to draw together existing knowledge, experience and research and to carry out pilot implementations which would demonstrate good design and practice and guide future applications.

As awareness of the exceptional properties of tyres has increased among coastal and river designers and engineers, new ways have been sought in which to utilise them in place of more expensive and traditional options. However, detailed and comprehensive technical information is required on the engineering, environmental and regulatory aspects of used tyre reuse if efficient design and controlled implementation is to be achieved.

This manual seeks to provide this information based upon the experiences and scientific knowledge gained not only from past designs and studies but also from hydrodynamic model testing and full scale pilot projects designed to address some of the questions and issues about post-consumer tyre use. This research also built on the recent work undertaken by HR Wallingford on the sustainable use of new and recycled materials in coastal and fluvial engineering (Masters, 2001) and Viridis which examined the use of tyres across a wide range of civil engineering applications (Hird et. al, 2002).

1.2 READERSHIP

This manual has been written primarily for designers and engineers. However it will also be of use to competent and relevant authorities previously unfamiliar in dealing with tyre applications of this nature. Those responsible for considering planning applications, waste management licence applications, construction site consents, health and safety, environmental protection and fire safety will also find valuable information that will help inform decision making processes. There is valuable new information regarding the environmental impacts of using tyres in the ways suggested based upon scientific monitoring, and also, the findings of specially designed and conducted fire safety tests which have defined safeguards governing application and design criteria.

The manual may also be of interest to a wider readership:

- To *environmental organisations*, because used tyres can cause environmental problems if not disposed of or reused properly, and there is the potential to save energy and resources if used tyres replace primary materials in products or construction.
- To *regulators and policy makers*, to assist them in implementing forthcoming legislation, and meet targets for the recovery and use of used tyres. Regulators and policy makers are relying somewhat on the existence of healthy markets for used tyres.
- To *tyre collectors, re-processors and re-users*, who have a commercial interest in supply, demand, the products derived from used tyres, and their commercial use.
- To *end-users of waste tyres and derived products*, who require reliable information on acceptable/potential utility and tyre reuse solutions.
- To *significant clients, customers and suppliers of end-users and their representatives*, who can affect, or be affected by, the market for used tyres and tyre derived products.

One of the reasons why the development of the reuse of tyres in engineering has been hampered in the last few years in the UK is the regulatory system. Post consumer tyres are deemed ‘waste’ until they are incorporated into a new ‘structure’. Thus any construction, treatment or storage site requires a waste management licence to handle scrap tyres in any form or configuration, even when baled. As schemes are often small in scale, the additional time and costs involved can be prohibitive when compared to primary aggregate as an alternative. This manual aims to aid the process of project management utilising tyres by ‘de-mystifying’ this process and by providing prior case example experience and illustration.

1.3 STRUCTURE OF MANUAL

This manual is structured (see Figure 1.1) in what is considered to be a logical layout for specific types of information and guidance likely to be required during the planning, design, construction and maintenance of coastal, port and river structures utilising post-consumer tyres.

Chapter two details general information useful and likely to be required by those responsible for the initial design and planning of any project considering tyre utilisation of this nature including comparisons with traditional materials, required licensing, sourcing, social factors, and environmental and economic costs and benefits.

Chapter three provides some relevant general technical data on tyre materials and products that may be useful to the civil engineer such as density, weight and other physical properties as well as known limitations on use.

Chapter four provides information for the planning and implementation of tyre bale solutions including design issues, production, typical properties and characteristics, and performance trials. Physical parameters of performance of tyre bales, such as hydraulic loads and responses are reported - gathered from full scale and modelled testing. Finally issues of production handling and storage are considered.

Chapter five illustrates and describes the design and construction of specific structure types and uses of tyres, tyre bales and tyre chips in coastal and river engineering, both historical and contemporary. Some suggestions for future innovation in design are also made.

Chapter six identifies the processes and characteristics that should be monitored and assessed at regular intervals to ensure performance and reduce any risk factors.

Chapter seven follows with a detailed look at the environmental issues and recent research conducted on the impact of using tyres and rubber-based tyre derivatives in civil engineering including comprehensive coverage of topics for Environmental Impact and Risk Assessment. This chapter is somewhat out of sequence, given the flow chart in Figure 1.1, but has been placed here because it draws on much of the information provided in earlier chapters.

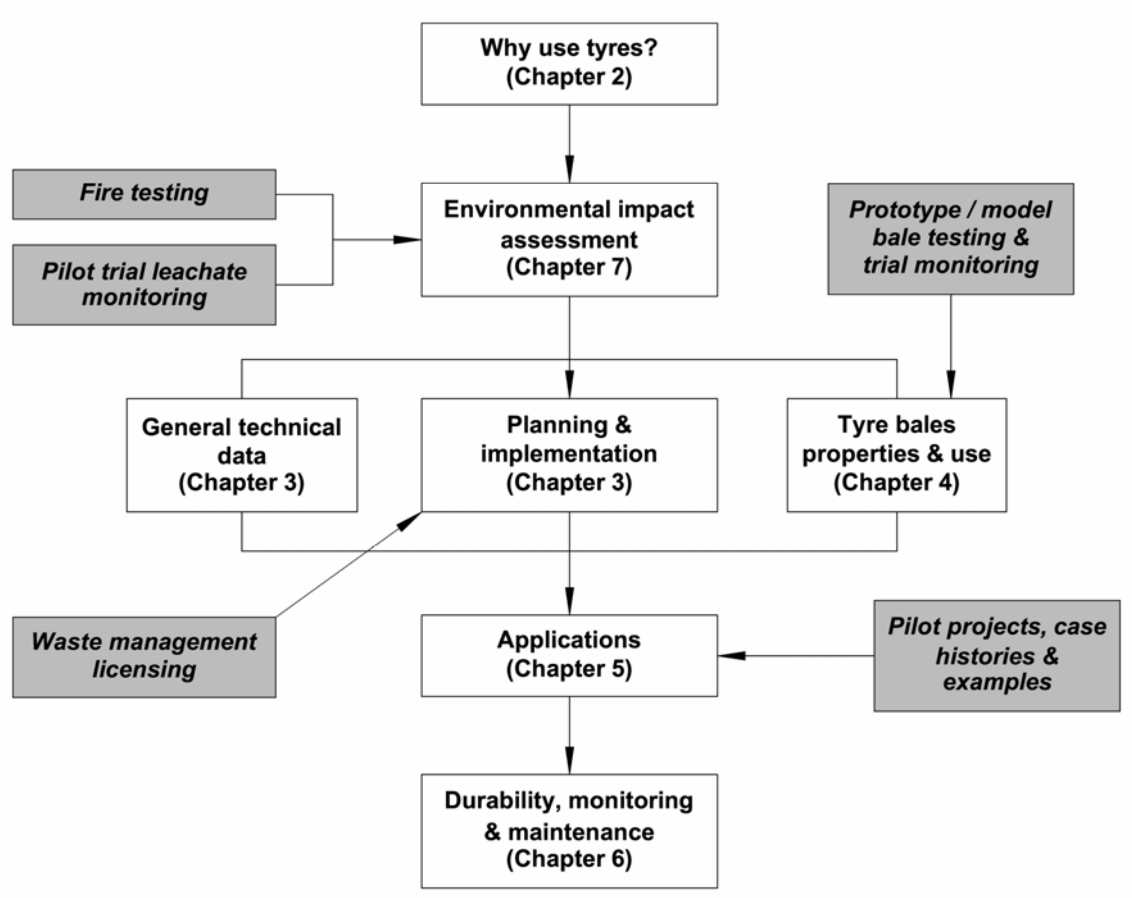

Figure 1.1 Flowchart illustrating the concept of the manual

The appendices provide the detailed background information relating to important aspects of the main report including accounts of the scale model, prototype and laboratory testing - establishing new knowledge on properties and performance, and summaries of the of pilot projects - providing information on the planning, design, construction and monitoring of the structures.

2. *Why use tyres?*

The benefits of using 'waste' tyres in port, coastal and river engineering are three-fold:

a) they can offer distinct engineering benefits over traditional aggregates
b) they can be used as an alternative to primary materials thereby reducing an environmental burden on extraction
c) their use can help to reduce burden of waste disposal (including illegal stockpiling and disposal, such as fly-tipping, with their associated risks) and the impacts on the environment associated with some other uses of tyres.

2.1 COMPARISONS WITH TRADITIONAL MATERIALS

Tyres have the potential to compete equally with traditional materials on technical grounds and can be the preferred option in some circumstances.

Tyres are a useful alternative to traditional aggregate materials for a number of port, coastal and river engineering applications. Tyres may be suitable where:

- they are relatively abundant and easily available
- a lightweight material is required to reduce the density of fill materials, or reduce the load on the original ground surface
- a flexible and durable material is required for long term performance
- there is a need for a free draining alternative to gravel in drainage applications
- the material to be used requires a high resistance to chemical activity
- there is a need for a large surface area such as in artificial reefs for marine organism growth and habitat creation
- there is a need to develop a stable structure (e.g. bales stacked as building blocks)
- they act as an aggregate replacement (e.g. in asphalt or hydraulically bound materials
- a low cost bulk fill material is required.

As explained in Section 2.4, tyres are already abundant and easily available in many locations around the UK and, as the EU bans on disposal options take effect, accessibility is likely to increase.

The physical and chemical properties of tyres or their derivatives determine whether or not they will be suitable for a particular application. These characteristics also permit determination of the most appropriate category of used tyre or derivative for each proposed application

The average weight of a used tyre in the EU is ± 6.5 – 7.0 kg per unit, equivalent to 153.8 per tonne. 80 – 100 whole passenger car tyres constitute 1 cubic metre of shredded, compacted and compressed material which is equivalent to $0.5 g/cm^3$ or $500 kg/m^3$ (Hylands and Shulman, 2004).

Table 2.1 below outlines the weight comparisons with traditional materials illustrating the advantage of the tyre bale where low density and/or low ground load performance specifications need to be met.

Table 2.1 Comparison of tyre bales and traditional materials by weight (Shulman, V., ETRA)

Material	Kg/m^3
Tyre Bale	544
Tyre Chips	640
Tyre Shred	450
Portland Cement (set)	2,931
Wet sand and gravel	1,890-2,506
Dry packed sand and gravel	1,601-1,922
Dry clay and gravel	1,601
Dry packed earth	1,521
Seawater	1,025
Water	1,000
Excavations in water:	961
Sand or gravel	1,041
Sand or gravel in clay	1,281
Clay	1,441
River mud	1,121
Soil	1,041
Stone riprap	

The CEN Workshop Agreement (2002) provides the following comparative table of performance properties for tyre shreds and chips.

Table 2.2 Engineering performance of tyre shred and chips

Properties	Measure
Compacted density	2.3 – 4.8kN/m^3 compared to soil at 15.6 – 19.5kN/m^3
Compacted dry unit weight	1/3 that of soil
Compressibility	3 times more compressible than soil
Density	1/3 to ½ less dense than granular fill
Durability	Non-biodegradable
Earth pressure	Low compared to soil or sand, up to 50% less
Friction characteristics	Higher compared to soil
Horizontal stress	On weak base: lower than with conventional backfill
Modulus in elastic range	1/10 of sand
Permeability	Greater than 10cm/s
Poisson's ratio	0.2 – 0.3 corresponding to K_0 values of 0.3 - 0.4
Specific gravity	± 1.14 – 1.27 compared to soil at 2.20 – 2.80
Thermal insulation	8 times more effective than gravel
Unit weight	Half the typical unit weight of gravel
Vertical stress	On weak base : smaller than granular backfill

2.2 ENVIRONMENTAL BENEFITS

Our dependence on tyres has an impact on the environment. Making tyres uses up non-renewable resources (see section 2.4.3). They impact on the environment during their production, use and disposal. With reducing opportunities for disposal there is a growing problem with recovering resources once tyres reach the end of their life. Tyres in use on vehicles contribute to pollution via road run-off. Inappropriate disposal can lead to tyre fires causing pollution of air and water and contamination to land and vegetation. Illegally dumped tyres are aesthetically displeasing and a fire risk. Table 2.3 summarises these impacts and the mitigation measures required to reduce them.

Table 2.3 Environmental implications of the tyre industry (Hird *et al.*, 2002)

Material	Impact	Action to avoid/reduce impact
Resource use during manufacture, use and reprocessing and disposal	Depletion of oil reserves Depletion of iron ore Depletion of zinc oxide	Increase recycled content of tyres Extend life of tyres Increase energy efficiency of processing
Atmospheric emissions during manufacture	Quality of atmosphere Human health (respiratory problems)	Remove potential pollutants from manufacturing process Increase energy efficiency Improve technology to reduce emissions Improve fuel quality or use low emission alternatives
Tyre abrasion during use	Quality of water courses Quality of atmosphere	Reduce abrasion rate of tyres (extend life of tyres) Maintain tyre pressures
Stockpiles of post-consumer tyres after use	Fire risk Quality of atmosphere Quality of water courses Quality of soil and vegetation Human Health Unsightly	Increase reprocessing capacity for post consumer tyres Encourage development of recycled products and markets Greater enforcement of regulations regarding illegal dumping

One of the largest problems to arise from the automobile industry, both in terms of disposal and environmental impact, is that of waste tyres. Table 2.4 indicates the scale of the equivalent problem for the European Union and which has led to the ban on disposal to landfill. The US Environmental Protection Agency (1991) estimated that in the US approximately 270 million scrap tyres per annum are discarded, adding to stockpiles totalling 2-3 billion tyres around the country.

Table 2.4 Tyre arisings and use of recovery options for various EU countries in 1998 (Hallet 2001)

	Tyre Arisings (Tonnes)	Overall recovery Rate (%)	Resuse (%)	Retreading (%)	Materials Recycling (%)	Energy Recovery (%)	Export (%)
Belgium	45, 000	94		22	11	33	28
Finland	30,000	80		6	60	2.5	11.5
France	370,000	39		20	9	7	3
Germany	596,000	92	2	24	15	45	16
Italy	333,000	60		25	9	33	3
Netherlands	45,000	100	16	29	8	47	
Spain	241,000	19		13.5	0.5	3.5	1.5
Sweden	58,000	98	19	8.5	6.5	54	10
UK	468,000	70	16	18.5	10.5	18	7.5

The physical size and structural composition of whole tyres makes alternative utilisation difficult. As a result huge stockpiles in massive land dumps have become established. The existence of these stockpiles has highlighted the potential hazards that whole tyres pose to the environment if not mitigated. Not all of these stockpiles are legal and illegal dumping of tyres is widespread.

The dumping of tyres, be it in rivers and estuaries, on the coastline, in towns or the countryside is aesthetically displeasing. This can occur on a massive scale such as in the Hampole Quarry in Yorkshire where it is estimated around 1.5 million tyres were dumped illegally between the late 1970s and the early 1990s. The major environmental risk to this site, like many scrap tyre repositories, is fire. In addition to atmospheric pollution from acrid smoke produced by tyre fires other mobile polluting contaminants such as zinc and phenol are released by combustion. In this particular case this is important as the Quarry is in magnesian limestone which is a major aquifer. Designation under the Control of Major Accident Hazards Regulations 1999 (COMAH) has been given to prevent pollution of this aquifer.

The use of scrap tyres in coastal and river engineering structures replaces the use of primary aggregates, reduces the environmental burdens of producing new tyres, and can, where responsibly managed, provide sustainable recovery capacity for used tyres.

2.3 WASTE MANAGEMENT LEGISLATION

Interest in new applications for used tyres, has been driven by changes arising from the European Waste Directives. The general disposal of whole tyres to landfill sites was banned from July 2003 and tyre shred is similarly to be banned from 2006. Hence options for the use of tyres which involve "recovery" i.e. conversion to a new product or use, rather than disposal have become very attractive. At the same time, however, regulatory agencies are becoming more cautious about the potential environmental impact of waste materials like tyres, particularly in regard to:

- the risk of chemicals leaching from such materials at concentrations that would be harmful to the environment
- the possibility of "sham" recovery i.e. recovery that is in fact waste disposal
- the risk of materials that have not been properly recovered re-entering the waste stream.

The Environment Agency confirms that used tyres are 'waste'. The regulations and controls governing storage, movement, use and disposal of different types of waste material feature strongly in any consideration of potential utilisation.

The current legal status of the definition of waste as it applies to tyres has been reviewed by The Environment Council. Their report (2003) reflects the definition as currently applied by the Environment Agency.

The Agency is working with industry with the aim of ensuring that beneficial recovery processes are not over-burdened with regulation. In connection with this there is a working group currently investigating the development of proposals for exemptions from waste management licensing for recovery activities with the aim of ensuring that the regulatory requirements are proportionate to the risk posed by the activity. However, this is likely to take some time and would involve amending existing regulations by making an effective case to Defra.

The European definition of waste is provided by Article 1 of the EC Framework Directive on waste (75/442/EEC as amended by 91/156/EEC). Waste is defined as any substance or object which the holder discards or intends to or is required to discard.

This definition has been transposed into UK legislation by Regulation 1(3) of the Waste Management Licensing Regulations 1994 (the regulations) as: "any substance or object in the categories set out in Part II of Schedule 4 which the producer or the person in possession of it discards or intends to discard." Schedule 4 - Pt II of the regulations list those material types that are classed as waste. Category 16 of Pt II, Schedule 4 of the Regulation however, states that "*any materials, substances or products which are not mentioned in the [other] categories can be waste when discarded*" – therefore anything can be 'waste'.

Government guidance was given on this in DOE Circular 11/94 but this no longer reflects the definition of waste as developed by case law and that part of the circular can no longer be relied upon.

Recent case law from the European Court of Justice (Arco Chemie and subsequent cases [1]) and the domestic courts[2]) has established three core principles that must be followed when deciding if something is waste:

- The scope of the term "waste" turns on the meaning of the term "discard".
- Whether a substance or object has been discarded and is in fact waste, within the meaning of the Waste Framework Directive, must be determined in the light of all the circumstances, having regard to the aim of the Waste Framework Directive and the need to ensure that its effectiveness is not undermined.
- The concept of waste cannot be interpreted restrictively.

The European Court has determined that material will be 'discarded' even if it is subjected to a disposal or recovery operation. Under European Case law it is clear that even if a contract is in place for the sale and subsequent reuse of arisings, then it may still be classified as Directive Waste if the holders intention is to discard (Stubbs, 1998).

The Environmental Protection Act (EPA) 90 Pt II and the Waste Management Regulations 1994 stipulate that a waste management license (WML) is required by anyone who deposits, recovers or disposes of household, commercial or industrial waste (called 'controlled wastes'). The Environment Agency (EA) in England and Wales and the Scottish Environmental Protection Agency (SEPA) in Scotland are the relevant authorities with duties under the regulations to administer the waste management licensing system (See Box 2.1).

A particularly important regulatory policy decision for materials such as tyres is identifying the point at which they have been processed to such a degree that they can be viewed as having been converted into a finished product. The current position being adopted by the Environment Agency in England, in the light of recent decisions of the European Court, is that processed items such as tyre bales legally remain waste until incorporated into an engineering structure. This view was adopted because "the essential characteristic of a waste recovery operation is that its principal objective is that the waste serves a useful purpose in replacing other materials…."

Thus once something is waste – it will remain waste until it is completely recovered. If waste is dealt with at an intermediate location, such as a civic amenity site or transfer station, it will remain waste from the time it is discarded until completely recovered.
The UK Environment Agency has therefore stated "that tyres processed or not into [items such as] tyre blocks cannot be said to have been fully recovered until they have

[1] Joined cases C-418/97 and C-419/97 ARCO Chemie Netherlands Ltd and others (15 June 2000)
Abfall Services Ag case C-6/00
Palin Granit Oy Case C-9/00
[2] R-v-Environment Agency ex parte Castle Cement Ltd (Queens Bench Division 22 March 2001)
Attorney-Genersals Reference No.5 of 2000 (Court of Appeal)

been put to use and are incorporated into an engineering structure" Because use of rubber and / or tyres is not an exempt activity for the purposes of the UK Waste Management Licensing Regulations 1994, it follows that Waste Management Licensing is required for each and every site at which waste is to be stored or recovered. This includes the construction sites where the bales are to be installed.

Box 2.1 UK legislation relating to waste

The main waste management legislation that applies to 'Directive' wastes and therefore applies to used tyres includes:

- The Environmental Protection Act (EPA) 1990, Section 33. – This states that it is an offence to deposit, knowingly cause or permit the disposal of controlled waste on land without a waste management licence.
- The Environmental Protection Act 1990, Section 34. – This imposes a 'Duty of Care' on all those who produce, handle or dispose of controlled waste. This duty is to keep waste safely and only transfer it to an 'authorised' person, and to provide an appropriate transfer note with it.
- The Environmental Protection (Duty of Care) Regulations 1991 – introduced a mandatory system of signed 'transfer notes' and require all those subject to the duty of care to keep records of waste transferred and/or received.
- The Waste Management Licensing Regulations 1994 – set out the procedures for obtaining a waste management licence. (A typical charge for a licence application is £1,500 to dispose of less than 5000 tonnes of inert waste in or on land) There is also an annual subsistence charge covering the cost of supervision and, in order to get a licence the applicant must undergo training.

The key principles that underlie the Government's waste strategy (DETR 2000) are:

- *The Best Practicable Environmental Option (BPEO)* – the option that provides the most benefits or the least damage to the environment as a whole, at acceptable cost, in the long term as well as in the short term.
- *The Waste Hierarchy* - the conceptual framework/ guide that places the options in order of priority, starting with waste reduction and followed by re-use, recovery (recycling, composting or energy recovery) and then disposal.
- *The Proximity Principle* – the principle that waste should generally be disposed of as near to its place of production as possible (recognising that transportation or wastes can have a significant environmental impact).
- *The Polluter Pays Principle* – the principle that if waste is created, it cannot be passed on or out, but must be treated and paid for by those who create it, adding that existing damage to the environment must be paid for.

The current situation in regard to requirements for Waste Management Licences was clarified by the Environment Agency during the course of the project and as a result the Witham pilot project (see Box 5.2.4) was required to have a Waste Management Licence. Details of the process for obtaining a Waste Management Licence for that project are described in Appendix 8 (section A8.1.3).

It was recognised that the need for Waste Management Licences for construction projects would potentially discourage the use of post-processed tyre-based items such as bales. Two initiatives to overcome this problem are underway at present:

1. Proposed exemptions to Schedule 3 of the Waste management Licensing Regulations
The Waste Tyres dialogue, of which the Exemptions Working Group is part, was initiated by the Environment Agency (EA) in 2001 to develop solutions to waste tyres in England and Wales. The Exemptions working group was established under the auspices of the independent Environment Council to clarify existing or to develop new exemptions, without bias to any sector, to assist used tyre markets to continue to operate without being subject to the full weight of waste management licensing requirements. The research team on this project played an active part in the working group and helped to develop proposals to modify paragraphs in the existing Schedule 3 of The Waste Management Licensing (England and Wales) Regulations. The proposals prepared by the working group (which assumed that the amendments set out in the Defra consultation paper June 2003 were already implemented) included the following amendments to the current exemptions:

- Modification of Paragraph 17 to permit the separate storage at a secure location, for a period not exceeding 12 months, of 3000 bales or 1500 tonnes of tyre chip, granulate or powder.
- Modification of Paragraph 19 to permit the storage and use of whole baled chipped granulated or powdered tyres for defined works of construction, maintenance or improvement on a site so long as:
  - any such material is not stored for more than 3 months
  - the construction works have Planning Permission
  - the waste does not exceed the final cross-section dimensions shown on the submitted plan.
- The manufacture of finished goods from whole tyres, including storage at the place of manufacture of not more than 15,000 tonnes of whole tyres at any time.

Defra have advised that it is likely to be several years before such exemptions can be considered for implementation

2. WRAP protocol for waste tyre products
WRAP are promoting the development of a protocol for the production of certain production processes involving post consumer tyres, including the manufacture of tyre bales, which should allow the outputs of those processes to be defined as fully-recovered product. In order for such a protocol to work, three requirements would need to be satisfied:

- Evidence that the tyre-based product was being manufactured to an agreed standard. (As there is no standard for many of the newer products such as tyre bales, the manufacturing standard will need to be prepared.)
- Evidence that the tyre-based product was being manufactured for a genuine end-market and not purely for 'sham' recovery.
- That the tyre-based product posed no risk to health or the environment.

As at the time of finalising this report, it is unclear if and when such protocol(s) will be available and readers are advised to contact WRAP for the latest information.

2.4 WHERE CAN TYRES BE SOURCED?

It is estimated that the EU produces over 2.5 million tonnes of used tyre material every year of which around 1.5 million tonnes are subsequently processed with the rest disposed to landfill (Kalid and Artamendi, 2004). These figures are likely to change due to recent and new EU incentives to restrict the quantity of used tyres disposed to landfill.

- Prohibition of the landfilling of whole tyres since July 2003 by the EU Landfill Directive.
- Prohibition of the landfilling of shredded tyres by July 2006 by the EU Landfill Directive.
- The reuse, recycling and recovery of vehicle components (including tyres) to be raised to 85% by 2007 by the EU End of Life Vehicle Directive.

Subsequently more tyres are becoming available for reuse, recycling and recovery. The 2003 landfill ban had little noticeable impact on tyre collection and recovery operations. The 2006 part of the Landfill Directive may or may not be more significant, however, it is possible that used tyre arisings in the UK will exceed national capacity by up to 140kt by 2008 (UTWG, 2003). Thus there is increased pressure on government and industry alike to expand existing markets and to find new ones to accommodate the increased flow. However, reprocessing capacity for tyres is not evenly distributed across the UK with some regions having a surplus (Midlands) and others a deficit (Southeast). Currently small reprocessing companies are finding it difficult to establish themselves because of instability in the market and the high costs of investment. The distribution infrastructure and regulation for supply and demand is not well established and what does exist is not well known outside of the tyre disposal industry.

2.4.1 Arisings

Figure 2.1 illustrates a common understanding of the life cycle of a tyre. Figure 2.2 however indicates that the journey from manufacture to disposal is more complicated and shows the many different tyre movements that make it difficult to monitor the number of used tyres arising from different pathways.

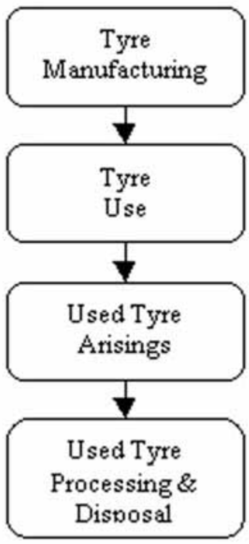

Figure 2.1 Simplified life cycle of a tyre

Considerable variability exists in the types of used tyres from cars, vans, trucks, buses, tractors, aircraft, motorcycles, bicycles and lawn mowers. There are approximately twice as many car tyres (including vans) as truck tyres (including buses and coaches) in terms of tonnage. However, there is no reliable data available to estimate the number of tyres arising from other sources.

When a tyre has come to the end of its design life, it can be replaced at retailers/garages or removed from an 'end of life' vehicle by dismantlers/scrap yards. Used tyres can also be imported for reuse as 'part-worn' retreads. The main legitimate sources of used tyres are shown in Figure 2.3.

In the UK tyres make up approximately 0.4% of the total annual waste arisings in commercial, industrial and municipal waste (DETR 2000).

Figure 2.3 shows that over three-quarters of used tyres are supplied by retailers. The National Tyre Distributors Association (NTDA) represents around 400 companies that in turn represent a larger number of outlets located throughout the UK. There are approximately 250 members of the Motor Vehicle Dismantling Association (MVDA) and the British Vehicle Salvage Federation (BVSF). In addition there are numerous small garages, vehicle breakers and dismantlers that are not allied to these organisations. Consequently, most used tyres arise in small numbers at a large number of locations throughout the UK.

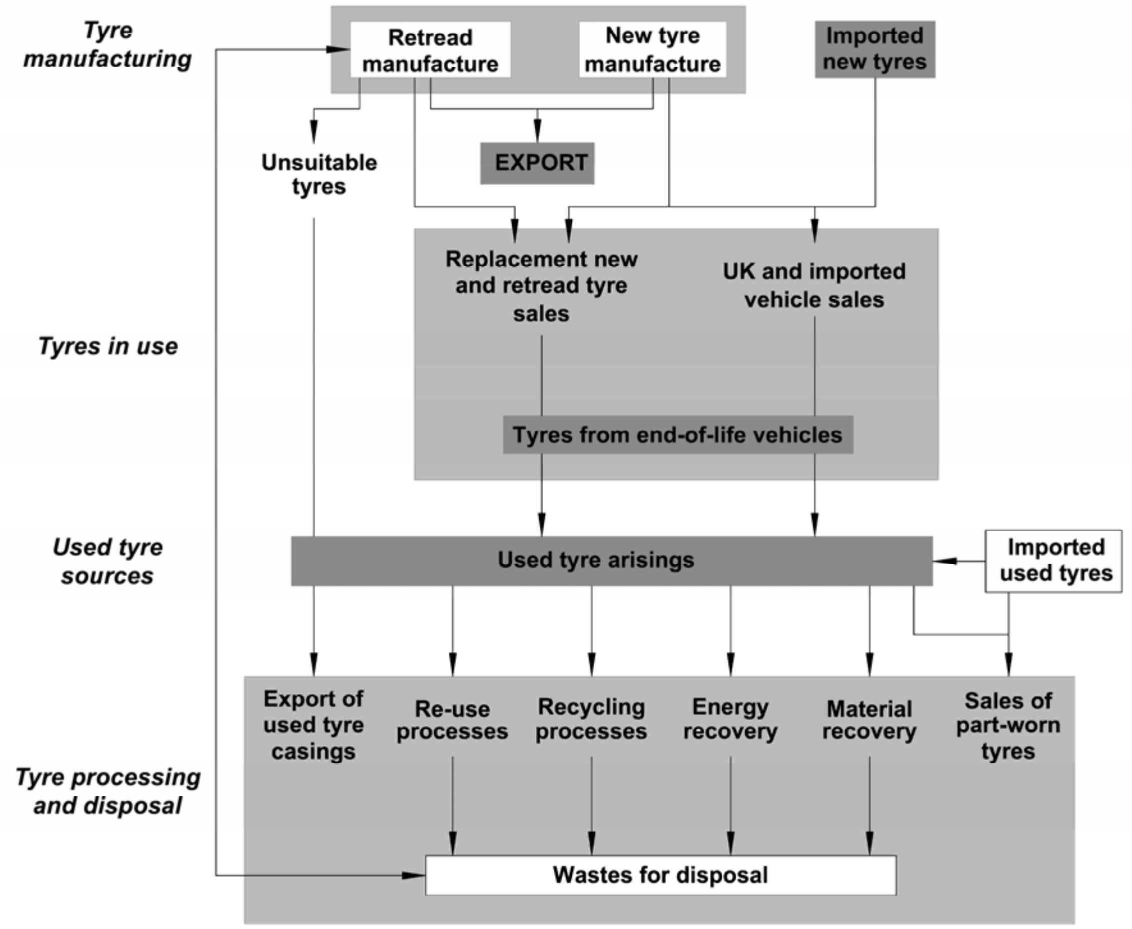

Figure 2.2 Full life cycle of a tyre in the UK (Hird *et al.*, 2002)

The number of used tyres arising in the UK each year is currently estimated. This number is difficult to determine accurately for several reasons:

- The number of tyres sent to landfill is not tracked.
- Some used tyres are illegally dumped or stockpiled.
- The number of tyres reused whole for applications (for example; to hold down silage clamp covers) is unknown.
- The number of commercial vehicles scrapped or dismantled is estimated.
- Of all vehicles scrapped or dismantled, the proportion of tyres removed before shredding is not recorded.
- The number of 'part worn' tyres imported and exported is not monitored.
- There is no formal system to record the number of tyres disposed by tyre collectors. (Only a paper trail of movements under the Duty of Care Requirements.)

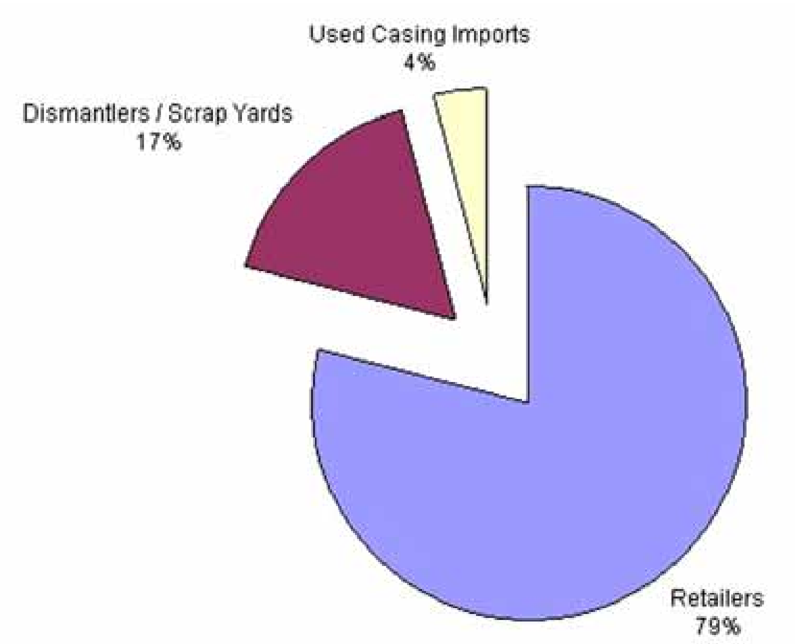

Figure 2.3 Sources of used tyres (Hird, *et al.*, 2002).

In 1995 the Used Tyre Working Group (UTWG) was set up to examine and report the number of used tyres arising annually in the UK. Their annual reports provide information on industry initiatives and track the estimated number of used tyres.

2.4.2 Stockpiles

There are significant stockpiles around the UK consisting of an estimated total of 14 million tyres (Hird *et al*., 2002) (See Figure 2.4) located in:

- South Wales 81 kt (~ 9 million tyres)
- Yorkshire and the Humber 18 kt (~ 2 million tyres)
- East of England 7 kt (~ 0.8 million tyres)
- An additional six stockpiles in England and Wales hold more than 0.90 kt (~ 100 000 tyres) and widespread observations confirm that significant numbers of used tyres are used to hold down plastic sheeting on silage clamps on cattle farms.

However, tyre reprocessing plants are not well dispersed, and so transport can incur increased cost in terms of bringing the tyres to the site of use from the reprocessing plant. These transport costs need to be considered if tyres are to be used in structures and schemes.

As well as the competing uses outlined in Table 1.1 tyres are also used in cement kilns as a supplementary fuel. This will continue to be a competitive outlet for tyres unless the cement industry identifies an alternative feedstock which is comparatively less expensive. [3]

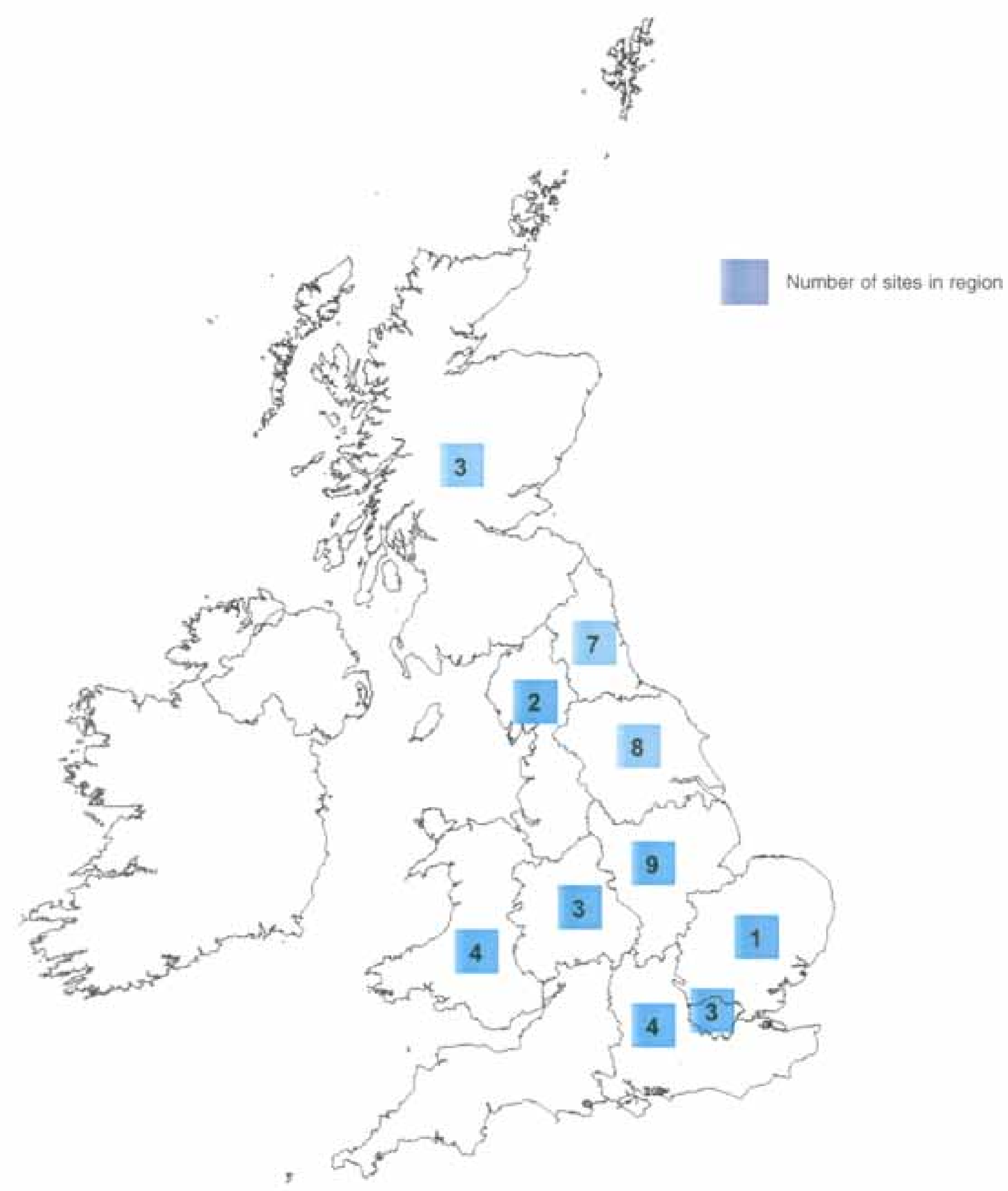

Figure 2.4 UK distribution of known tyre stockpiles (ETSU, 1995)

[3] Compliance with lower emission standards proposed in new EU legislation (2000/76/EC) due in 2008, could effectively close 'wet kilns' which treat 20% of tyres used in cement kilns (111,706 tonnes)

Figure 2.5 A typical tyre stockpile

2.4.3 Mass balance

The modern approach to assessing the total environmental resource cost of a product or industry is to calculate the mass balance of natural resources consumed and wastes produced over the lifetime of the product or process under scrutiny.

A mass balance of the tyre industry was established by Hird *et al* (2002) which included resource inputs, and product waste outputs. Wastes were split into solid/liquid waste and gaseous waste or ‘emissions’. These were combined to create a total mass balance of the tyre industry from which the major resource flows could be identified. These are summarised in Figure 2.6.

The key points from the resource flows were summarised in their report as follows:

- 82% (391kT) of UK manufactured tyres are exported. Only 18% are used in the UK. 432kT of tyres are imported to satisfy the market demand.
- The greatest resource use is associated with tyre use, particularly the fuel used to overcome the rolling resistance of tyres. As a result the greatest outputs are emissions (CO_2 and H_2O) resulting from fuel combustion.
- In 1998 the stock of vehicles and thus tyres on the road increased by over 27kT. Other changes in stock included an additional 32kT held at tyre manufacturers/ retailers, and an additional 23kT stockpiled at reprocessers or disposed of illegally. Consequently, an additional 82kT of resources were retained within the system.
- Tyre wear creates solid waste. The rubber loss during 1998 results from the whole stock of tyres on the road (between 815 and 974 kT), not just those added that year.
- Only a small amount of material (<2%) is recycled within the system, in the form of retreaded tyres.

- A proportion of recycled tyres used whole (for applications such as silage clamps) will return as 'post-consumer tyre arisings' in subsequent years. The number of tyres re-entering the reprocessing/disposal chain in this manner in 1998 was an estimated 5kT.
- A large proportion of the post-consumer tyre arisings (41%) were disposed of in landfill, stockpiled or illegally dumped.
- The UK is a net exporter of post-consumer tyres.

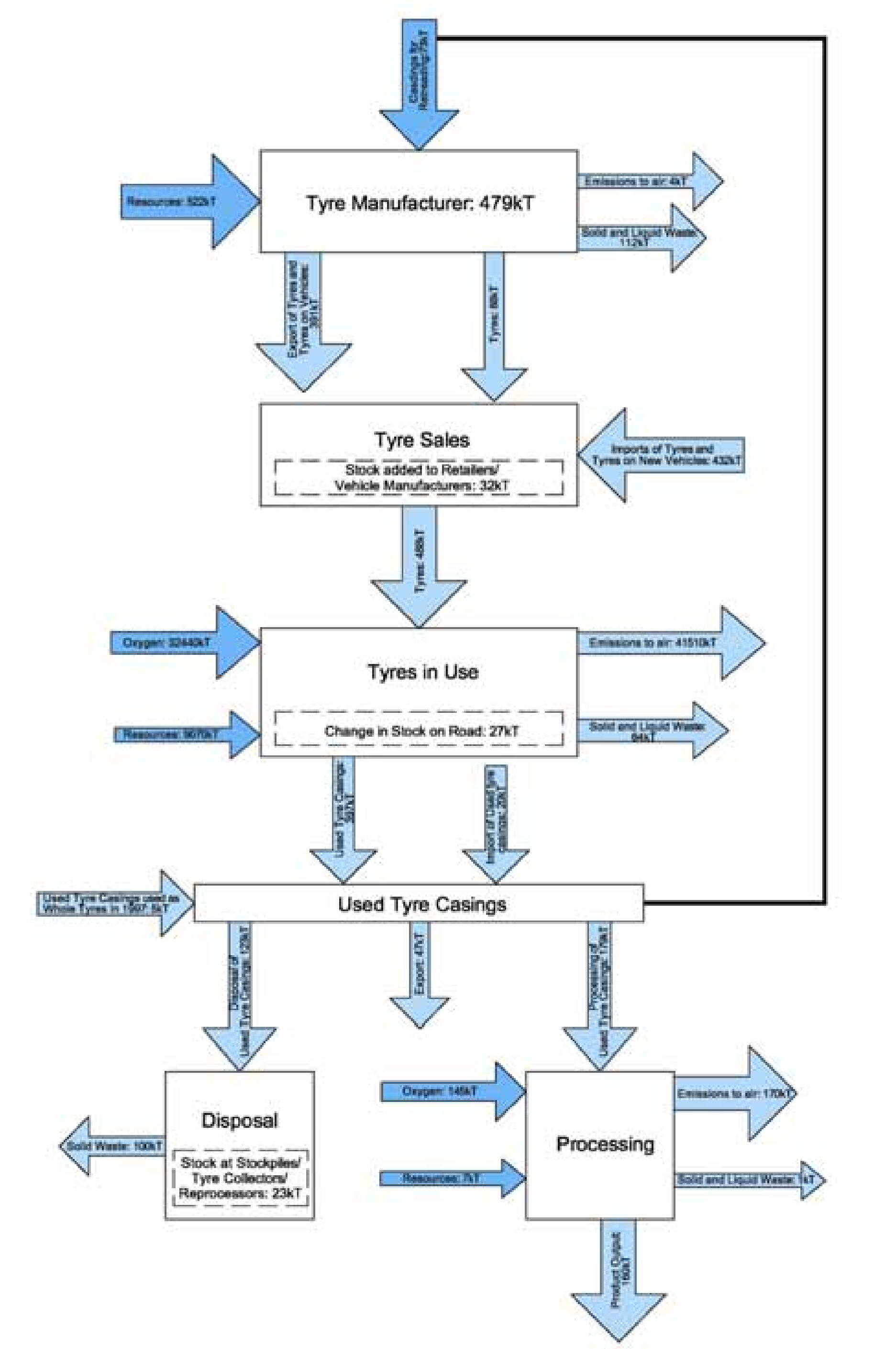

Figure 2.6 Mass balance resource inputs and waste outputs in the tyre industry in the UK. (Viridis, 2002)

It is useful to visualise the discrepancy between resource use and waste outputs produced by UK tyre production and that which would occur if all tyres imported were also produced here. Figure 2.7 represents the imported faction as 'UK equivalent tyre manufacture'.

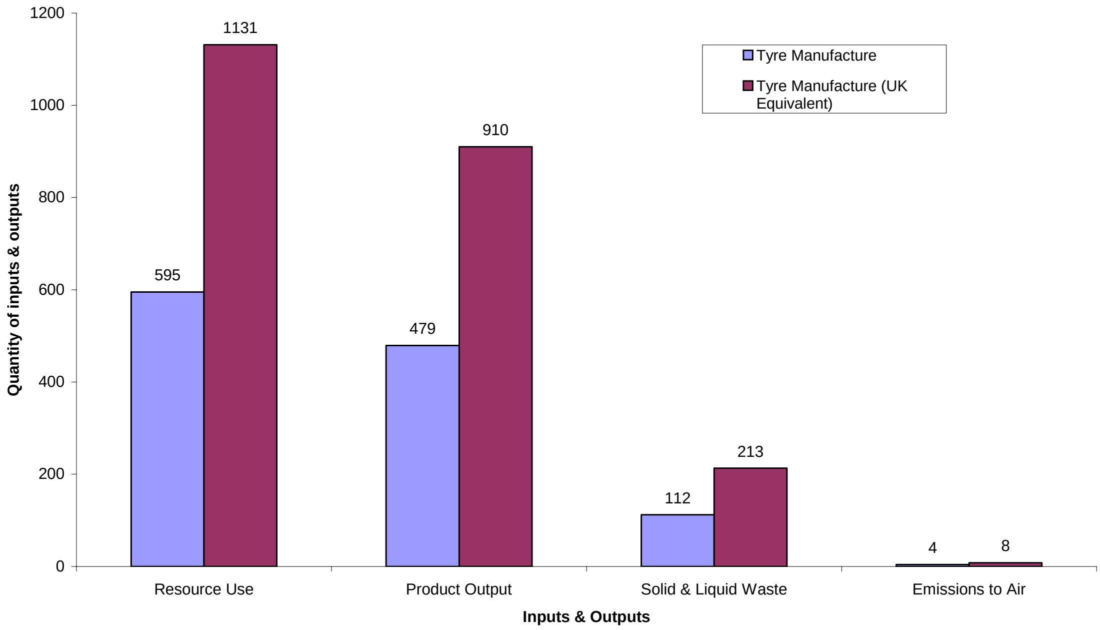

Figure 2.7 Comparison of the mass balance of UK tyre manufacturing and UK equivalent tyre manufacturing (from Hird *et al,* 2002)

This highlights the fact that even though not all the raw materials and energy required to make all the tyres consumed in the UK, come from the UK, and not all the wastes and emissions are released in the UK, it is none-the-less UK tyre use that drives the need. As Figure 2.7 indicates, almost twice the amount of resources and impacts are associated with manufacturing all the tyres required in the UK compared to those actually manufactured in the UK.

Identifying the quantities of materials consumed and produced, although important in terms of resource use and depletion of non-renewable resources, may give a false impression in terms of the environmental impacts of wastes and emissions. It is a combination of the concentration and physical/chemical characteristics that determines its environmental impact. Table2.3 summarises some of the material flows in the tyre industry that have significant environmental impact, and generic actions that can be taken or are being taken to reduce the impacts. At present the greatest impacts result from the use of non-renewable resources, and emissions resulting from the energy required to over come rolling resistance.

The principles of the waste hierarchy are that efforts should be focused on minimising, reusing and recycling waste, rather than energy recovery and disposal. While the first priority is to find alternatives to landfill (with energy recovery being an obvious choice), ultimately the danger is that the recycling markets will not be able to develop because of the dominance of energy recovery. A balance is required between energy recovery, reuse/recycling and minimisation if used tyres are to be dealt with in a sustainable way.

Figure 2.8 shows the estimated increase in used tyre arisings compared to past and existing, and planned processing capacity. There is great uncertainty as to whether all the predicted capacity will actually come on line in the future, or whether it will come on line soon enough to be in place by 2006 when the ban on disposal of tyre chips and shreds to landfill comes into force. If none of the new planned infrastructure comes on line by this time then there is likely to be a large shortfall in capacity. Therefore there is a risk that the tyre industry will not be prepared for the full implementation of the landfill directive in 2006 and a large and increasing number will be illegally dumped or stockpiled.

To address both this potential shortfall in capacity and to maintain a balance of processing solutions, there is a need to further develop recycling applications, products and markets such as civil engineering applications for whole tyres and shreds.

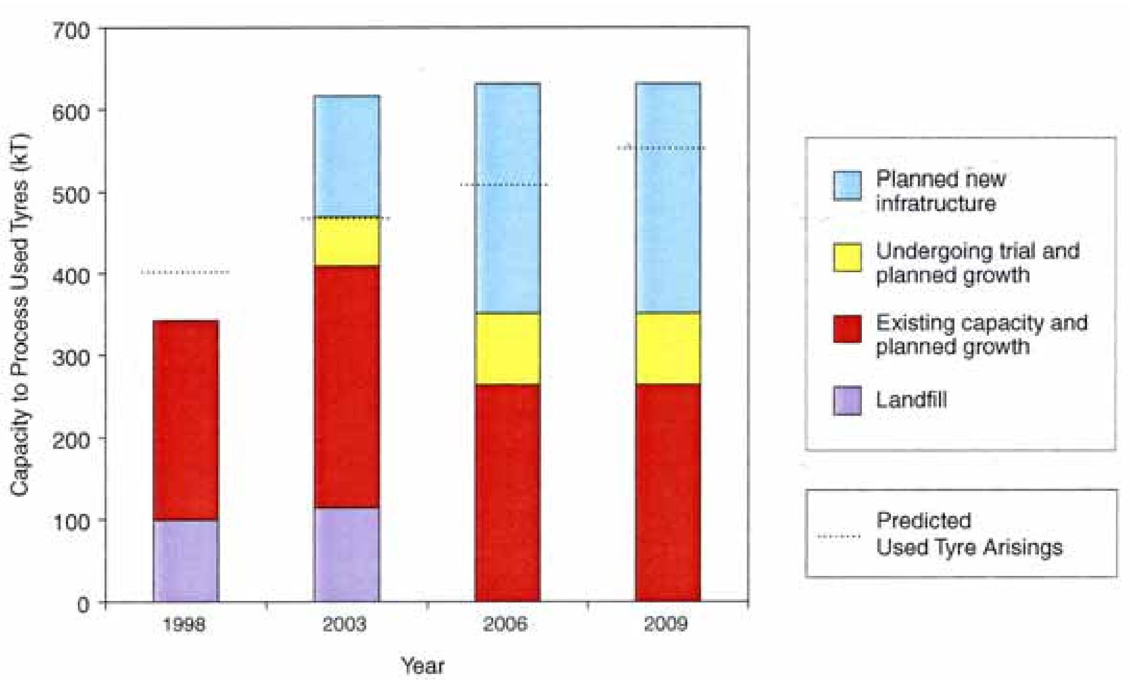

Figure 2.8 Existing and planned processing capacity compared to the estimated increase in tyre arisings (Hird *et al.* 2002)

2.5 ECONOMIC FACTORS

Congruent with the change in use and application of large numbers of used tyres will be a change in monetary market values. Tyres will have to compete favourably with traditional or 'main stream' materials. Applications for tyres are currently concerned with low cost options and the availability of the resource in comparison with other materials of choice. As such, potential applications utilising only limited quantities of tyres will be of lesser interest, but, those requiring large numbers will prove to be economically worthwhile due to improved economies of scale, as will uses where tyres possess inherent properties that other materials do not, for instance as a lightweight fill material.

2.5.1 Used tyre recycling production costs

The typical capital cost for setting up a processing/production facility for tyre bales is greater than €100,000 (Hylands and Shulman, 2004). The costs incurred from post-consumer tyre use are proportional to the degree of treatment, processing and transportation required in producing and delivering the finished article to the construction/scheme site. Obviously there is a balance to be struck between environmental protection, performance and cost of processing. (Costs for tyre shredding are low, but production of tyre crumb is more expensive.)

2.5.2 Cost savings by material substitution

Cost savings can be made by substituting aggregates for tyres. Tyres weigh less than most other options. The cost of transporting the equivalent m^3/mile in tyres will thus be less than for other aggregates, however, the distance differential should also be considered carefully to ensure that any additional mileage required to deliver tyres or tyre materials does not negate the advantage.

2.5.3 Cost savings through performance

One of the most powerful drivers for engineers to adopt alternative recycled materials is if they can be shown to offer significant technical advantages. The increasing use of industrial by-products such as pulverised fuel ash since the 1950s either as lightweight fills, lightweight aggregates for low-density concrete and for low bearing capacity ground fills, was entirely driven by their low weight and durability advantages. Tyres can also now offer significant technical advantages and associated cost savings. For example, tyre bales offer the following:

- The lower weight of structures utilising tyre bales may remove the need to pay for deep foundations to be sunk into soft ground.
- The ability of tyre bales to form a steeper profile/slope than, for instance, clay, reduces the volume of material that would otherwise be needed to make embankments and slopes structurally stable (see Box 5.2.4), avoiding additional procurement, extraction and transport costs.

Extended life expectancy and the increased durability of structures using tyres should add cost effectiveness over the long term by offsetting renewal and reducing repair and maintenance costs.

In general there will also be a cost saving to society and the environment by substituting primary materials for tyres. Reuse and recycling (generally) costs the environment less in resources to the benefit of wider society.

2.5.4 Whole life costs

The cost savings potentially afforded by tyres through material substitution and performance (lower construction, maintenance and renewal costs) could over the lifetime of a structure significantly reduce its ‘whole-life cost’. The objective of whole-life costing is to minimise long-term expenditure by taking all costs associated with the provision of a structure into account including initial construction and subsequent maintenance, and monitoring and selecting the approach that offers the best value in the longer term.

2.6 SOCIO-ENVIRONMENTAL FACTORS

The consideration of the use of a material such as waste tyres cannot be complete without an investigation of the public perceptions that can and have arisen when such a scheme or structure is proposed.

A common perception of used tyres is that they are dirty, contaminated, polluting, toxic, and should be either chopped up or burnt. Many initially rise an eyebrow in slight surprise if confronted with the 'new' idea that used tyres can be usefully and safely put to good use in construction and civil engineering schemes.

2.6.1 Stakeholder involvement

It is not always understood that reactions to proposals are often a product (but not always) of the mechanism and nature by which information or knowledge is divulged, i.e. not necessarily solely due to the proposal itself. Adverse reactions are often the result of a failure in information provision. Often this failure is due to insufficient attention being paid to stakeholder engagement early enough in the process.

Unfortunately late involvement does not always mollify the criticism as the divergence of opinions and personal stances have already formed and been made. This makes reconciliation, even in the face of scientific fact and professional confidence, very problematic, and requires a skilled and experienced facilitator/negotiator to resolve.

It should be a priority, especially for anyone considering using used tyres (in any form), to consider carefully involvement by stakeholders. Time and effort spent at an early stage building rapport, trust, a willingness to listen and confidence in communication among stakeholders can save much time, difficulty and anguish later on in the process.

Opinions are often formed in the light of existing knowledge that is incomplete or limited. This is why sometimes, many new ideas and developments are strongly opposed. Opinions can be changed by updating or taking on new knowledge that furthers understanding. To gain consent requires both a willingness to disclose information by those who have it and a willingness to listen and learn by those who don't. This does not mean that the flow of knowledge should be unidirectional but that all parties involved should be willing and feel empowered enough to do both.

For this process to take place requires time, effort and mature aspects of social interaction to be present. It is also important that this is understood by all concerned. On the whole, better solutions result from the wide interaction, information exchange and learning process that the right approach facilitates.

It is important that local stakeholders especially are allowed a sense of 'ownership' over new proposals and developments – that the project is being conducted with their express consent. This is because often their perception is that they have the most to gain or lose from any changes. Constructive participation is more likely to be forthcoming if they are given the opportunity to be involved early in a process which allows consideration, understanding and mitigation of their views and standpoints. This approach helps to 'legitimise' the process and encourages 'buy-in' to the scheme.

Experience gained from the deliberative inclusion of stakeholders in project pilot schemes indicates that early involvement and proactive participation does work but, equally, even with the best intentions and consultation practices sometimes the presence of ulterior or political motives, not directly relevant to the project, can stir emotions and propagate divergence of opinion. These factors are always difficult to accommodate within a consultation framework and may require a strong steer to keep stakeholders focused on the pertinent issues.

2.6.2 Socio-environmental costs and benefits

Economic analysis is primarily concerned with the well-being of people, through the allocation and consumption of the factors of economic production. Economics interacts with the environment because the natural resources, which form one major factor of production, are inherently scarce. The others are labour and capital in the form of technology and know-how. The application of labour and capital should increase the availability of natural resources through extraction and recycling. In addition, a socially valued and habitable environment is also a scarce resource, the allocation, ownership and management of which is a major focus of environmental economics (Adger, 2000).

The socio-environmental costs and benefits are really a composition of all those benefits and costs previously discussed in Section 2.5:

- whole life costs (and mass balance) (new tyres)
- production costs (used tyre processing/recycling)
- primary (natural) material resource savings
- disposal savings
- performance/maintenance savings
- environmental costs and benefits (monetary and unpriced)
- stakeholder participation benefits (social equity).

The legislation and strategies described in Box 2.1 provide checks and balances to these costs and benefits to ensure that they are distributed in a consistent way across society.

The Best Practicable Environmental Option (BPEO) for used tyres is one which provides the most benefits or the least damage to the environment as a whole, at acceptable cost, in the long term as well as in the short term. In other words, the BPEO is the option that performs the best when assessed according to all the socio-environmental cost and benefit criteria listed above.

2.6.3 Perceptions of risks and liability

To date the use of secondary and recycled materials in coastal and river engineering has, in general, been insufficiently researched, and existing applications are poorly publicised and documented. This has lead to a perception of extra risk in the design and construction of such schemes if such materials are used, although it is difficult to quantify any increase in the risk. This perception is based on the supposition that extra risks could arise from the quality, availability or environmental effects of such materials. Should problems arise, during or after construction of a scheme, as a consequence of choosing to use, for instance, tyres, then the liability of the engineer may be increased. This perception therefore acts as a barrier to use at the design stage, encouraging the engineer to opt for tried and tested materials as a safer approach, bearing in mind the burden of professional indemnity insurance.

Uncertainty about the performance of tyres - i.e. their safety and durability - is the main factor in the perceived increase risk associated with their use in coastal and river engineering to the extent that, as Figure 2.9 shows, it makes a newsworthy story. This report seeks to reduce this uncertainty by providing information on the use of tyre materials and how they perform in comparison with primary materials, since the risk associated with used tyres is based on perception rather than fact.

The barrier of uncertainty about the use and performance of tyre materials can be reduced in three ways.

1. Specific, detailed facts about the quality, availability and environmental acceptability of tyres such as provided in this report can alter the perception of risks.
2. Convincing demonstrations of the suitability of tyres will come from the proven success of previous schemes similar to the one under consideration by the client. This report describes several pilot projects which will help in this regard.
3. Most river and coastal engineering projects are built with public funding, and reducing the use of primary aggregates is in the best interests of the country. It seems logical, therefore, that the clients and funders of such schemes should show tangible support for the use of tyres. Consideration needs to be given to these public bodies accepting any extra risks arising from the use of such materials, such as setting up project specific insurances. Such action will demonstrate their support for the sustainable use of resources and reducing the concerns of, and risks to, designers and engineers in using them.

In summary, it seems that it is the perception, rather than the reality of extra risks in using tyres, that is a barrier to their use. If funding agencies were to accept part of the risk in schemes using tyres, and set targets for their usage, progress will be made towards greater uptake.

ESTABLISHED 188 1501 - 2001

Pioneering tyre plan to fight erosion threat

By Peter Homer
peter.homer@chiobserver.co.uk

Michelin, Bridgestone and Pirelli may soon be protecting the Chichester district's vulnerable coastline from the ravages of the sea.

A pioneering scheme to use 20,000 old tyres in the first coastal defence scheme of its kind in the country looks set to get government backing.

If it goes ahead, as proposed, at Selsey, there could be huge potential benefits for other local seaside areas in need of improved protec-

Hoop-la tyres to prevent erosion

A FARMER believes his use of old car tyres to

unacceptable.

Tyres ideal for protecting coast

As a marine scientist who has been studying the environmental impact of tyres since 1985, I am responding to concerns expressed in RT O'Brien's letter of April 17 over the proposed use of tyres for a coast protection trial at Selsey.

Millions of tyres are in use around the world as artificial reefs to successfully promote fisheries.

Tyres, resulting from of over 100 years of technological development, are extremely tough and thus difficult to dispose of.

They are particularly stable in seawater, illustrated by the fact that tyres recovered from second world war wrecks are still in good condition.

I have been studying marine organisms from my experimental tyre reef in Poole Bay and other marine tyre structures around the world and found no evidence for contamination by the tyres (see attached photo).

Currently a coastal protection trial using blocks of compressed tyres at Pevensey is demonstrating the risks to be very low.

There is limited leaching from tyres in water and this is small in comparison to the pollution caused through their use on roads.

As vehicles are driven they leave a fine trail of dust from tyre wear as well as brakes, oils and fuel, which have a far greater effect than the whole tyre.

Rain washes chemicals from the road dust into the drains, rivers and the sea. I suspect that the roads of Selsey will have a far greater impact on the local marine environment than the tyre coastal protection trial.

Each of us produces one waste tyre per year. I suggest that protecting our coast is a worthwhile use of these waste tyres, saving on concrete using gravel dredged from the seabed with attendant loss of marine habitat or using rock quarried from the countryside.

There are both environmental and economic benefits to be gained from local recycling of scrap tyres.

Dr Ken Collins
Senior Research Fellow
School of Ocean and Earth Science
University of Southampton

Mr O'Brien is voicing the concerns of many others in his letter published in the *Observer*.

These concerns must be answered. Southampton University has completed a project on this topic led by Dr Collins. A reef of car tyres was constructed in the tidal harbour at Poole, it was closely monitored for six years.

This ongoing work of Dr Collins is the basis of the claim for non-toxicity of car tyres in tidal sea water.

This work has been accepted by the Environmental Agency without whose consent and stringent testing protocol the car tyre project would never have been sanctioned.

Mr O'Brien should ponder the following:

1. Car tyres have been used as boat fenders the world over since car tyres were invented.
2. Fishermen have used car tyres for binding steel framed lobster pots since willow pots went out of fashion, anyone walking the shingle bank at the end of Hillfield Road in Selsey will find ample evidence of this practice by the strips of car tyre washed ashore from disintegrating lobster pots at sea.
3. What happens to car tyres worn down in their normal usage? It is washed into the normal drainage system of ditches, streams, canals, ponds, rivers and ultimately the sea.
4. Water from these sources is what we drink, irrigate our field crops and greenhouses. Where is the evidence off these 'daily pollutants'?

Edwin J Wrigley
Golf Links Lane,
Selsey

Figure 2.9 News articles on the use of tyres in erosion protection schemes

2.7 SELECTING TYRES AS AN OPTION IN THE DESIGN PROCESS

Consideration of the use of alternative materials such as tyres or tyre derivatives for construction should begin early in the stages of planning and design if the structure or scheme is to be successful.

The design process as shown in Figure 2.10, is a complex, iterative process. The principal stages are described in more detail in Box 2.2.

The design process involves a great deal of consideration by the designer. His/her deliberation requires the careful accounting and balancing of a range of issues. These are commonly summarised as the three 'Es': Engineering, Economics and Environment. These are described further in Box 2.3.

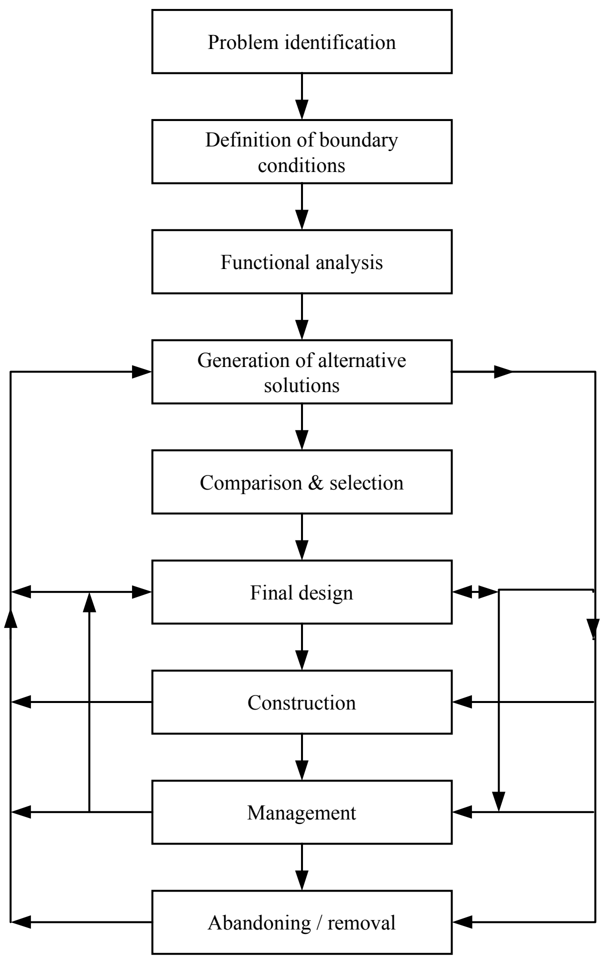

Figure 2.10 The design process (CIRIA, 1991)

Box 2.2 A summary of the principle stages in the design process (CIRIA, 1991)

Problem identification:

- The presence of an existing or future problem is acknowledged and defined.
- The decision to find an appropriate solution is made.
- Boundary conditions that influence the problem and its potential solution are identified.

Functional analysis:

- The functions that the structure has to fulfil in order to remove the stated problem are analysed.

Generation of alternative solutions:

- Generation of alternative design concepts to meet the boundary conditions and functional requirements.
- The following key areas are covered:
  Environmental considerations
  Determination of material sources and properties
  Understanding relevant hydraulic and geotechnical processes
  Structure specific design methods
  Construction considerations

Box 2.2 A summary of the principle stages in the design process (CIRIA, 1991) (continued)

maintenance considerations.

Comparison and selection:

- Comparison of alternatives and selecting preferred options using techniques such as multi-criteria analysis (MCA) or benefit-cost analysis (BCA).
- Selection process can include the following:
  Risk assessment during construction and operation
  Comparison with political, social and legislative conditions
  Environmental impact assessment
  Complexity of operation and maintenance relative to local technological experience and resources.

Final design and detailing:

- Essentially consists of a series of calculation and/or model tests to check and adjust as necessary all details of the structure to produce contract documents and a design report.
- The design report will generally contain the following components:
  Description of selected structure and selected process
  Materials to be used, reasons for selection and anticipated method of production and transport to site
  Description of how the selected structure meets the functional criteria up to defined limit states
  Probabilities of failure in various hydraulic and geotechnic failure modes, ideally linked by a fault tree
  Construction methods and equipment envisaged
  Description of maintenance strategy agreed with future owner
  Environmental impact statement
  Cost estimates
  Economic benefit-cost justification.

Box 2.3 The three ‘Es’

Engineering
The design must be sound technically, be fit for purpose and last for the required lifetime (allowing for any planned replacements).

Economics
The costs of the scheme, both capital and maintenance must be evaluated over the entire projected life of the project (including maintenance renewals and disruption costs). These costs must be affordable and commensurate with the benefits they deliver, whether those benefits are economic (for nationally funded works) or financial (in terms of privately funded work).

Environment
Here it is commonly understood that the scheme must have an acceptable impact on the environment in which it is constructed. Ideally, the impact (as assessed under the requirements of the EU directives and national legislation) will be positive, e.g. aesthetically, socially and biologically. If negative impacts arise they must be more than balanced by positive impacts and mitigated or compensated for as far as is possible.

Historically, the view of environmental issues in coastal and river construction has excluded any consideration as to the sustainability of the construction materials themselves. This view is slowly changing and together with the recent transposition of EU directives, for instance on the disposal of waste materials and landfilling, is putting pressure on authorities and industries to find new ways of utilising materials that previously would have been discarded or not considered as construction materials.

An interest in new applications for post-consumer tyres has been driven by changes arising from the European Waste Directives (See Section 2.3). The general disposal of whole tyres to landfill sites has been banned from July 2003 and tyre shred is similarly to be banned from 2006.

Here we provide a guide as to how a coastal or fluvial designer or engineer may consider the use of tyres or rubber-based tyre derivatives as part of the design process. There are a number of important questions to be asked – the answers to which will help the designer/engineer to determine relatively quickly early on in the process whether or not used tyres are suitable for a particular application.

These include, but are not limited to:

- What is the function of the structure or application?
- What engineering properties are required and do post consumer tyres provide these necessary properties?
- What is the intended life-span of the structure?
- Will the client or the regulator support the use of tyres?
- Are there any conveniently located suppliers close to the site?
- What specific or other design considerations have to be addressed (i.e. groundwater level or geology)?
- Do tyres have a strong economic case for use?
- Have any specific hazards been identified?

These questions should be answered methodically at an early stage in the design process. However, consideration may not be given to the use of tyres until a problem is discovered in an original design which may require the specific properties of tyres (e.g. low density) to solve.

The flow diagram shown in Figure 2.11 provides an overview as to how alternatives to primary materials such as tyres and rubber-based tyre derivatives should be integrated within the design process.

As a result of the many different processing techniques now available there are many forms of post-consumer tyre products for new and existing applications (See Section 3.2). Guidance on the use of many of these can be found in the Viridis report 'Civil engineering applications of tyres' by Hylands and Shulman (2003).

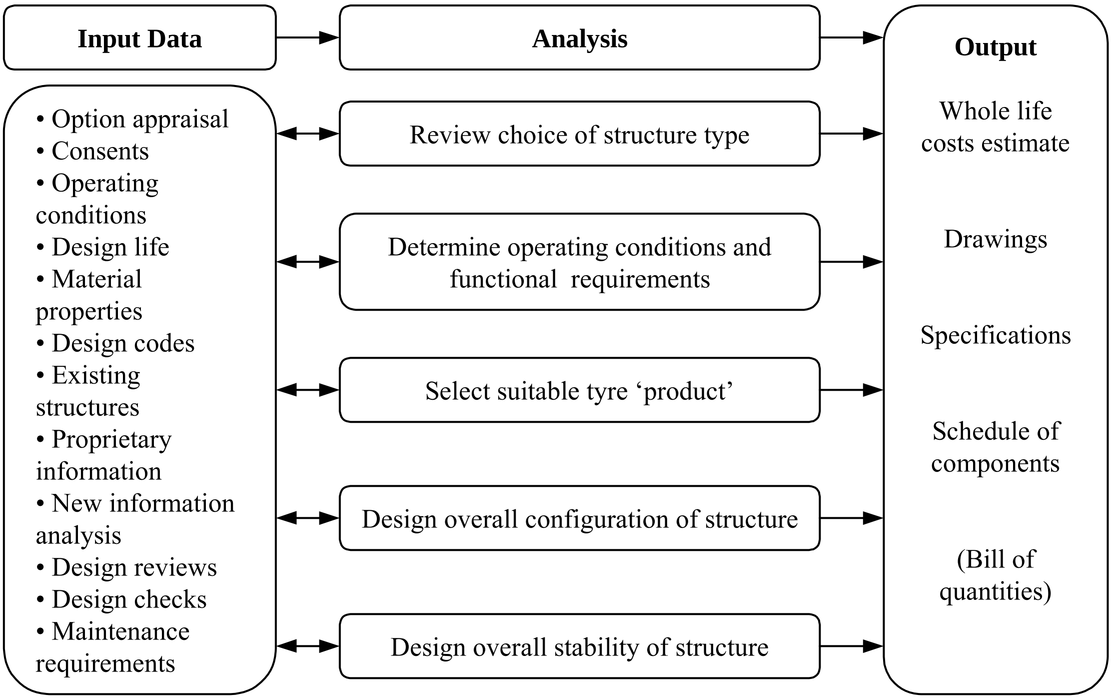

Figure 2.11 Design methodology

3. Introduction to tyre properties, re-processing and re-use

3.1 BASIC PHYSICAL AND CHEMICAL PROPERTIES OF TYRES NEEDED FOR PLANNING AND DESIGNING

Tyres are thought by many to be mostly made of rubber. They are in fact a complex combination of metals, minerals and hydrocarbons. Of the many constituent materials that go into making a tyre, the principle ingredient is indeed rubber. However this may be virgin rubber, synthetic rubber or recycled tyre rubber. Car and van tyres are mostly made of artificial rubber (Styrene and Butadiene polymers) and lorry tyres mostly of natural rubber (Evans 1997). Rubber constitutes approximately 30 percent of a tyre by weight with the remainder made up from other constituents including steel, nylon, polyester, rayon, carbon black, fiberglass, aramid and brass (Sonti *et al*, 2000).

Tyres are designed for specific uses and therefore can be found in a wide range of different size shapes and forms. However there are four main components common to most designs. These are:

1. the tyre 'Tread': the area of the tyre in contact with the ground providing traction
2. the 'Sidewall': which provides the shock absorbing/cushioning capabilities of the tyre and transfers the loads associated with steering, acceleration and braking
3. the 'Bead': made of high tensile steel fibre wrapped in woven rubberised textile which reinforces the interface between the wheel rim and the tyre
4. 'reinforcing cords': twisted fibres or filaments of nylon, rayon, polyester or steel that provide strength and stability.

These and other components are illustrated in Figure 3.1.

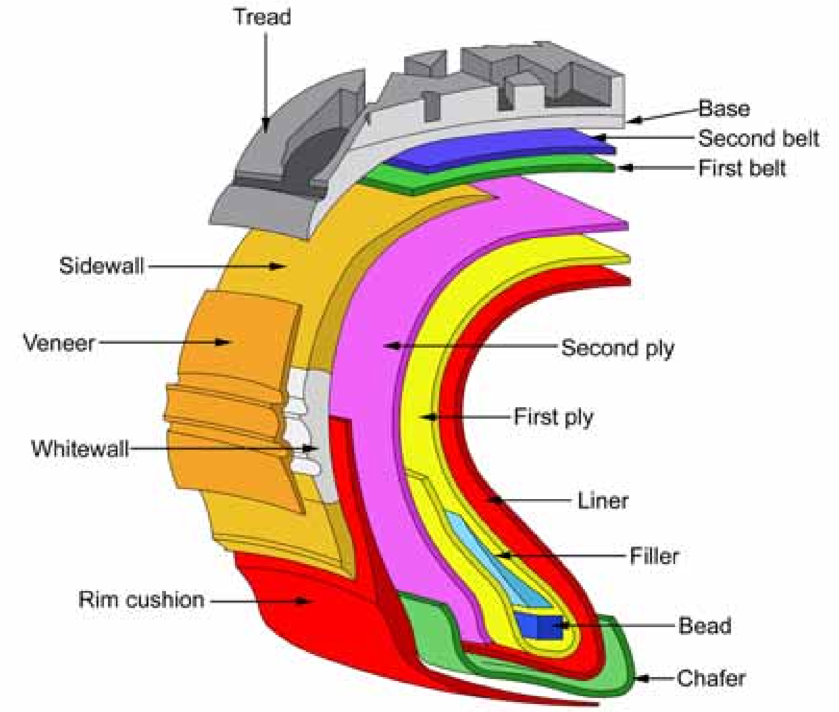

Figure 3.1 Structure of a typical radial car tyre (courtesy Cooper Tire and Rubber Company)

Tyres are made of vulcanised (i.e. cross-linked polymer chains) rubber and various reinforcing materials. The most commonly used tyre rubber is styrene-butadiene copolymer SBR containing about 25% styrene (O'Shaughnessy and Garga 2000).

The four principle ingredients used in the production of tyres are:

- natural and synthetic rubber
- carbon black and silica
- metal and textiles.

The percentage by weight of these and other components in car and truck tyres is shown in Table 3.3)

The remaining minor ingredients mainly consist of additives for facilitating compounding and vulcanisation.

Extenders: petroleum oils, used to control viscosity, reduce internal friction during processing, and improve low temperature flexibility in the vulcanised product, and Vulcanising agents (accelerators, activators and antioxidants): organic compounds (thiurams, dithiocarbamates, sulfenamides, guanidines and thiazoles (Evans 1997)) used as catalysts for the vulcanisation process, and zinc oxide and stearic acid, used to activate the curing system and to preserve cured properties (Amari, Themelis *et al.,* 1999)

Tyre sizes are classified according to the rim diameter. Car and van tyres are typically 35-41cms and lorry tyres 38-46cms in diameter. The sidewall of a tyre provides information such as the manufacturers name, the diameter of the wheel, the width of the tyre, ply composition, materials used and inflation pressure values.

Further information on the performance properties of tyres and comparisons with traditional materials are given in Section 2.1.

3.2 HOW CAN TYRES BE PROCESSED?

There are many processing methods for tyres many of which are now in common use:

- bead removal
- sidewall removal
- cutting
- compression
- shredding
- chipping
- ambient grinding
- cryogenic processing
- rubber reclaim
- reactivation
- surface modification
- pyrolysis
- resonance disintegration
- additive modification.

Table 3.1 outlines a number of applications for which tyres are suitable, and includes the grade of processing required to turn it into various products.

Table 3.1 Processing techniques, products and applications for post-consumer tyres (Shulman, V., ETRA)

CWA 14243 Post-Consumer Tyre Product Classification	Level 1 Mechanical treatment to enable the use of the tyre structure	Level 2 Size reduction to liberate and separate rubber, metal, textile, etc.	Level 3 Multi-treatment procedures to further process rubber	Level 4 Post-treatment process to upgrade the material
Type	Whole tyres	Cuts, Shreds, Chips, Granulates and Powders	Refined Powders or Char	Upgraded materials
Processing Method	Bead Removal Sidewall removal Cutting Compression	(+50mm and 7-15mm) Shredding, chipping Cryogenic processing Ambient grinding Repeated processing for finer materials	(0-0.5mm, 0.5-2mm and 2-7mm) Rubber reclaim Reactivation Surface Modification Pyrolysis	(<50µm) Carbon products Enhanced reclaiming Size reduction Surface treatment
Application	Construction bales Artificial reefs Reinforcement and Stabilisation of porous areas Temporary roads Landfill engineering Sound barriers	Shred and Chip: Landfill engineering Drainage for roads and construction Insulation Lightweight fill for roads, embankments, etc. Backfill Granulate and powder: Sports safety and play surfaces Road construction Footwear Flooring and roofing materials Livestock mattresses	Cable bedding compounds Insulation mats Sports and play equipment Domestic solid fuels Brick production Compounds for tyre inner and under liners	Pigments, inks, coatings Automotive appearance parts – strips, fenders Automotive engine parts Belts, gaskets, linings Thermoplastic elastomers

Brief explanations for some of these treatments/processes are:

Size reduction:

- mechanical treatment – any mechanical process by which tyres are compressed or cut, ripped or torn into irregular pieces, examples of which are baling, ripping or cutting
- ambient grinding – size reduction at or above ordinary room temperature
- cryogenic size reduction – size reduction at very low room temperature using liquid nitrogen or commercial refrigerant to embrittle the rubber.

Multiple-treatment technologies (e.g., rubber reclaim, devulcanisation):

- devulcanisation – the treatment of rubber that results in the reduction of crosslinks
- rubber reclaim – rubber produced by treating a vulcanisate in a manner to bring back some of its original characteristics

- surface modification – the result of treating the surface of granulates or powders to impart specific properties to the particle.

Other technologies:

- pyrolysis – the thermal pre-treatment of tyres in the absence of oxygen which chemically breaks them into oil, gas, char and steel
- post treatment of pyrolytic char – mechanical separation, physical or chemical treatments of the pyrolytic char.

3.3 HOW CAN THE QUALITY OF TYRE-DERIVED MATERIALS BE CONTROLLED?

The key standards for gradings, properties and products of tyres are listed here as given in the CEN Workshop Agreement (CWA).

It is the responsibility of the supplier of the materials to ensure that the necessary performance requirements are met by supplying a consistent and quality assured product.

Tyre processing can result in a wide range of material and product sizes from tyre bales down to fine powder. Table 3.2 lists the gradings within this range.

Table 3.2 Product grading sizes available from used tyres (Shulman, V., ETRA)

Material size	Minimum (mm)	Maximum (mm)
Powder	0	1
Granulate	1	10
Buffings	0	40
Chips	10	50
Shreds (small)	40	75
Shreds (large)	75	300
Cut	300	½ tyre
Whole tyre	-	-
Tyre bales	-	-

The applications or uses of post-consumer tyres broadly fall into two categories, civil engineering and construction uses, or, consumer and industrial products. ‘Applications’ generally refer to civil engineering; road construction and civil engineering, and sports and safety surfaces.

Generally, civil engineering and construction applications utilise large materials, i.e., whole treated or untreated tyres, shred and chips, whereas consumer and industrial products utilise the smaller sized materials, i.e. granulates, powders and buffings, for use in road and play surfaces and as specialised powders for sealants and coatings.

Most applications in coastal and river engineering fall into the first category, which is why this report focuses on the use of whole tyres, shred and chips.

There are three main ways (see chapter 5) that these materials can be utilised in coastal and fluvial engineering projects. These are:

- direct reuse, e.g. bank protection, breakwaters, fenders and artificial reefs (see case examples in chapter five) – in which the tyres require no prior processing
- compressed and baled into blocks using a mobile tyre baler (see Chapter 4) and used as fill material replacement/substitute, bank protection, and dam wall construction
- processed into rubber crumb and used in landscaping, soil conditioning, concrete and asphalt. (See section 5.3.2).

Standards and Specifications are required to ensure that a material meets the necessary performance criteria for any given application. In the case of tyres they play a major role in the decision making process. They reflect:

- whether tyres will perform adequately to meet the intended use
- whether project specifications allow or bar their use
- whether they are deemed as a suitable alternative material under published codes of practice.

Specifications therefore verify whether a product is deemed fit for purpose and ensure quality and conformity in the industry. However development of specifications takes time and often lags behind industry initiatives when it comes to utilising alternative materials.

The 'ASTM D-6270-98 Standard practice for use of scrap tyres in civil engineering applications (1998)' is a standard devised in North America primarily to meet the demand for tyres as an engineering material and to impose controls on their use and ensure fitness for purpose. It also provides guidance for the testing of physical properties and data for the assessment of leachate generation potential of processed tyres. It covers the use of shredded and whole tyres in lightweight fill and drainage applications, reinforced retaining walls and thermal insulation. No equivalent exists within the UK at the moment, although ASTM 1998 could provide a template for future development. Alternatively co-operation through partnership-based contracts could lead to the development of project specific standards.

In the UK guidance is available from the Environment Agency on the specific use of tyre shreds as a drainage medium in landfill sites. Specific engineering requirements are also given in the Landfill regulations.

The recent development of specifications for various forms of tyre products by the Comité Européen de Normalisation (CEN) should enable engineers to place confidence in their ability to build structures to the required design specification. Furthermore, as the new EN standards arising out of the Construction Products Directive do not distinguish between primary and alternative materials (i.e. the same quality requirements apply to all materials) there is no reason to exclude tyres or tyre derivatives unless they fail to comply with the general or 'fit for purpose' requirements. Proof of performance can be obtained through:

- investigation and research to determine acceptability prior to use
- reference to performance characteristics from a previous use outside the UK.

In any event the environmental regulators should always be consulted on all aspects of used tyre use in engineering projects to ensure they have no objection to proposed applications. This includes:

- the Environment Agency – for England and Wales
- the Scottish Environmental Protection Agency - for Scotland
- the Environment and Heritage Service for Northern Ireland.

The CEN specification lists some special considerations for using tyres or derivatives in civil engineering applications.

- All metal fragments shall be firmly attached and at least 95% embedded in the tyre fragments from which they are produced.
- No free metal wires or particles shall be included without being contained within a rubber segment.
- The ends of metal belts and/or beads are expected to be exposed only in the cut faces of some tyre fragments.

3.4 DENSITY OF TYRE MATERIAL

Tyres are made from a cross-link polymer and contain hundreds of compounds. The main components for tyres generally can be represented thus:

Table 3.3 Composition of passenger car and truck tyres in the EU (by % weight) (Shulman, V., ETRA)

Material	Density T/m^3	Car/Utility %	Truck/Lorry %
Rubber/Elastomers*	0.91	~48	~45
Carbon Black and Silica	2.3	~22	~22
Metal	7.6	~15	~25
Textile	N/A	~5	--
Zinc Oxide	N/A	~1	~2
Sulphur	N/A	~1	~1
Additives	N/A	~8	
* Truck tyres contain proportionately more natural rubber in comparison to synthetic rubber than do passenger car tyres.			

Using Table 3.3 and assuming that all metal is steel and that textiles and other small components and additives have a similar density to rubber, it is possible to estimate the density of tyre materials as follows:

Estimated car tyre density = 1.25 T/m^3
Estimated lorry tyre density = 1.28 T/m^3

Tests carried out by HR Wallingford (see Appendix 1) to determine the density of some tyre samples concluded that:

- measured tyre density on average equals 1.31 T/m^3, with a range of 1.27-1.34 T/m^3
- tyres of a greater radius are likely to be of a greater density than tyres of smaller radius.

Variations in the composition of tyres determines their differing properties of strength, durability and rigidity. Although these properties do vary it is generally accepted that composition is fairly consistent among European manufacturers. Table 3.3 shows the typical composition profiles for passenger car and truck tyres.

3.5 WEIGHTS OF WHOLE TYRES

Table 3.4 gives a range of weights for different tyre types.

Table 3.4 Average weights of used tyres (Shulman, V., ETRA)

Tyre Type	Average weight kg	Number per tonne
Passenger car	6.5 – 7.0	153.8
Utility	11	90.9
Truck/Lorry	52.5	19

3.6 OTHER PHYSICAL PROPERTIES OF TYRES AND DERIVATIVES

The physical properties of tyres that make them suitable for civil engineering are listed in the published guidance, CEN, 2002, and tabulated below.

Table 3.5 Typical values for physical properties (Shulman, V., ETRA)

Physical property	Typical Values
Angle of friction	19 – 26^o
Bulk density	~350 – 500 kg/m^3
Compacted density	600 – 700 kg/m^3 (rising to 990 kg/m^3 under 400kPa vertical stress)
Cohesion (kPa)	5 – 1
Compressibility	20 – 50% (at 21 – 147 kN/m^3)
Hydraulic conductivity	1 x 10^{-2}-1 x 10^{-3} m/s
Loose bulk density	3.3 – 4.8 kN/m^3
Particle size	Chips to bales
Poisson's ratio	0.2 – 0.35
Resilient modulus	1 – 2 MPa
Specific gravity	1.1 – 1.27 t/m^3
Thermal Conductivity	0.15 – 0.23 W/mK
Water absorption	2 – 4%

Field trials with appropriate testing will usually prove sufficient to indicate whether tyres are suitable for a particular application or not. Greater knowledge will come from the experience of developing testing regimes and pilot studies specifically designed to assess their performance.

Tyres provide the following properties which engineers will find useful in appropriate situations (also see Table 2.2).

Compacted dry density – for shredded tyres is one third to a half that of a typical soil (Humphrey *et al*., 2000). This makes them attractive for use as lightweight fill for embankment construction where the foundation soils are weak or compressible, and where stability or excessive settlement is a concern (embankments or for stabilisation of landslides).

Thermal resistivity – is around seven to eight times greater than for a typical granular soil (Humphrey *et al*., 2000). This makes tyres suitable as an insulating layer to resist freezing better than traditional construction materials under winter conditions.

Hydraulic conductivity – shredded and whole tyres have a high hydraulic conductivity making them useful for drainage applications such as French drains, drainage layers in landfill liner and cover systems, and leach fields for on-site sewage disposal systems.
Combined properties – The combination of low compacted dry density, high hydraulic conductivity and low thermal conductivity makes tyres attractive for use as backfill for retaining walls.

Horizontal stress – tyre shreds produce low horizontal stress due to their low compacted dry density that reduces the pressure on a backfilled structure. This renders them suitable for use as fill behind walls and bridge abutments. This can prove useful where thinner walls are required. (See section 5.3)

Construction – whole tyres and sidewalls can be used to construct retaining walls or be bound together to form drainage culverts. (See section 5.1)

Tyres thus far have been found to be a useful alternative to primary aggregates for a number of applications where:

- they are relatively abundant and freely available
- a lightweight material is needed as a low density fill material, or to reduce ground loading. Materials normally used for lightweight fill applications include:
  - light weight expanded clay aggregate
  - lightweight concrete
  - pulverised fuel ash (PFA) – where sources are still derived from the burning of stocks of coal that produce a lightweight residue
  - expanded polystyrene blocks

- a durable and flexible material is required. (This may be important for uses intended to prevent or reduce damage to the local environment, such as in sports and recreational facilities.)
  Other materials which have been used for sports and recreational facilities include:
  - traditional asphalt
  - gravel
  - natural turf
  - woodchips
  - sand and bound sand
  - wax

- a free draining alternative to gravel is needed
- a material with a high resistance to chemical activity is needed such as in hydrocarbon retardation ground barriers
- there is a need to develop a stable structure, for instance where baled tyres can be stacked as building blocks (e.g. as a noise barrier).
- other materials normally used for noise barriers include:
  - expanded polystyrene
  - lightweight clay aggregate
  - earth
  - timber
  - coarse sand and gravel

- there is a need for a large surface area such as in artificial reefs for marine organism growth and habitat creation

Other materials normally used for artificial reefs include:
- concrete blocks and structures
- aggregate blocks

- they act as an aggregate replacement such as in asphalt, concrete or other hydraulically bound materials.

Further details of these and other uses can be found in Hylands and Shulman (2003).

3.7 LIMITATIONS TO THE USE OF TYRES IN CEMENTITIOUS CONCRETE

There are limitations however to the use of tyre materials, specifically for Portland Cement in concrete applications. The durability of coastal structures, such as concrete seawalls, and their ability to resist abrasion and chemical attack is very important. Any structure on a sand or shingle foreshore will be subject to some degree of abrasion as a result of the impact of particles driven by hydrodynamic forces. This abrasion (for example see Figure 3.2) can significantly affect the residual life span of a concrete structure. Abrasion rates in excess of 6mm/yr have been experienced at sites where concrete structures are located in very aggressive environments.

Figure 3.2 An example of hydrodynamic abrasion exposing steel reinforcement in a concrete seawall

The exposure conditions, the quality of aggregate, the density of the concrete mix and the cover to steel reinforcement are all key factors that influence the durability and design life of such structures. To minimise the damage done by abrasion, it is essential in susceptible areas of the structure to use concrete with a strong and dense mix comprised of hard aggregate and strong cement.

Past research by the Universities of Nova Scotia and Pennsylvania (Ali *et al*, 1993, and Rostami *et al*, 1993) indicated that the inclusion of rubber in Portland cement concrete interferes with the adherence of the cement matrix to the aggregate, such that areas of weakness occur in the transition zone (i.e. the aggregate/matrix interface). As a result, the compressive strength of concrete that contains ground rubber or tyre crumb is significantly less (between 10 and 20N/mm^2) than a typical design mix used during the construction of coastal defences (e.g. 40N/mm^2).

Studies by the University of Pennsylvania confirmed the conclusions arrived at by the Technical University of Nova Scotia in that:

- the addition of ground tyre rubber (GTR) to Portland Cement concrete decreases both the compressive and tensile strength properties and increases air content
- further research, specific to the intended service conditions of the material, is required to determine the feasibility of using GTR products.

Further questions also arise over the use of GTR in concrete such as:

- the bonding potential with steel reinforcement
- cracking as a result of thermal contraction during cement hydration
- the potential for chloride ingress and corrosion of steel reinforcement.

Further scientific research would be required to resolve questions arising from these concerns.

Another concern is with the concept of using whole tyres and tyre bales as a hearting in concrete blocks or mass concrete. Tyres are ductile and responsive to temperature changes. Without a method of 'fixing' the expansion and contraction properties of tyres, internal micro-cracking of the cementitious mix would be anticipated. A progressive deterioration of the cement/filler matrix would follow as seawater would be able to penetrate further into the body of the wall, gradually diminishing its structural integrity and leading eventually to failure.

For these reasons the use of whole tyres, baled or otherwise, or other tyre derived products (such as chips, shreds, granules or powders) are not currently deemed suitable for use in 'marine grade' concrete where minimum tensile and compressive strengths are specified.

The only exception would be where whole tyres or tyre bales are used as a hearting to reinforced concrete blocks. Here the reinforcement would need to be designed, amongst other loadings, for the expansion and contraction of the tyres inside. No information is currently available on the magnitude of these loadings.

4. Tyre bales – production, properties and use

The type of technology now available for tyres to be baled together is shown in Figures 4.1 and 4.2. These bales consist of approximately 100 tyres compressed by a down-stroke baler and held in compression by plastic strapping or galvanised wire (see Figure 4.3 and 4.4).

Figure 4.1 Loading baler hopper

Figure 4.2 Baler discharge

These tyre blocks or bales are suitable for use in a range of engineering applications including:

- construction of flood embankments, dams and breakwaters
- road sub-bases
- river and stream banks.

The equipment used to bale tyres may be a fixed or mobile unit. Mobile balers can be of great cost benefit as it can avoid the costly transportation of loose tyres to a processing/baling centre, or/and from the site of baling to a construction site.

The most common version of this type of equipment is a vertical down-stroke baler that compresses passenger car and light utility van tyres, although there are larger units available for truck tyres.

4.1 BASIC PROPERTIES OF PROTOTYPE BALES

The size of the bale is determined by the chamber size of the baler and the length of the wrapping wires or straps. Firstly about 100 or so tyres (car/van or ~ 90 truck) are placed into the bale chamber in a weave pattern. Next the hydraulic compactor compresses the tyres for 10 to 20 seconds with around 65 tonnes of pressure into a rectangular block measuring roughly 75cm x 150cm x 135cm and weighing about 1 tonne. This block is then 'baled', bound up with five, 4 metre long bands of 4mm thick high tensile, high carbon, electro-galvanised or stainless steel wires. These wires have a tensile strength of 1500 to 170N/mmz. Revetment cord is also sometimes used.

Figure 4.3 Galvanised steel wire fastening

Tests have shown that once compressed the tyres will not regain their original shape if the retaining cords/wires are removed. After thirty months retained in a bale the contents were shown only to expand by 5% (Hylands and Shulman, 2003).

Completed bales can be used as they are or further treated by encasing them in concrete, wrapping them in plastic or wire mesh, or facing them with a veneer of other material such as stucco, marble or stone.

Figure 4.4 Baled product containing approximately 100 used tyres (courtesy Environment Agency)

In order to reliably define the performance characteristics of tyre bales in fluvial and marine structures investigations were undertaken in the hydrodynamic testing facilities at HR Wallingford. These investigations followed a proven method of submitting scale models to a series of replicated hydrodynamic forces until structural failure occurs (See Appendices 4,5 and 6).

4.2 WEIGHT/POROSITY

The porosity of the tyre bales is important to measure due to its effect on hydraulic and geotechnical interactions i.e. pore pressures, bulk density and their effect on stability and settlement. For example, the accepted average porosity value for large, well-placed normally graded stones is about 42% but widely-graded mixtures may have smaller porosities (CIRIA/CUR, 1991).

Porosity and weight was measured in tests undertaken at HR Wallingford, an account of which is given in Appendix 2. Two bale types from different bale producers were tested. The two bale types supplied looked to have different degrees of compression and therefore porosity. The tests reported in Appendix 2 set out to establish what the porosities were and how much they differed between the two bale types.

The tabulated results of the tests are shown below. The study concluded that:

- tyre bale porosity is comparable to aggregates such as gravel (i.e. it is in the same order of magnitude)
- generally the porosity of tyre bales is high, over 50%
- the smaller bales had a slightly higher porosity than the large bales
- in the small bales the packing density of tyres is slightly less. The effective porosity (i.e. the amount of interconnected pore space available for fluid transmission) is greater for small bales which is expected as the tyre packing is more random.

Table 4.1 Tyre bales size, porosity and bulk density

Bale label	Total volume (m^3)	Porosity %	Bulk density (Kg/m^3)
3	1.09	50	655
5	1.25	56	580
7	0.74	65	458
8	0.74	59	542
9	0.71	57	561

N.B. Bales 3 and 5 are larger bales and from a different manufacturer.

Table 4.2 Tyre bale size, solidity and sealed volume

Bale label	Weight of bales (Kg)	Volume of tyre material (m^3)	Solids as % of whole	% of voids sealed
3	712.5	0.54	50	15
5	725.0	0.55	44	10
7	337.5	0.26	35	15
8	400.0	0.31	41	19
9	400.0	0.31	43	17

Table 4.3 Comparison of total and effective porosity with other building materials (EAD, 1993)

Material	Total porosity (%)		Effective porosity (%)	
	Range	Arithmetic mean	Range	Arithmetic mean
Gravel (coarse)	24 - 36	28	13 - 25	21
Sand (coarse)	31 - 46	39	18 - 43	30
Sand (fine)	25 - 53	43	1 - 46	33
Silt	34 - 51	45	1 - 39	20
Weathered granite	34 - 57	45	-	-
Tyre bale - large	50-56	53	42-50	46
Tyre bale - small	57-65	60	47-55	50

- *denotes no data available*

The tyre bales have a greater porosity than coarse gravel which the bales would hope to replace. However, the permeability of the bales is of a similar order to gravel (see Section 4.5). This is believed to arise because of the tortuosity of the void volume within the bales.

Under static loading porosity may be affected over a medium to long time frame.

Bale porosity may decrease with intrusion of sediments (e.g. from beaches). The extent and rate of the intrusion is not known but, if significant, may have important effects on the bale bulk density, settlement, porosity and permeability.

4.3 INTERBALE FRICTION

Interbale friction forces were also measured in testing at HR Wallingford (see Appendix 3). The test revealed that the interbale friction coefficient, μ, averages 0.7 (range from 0.6-0.8) where interbale friction force, F = μ x normal force between bales.

4.4 RESISTANCE TO DEFORMATION AND CREEP

Conclusions from the Pevensey Bay pilot project (see Box 5.2.3) monitoring on settlement, deformation and creep (see Appendix 8) indicate that tyre bales are very stable and deform very little even under compression and strain, and a marginal benefit is gained by filling the bale voids with aggregate. The conclusions drawn from the monitoring of the site were that:

- long term settlement/creep of filled bales over 18 months (about 0.4% strain) was about half that of the bales which were only wrapped (0.9% strain)
- there was no evidence of bales moving up through the beach
- the bales appear structurally to be very stable.

4.5 PERMEABILITY

Permeability is usually referred to for soil structure stability. It is important for the geotechnical problems of seepage through beach sand, consolidation of backfills and hydraulically placed fills and settlement of foundations (Hughes, 2002). Tyre bales are sought to replace soil fill and so permeability needs to be determined.

The permeability of tyre bales was determined in the high discharge flume at HR Wallingford (see Appendix 4). Darcy's law was used to determine the permeability of each tyre bale.

The study concluded that:

- the tyre bale permeability is of the order of 0.1m/s and thus is similar to gravel or very coarse sand.
- despite the large size of tyres, they have a large surface area and create a long flow length.
- permeability is greater when the length of pathway is short (i.e. the bale is upright in position). When the bale lies flat the length of pathway is long and the permeability is less. This could be as a result of how the bales are manufactured.
- when the pathway is long the tyre rims are obstacles creating a long flow path. More direct flow paths are available when the pathway is short.

4.6 USE OF TYRE BALES AS PRIMARY ARMOUR

One consideration of the use of tyre bales has been for primary armour units - for example as erosion protection in coastal and river revetments. However due to their light weight it was necessary to establish exactly what forces such a structure would be able to sustain without damage or failure. The quickest and easiest way to do this was to replicate a model/scale version of a possible structure built of tyre bales and test it against those forces in a controlled environment.

Firstly scale models of tyre bales had to be made that as closely as possible possessed the same physical characteristics as the full size versions (see Appendix 5). Experimental mock-ups of two types of structures, a wave revetment and a river revetment, were conducted to discover the best method and configuration of construction. The final models were then tested in flumes for hydrodynamic performance, one for wave attack and the other for river flow. Details of the studies are described in Appendices 5 and 6.

4.6.1 Tyre bales as primary armour under wave action

Tyre bales are entirely unsuitable for use as primary armour in any situation where they are subject to any significant wave action. Even after trying a range of placement techniques, the bales were only stable to wave heights of about 0.2m. The explanation appears to be related to the fact that the permeability of the bales, at about 0.1m/s is too slow to respond to dynamic water level and pressure variations. As a result, the bales, which do not contain water when wave action commences, cannot absorb the water before buoyancy forces lift them out of the slope.

4.6.2 Tyre bales as primary armour under conditions of steady flow

The results of the tests described in Appendix 6 suggest that tyre bales may be suitable in certain circumstances as primary armour when subjected to river flows alongside them. A configuration in which the bales were placed to an angle of 6^o to the vertical proved stable up to flows of 4m/s in water depths less than 2.5m.

Caution should be applied in using these results. In particular:

a) The results appeared to be highly dependent on the nature of the backfill. In the tests, failure arose from settlement of the backfill rather than toe instability; this suggests that more impermeable backfill (clay) may be preferable to granular materials, so long as an appropriate geotextile interface is used.
b) The applicability of the results should be limited to small streams and river situations where wave heights will not exceed 0.2m (see 4.6.1 above).

Subject to these constraints, it does appear that tyre bales can be considered for use as primary protection in river situations similar to those in which stone-filled gabions might previously have been employed.

4.7 PRACTICAL ASPECTS OF DESIGNS USING BALES

Tyre bales provide particular advantage in areas with poor soil conditions. In wet soils bales can be used effectively as a sub-grade base to ‘float’ over marginal areas.

Bales used in structures built above ground should be placed on a cement pad or geotextile liner. Under water use or below the water table, such as a foundation layer for a dam or artificial lake does not require the installation of a geotextile. However installation is specific to each site and consideration must be given to the local conditions such as:

- soil quality
- water quality
- proximity to receptors
- stability
- climate, etc.

If the bales are to be used in bulk and it is necessary to keep consistent permeability, it is suggested that the voids between the bales be filled with gravel and/or coarse sand. This will not be necessary if the whole bale structure is being wrapped in a geotextile.

The surround may be finished with stone or other construction materials.

Each structure must be designed (and monitored) by a professional civil engineer or geotechnical designer.

4.8 PRODUCTION, HANDLING AND STORAGE

When processing into bales, tyres should be relatively dry, clean and free from mud and contaminated materials (either on the surface on inside the tyre cavity). Tyres should be placed carefully when loaded into the hopper of the baler; orientated sidewall to sidewall and slightly overlapping tread to tread (When compressed this produces the distinctive ‘herring-bone’ pattern visible on the surface of the bale). Foreign material on the tyres may inhibit uniform compression and result in distortion of the bale. This is undesirable because dimensional consistency is an important characteristic in construction.

Personnel involved in the baling operation should wear appropriate protective clothing such as gloves, overalls and toe-capped boots when handling used tyres. Hazards include exposed wires, tripping, and abrasion from lifting, dropping and handling tyres increasing the risk of back, limb and digit injury such has rubber burns, skin puncture, muscle strains and foot crush injury. A risk assessment should be undertaken to assess whether additional precautions should be taken.

Operators should be aware at all times when the machine is in operation and ensure that the discharge area is clear of all personnel when ejecting the bale from the baler. Wrapping fasteners should be immediately checked to ensure that they are secure. Ear protection should be worn if noise generated by the machinery is above the prescribed limit.

Health and Safety at Work regulations (1992) and guidelines should be consulted with respect to these concerns and others such as lifting and handling of goods. They should be considered and enforced by those responsible for health and safety during the baling operation. Crane, forklift or other machinery operators should be adequately trained and ensure that they comply with the regulations and that their vehicle is capable of performing the required lift, movement and placement of tyres and bales in a safe manner under the prevailing site/ground conditions. Employers should ensure that they, their machinery and their operations comply with all relevant legislation including:

- Health and Safety at Work etc. Act 1974
- Management of Health and Safety at Work Regulations 1992
- provision and use of work equipment regulations 1998
- lifting operations and lifting equipment regulations 1998.

Tyre bale storage requirements are generally determined by local authorities. The bales do not retain much water and their decreased surface area and lack of air ingress greatly reduces the threat of fire. Recent fire tests commissioned for this project (see Appendix 7) concluded that:

- the ambient temperature of the tyre bales in storage and when used in civil engineering works should be maintained below the calculated lowest critical ignition temperature of 182°C, in order to avoid self-heating
- the use of inert material, such as gravel, in construction to surround tyre bales would be advantageous, as it can be assumed that the bales are single entities and this would increase the critical ignition temperature of a single bale to 224°C

- the tyre bales should not be used in civil engineering works in areas where there may be an increased risk of heating from external sources such as subterranean fires
- if the characteristics of the final product material were to change significantly, i.e. different tyre bale material, it would be necessary to re-assess the self-heating properties of the material
- bales should be stacked/stored facing sidewall to sidewall.

Loading and offloading tyre bales from flat-bed lorry trailer units are easily and safely facilitated with the use of a mounted crane and pallet grab (See Figure 4.5). Placement of the bale into a structure is best achieved with a similar attachment as shown in Figure 4.7. The hydraulic functions of the gib and head-stock allow precision and accuracy of movement for optimal control including 360^0 plane rotation of the bale for choice placement.

Figure 4.5 Offloading tyre bales from a delivery vehicle at a project site. (courtesy Environment Agency)

Around $30m^3$ of tyre bales can be transported by one lorry as opposed to, for instance, $10m^3$ of clay. This is because tyres are significantly lighter than clay. The same comparison would apply to all other aggregates and alternative materials under consideration in construction. Fewer trips for the same volume and less weight in transport terms also equates to less fuel consumption. Thus, so long as there is a local supply of used tyres there will often be a net benefit in terms of traffic and transport impacts by using tyres as opposed to traditional aggregates in construction projects specifically.

Figure 4.6 **River transport of bales on final journey to construction site (courtesy Environment Agency)**

Figure 4.7 **Placement of tyre bale into structure using a pallet grab attachment (courtesy Environment Agency)**

The low-density high volume nature of tyre bales also makes for easier access to remote sites utilising vehicles other than lorries. At the River Witham bales were transported from their delivery point to the construction site by barge as shown in Figure 4.6. In the Scottish highlands near Glen Urquhart, bales were carried a short distance from a forest track to the construction site (see Box 5.2.5), offloaded, and placed using an articulated forestry transporter with a standard log grab attachment as shown in Figure 4.8.

Figure 4.8 Forestry log transporter used at Glen Urquhart to access the site with tyre bales (courtesy Northern Tyre Recycling)

5. *Port, coastal and river engineering applications of tyres*

There are many instances of the use of tyres in port, coastal and river engineering, but they are not well documented and what is recorded is not very comprehensive. Here we have attempted to draw together illustrations, designs and case histories of specific structure types from both new and old schemes[4]. Some suggestions for future innovation in design are also made. Uses have been classified into three distinct categories:

a) Whole tyre solutions including:
   - embankments/retaining walls using loose tyres
   - embankments/retaining walls using linked tyres
   - tyre and post erosion protection
   - anti-scour mattresses
   - floating breakwaters
   - submerged reefs
   - fenders for shipping

b) Tyre bale solutions:
   - hearting to concrete structures
   - hearting to coastal rock structures
   - beach nourishment substitute
   - hearting to embankments
   - armouring to banks of small rivers/streams

c) Tyre chip solutions:
   - lightweight backfill behind retaining walls
   - aggregate in asphaltic concrete

5.1 WHOLE TYRE SOLUTIONS

5.1.1 Embankments / retaining walls using loose tyres

Loose tyres, typically with one sidewall removed, have been used as singular building blocks filled with gravel, shingle, soil or sand in retaining walls or for slope stabilisation in embankments. One example is the retaining wall on the Mill Burn near Inverness in Scotland (see Box 5.1.1) where successive tyre layers were stepped back to increase stability.

[4] These case studies and examples are for illustration only. Inclusion here does not infer that the authors recommend these applications.

Box 5.1.1 The Mill Burn landfill revetment, Inverness

The Mill Burn cuts across the Longman Landfill Site (see Figure 5.1) just outside Inverness and discharges into the Moray Firth which is inhabited by many protected species. Flow through the Burn is highly variable with contributing urban drainage from nearby industrial areas and flood flow from the A9 road as well as being tidal.

Figure 5.1 The Mill Burn as it cuts through Longman Landfill Site (courtesy Environment Agency)

Figure 5.2 The tyre revetment beside the Mill Burn (courtesy Environment Agency)

Box 5.1.1 The Mill Burn landfill revetment, Inverness (continued)

To accommodate the landfill site here the Mill Burn route itself had to be engineered in order to prevent erosion of the adjacent landfill area by the river.

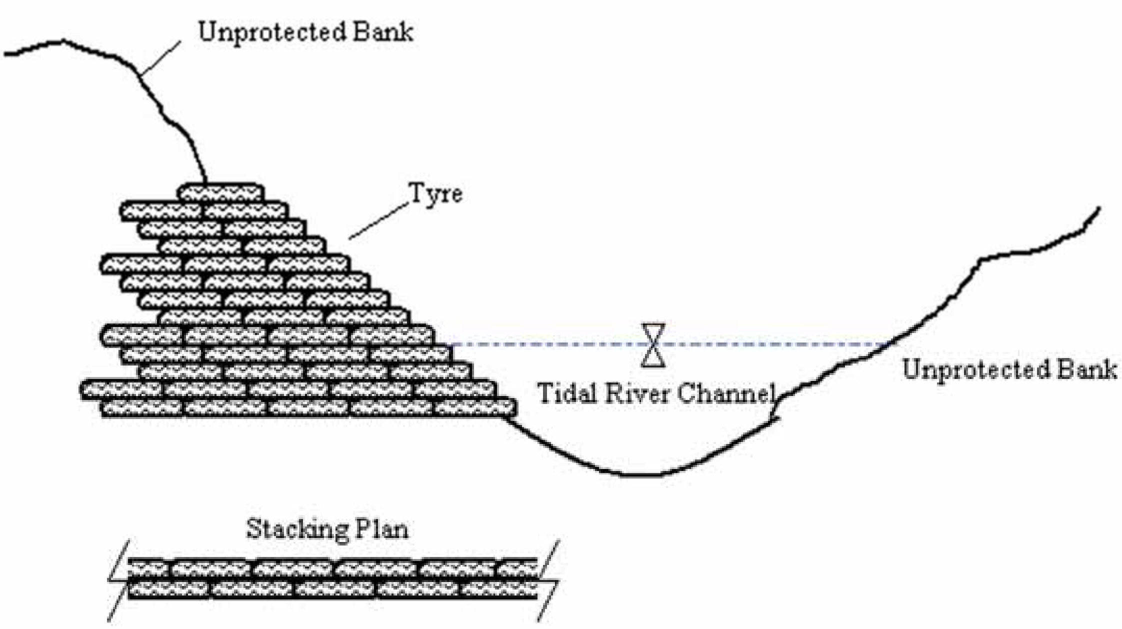

Figure 5.3 Schematic of the tyre revetment/retaining wall on the Mill Burn

This application presents a potential alternative to stone filled gabion boxes. However, where the tyres are less subject to wetting and more accessible to the public, there is a fire risk.

Construction took two men six months in 1984 to build a wall four metres high by 240 metres in length made of tyres (with one sidewall removed) filled with gravel.

The trials in Brazil reported in Box 5.1.3 alluded to the problems of using whole tyres (i.e. without the sidewall removed) in gravity walls. There is a potential conflict between the time spent filling tyres and stability of the structure. The more the tyres are filled, the higher the composite density becomes. This has the advantage that the width of the wall and the number of tyres can be reduced and the rigidity of the wall increased. However to obtain greater filling of the tyres requires more time and effort. Furthermore, any void formed by incomplete filling would tend to disappear as the wall height and vertical load built up and the tyre distorted. This distortion is beneficial in that it increases contact area and interlock between tyres. Conversely of course the tyre preparation involved in removing sidewalls also takes time, however filling is easier and composite density higher (WYMCC, 1977).

Loose truck tyres have been used to construct a seawall in a sheltered environment within a small harbour in Scotland (See Box 5.1.2). Currently from a structural perspective the tyres perform adequately. However in the longer term physical degradation from UV light exposure would be anticipated together with loss of structural integrity due to loss of covalent bonding chemicals through continual leaching.

Box 5.1.2 Avoch harbour seawall defence, Scotland.

Although relatively low in height this wall is retained in place by tyres used in the same manner as those at Mill Burn. In this instance they also serve as some protection against erosion of the former seawall defence. The tyre voids were filled with coarse local chippings. Washout of fines is apparent with the formation of some voids and loss of fill from inside and between some of the tyres. However sufficient material remains to keep the structure stable in this relatively wave sheltered environment.

a)

b)

c)

Additionally the structure is not particularly aesthetically appropriate in this setting, although vegetation has established on part of an earlier build slightly improving the appearance here.

Figure 5.4 Avoch harbour tyre wall, Scotland

5.1.2 Embankments/retaining walls using linked tyres

Some tyre walls have experienced lateral deformation where negative wall friction at the back of the wall (caused by the higher compressibility of tyre retaining walls) has significantly increased the active pressure acting on it. To reduce the risk of lateral deformation it is recommended that tyres are connected in some way and anchored at intervals into the backfill. The research conducted in Brazil described in Box 5.1.3

examined the effects of using tyres with and without one sidewall removed and in using tyre linkage and tie-back methods.

Box 5.1.3 The geotechnical behaviour of soil-tyre gravity walls

A research project conducted in Brazil run by the Catholic University of Rio de Janeiro (PUC-Rio) jointly with the University of Ottawa, Canada, and the Geotechnical Engineering Office of Rio de Janeiro (Geo-Rio) investigated the geotechnical behaviour of soil-tyre gravity walls (Sayão *et al*, 2002).

Approximately 15000 car/van tyres were used to build a wall 4m high and 60m long. Tyres were placed side by side, in successive horizontal layers, some with sidewalls removed, others not. A comparison was also made between 6mm polypropylene rope and 2mm thick plastic-coated galvanised zinc wire for tying the tyres together in their layers.

Compaction of soil inside the tyres was carried out manually with a vibratory plate. The backfill to the wall was made out of compacted soil at optimum water content. The locally available soil, a gneissic sandy silt residue soil was used. When the wall was finished an additional 2m surcharge of soil was added to the backfill.

Subsequent displacement measurements indicated that although all sections were within acceptable limits, the wall section that comprised of a combination of cut tyres (sidewall removed) with galvanised wire fastenings proved to be less deformable and had less horizontal displacement than the other options.

Following the trial several slope stabilisation projects in Brazil built tyre-soil gravity retaining walls.

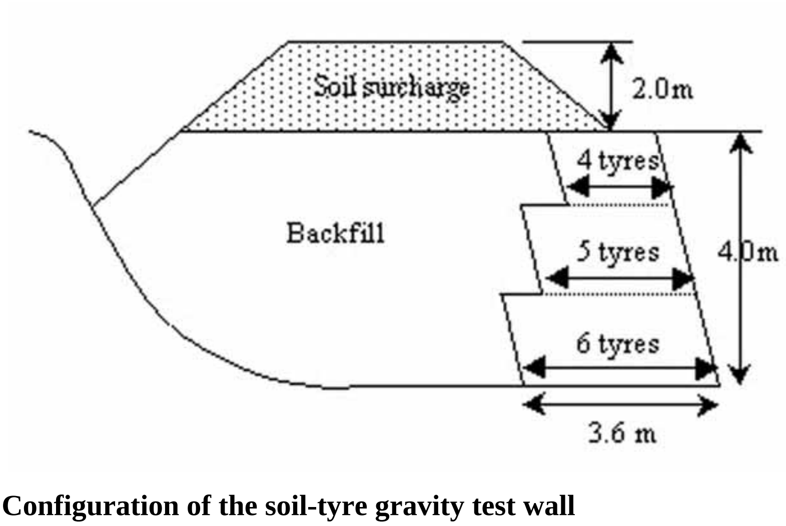

Figure 5.5 Configuration of the soil-tyre gravity test wall

Dalton and Hoban (1982) conclude that anchored or tied-back walls offer a more efficient solution than those without, in that fewer tyres have to be prepared and filled for a given length of wall. The face of the wall should be formed from a single line of tyres laid tread to tread with alternate layers secured to anchor tyres at regular intervals (as shown in Figure 5.6) with Paraweb webbing or similar. This provides sufficient tensile strength to resist the forces causing local failure to the tyre wall face and preventing wedge and slip circle failure within the block.

Truck/lorry tyres can also be used in this way. Removal of the sidewall from truck tyres is not so important as these tyres are heavier and access for filling the tyres with 'ballast' is easier due to their larger size. Linkage of the tyres however is still recommended as lateral deformation or loss of individual units may still occur, especially if subject to wave or tidal forces as described in the Copperas Wood example in Box 5.1.4.

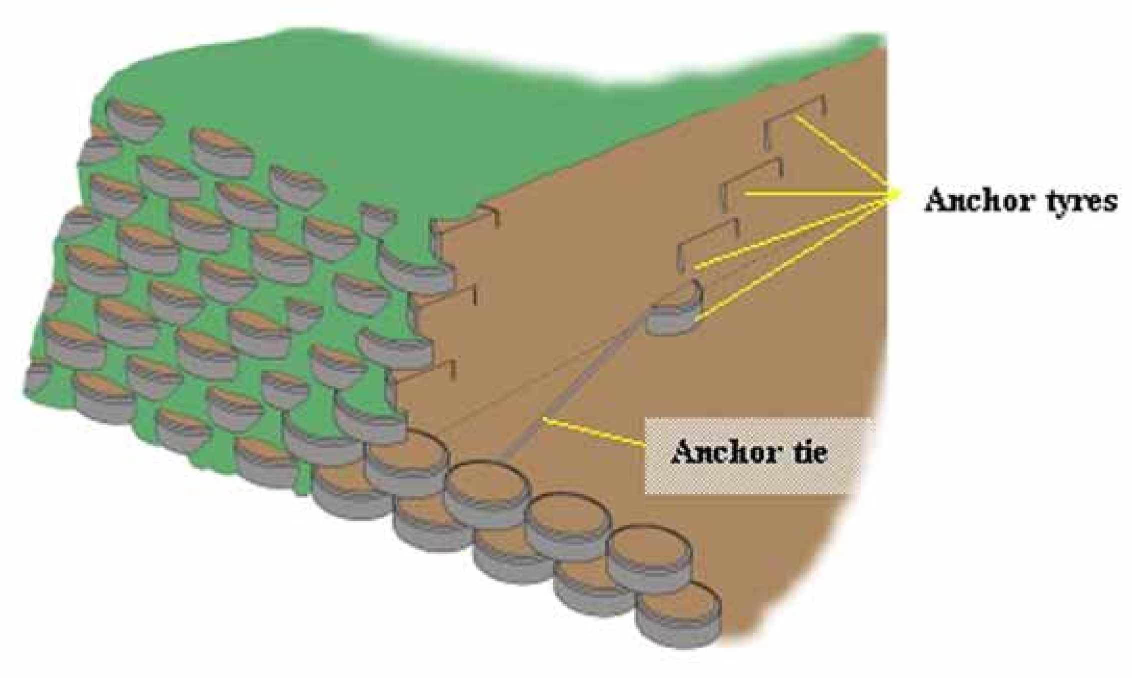

Figure 5.6 Gravity retaining wall structure showing anchor ties and tyres

Box 5.1.4 Retaining wall/erosion protection - The Sorrell system (EU Patent: 0537261)

Whole tire mats (two tyres deep) stacked 4 high into rafts were used to protect 150m of foreshore in Copperas Bay in the Stour Estuary (Suffolk /Essex boundary, UK) (see Figure 5.7). The Stour estuary has exhibited some of the highest rates of historical salt marsh loss in the UK. Copperas Bay has experienced near total saltmarsh loss, and ancient oak and coppiced woodland begun to be lost as the toe of the low cliff was destabilised by wave action.

Figure 5.7 The Copperas Wood defence soon after construction (courtesy of Sorrell Flood Protection)

Figure 5.8 The same defence after 4 years (courtesy of Sorrell Flood Protection)

Box 5.1.4 Retaining wall/erosion protection - The Sorrell system (continued)

Partly buried within a shallow trench cut into the upper foreshore along the cliff base keeps the tyres stable under all the tidal conditions experienced with no evidence of floating up during high water levels (Watson and French, 1999). Post installation monitoring has shown the system to be extremely stable and with no discernible displacement observed during the first 18 months. Shortly after installation when a high tide overtopped the defence, some removal of soil from the voids between the tyres and from on top of the structure was observed. However since then no subsequent problems of this nature have occurred (See Figure 5.8) and seaweed has successfully colonised areas of the structure reached by the tide (see Figure 5.9).

Figure 5.9 Algal growth on the Copperas Wood tyre embankment (courtesy Dr Ken Collins)

The structure has successfully halted further erosion of the woodland above the low estuary cliff and no further trees have been lost from the slopes behind the defence.

Garga and O'Shaughnessy (2000) came to the following conclusions that used or whole tyres could be used for reinforcing slopes and retaining walls after conducting trials using whole and part-whole tyres tied together with polypropylene rope. They found that:

- such structures are relatively simple to construct using conventional fill-placement equipment
- reinforced earth structures using used tyres can be constructed with both cohesionless and cohesive soils

- with cohesive backfills only tyres with one sidewall removed should be used to improve compaction capabilities
- negative wall friction at the back of the wall, brought about by the higher compressibility of tyre retaining walls can significantly increase the active pressure acting on the wall. This can be reduced by inclining the wall
- the angle of inclination of the retaining wall should not exceed 70^0 when using low quality compressible backfill
- compaction should be undertaken behind the retaining wall to limit development of high lateral stresses and reduce outward lateral deformation
- lateral deformation of walls using tyres with one side wall removed is significantly less than that with whole tyres
- tyre reinforced fills can provide satisfactory foundation for medium to lightweight structures.

5.1.3 *Tyre and post erosion protection*

Tyre and post revetments have also been built to prevent coastal erosion but with limited success. Tyres placed around posts piled into the beach are then filled with gravel to consolidate the structure. However washout of the fill from the tyres by wave action reduces their weight allowing them to become displaced relative to one another. Increased movement and disturbance of the tyres accelerates degradation of elements such as the geotextile and allows erosion of the backfill material.

Box 5.1.5 Tyre and post revetment in Oak Harbour, Washington

The tyre and post revetment in Oak Harbour, Washington, in the USA consisted of two lines of vertical posts driven into the beach (see Figure 5.10). Car tyres were laid over the posts, filled with gravel and a filter cloth placed between the tyres and the backfill. The structure performed successfully but the gravel fill was lost from inside the tyres and there was some erosion of backfill.

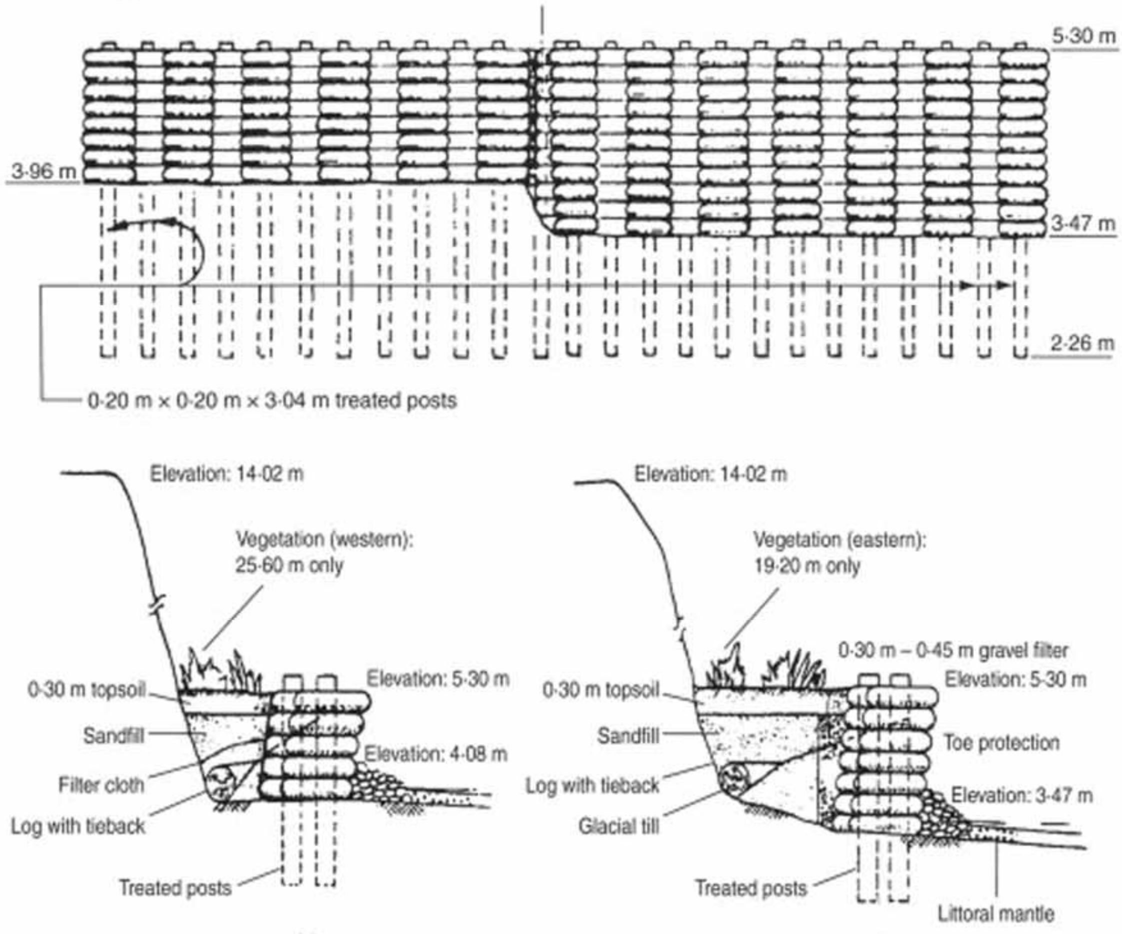

Figure 5.10 Schematics of the tyre and post revetment at Oak Harbour, Washington, USA (Motyka and Welsby, 1983)

Performance of this structure could have been improved by filling the tyres with a lean concrete mix instead of gravel.

Similar problems have been encountered on river bank/training walls of similar design to that at Oak Harbour. The River Bure example in Box 5.1.6 illustrates how tyres can ‘slump’ on their poles allowing further subsidence and erosion of the backfill material.

Future works contemplating similar tyre and post revetment designs would be strongly advised to consider filling the tyres with a lean concrete mix or using another method to stabilise them under wave or fluvial action.

Box 5.1.6 River training wall on the Bure in Norfolk

The Environment Agency used rubber tyres in bank protection along the River Bure near South Walsham in Norfolk. Constructed in 1987 on the outside of a meander, it was designed to protect the riverside footpath from undercutting by erosion. This was carried out as part of a trial along with other methods of bank protection and proved to be successful. However, it did prove difficult to install the tyres underwater as horizontal connections could not be obtained and backfill material was lost owing to the movement of the tyres under wave attack. Although tidal at this point on the Bure only the top two or three tyres in each stack are subjected to wetting and drying. Latterly it has been observed that the tyres had partially filled with silt and had good reed growth on the backfill.

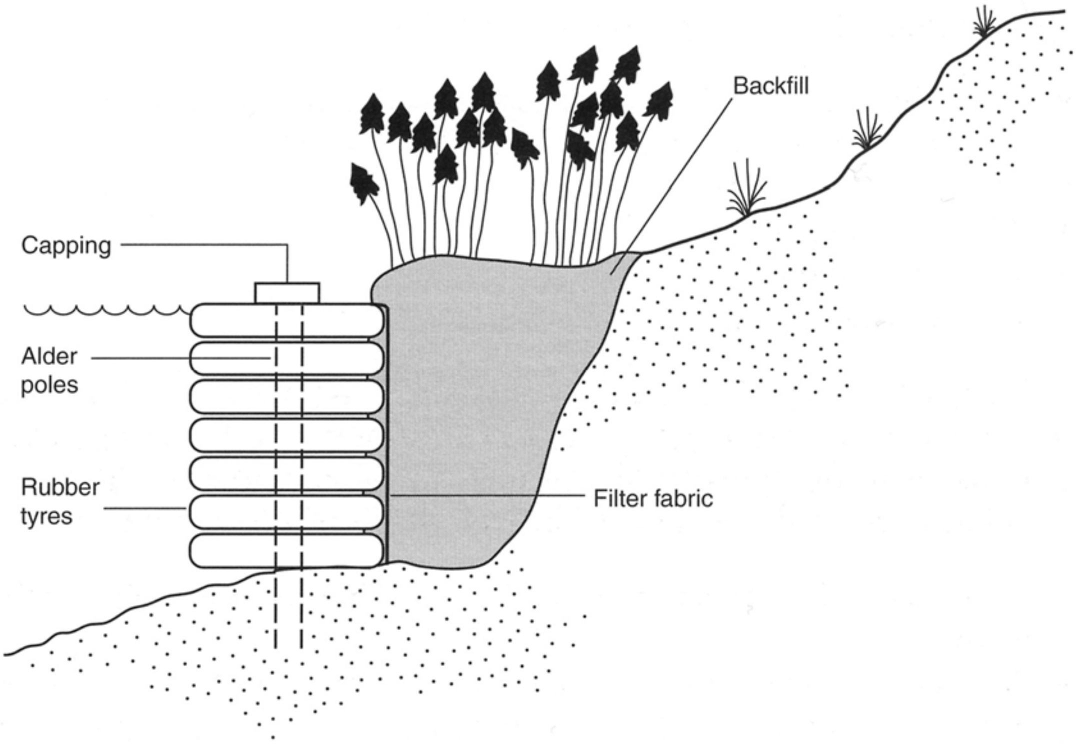

Figure 5.11 Schematic of the vertical tyre defence on the River Bure, Norfolk, UK

Figure 5.11 shows the design where tyres were threaded onto alder poles after which a 'capping' beam was placed across the top. The structure was secured by tie rods and anchor blocks into the bank. A geotextile was placed behind the tyres to prevent wash out of fines from the fill material used to fill the cavity between the bank and the defence structure. The 'new' riverbank was then planted up with vegetation to aid in earth retention and stabilisation.

Box 5.1.6 River training wall on the Bure in Norfolk (continued)

Figure 5.12 Tyre and post bank protection (courtesy Environment Agency)

It is apparent from Figure 5.12 that the defence has become less effective due to the slumping of the tyres from their stacks; probably due to the loss of backfill and allowing greater movement of the tyres on their poles. Some design modifications may be needed to this type of structure to extend its life expectancy.

5.1.4 Anti – scour mattresses

Sediment scour around marine structures is a serious problem for the marine engineering industry. The undermining of bridge piers, oil and gas pipelines and platforms by wave or current action is difficult and expensive to remedy.

Erosion protection mats using tyres can be used to prevent or reduce scour at bridge piers, at the toe of seawalls, on unprotected shorelines (see Box 5.1.8) and under pipelines (see Box 5.1.7). These mats can consist either of whole tyres bound together tread to tread with artificial rope, or, of tyre treads only (tyres with both side walls removed), woven together. Both systems seem to provide a level of erosion and scour protection.

Box 5.1.7 Pipeline anti-scour mattresses – The Sorrell system (EU Patent: 0537261)

There are in excess of 80,000 miles of offshore oil and gas pipelines around the world. A failure of a pipeline can be disastrous both environmentally and economically and so protection of them is a high priority.

Large quantities of sediment can be removed from beneath pipes due to wave and current action, for example a 60cm diameter pipeline off the East Anglian coast was found to have a scour hole 1.8m deep. Such scour results in the development of 'free spans' which can exceed the original design span of the pipe. Failure is unlikely to occur because of sagging into a scour hole, but rather due to metal fatigue caused by resonance set up by vortices around the pipeline inducing the vibrations in the pipe.

Scour also increases the likelihood of a pipe becoming detached from the seabed and moving large distances with offshore currents as it decreases the lateral resistance that the bed sediment provides.

Experiments and field applications have shown that tyre mattresses are very effective in preventing scour. They can completely prevent scour from occurring around the pipe in the area where they are placed.

This system is much cheaper than alternative methods and the tyres are able to fill a large scour hole more easily than gravel, bags of concrete or other materials. Each tyre takes up a comparatively large volume and can be lowered into place bound in large groups reducing installation time and costs. The hollow nature of the tyres allows easy anchorage to the pipeline and in addition exhibit low buoyancy as they become filled with sand (Garnsey and Leacock, 1998).

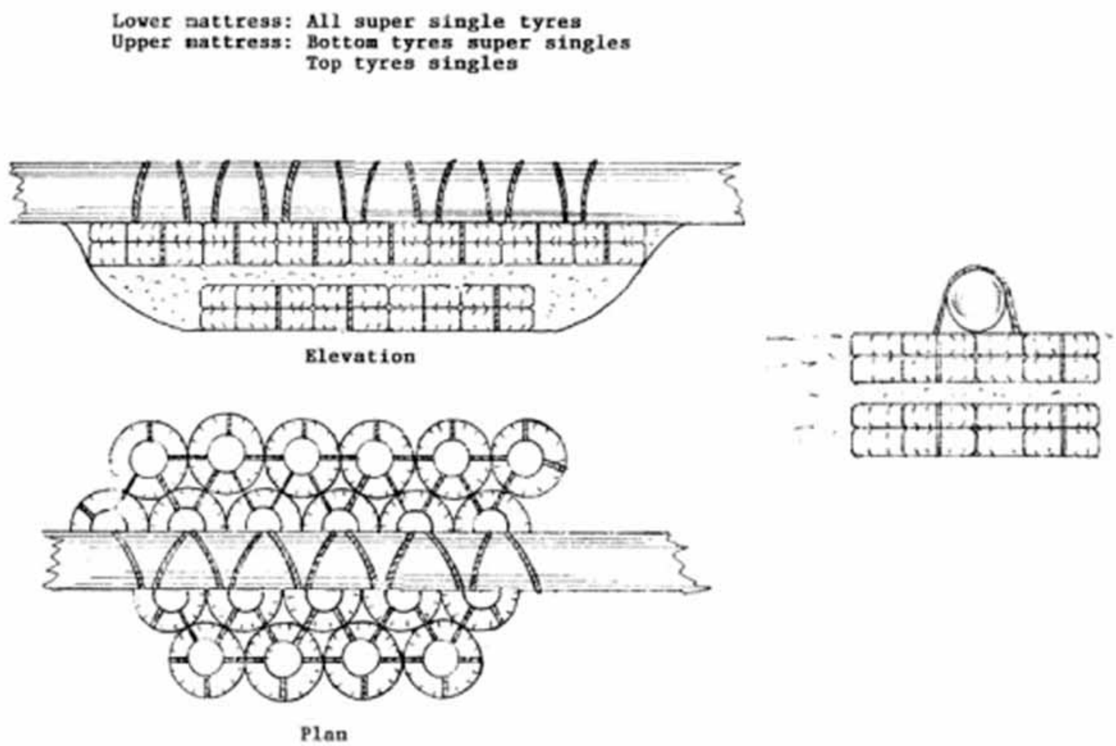

Figure 5.13 Schematic design of the 'Sorrell' anti-scour mattress

Box 5.1.8 The RINGtech® matting system

A co-operative initiative of the companies RINGtech® Renate Streuer and Unternehmer-Tun GmbH in Germany has developed a way of weaving scrap tyre treads into versatile matting systems. The tyre walls are removed to leave the tread of the tyre with the metal reinforcing still encapsulated within the rubber. These 'loops' of tread are then woven together (without cutting) into various designs of rubber mats. These mats have proven to be successful for several applications such as:

- bed protection/scour prevention at ship loading berths
- groyne construction
- protective screens for cables and pipes
- artificial reef construction
- large-dimension fender for the protection of a quay wall
- construction of a tidal deflector in a yacht harbour.

These systems have only been tested so far in marine applications. An assessment by the Federal Institute for Hydro-construction confirmed the anti-erosion properties of the RINGtech® products, especially in marine construction. This recommendation refers specifically to erosion protection for marine structures, e.g. bed or scarp protection and the construction of groynes and reefs. After successful tests with propeller induced currents during ship-berthing manoeuvres as well as a number of flexibility tests, carried out in March and in October 2000, the Federal Institute for hydro-construction certified RINGtech® mats specifically as a suitable bottom protection system.

Figure 5.14 RINGtech® erosion protection matting and hollow bodies (courtesy RINGtech®)

Box 5.1.8 The RINGtech® matting system (continued)

The hollow bodies can be filled with rip-raps or with slags and then closed by interlacing so that they can be used as gabions. In contrast to conventional wire cages RING*tech*® gabions are distinguished by their mechanical durability, anti-corrosion properties and their resistance to abrasion. Another advantage is that RING*tech*® gabions can be pre-assembled and transported in any form and size, and be filled on site before deployment.

5.1.5 Weirs

Used tyres have been used to a limited extent in smooth crested weirs where their resistance to abrasion and impact absorption characteristics can extend the life of the structure. Box 5.1.9 describes a successful application in the UK.

Box 5.1.9 Limbury Park Weirs

On the River Lee where it runs through Limbury Park in Luton (UK), two weirs were built of tyres in 1987 (See Figure 5.16). They were subsequently removed 15 years later in 1997 due to worries over erosion of the riverbed and banks downstream. It was also felt that the costs incurred by a biannual scrub to remove algal growth (which made the tyres slippery and a hazard to children walking on them) could no longer be justified (Clarke, 2000).

The weirs were constructed to impound the headwaters of the river in order to maintain water in the channel during low flow periods thereby improving the amenity value of the river.

As shown in Figure 5.15 the tyres were laid tread to tread on their sides on the riverbed in three arcs between the banks. A third row was then laid on top and over lapping the two upstream arcs. Concrete was then used to fill the voids in and between the tryes, binding them together and in place. The concrete provided most of the structural strength while the tyres provided the form and shape of the weir and also protection from chipping and abrasion of the concrete.

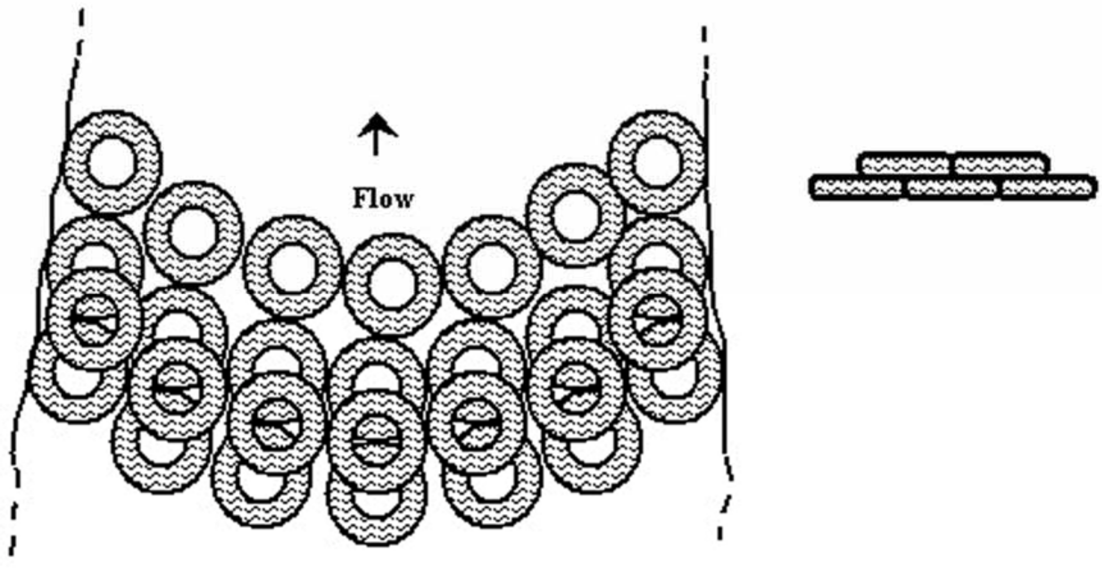

Figure 5.15 Schematic of the design of the Limbury Weirs, Luton, UK

Box 5.1.9 Limbury Park Weirs (continued)

Figure 5.16 One of the tyre weirs in Limbury Park, Luton before removal (courtesy Environment Agency)

The weirs were bounded on the banks of the river by 4 metre long lengths of 'Dytap' revetment block work which prevented bank erosion. A lack of such protection led to scouring and bank erosion downstream of the weirs. Removal of the structures in 1997 was based on the concerns over erosion and scouring downstream and the costs incurred for maintenance to allay safety concerns, not for structural repair. There were no concerns noted over the performance of the design, and when they were removed they were found to be still in good condition 15 years after construction (Clarke, 2000).

5.1.6 Floating breakwaters

Tyres have been used successfully in floating breakwaters - connected together to form large mats which float on the surface of the water. Their properties of elasticity and resilience reduce wave energy by creating turbulence.

Floating tyre breakwaters can be designed to suppress waves in a mild sea state but must also be able to survive the worst conditions that are likely to occur at the site. In order to significantly attenuate wave action it will need to have a beam width of the same magnitude as the incident wave height. This means for instance that for a storm with a significant wave height (Hs) of three metres and zero-crossing periods of ten seconds, the approximate dimensions of the structure would need to be three metres deep and nearly a hundred metres wide if placed in a water depth of ten metres. Thus an efficiently performing structure together with the mooring system required would need to be massive and inordinately expensive to install.

A study by Motyka and Welsby (1983) which gathered experience from seventeen of these structures in the US found that there are two main problems associated with them; a gradual loss of buoyancy, and the need for strong anchorage capable of surviving severe wave conditions.

Loss of buoyancy can be combated by the addition of polyurethane foam within the tyre cavity or periodic reinflation of the tyre crowns, and marine growth can be removed by periodic cleaning.

Whilst tyres themselves are inherently very strong, problems have arisen with methods of connecting them together. Motyka and Welsby (1983) suggest that from field tests and case histories of those investigated (steel wire, synthetic ropes, steel chain and rubber belting) rubber conveyor belting, connected by nylon bolts to form loops, was by far the best method. This system has a high tensile strength, is flexible, resilient and inert in the marine environment.

Motyka and Welsby (1983) also concluded that floating tyre breakwaters are only suitable for use in areas with short fetches (<10km) and are unlikely to survive an open/exposed coastal environment. The life expectancy of a structure even in sheltered environments with short fetches is probably ten years or less - although the Port Lothian breakwater featured in Box 5.1.10 is still working more than twenty years after it was first deployed.

Box 5.1.10 Floating tyre breakwater in Port Edgar

A floating tyre breakwater was built in Port Edgar, Lothian from Truck tyres in 1979 (see Figure 5.17). The structure successfully reduces wave action in the harbour. Waves with periods of up to five seconds are damped significantly. The major problem encountered is the growth of marine organisms on the structure causing a loss of buoyancy. This requires regular maintenance.

Figure 5.17 Floating tyre breakwater at Port Edgar

The system used for the Port Edgar breakwater is known as the ‘Goodyear module’. Figure 5.18 shows the configuration and fastening of the design.

Box 5.1.10 Floating tyre breakwater in Port Edgar (continued)

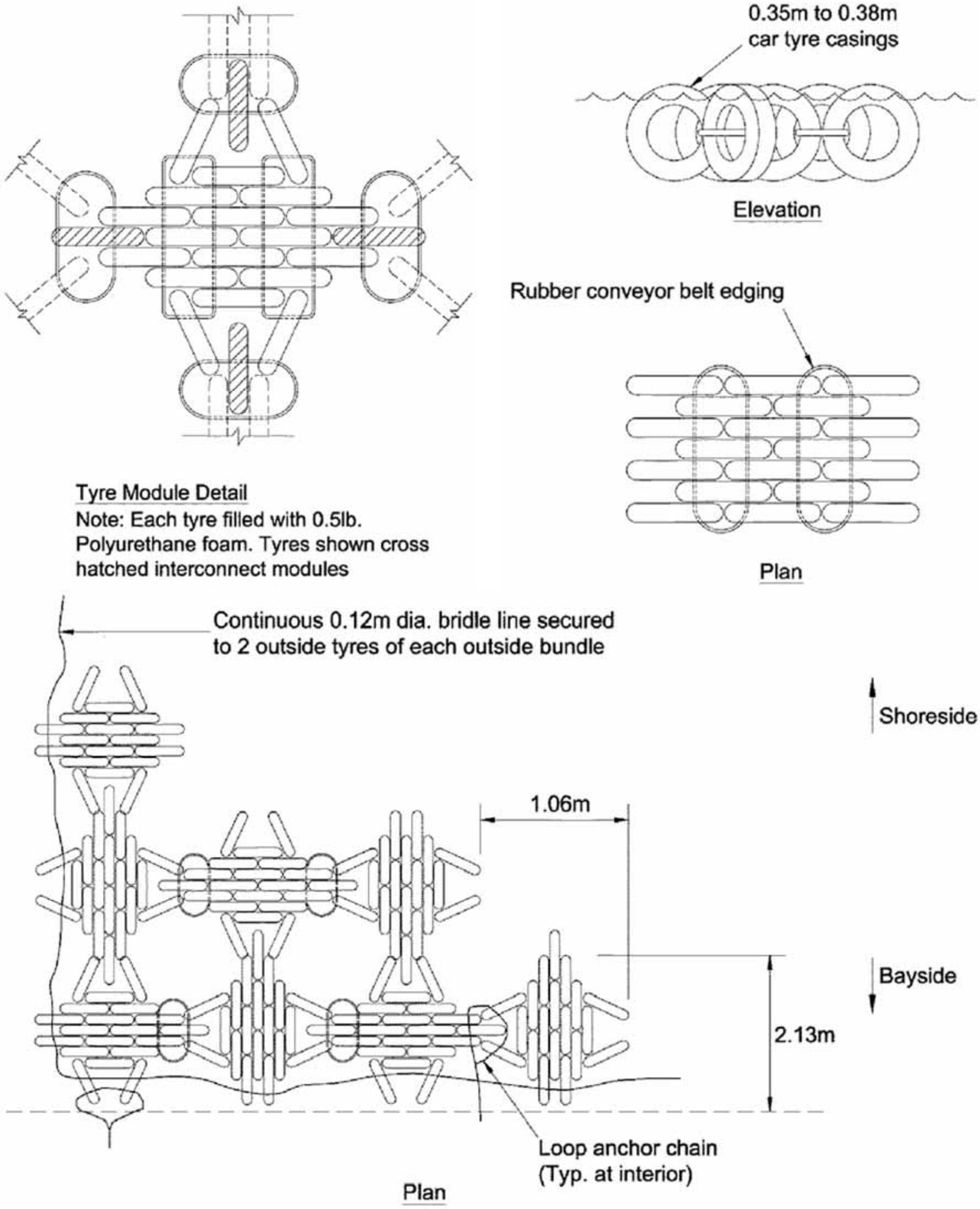

Figure 5.18 Schematic of the 'Goodyear' Tyre Module

5.1.7 Submerged reefs

Artificial reefs are man-made or natural objects placed in selected areas of the marine environment to improve or provide rough bottom habitat for aquatic organisms. By increasing the amount of this type of habitat, artificial reefs provide the potential for increasing the total number of reef fish and other commercial species such as crabs and lobsters as well as for organisms that settle and grow on the surface of the substrate. Potential benefits that have been stated are:

- creation of new habitats
- provision of hard substrate for larval settlement in areas dominated by soft substrate
- provision of a variety of surfaces for attachment relative to current direction
- crevices provide shelter for fish and shellfish from predation
- protection of fishing and nursery grounds and benthos against overfishing by trawling
- offshore barriers for coastal protection.

Artificial reefs built from tyres are particularly popular in the south west Pacific around the Philippines and Malaya. In Malaya more than 50 reefs have been created using about 1.5 million tyres (Zakaria, 1993). Australia has built at least 30 tyre reefs (Kerr, 1992). There are about 40 on the US east coast that used approximately 700,000 tyres (Stone *et al, 1975*) and at the last count, 73 on the Atlantic seaboard (McGurrin, 1988).

Tyres are a particularly popular choice of reef material because they are:

- readily available
- low cost
- simple to assemble into units
- easy to handle manually or with mobile equipment
- durable, and
- they provide a large surface area to volume ratio providing more useful habitat than other materials.

There are a myriad of tyre configurations that have been used to form 'reef blocks' over the years - some of which are illustrated here.

Figure 5.19 Stacks of car tyres forming a cylinder, compressed and filled with concrete (often referred to as 'rubber rocks')

Figure 5.20a Open lattice reef structure (using either just 4, or 13 or more tyres held together by stainless steel bolts and with the basal tyres filled with concrete)

Box 5.1.11 Artificial reef in Poole Bay, Dorset

In July 1998 tyre modules and concrete blocks (as control modules) were deployed alongside an existing stabilised coal ash reef study site in Poole Bay off the central south coast of England. Five hundred tyres were used in a range of configurations including rubber rocks, open lattice tetrahedra and concrete filled single tyre structures. Divers monitored the reef at 2 monthly intervals to determine colonisation of the structures in comparison to the concrete control blocks and also collected marine organisms for bioassay. The study continues but indicates thus far that:

- there is no significant difference between concrete colonisation and tyre colonisation
- no traces of indicator organic compounds can be detected in seabed sediments surrounding the reef
- the concentrations of zinc were not significant in the organism bioassays in comparison with either the natural reef or the concrete controls.

Box 5.1.11 Artificial reef in Poole Bay, Dorset (continued)

Figure 5.20b The tetrahedral design used on the artificial reef in Poole Bay, Dorset, UK (courtesy of Dr K.J. Collins)

Often, as illustrated (Figures 5.20a and b), tyres are built into 3D units or ‘modules/lattices’ of various sizes fastened with rope or plastic strapping. This is a common practice in areas where they are to be deployed in relatively low energy environments. These fastenings are not satisfactory for higher energy environments where bolting the tyres together is considered more advisable.

There are basically three types of tyre reef structures:

a) ‘Rubber Rocks’ – stacks of 6/7 car tyres forming a cylinder filled with concrete (see Figure 5.19). This design has been employed in the USA and elsewhere. Each ‘rubber rock’ is composed of up to 10 car tyres stacked vertically, compressed, secured with bands and then the centre filled with concrete. This forms a unit 1m high by 70cm in diameter and weighing 200kg. These ‘modules’ can then be linked together via a steel eye set in the concrete to construct a reef unit.

b) ‘Tetrahedra’ – open lattice structures using either 4 or 13 tyres held together with stainless steel bolts and with the basal tyres filled with concrete (Figure 5.20a). This type of structure is widely used in Southeast Asia and Australia to attract fish. Tyres are usually drilled and bolted together with stainless steel fixtures to achieve the desired shape with three tyres making up each of the four sides. Smaller tetrahedra utilising four tyres (1per side) have been used in an experimental tyre reef in Poole Bay off the south coast of the UK (see Figure 5.20b).

c) Concrete-filled single car and lorry tyres. Single tyres filled with concrete to form a solid disc can be held in place by a steel pole driven into the seabed through a hole in the centre.

The modular form of these units allows easy handling and deployment. However the construction, securing and anchoring of the modules underwater into an arrangement to form a reef typically requires the help of specialist divers.

There are numerous reef structures built with these modular types either exclusively or in combination but typical arrangements are illustrated in Figure 5.21.

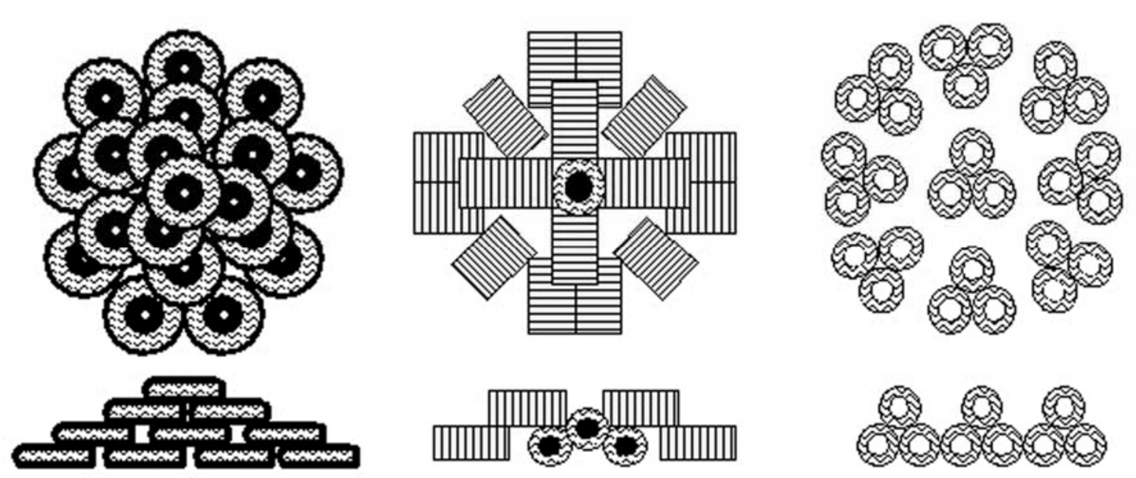

Figure 5.21 Plan and side elevations of modular tyre reefs

Reef design is not an easy process as many amateur clubs and groups have discovered. Poorly conceived efforts in the past have incurred a variety of problems and attracted bad publicity. Typical problems encountered were:

a) The use of light insufficiently weighted materials, which ended up miles away from the intended reef site or on popular bathing beaches. Strong winter storms can up-route and transport materials away. Shifting reef materials can obstruct commercial trawl nets. (This led to restrictions on their use or banning in some States such as Washington and California (Stone, 1985)).
b) Inadequate buoys and buoy chains, which resulted in the loss of the markers - and the location of the reef. A reef without buoys can be extremely difficult to find even with modern bathymetric echo-sounding equipment.

These structures must be placed so that they do not conflict with other users of the marine environment such as commercial fishing, shipping, or dredging.

To increase stability of the structures and to reduce the risk of scattering of reef components during storm wave action the tyre modules should be linked together with steel cable or chain, ballasted with concrete and if required secured to the seabed with anchor poles/piles or equivalent.

In 1986 and 1987 the New Jersey Division of Marine Fisheries constructed and deployed a number of reefs using a variety of structures and module designs, some ballasted with concrete and some not. Ten different module types were tested in the Atlantic off the New Jersey coast (Myatt *et al*, 1989). The stability of the units was assessed according to whether or not they moved and how far they moved if they did (or even if they could be found again!). The following inferences were drawn from the experiment:

- In general, reef units with increasing submerged unit densities showed better stability. The range for submerged unit densities for the successful tyre types were 266 to 499 kg/m^3.

- Stability increased with increasing ballast-to-rubber ratios. Those units with a minimum of 10 kg of concrete per 1 kg of rubber were the most stable.
- Higher ballast-to-tyre ratios also increased stability for units with 12-42 kg per tyre.

From these findings a minimum submerged density of 275 kg/m^3, a submerged ballast-to-rubber ratio (by weight) of 10 and ballast to tyre ratio of 11 could be recommended for a performance-based specification for artificial reef module construction using tyres. This does not preclude variable modular designs so long as they meet the performance criteria.

To alert fishermen and other mariners to its position marker buoys should be strategically placed about the reef. The number and size of buoys required will depend on the placement, depth and extent of the reef scheme. However a minimum of two is recommended for even the smallest scheme in the event that one may be lost during a storm event, or become damaged or stolen.

Maintenance and inspection of reef units, anchors, buoys, buoy chains and the structures themselves need to be conducted regularly (see chapter 6). These are all reasons why habitat enhancement with artificial reef structures should be managed by qualified individuals with financial support.

5.1.8 Fenders for wharf's, boats and shipping

Whole tyres have been used for many years on small water craft, boats, barges, docks (see Figure 5.23) and wharves (see Figure 5.22) as fenders for mooring. Laminated rubber offers good durability for these tasks because of its good load deflection, energy absorption and toughness. Some commercial users prefer to use used aircraft tyres which do not contain steel radial wires. Radial wires can cause damage to shipping if tyres are accidentally lost into the water and become entangled with propellers.

Usually tyres are slung singly by ropes or chains over the gunwhale or quayside to absorb mooring energies and prevent damage to vessel and quay alike.

Figure 5.22 Tyres used as mooring fenders on Lowestoft wharf s (courtesy Sorrell Flood Protection)

Figure 5.23 Tyres used as fenders on tugs and workboats (courtesy Sorrell Flood Protection)

Another use commonly found in yacht harbours and estuaries around the country is that for cushioning yacht hulls against pile rubbing strakes during periodic cleaning and maintenance. Cut tyre treads are also used on the corners of pontoons to protect against hull damage.

There are also more sophisticated commercial tyre fender designs for much larger vessels such as the Reykjavik Truck Tire Fender system described in Box 5.1.12.

Box 5.1.12 Reykjavik Truck Tire Fender system

The Port of Reykjavik in Iceland developed the Reykjavik Truck Tire (RTT) fender system (see Figures 5.24 and 5.25). The system is primarily intended for freighters and container vessels up to 170m length overall (Loa) or up to a maximum of 17,000 dead weight tonnage (DWT). Fenders have proven to provide very good protection for freight and container ships. Each fender consists of 6 truck tyres, connected in one stack by four steel rods which are suspended horizontally on the quay face. For quay walls that are constructed of steel sheet piling, the RTT fenders are placed in the flutes of the steel sheet pile bulkhead (see figure 5.24). Usually the whole quay wall is covered with fenders, with either one or two fenders stacked vertically (see figure 5.25).

The diameter of a typical RTT fender is about 1.1mm. With the steel sheet pile bulkhead having flutes of 0.2m depth, the fenders reach approximately 0.9m out from the quay-line. Usually, cylindrical or arch fenders, protruding about 0.4m out from the quay-line, are placed along the cap beam. For approximately 45-50% deflection of the RTT fenders, the cylindrical or arch fenders come into play.

Box 5.1.12 Reykjavik Truck Tire Fender system (continued)

The deformation characteristics for RTT fenders are similar to that of pneumatic type fenders and often the same assumptions may be used for RTT fenders as for pneumatic type fenders.

The reaction force and the energy absorption for the RTT fenders, determined from 33 repetitive compression tests on steel sheet profile, are:

$P_{50\%}$ = 9.7t $E_{50\%}$ = 2.36t/m with $P/E_{50\%}$ = 4.1t/t-m

The Reykjavik design found that by covering the whole quay with RTT fenders, two rows in height, spaced at 1.6m o.c., the RTT fenders can provide adequate energy absorption for berthing impact loads for ships up to 17,500 DWT (*assuming the mean deflection of the fenders engaged is 25%*).

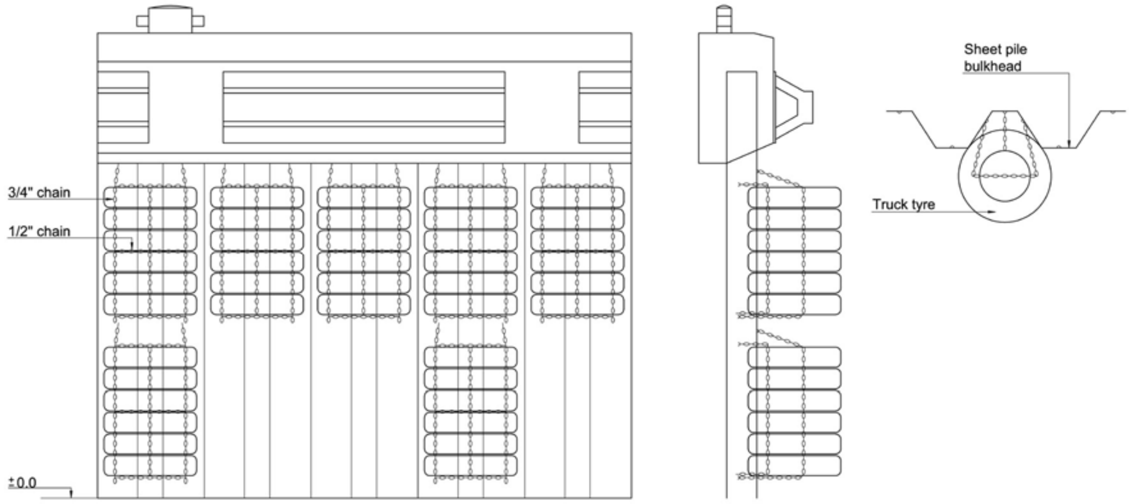

Figure 5.24 RTT ship fender system 1

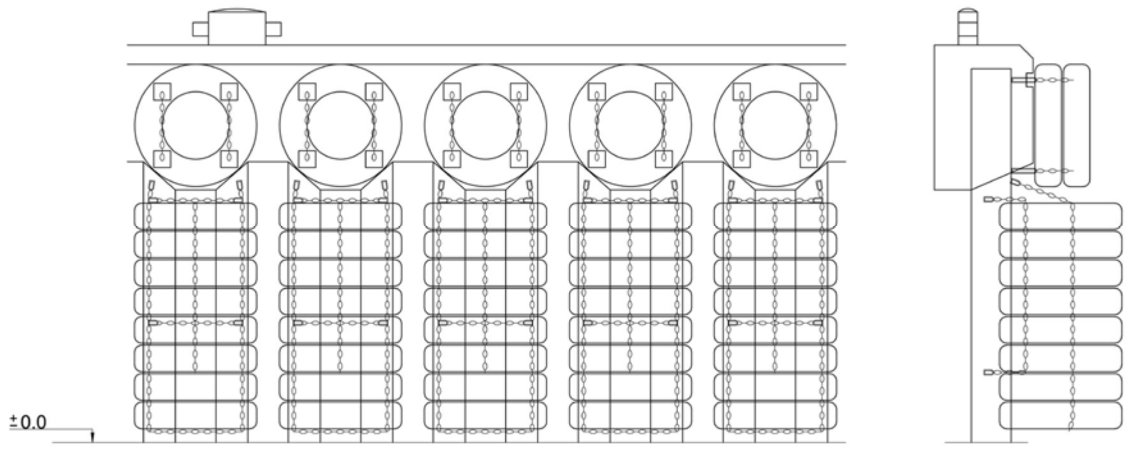

Figure 5.25 RTT ship fender system 2

5.2 TYRE BALE SOLUTIONS

5.2.1 Hearting to concrete structures

Tyre bales can and have been used quite extensively especially in the USA (see Box 5.2.1) as hearting for concrete structures. Although viable for non marine applications (see Section 5.2.7) the use of bales in this way does not demonstrate a best value engineering solution for tyre bales; i.e. this use does not make the best use of the properties of tyre bales other than as a bulk fill substitute. There may be mitigating factors however such as a saving on transportation costs and reduction in energy emissions or a scarcity in other reuse options.

Box 5.2.1 Pecos river concrete block retaining wall

Tyre bales were used in 1997 by the New Mexico Environment Department (NMED) to stabilise the bank of Lake Carlsbad on the Pecos River in New Mexico in the United States. There was bank erosion due to the wave action caused by passing water traffic. Around 700 000 scrap tyres were utilised in the project to stabilise approximately four thousand feet of river bank. The water was drained and the tyre bales were placed in a trench about one metre deep along the edge of the river. They were placed on a concrete foundation containing steel reinforcing bars and encapsulated in concrete. A concrete block retaining wall was constructed on top of the bales and fill placed behind (see Figure 5.26). (Encore Systems Inc, 2003.)

Figure 5.26 Bank stabilisation of the Pecos River in New Mexico using tyre bales (courtesy Encore Systems)

5.2.2 Hearting to coastal rock structures

The model testing of a tyre bale revetment under wave action as described in Appendix 5 concludes that they weigh too little to withstand even moderate wave forces without substantial anchoring. An alternative is to utilise them as fill material within conventional defence structures such as rock groynes, rock revetments, beaches (see Boxes 5.2.2 and 5.2.3) and concrete walls (see Section 5.2.1). This application makes use of the energy absorption capabilities of the bales in withstanding wave energy transmitted through the overlying rock armour layer.

Box 5.2.2 Selsey rock armour coast protection

There are advanced plans to use tyre bales as a filter layer beneath rock armour in a coastal defence structure at Selsey, West Sussex, UK. A design (see Figure 5.27) has been drawn up to test them in a shore parallel rock revetment at the top of an eroded beach.

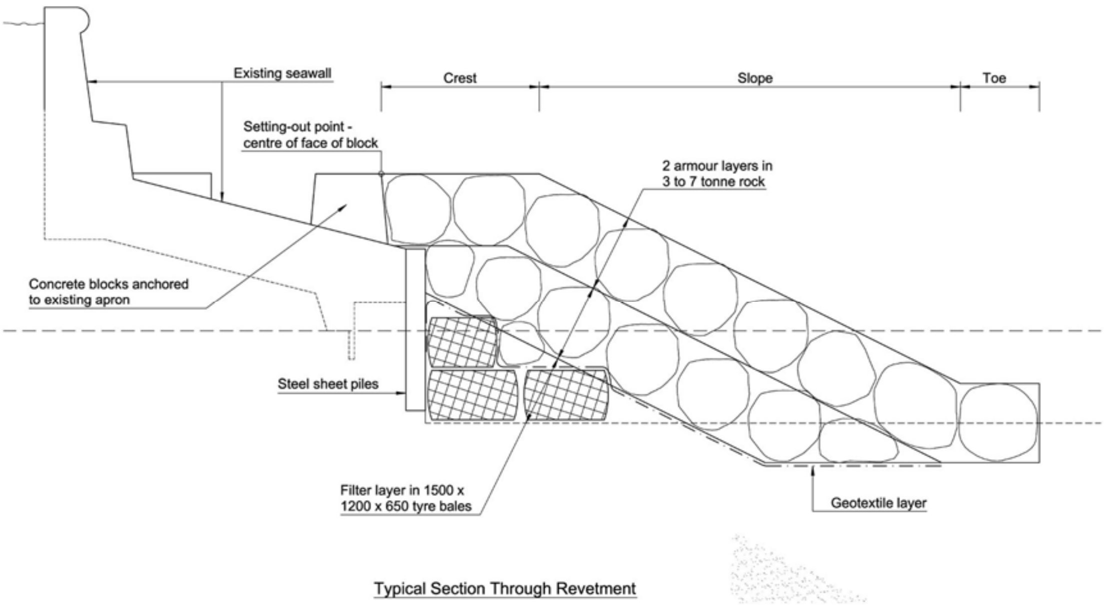

Figure 5.27 Design for the rock armour revetment at Selsey in West Sussex

Tyre bales were considered for use in this case for several main reasons:

- a potential cost saving
- demonstrating the potential reuse of a waste material
- to examine the performance characteristics of tyre bales in a full scale toe revetment structure under rock armour.

By April 2004 draft contract documents had been prepared and a FEPA licence had been obtained. However, further progress was delayed whilst Defra approval was sought.

It was apparent by November 2004 that it was highly unlikely that approval for the scheme would be given within the timescale of the overall research project, but it was thought important to report as much as possible of the scheme development for future reference (See Appendix 8, Section A8.3).

Present indications suggest that it is unlikely that the scheme will go ahead during the financial year 2004/5. The scheme may become subject to the emergency provisions under the Coast Protection Act if the condition of the seawall further deteriorates.

Rock armour groynes may also be envisaged as shown in Figure 5.28. A hearting of tyre bales could be overlain with conventional armour rock to aid in wave energy absorption. However model testing and prototype assessment has yet to be conducted on this design. One of the main questions relates to the potential long-term deformation of the bales under the weight of the overlying rock.

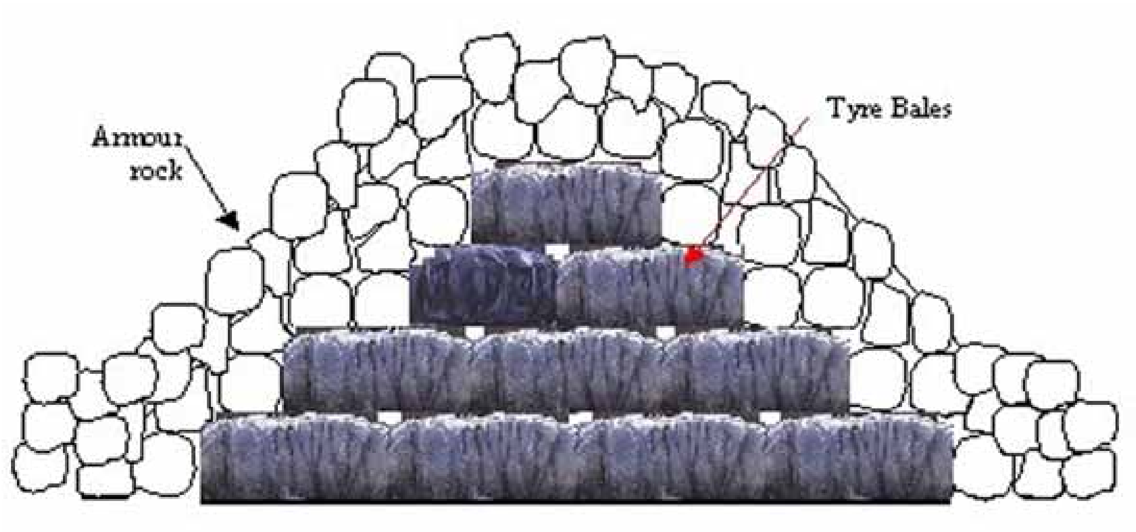

Figure 5.28 Suggested test tyre bale configuration as hearting for rock groynes

5.2.3 Beach nourishment substitute

On first consideration the idea of using tyre bales as a bulk fill in shingle beaches may appear to have as limited benefits as when used as bulk fill in concrete hearting (See Section 5.2.1). However here they are a part solution to a resource scarcity problem. Beach shingle is dredged from the seabed in vast amounts for renourishment schemes in the UK. Any reduction in dredging is welcome as it preserves the offshore shingle resource for the future and for higher value applications.

Box 5.2.3 Pevensey Bay shingle beach nourishment substitute

Pevensey Beach is a 9 km shingle embankment that protects 50 km^2 of the low-lying Pevensey Levels, 35 km^2 of which is a Site of Special Scientific Interest (SSSI). A major beach replenishment took place during the summer of 2002. However, littoral drift through Pevensey bay results in a net loss to the frontage of 20,000 m^3 per year. This amount has to be replenished annually to maintain the level of defence. This would normally require the import of large amounts of natural shingle to build up the beach to the required level. A pilot trial was carried out in which 350 tyre bales were buried in the landward side of the beach in November 2002, generating shingle that could be used on the seaward beach slope and crest.

The bales were used, placed in a block 14 bales long, 5 bales wide and 5 bales high. A geogrid (Tensar SS20) (4mtr wide) was placed on the shingle below the bales and wrapped round them as they were placed, so that the entire block was enclosed within it. Early construction is shown in Figure 5.29.The geogrid is a reinforcing geosynthetic fabric which holds the bales together, but has open mesh spaces in a grid pattern large enough to allow shingle to migrate into the bales. The first 8 rows (East to West) had shingle placed into the voids between the tyres which were then washed over with water pumped by a 2” centrifugal pump for 2hrs to assist shingle ingress. The other 6 rows were encased with ‘lotrak 1800’ geotextile with no shingle placed between the voids. The geofabrics were overlapped by 500mm and the geogrid tied together with 6mm nylon rope. The geogrid was stitched together along the landward edge using 10mm rebar bodkins.

Box 5.2.3 Pevensey Bay shingle beach nourishment substitute (continued)

Figure 5.29 Installation of bales in the beach at Pevensey Bay in East Sussex (courtesy PCDL)

To assess leaching, five groundwater sampling wells (vertical pipes of 100mm diameter ‘Osma’ drain) were placed in and around the tyres bales on Pevensey Beach (see Figure A8.14), one in the centre of the bales at row 7, one at each end, and two more distant ones in the surrounding beach. Zinc was used as the main indicator of tyre leaching. Detailed monitoring (See Figure 7.1)of the Pevensey beach tyre bale trial has demonstrated that levels of zinc leachates in beach interstitial water are below EQS levels and are declining with time. It has proved possible to model the levels of zinc observed within the tyre bales and no evidence of cadmium contamination has been found even within the tyre bales (Collins *et al*, 2004). (A full account of the monitoring is given in Appendix 8).

Box 5.2.3 Pevensey Bay shingle beach nourishment substitute (continued)

Figure 5.30 Pevensey Bay project near completion with sampling pipes in situ. (courtesy PCDL)

Once buried the tops of the tyre bales were about 1.15 m below the surface level of the beach. In addition, the area was surcharged by 0.25 m to allow for settlement. The area is crossed by traffic from the adjacent Environment Agency Salt Haven Depot on Coast Road, which accelerated settlement and compaction of the overlying fill. Settlement plates were installed in the structure at rows 4 and 11. The bottom plate was placed on top of the geogrid underneath the bottom bale. The top plate was placed underneath the top bale. Movement was monitored over two years from construction, and the results showed that the long term settlement/creep of filled bales over 18 months (about 0.4% strain) was about half that of the bales which were only wrapped (0.9% strain). Also there was no evidence of bales moving up through the beach and they appear structurally to be very stable.

Tests carried out by HR Wallingford show that tyres bales have high permeability in both the horizontal and vertical directions, similar to the clean, rounded gravel of the surrounding shingle (See Appendix 4). Measurements of water levels were made in the groundwater sampling wells to see if the bales caused any difference in water levels compared to surrounding areas of the beach.

The basal layer of tyre bales is founded just below the high water level of neap tides. It was thought that this would ensure that the basal layer was flooded daily. However, in practice it was found that the hydraulic gradient across the beach was higher than anticipated, and it was only at spring tides that any water was recorded in the wells.

Box 5.2.3 Pevensey Bay shingle beach nourishment substitute (continued)

Tyre bales could be used for bulk fill on a much larger scale at Pevensey and other beaches, and result in a significant demand for the number of bales in the Southeast of England.

(A method statement for the installation of the bales was prepared by the client, Pevensey Coastal Defence Limited. In addition, Planning Approval had to be obtained from the Environment Agency, and a waste management licence was required for the use of the tyres).

The performance of the tyres bales at Pevensey has been monitored over two years since construction. This trial could pave the way for much wider use of tyre bales for this purpose in beaches around the UK.

5.2.4 Hearting to embankments

The inherent properties of tyres mean that they can provide a useful alternative to natural aggregates for use as lightweight fill in embankments. The aim of using lightweight fill is to reduce the overall ground (or vertical) pressure, thus reducing the settlement and the risk of slope or foundation failure. Tyres allow for a reduction because they reduce the load in comparison with traditional materials.

Lightweight fills can be developed using:

- tyre bales
- whole tyres
- cuts –300mm to ½ tyre
- tyre shreds – 50mm to 300mm
- tyre chips – 10mm to 50mm.

The choice will depend on the relative costs of treatment, transport and locally sourced materials as well as the site or structure-specific requirements

Lightweight tyre fill (in whichever grade) may replace materials commonly used such as:

- light weight expanded clay aggregate
- lightweight concrete
- pulverised fuel ash (PFA)
- expanded polystyrene blocks.

As a potential major user of used tyres, this area has received much attention. In the US, ASTM standards (1998) have been developed for tyre use as lightweight fill in civil engineering applications.

The specific advantages for use as embankment fill are:

- reduced settlement (after initial loading)
- increased stability due to low density
- improvements in strength and reduced deformation when mixed with moderately plastic clay soils
- improved angle of friction when mixed with silty plastic clay

- high compressibility on initial loading, but reduced compressibility on subsequent unloading and reloading
- a cohesion intercept for tyre shreds ranging from 8 to 11kPa
- a high Young's Modulus during unloading and reloading cycles.

Tyre shreds and tyre bales have been used in embankments and levees. One such example is the use of tyre bales in an embankment on the River Witham near Lincoln in the UK.

Box 5.2.4 The River Witham flood defence embankment improvement

In 1997 an Environment Agency (EA) Strategy Study carried out by Bullen Consultants for the lower River Witham system in Lincolnshire concluded that some of the flood embankments were in poor condition. A phased scheme of improvements was drawn up involving approximately 130km of defences, storage embankments and berms. A contract package to address the most urgent embankment works was progressed as a partnership between the Environment Agency, Bullen Consultants and May Gurney Construction.

The site utilising tyre bales is a 1500 metre stretch of river embankment, however the same embankment serves as a flood defence barrier for Branston Island. This is an emergency flood storage area during times of extremely heavy rainfall and high water levels in the system.

An assessment of the embankment reported that it was only approximately 2.5 metres wide at the crest and badly eroded. The crest needed to be widened to improve structural integrity and performance and also to improve safety during access along the bank for maintenance works. The plan involved stabilisation of the flood defence by widening the crest to 4 metres, reprofiling the embankment, berm reinstatement and toe protection (see Figure 5.31 and 5.32).

However there were problems to be overcome. A peat base underlies the embankment. In order to prevent slippage of the embankment, its slope would have had to be 1:4. This would widen the footprint of the base of the embankment encroaching on 11kV powerlines and a drainage ditch (locally known as a soke dyke) both running parallel to its entire length. Moving the soke dyke and the power lines would have had several environmental disbenefits as well as being costly. Tyre bales being of lesser density material meant that the footprint of the embankment could be reduced and concurrently the slope made steeper, removing the need for additional works and related costs. It is estimated that when complete the scheme will have utilised over a million tyres.

Box 5.2.4 The River Witham flood defence embankment improvement (continued)

Figure 5.31 Design and works for the River Witham Flood Embankment (courtesy Environment Agency)

Box 5.2.4 The River Witham flood defence embankment improvement (continued)

Figure 5.32 Construction of the River Witham Flood Embankment, near Lincoln (courtesy Environment Agency)

Because the scheme was a pilot project the Environment Agency set up a water-monitoring programme. There are currently two surface water quality monitoring points that are already part of a regular sampling programme, and further sampling points have been installed at various points along the length. Samples are tested using a suite of analyses routinely used by the Environment Agency. Preliminary results from this monitoring are given in the pilot project summary in Appendix 8.

Box 5.2.5 River Enrick flood embankment near Glen Urquhart, Scotland

The River Enrick near Glen Urquhart in Scotland needed remedial works to prevent spate flooding of adjacent land. Initially it was hoped that piles could be used to secure a new bank however only two were driven (see Figure 5.33) before it was decided that the ground was too hard for the wooden piles and another solution had to be found. Tyre bales had already been used on Forestry land to build and repair remote roads on very soft ground and they were keen to trial other applications. In this instance the bales were locally available and a preferred option to heavier aggregate which would have caused more extensive damage by lorries accessing the site.

Figure 5.33 Construction of the Enrick embankment (courtesy Northern Tyre Recycling)

Box 5.2.5 River Enrick flood embankment near Glen Urquhart, Scotland (continued)

Figure 5.34 The finished river embankment

Figure 5.35 Rock armour placed for bank toe protection

5.2.5 *Armouring to banks of small rivers or streams*

The benefits of using tyre bales as armouring to banks of small rivers and streams may be two-fold; improved drainage and erosion protection. The permeability qualities of tyre bales allows adequate drainage of water through them into the watercourse, and their durability will ensure maintenance of the bank slope and position if surface cover is lost. Bales in their 'natural' form may also be useful for providing bed or toe protection when buried under a layer of natural bed material.

Box 5.2.6 The Nairn River near Clava in Scotland

One such scheme that could be described as armouring is that of the River Nairn near Clava in Scotland. This is a privately owned section of the riverbank sited immediately downstream from a bridge abutment (See Figure 5.36). Here erosion of the soil bank downstream of the abutment was creating concern for the landowner that during high spates the river would flood onto his property. A loss of amenity was also an issue as this is also a popular fishing location.

Figure 5.36 The Nairn River Bank, during construction (courtesy Northern Tyre Recycling)

Box 5.2.6 The Nairn River near Clava in Scotland (continued)

Figure 5.37 The Nairn river bank with topsoil replaced (courtesy Northern Tyre Recycling)

Figure 5.37 shows the bank slope that was achieved by using bales placed at the desired angle (Figure 5.36). Figure 5.36 also shows the rock toe that was created to prevent undermining of the bank and the bales. This also serves as a fishing platform for easy access to the water's edge after descending the steps built into the bank. To secure the bales, wires were anchored into the bank with metal pinions at either end of the structure, and then stretched horizontally across them and pinned at intervals. Topsoil was replaced to cover the bales and re-seeded with grass. Drainage is reported to be good and the grass has established well. However the bank shows signs that the topsoil is vulnerable to being stripped away during spate flows as erosion is becoming apparent in places. A more natural vegetative cover would be preferable to the 'manicured' grass as seen here. A mix of indigenous planting would help to stabilise the topsoil further as well as visually blend the embankment into the surroundings and make it look more natural.

5.2.6 Bales in gabions

There is also the potential for tyre bales to be used in gabion boxes for revetments provided they are stable under fluvial flow conditions. Encasing the bales in mesh boxes (see Figures 5.38 and 5.39), filling the voids around it with suitable aggregate, wrapping them in geotextiles and finishing the structure with a vegetative/turf cover may be a suitable option for upper river banks.

Figure 5.38 Tyre bale as centre fill for gabion box (courtesy Northern Tyre Recycling)

Figure 5.39 Tyre bale as rear fill for gabion box (courtesy Northern Tyre Recycling)

Caution would need to be applied to the use of the tyre bale as rear fill to a gabion as shown in Figure 5.39 as this makes the gabion heavier on the front (face) side. Appropriate design and attention to any stability and anchoring issues would perhaps be worth-while as there is the benefit of saving significant weight through the reduction in aggregate used to fill the gabion.

It should be noted that no flume testing of gabion baskets containing tyre bales has yet been conducted and currently there are no formal recommendations for their use.

5.2.7 Other potential uses

There is the potential for other uses that have not yet been fully developed, demonstrated or used extensively in the UK, for instance:

- **tyre bales as a bulk fill replacement in block concrete** access ramps/slipways (Bales may require holding down to prevent uplift in fluid concrete, see Figure 5.40). Here concrete in the core of the structure would be replaced by tyre bales, however, the structural loads would still be carried by the surrounding concrete. The finished product looks just like a traditional concrete block (see Figure 5.41), yet it is much lighter. The main benefit here would be in lower transport costs and the ability for use on ground of restricted weight bearing capacity. Less weight may also aid in accessing areas traditionally difficult to get heavy plant into; i.e. lighter construction/lifting plant can be used instead of heavier vehicles.

  Figure 5.42 shows an example of a car ramp constructed from these blocks. Similarly designed coastal and river structures such as boat launching ramps or promenade access ramps for example could be envisaged (subject to the restrictions discussed in Section 3.7).

Figure 5.40 Concrete being poured around tyre bale into block cast (courtesy Northern Tyre recycling)

Figure 5.41 The tyre bale/concrete block product (courtesy Northern Tyre Recycling)

Figure 5.42 Car ramp constructed of tyre bale/concrete blocks (courtesy of TRL Ltd ©)

- **tyre bales as a bulk fill replacement behind vertical walls.** Conventional backfill material could be replaced by tyre bales as an engineering alternative to reduce active pressures on the wall and/or to increase permeability of the fill. This concept has been used in highway engineering but to date there are no known applications in port, coastal or river engineering.

- **tyre bales as the structural element in pontoon buoyancy units.** Bales wrapped in a suitable buoyant membrane may make effective pontoon floatation units (– dependant on the development of a suitable membrane).

- **tyre bales combined with an impermeable layer as a temporary flood wall.** This use was trialed on the River Derwent in Yorkshire with moderate success. (Further testing is required to establish hydrostatic limits and methods of securing/anchoring the bales).

5.3 TYRE SHRED/CHIP SOLUTIONS

5.3.1 Lightweight backfill behind retaining walls

Whole tyres, shreds and chips can also be used as lightweight fill behind retaining structures. Here the aim is to reduce the horizontal earth pressure on the back of the wall. Box 5.3.1 shows the simplified equations that illustrate this principle.

Figure 5.43 A sample of tyre shred

Box 5.3.1 Pressure equations for retaining walls

The equations below are based on Rankine's theory of earth pressures. Equation 1 is for drained conditions in granular soils with a smooth frictionless vertical wall and horizontal surface to the retained ground. Equations have also been developed for cohesive soils, battered back walls, and sloping retained ground (Smith, 1990).

Equation 1: Coefficient of active earth pressure

$$k_a = 1 - \sin \phi' / 1 + \sin \phi' = \tan^2 (45^o - \phi'/2)$$

Equation 2: Active pressure at failure

$$p_a = k_a \gamma' z$$

Where:

k_a	=	coefficient of active earth pressure
p_a	=	horizontal active pressure on wall
γ'	=	effective density of retained fill
z	=	depth below ground surface
ø'	=	effective angle of internal friction

For tyres the effective density of retained fill (γ') will be much lower than for natural aggregates, reducing the horizontal stress behind the wall. Reduced horizontal stress here lowers the active pressure (p_a) on the back of the structure. This allows for a lighter and more economical construction of the retaining wall.

There is quite an extensive history of research undertaken in the area of tyre lightweight fills by a number of researchers including Drescher and Newcomb, 1994; Humprey *et al*., 1993; Ahmed and Lovell, 1993; Tatlisoz *et al*., 1998 and Lee *et al*., 1999.

Specific advantages for use as backfill to retaining walls that have been identified include:

- an increased factor of safety (Cecich *et al*., 1996)
- soil-tyre chip mixtures have significantly higher shear strength than soil alone
- tyre chips and soil-tyre chip mixtures have a similar geosynthetic pull-out force to soils
- large amounts of exposed steel belt produce a lower coefficient of earth pressure at rest (k_o), and a lower shear strength, indicating a potential advantage in steel bound tyre shred for retaining wall backfill. For a normally consolidated soil a higher shear strength (ø') would normally produce a higher k_o.

5.3.2 Rubberised asphalt

Crumb rubber may be used to produce rubberised asphalt, or poroelastic asphalt, as it is also known. The material is an open-textured asphalt mixture with a very high void percentage made possible by the addition of rubberised bitumen as a binder. It provides a variety of benefits that include a longer lasting surface, resistance to rutting and cracking, reduced road noise and reduced costs. Blending crumb rubber with asphalt and aggregate under specific conditions produces rubberised asphalt. A crumb rubber producer grinds waste tyres into crumb rubber. The crumb rubber is then blended with the asphalt and aggregate in a preset formula at the asphalt plant under the 'wet' process and shipped to the construction site for use. Rubberised asphalt can be used on a large scale, employing technology already available in the road-building industry.

The County of Los Angeles began limited use of rubber in asphalt in the 1970s. It now uses it on 75 percent of its highway resurfacing projects, using funds for road construction generated by gasoline taxes.

The use of rubberised asphalt in road surfacing has provided a number of benefits that include:

- a longer lasting surface (50 - 100%)
- resistance to rutting and cracking
- reduced road noise (50 – 80%)
- reduced cost of project and/or ongoing maintenance expenses.

The use of rubberised asphalt in the UK was certified by the Highways Agency after it performed well in a two year trial in Surrey and an evaluation was made of other roads.

The County of Los Angeles has also been using rubberised emulsion aggregate slurry (REAS). REAS is defined as crumb rubber blended into asphalt emulsion at ambient temperature and used as slurry on road surfaces. Los Angeles has used REAS since

1993, paving more than 1,330 lane miles. This has utilised 104,000 tyres (at 78 tyres per lane mile) (Amirkhanian, 2001).

There are no known examples of the use of either rubberised asphalt or REAS in any port, coastal or river engineering schemes however there is the potential to develop uses such as:

Structure	**Use**
Dune protection and seawalls	Revetment above high water
Protection of sea/river bed	Aprons placed in the dry
Groynes	Special cases (capping)
Dykes and closure dams	Revetment above high water

Development of these applications would require a programme of pilot studies for testing and monitoring performance before any recommendations could be made as to the suitability of the materials for these uses. The few recent applications of conventional asphaltic materials in the UK have been focussed on the use of open stone asphalt and open sand asphalt (see Masters, 2001). These materials are efficient at absorbing wave action in their open structure, but it might be possible to improve this further with the inclusion of rubber crumb, given the increased resilience to dynamic loadings of road surfaces constructed with rubber crumb materials. If such structures were to be considered, care would need to be taken to examine the nature, rate and consequences of any leachates.

6. Durability, monitoring and maintenance

6.1 WEAR AND ABRASION

Tyres are designed to be strong and durable. Worn or 'used' tyres that have served their original purpose on vehicles still have a structural durability that can be utilised.

Prevention of the Ultra-Violet (UV) light degradation of the rubber surface of tyres is important when considering the re-use of whole tyres. As well as reducing the rate of leaching of metals from the tyre (see Section 3.1) it also helps to maintain the integrity of the tyre by preventing water ingress between its structural elements and thus preventing loss of cohesion. This is another reason for being careful to select tyres that have not been worn to the belt or canvass, or that have large or numerous deep splits and cuts in the outer rubber layer that penetrate to these layers. Generally, if these layers or metal reinforcing wires can be seen, the tyre should not be deemed suitable for reuse as a 'whole' tyre for engineering purposes.

Figure 6.1 Damaged tyre with exposed radial and reinforcing wires

Tyres may be exposed to abrasion from suspended sediments in water, or by mobile beach materials. Tyres exposed to repetitive impacts, abrasion or wear should be regularly checked for condition and damage. For example river pile and post revetments utilising tyres are exposed to the mooring activities of river craft which may result in cuts, gouges, rips and tears of the tyre fabric. Severe damage may result in the emergence of the steel reinforcing wires which not only impairs the structural performance of a tyre but may also be an entrapment and puncture hazard to wildlife or to people. Exposed wires may also damage adjacent components such as geotextiles - which in turn could lead to further structural problems (for instance, loss of fines from backfill material).

A single tyre failure may lead to the partial loss of a structure such as a floating breakwater where structural integrity under severe conditions may depend on all components working properly. Punctures through the tread and sidewalls of tyres in breakwater structures can significantly affect their performance. Their margin of positive buoyancy is slight to begin with and some have had to have supplementary floatation added to improve their performance. Leakage of air from the tire cavity through cuts and punctures would decrease their ability to remain afloat even more.

6.2 ULTRA-VIOLET LIGHT DEGRADATION

Carbon black, used to strengthen the rubber in tyres and aid abrasion resistance, also serves to block the damaging ultra violet component of sunlight, extending the life of rubber. Sulphur and zinc oxide in the tyres also prevent rubber degradation by providing covalent bonding allowing elastic deformation. Loss of these chemicals through leaching can thus accelerate the ageing process. If tyres are kept away from sunlight, placed underwater or buried underground however, surface degradation is effectively eliminated and leaching substantially curtailed (Collins *et al,* 2002.)

It is therefore recommended that, where possible, tyres are either used in buried applications or where they are permanently covered by vegetation.

Site inspections should therefore note any topsoil slippage, erosion, structural settlement, cover or capping removal etc., that has or is likely to result in the exposure of the underlying tyre structure, and then recommend remedial action.

Baling tyres already largely degraded by UV light to the point where the rubber has become ‘brittle’ (flaky, light grey/faded black or brown and easily split) should be avoided as these may simply collapse under compaction and serve no useful purpose in the bale.

6.3 OVER-COMPACTION

Other factors may affect the durability of tyres that are compacted into bales. Over-compaction of tyres (which may occur if an attempt is made to compress too many into a bale) could lead to a reduction in durability. Splitting and cracking of the rubber layer may occur due to excess compaction, bending, twisting and so on during the baling process - exceeding the ‘tolerance of flexibility’ of the tyre bale.

6.4 SURFACE GROWTH OF ORGANISMS

Growth of organisms on tyre surfaces may or may not be desirable. Artificial reefs are expressly designed and built to provide additional settlement surfaces for colonising organisms as well as habitat for motive benthic and pelagic species. Aesthetically, growth may be beneficial for terrestrial structures too. It may help to ‘blend’ the structure into the landscape if, for instance, tyres are exposed in a sensitive location. If this growth however, is on tyre surfaces that may be encountered by pedestrians then it may be a safety hazard, especially when wet. Smooth rubber surfaces are also hazardous when wet and thus when combined with, for instance, a covering of algae, they can become treacherous underfoot (see Box 5.1.9). For this reason a schedule of cleaning/removal of surface organisms may be required for some structures or exposed surfaces (e.g. tyre steps).

6.5 CONDITION OF FASTENINGS

While tyres themselves are inherently strong as well as flexible, these characteristics have posed a problem for connections and fastenings. Tyres may need to be fastened tyre to tyre, or tyre to anchor or structure etc, for many applications especially where the tyre structure is to remain flexible such as in floating tyre breakwaters. (See Box 5.1.10).

Catastrophic failure of fasteners in some marine tyre structures during severe conditions in the US resulted in the dispersal of tyres along coastlines and led to the banning of tyres for this use in several States.

Thus selection of fastenings for particular applications should be conducted with some prior thought. Careful consideration should be given to both the ability of the fastener to effectively withstand the structural stresses that it is likely to be submitted to, and to its ability to resist corrosion and abrasion if used in the marine environment. Any future monitoring and maintenance schedule of fastening components is likely to be governed by these factors.

Connectors and fasteners that have been used with variable success include synthetic rope, galvanised steel chains, wires and bolts, rivets, nylon bolts, rubber conveyor belting, and plastic strapping.

Rope or wire connections are not recommended if the structure is likely to be subject to frequent and repetitive movement as these can cause chafing of the tyre casings eventually leading to exposure of the steel reinforcing within the tyres (or failure of the rope fastener where rope is used). In water this also allows ingress to the internal tyre fabric further diminishing the structural integrity and performance of the tyre.

Galvanised chains, wires and bolts, may not survive if submitted to long term marine exposures. Once the zinc coating is removed by corrosion or abrasion, the underlying steel is likely to deteriorate rapidly (especially in salt water). Increasing the longevity of the fastener by increasing its thickness will also increase its weight - not a desirable option when designing a floating breakwater as this would reduce the buoyancy of the system.

Failures can also occur as a result of bolts and washers pulling through holes in the tyres and snapping of the bolts has also been known (Motyka and Welsby, 1983).

Ropes should be checked regularly for chaffing and fraying. Synthetic rope tends to deteriorate over time due to UV light exposure.

Rubber conveyor belting should be checked for cuts, splits, cracks, abrasion and wear. This should be examined carefully if the connection serves as a ‘flexible’ joint in the structure.

Consideration of fastener failure can be made during the design stage and mitigated through improved design. For instance, the River Witham embankment was designed so that the tyre bales were orientated such that the bales would contain themselves in the event of bale fastener failure, i.e. the bales were placed side to side along the structure length as opposed to end to end (see Figure 5.32). Full bale failure is unlikely, as typically there are five wires or bands used to bind the module. Over time as the tyres loose their original shape ‘memory’ the fasteners are required even less to hold the tyres in a compressed state.

6.6 RESISTANCE TO IGNITION AND PROPAGATION OF FIRE

Two issues were raised during the course of the research in regard to tyres and fires. The concern was that an increased risk of fire might arise from the bulk use of tyre bales, even though anecdotal evidence suggested that bales significantly reduced fire risk in comparison with loose tyre dumps.

1. Was there a risk of a self-heating hazard arising from the bulk use of tyre bales? It was thought that an exothermic reaction resulting from steel wires in the tyres the presence of moisture, could cause self-heating. This could then lead to spontaneous combustion, as the heat generated would be dissipated slowly due to densely packed bales providing good thermal insulation.

2. How serious was the risk of arson when baled tyres are stockpiled waiting to be used in a civil engineering project? There could be a large number of exposed bales that could become a target for malicious attack and it was not certain how easily such bales might be ignited.

A set of fire tests was commissioned specifically for this project to address these issues. A full account of these tests is given in Appendix 7, but the key findings are summarised here:

6.6.1 Ignition by self-heating

Tyre bale material was tested isothermally to determine its self-heating properties and critical ignition temperatures. The material was found to be susceptible to self-ignition, but only at elevated temperatures far in excess of the expected ambient temperatures experienced during the normal use and storage of the tyre bales in civil engineering projects.

1. The lowest and therefore most critical ignition temperature determined for the tyre bales, when analysed in three different configurations, arose when used in the type of bulk fill design applied in the Pevensey Bay trial, and was determined to be 182°C.

2. If the tyre bales are to be surrounded by gravel, forming a non-combustible insulating layer, then the tyre bale can be taken as a single entity. In this case the bale would not become critical until an ambient temperature of 224°C is reached.

3. Only where tyre bales are used in ground engineering works in an area subject to heating from an external source, for example a burning landfill site or coal seam, might the ambient temperature experienced reach the critical temperature for ignition. They should not therefore be used in civil engineering works in areas where there may be an increased risk of heating from external sources such as subterranean fires.

6.6.2 Malicious ignition and fire growth

The threat of arson is perceived to be a potential problem when tyre bales are stockpiled – waiting to be used in a civil engineering project. Firstly, it was not certain how easily such bales might be ignited, and secondly, once alight, how the fire might propagate.

Under test conditions in a nine metre calorimeter, ignition was achieved using a No.7 wooden crib as described in BS 5852-2:1982 Fire tests for furniture: Method tests for the ignitability of upholstered composites for seating by flaming sources. This gave an ignition source equivalent to four sheets of full size newspaper.

The first attempt to ignite the bale with the crib at one corner failed. Although the ignition source did cause localised burning, the heat source was insufficient to allow burning to continue once flaming from the crib had ceased.

Although it was thought unlikely that the bales would be stored with open rims exposed, a second attempt to ignite the bale was made by placing the crib inside the rim of one of the tyres. Initial ignition of the bale was slow with the fire remaining inside the bale for eight minutes before the flames managed to take hold of the tyres. It should be noted that this may be less likely as an area for an attempted arson attack, as this face of the bale is usually facing internally when stacked (although the ends of the stack will have this face open to access). Hence, during storage the risk of tyre bales being ignited may be reduced by storing the bales in such a manner that only the surface with ease of access is the side of the bale with the tyre tread.

The growth of temperature and maximum heat output which occurred after ignition had eventually been achieved, was significantly less for the bale test where burning was achieved than with comparable tests with an equivalent volume of tyre crumb. The bale fire was terminated after 23 minutes by which time the temperature had only reached 120 degrees Celcius and the heat output 0.7mW. In comparison in the crumb test ignition occurred almost immediately and after just 8 minutes, when the test had to be terminated for safety reasons, the maximum temperature had already reached 700 degrees Celcius and the heat output had reached 1.5mW. The slow rate of growth of the fire during the first 16 minutes of the test indicates that, even if ignition was achieved in a storage facility, there would be sufficient time for fire service intervention before the fire became too large.

During the second bale fire test two of the five wire straps snapped (this may have arisen due to over-stressing of the wires during improper handling of the bale). However the bale remained intact and did not collapse.

6.7 CHEMICAL AND BIOLOGICAL DEGRADATION

Tyres are an inert material, they do not readily react with other materials or compounds common in the environment. However microbial organisms are known to degrade rubber materials. A study by the Firestone Tyre and Rubber Company in co-operation with Rutgers University found that several micro-organisms utilise the oils and hydrocarbons of tyre rubber (Crane *et al*. 1975).

The study though did not reveal any micro-organisms which selectively and completely cleaved the sulphur bonds in tyre rubber. Also the growth of the organisms that utilise extender oils and rubber hydrocarbons are suppressed by zinc oxide, anti-degradants and vulcanisation accelerators. In all the study experiments only a few percent of the scrap rubber was actually consumed by micro-organisms

A previous study by Heap and Morrell (1968) concluded that both bacteria and fungi may obtain carbon for growth from tyres by breaking rubber down enzymatically. Thus it is suggested that bacteria and fungi are potential destructive agents for rubber. Also protective agents in the rubber such as paraffin wax used to prevent ozone attack "bloom" to the surface of the rubber and might be a source of food for micro-organisms. Heap and Morrell also stated:

- ***Spicaria violacea, Metarrhizium anisopliae, Fusarium*** species and ***Stemohyliopsis*** caused visible pitting and macro porosity in underground rubber-cased cables.
- ***Thiobacterium thio-oxidans*** attack sulphur in the vulcanised rubber by converting sulphur to sulfuric acid. (A free sulphur content of <0.1% would probably avoid this problem)
- vulcanised natural rubber may be attacked by ***Stemphylium macrosporoideum***
- long chains of repeating Isoprene units in natural rubber are liable to oxidation
- butyl and nitrile rubbers are resistant to oxidation and there is little evidence of microbiological attack despite the presence of poly-isoprene units in butyl rubber
- silicone rubbers are generally considered to be resistant to microbiological attack.

Based on the available information the potential impact of microbial rubber degradation is not clear. Further research into microbial processes over the long-term would be needed to establish the long-term performance of rubber materials in structures.

7. Environmental impact and risk assessment

The *EU 6th Environmental Action Plan Article 8(2) iii* requires "environmentally sound recycling" (EU, 2002). The Defra guidance on the role of flood and coastal defence in nature conservation in England (1999) *High Level Target 9A* states that "flood and coastal defence work should avoid environmental damage and ensure that there is no detriment to Biodiversity Action Plan (BAP) Habitat" (EA, 2001).

As with any material not previously used to any great extent in construction, investigations into the environmental impact and an assessment of risk involved with their use need to be conducted.

Risk assessment is a standard process used by environmental managers to assess the impact of any individual project or manufacturing process, each of which will have varying degrees of environmental risk associated with it. However, for the purpose of the review of WML exemptions, it was also necessary to take a higher level, more generic view of environmental risk and its management.

Any consideration for the adjustment of exemptions to the existing waste management licensing regulations as it applies to used tyres, must address all the main aspects of re-use of tyres from the point (after a tyre legally becomes waste) at which the exemption would start to apply. This therefore applies to storage, processing, construction, 'reuse' or operation, and final disposal. In some circumstances used tyres or tyre derivatives may be reused more than once.

This environmental risk assessment provides a high level, generic view of environmental risks associated with the use of tyres in construction and their management and is based upon the 'Guidelines for environmental risk assessment and management' (ERAM) issued by DETR, the EA and the Institute for Environment and Health (2000). The assessment follows the same protocol of:

- hazard identification
- identification of consequences
- estimation of the magnitude of the consequences
- probability of the consequences
- evaluation of the significance of the risk.

This risk assessment is divided into two levels, a screening level (Tier 1) to identify the primary areas of concern, and a generic level (Tier 2) to quantify some of the risks facing the environment.

Particularly relevant information on risk management, monitoring and field studies on leachates from construction project are also included here.

7.1 HAZARD IDENTIFICATION

7.1.1 General

Data amassed over more than 30 years concerning the potential impacts of used tyre materials on human health and the environment indicates that they are neither hazardous nor dangerous. They do not appear on any EU or Basel Convention list of hazardous materials.

Used tyres and related materials do not pose a threat to the environment or to human health so long as normal precautions are followed for treatment, processing, storage and use. This applies to the whole range of used tyre materials, such as whole or cut tyres, shreds, chips, granulate or powders regardless of the treatment technology applied (Hylands and Shulman (2004).

The principle concerns which need to be addressed in an environmental risk assessment of the re-use of tyre materials include their potential environmental impact due to storage, the risk of fire, the potential leaching of chemicals and compounds into local water courses and potable supplies, human health and safety issues and energy usage.

7.1.2 Fire

The spontaneous combustion of whole tyres is unknown. Following ignition a temperature of at least 350^0C must be maintained for the fire to propagate.

There are no known explosive hazards associated with any tyre material.

Under very special conditions it has been known for tyre chip to react exothermically, resulting in the release of heat from chemical or biochemical reactions. According to Humphrey (1996) this phenomenon is potentially caused by oxidation of exposed steel belts and wires, oxidation of rubber, microbes consuming exposed steel wires or generating acidic conditions and microbes consuming liquid petroleum products.

The main risk of fire arises from arson, either as whole or semi-processed tyres, mainly of open air or poorly ventilated indoor storage areas.[5]

Used tyres are commonly transported in large quantities on land and water within the context of ADR regulations (Accord européen sur le transport des marchandises dangereuses par route) revised in 2001. These regulations state that tyre shred, chips, granulate and powders are not subject to the provisions of the Flammable Solids class because the results of the UN standardised test (test N1 – the fire train test) indicated that the burning rate is too slow to pose a risk during transportation when normal guidelines are followed.

7.1.3 Leachates

The principal leachates that might be of concern from tyres are metals and metallic compounds and benzothiazole and its derivatives.

Vashith *et al* (1998) analysed water samples from crumb rubber asphalt runoff for six metals: chromium, lead, nickel, copper, cadmium, and zinc. A general trend for these metals indicated that zinc was leached in higher concentrations than other metals.

Collins *et al* (1995) examined leachates from whole tyres and also identified zinc as the major tyre leachate, totalling 10 mg/tyre after 3 months. The reason for this seemingly low leachate concentration (the total zinc content is in the region of 200g/tyre) is that the chemicals are only leaching out of the outside 2mm of the tyre.

[5] (Environment Agency licensed storage sites are required to follow the Home Office guidance on fire safety for tyre sites, 1995)

The use of tyre chips or shreds can increase the release of other metals, due to the exposure of the metal reinforcements (O'Shaughnessy and Garga, 2000), including aluminium, iron and manganese as well as zinc. Shredding and chipping exposes metal within the tyres, increasing the risk of leaching of iron and manganese, and also increases the area available for leaching of zinc and PAH. Cadmium, copper and lead have also been shown to leach from shredded waste tyres but only in small quantities (Lagerwerff, and Specht, 1970).

Test results indicate that tyres do not leach volatile organic compounds. Research into long term safety indicates that most of the compounds detected in water samples are at, or near lower detection limits at only trace levels - 10 to 100 times less than regulatory limits for drinking water. They should not, therefore, pose a threat to health or the environment.

The pH level has been shown in field and laboratory tests to affect leaching. Organic materials may leach more freely under neutral conditions while metals leach more freely under acidic conditions. In proper applications though, used tyres are not considered a soil contaminant as the leached amount of PAHs and metals under laboratory conditions is negligible (Westerberg and Màcsik, 2001).

PAHs have not been produced in leachate at significant concentrations when tyres are placed below the water table, and appear to be even less of a problem when tyres are placed above the water table.

7.1.4 Health and safety

The most significant health and safety issues associated with tyres relate to air borne crumb, dust, noise and vibration during *manufacturing* of finer products from tyres or during *tyre remoulding*.

There are no known permanent effects from physical contact with whole tyres or shredded, chipped or granulated products. The most enduring known risks arising from tyres in the workplace are from manual handling operations leading to strains and sprains.

There is an added risk of injury that pertains particularly to tyre bales during storage and/or loading and unloading. Tyre bales weigh around one tonne and there is a risk of injury to staff if not handled with the correct machinery or stacked appropriately.

7.1.5 Landscape and visual quality

Tyres, especially used ones, are not aesthetically pleasing. Processing which changes the structure of tyres such as shredding, chipping etc, can overcome this problem. For whole tyre applications (on land) though, this may still be a problem. To some degree this may be a planning issue which can often be mitigated by good design and suitable material / vegetative cover. From an engineering standpoint cover is beneficial anyway as this prevents UV light from degrading the tyres, potentially prolonging the life of the structure and preventing further leaching of compounds from the material. (Placement under-water has the same effect).

Thus generally tyres are not going to be visible following completion of a civil engineering application.

To prevent loss of tyre floating breakwaters and artificial reef units in adverse weather the structures should be securely anchored to ensure that they do not break up and cause environmental damage along the coastline.

7.1.6 Environmental issues where no known hazard exists

Odour

There is no reason why the re-use of used tyres themselves would produce adverse odour. Tyres and rubber do have an odour but it is considered as being of little significance in use in civil engineering. Risk of odours from manufacturing activities (retreads or products from tyre derived materials) has been discussed under "health and safety" (Section 7.1.4).

Noise and vibration

Used tyre products have the potential to absorb shock and vibration thus providing a measure of insulation against sound and vibration. Risk of noise and vibration from manufacturing activities (retreads or products from tyre derived materials) has been discussed under "health and safety" (Section 7.1.4).

Flora and fauna / Habitats and species (other than leachate issues)

Other than the issue of the potential and impact of leachates discussed above, when carrying out any *construction* works using used tyres interference in ecosystems will occur and will result in a new equilibrium condition. However such changes are completely project specific and should be assessed as part of the normal environmental impact assessment process including the checking that any rare flora and fauna will not be adversely affected by establishing structures.

Tyres are resistant to burrowing animals especially if the surrounding matrix is not conducive to habitation. This may be important in some cases to avoid creating undesirable habitats. An example might be where tyre bales are being used in embankment construction or slope stabilisation where bales may help to prevent burrowing that might cause stability problems.

Artificial reefs made of whole tyres have been deliberately put in place underwater to create habitat substrate and shelter for marine life and have been successful in this regard.

Archaeology and unknown assets

The processing, including temporary storage, of tyres into final product has no significant potential for any hazard. The low weight of tyres when compared to that of aggregates and other civil engineering fills means that their use is considered a distinct advantage to archaeological remains and unknown buried assets. Compression of the ground or foundations sunk through soft ground can damage or destroy underground remains. The low weight of tyres results in less ground compression and reduces the need for foundations on soft ground.

Around $30m^3$ of tyre bales can be transported by one lorry as opposed to, for instance, $10m^3$ of clay. This is because tyres are significantly lighter than clay. The same comparison would apply to all other aggregates and alternative materials under consideration in construction. Fewer trips for the same volume and less weight in transport terms also equates to less fuel consumption. Thus, so long as there is a local supply of used tyres there will often be a net benefit in terms of traffic and transport impacts by using tyres as opposed to traditional aggregates in construction projects specifically.

In summary, if there are important energy issues associated with the re-use of tyres in engineering works, they revolve around the degree of environmental benefit arising. None of them represents an environmental hazard.

7.2 IDENTIFICATION OF CONSEQUENCES

7.2.1 Fire

A tyre fire creates dense oily smoke which can be toxic if inhaled, causing dizziness, central nervous system (CNS) depression, potential carcinogenicity. Combustion products and runoff from the fire fighting process can contaminate the ground and local water receptors.

7.2.2 Leachates

The use of tyres in aquatic applications may permit leaching of chemicals as outlined above. Evans (1997) has compiled one of the most comprehensive reviews of tyre leachate studies for land based applications, and freshwater, estuarine, and marine exposure studies. He concluded that, if there is a threat at all, tyre leachates are probably a greater threat to freshwater habitats than brackish or marine habitats. However, it is unlikely that the pollution load from a tyre-based structure will have any significant effect on the environment; leachate levels are low in comparison with leachate in rainwater run-off from roads, which has been received in watercourses for many years without adverse impact.

Field studies have shown no significant differences between waste tyre areas and control areas for soil samples taken for a biological survey (Minnesota Pollution Control agency, (1990).

Zinc undergoes reactions in sediments and soil involving precipitation/dissolution, complexation/dissociation, and adsorption/desorption. These reactions are controlled by the pH, redox potential (Eh), the concentration of zinc ions and other ions in the pore water, the number and type of adsorption sites associated with the solid phase, and the organic ligands present that are capable of forming complexes with zinc.

Zinc is relatively insoluble as an oxide and mobility is limited by a slow rate of dissolution. Clay and metal oxides are capable of sorbing zinc and tend to retard its mobility in soil. At pH 6.5, for example, zinc has been found to bind with the iron mineral goethite and to humic acid, although this effect is less apparent at a pH of 4.5. On the other hand, the amount of zinc in solution generally increases when the pH is >7 in soils high in organic matter. Anoxic conditions may promote the formation of soluble zinc salts.

Normal pH in soil will generally limit the mobilisation of zinc; thus zinc from tyre shreds will be less available and become immobile with soil interactions.

7.2.3 Health and safety

There are no permanent effects from physical contact with used tyre materials in whole or ground form. There are no known health effects due to short term exposure to the material. Prolonged dermal contact can create skin irritation, sensitisation or disorders with repeated exposure.

The material contains untreated naphthenic or aromatic oils, which are classified as carcinogenic and could be released from the surface through skin contact. Prolonged contact has caused skin cancer in studies with animals.

When subjected to heat potentially carcinogenic materials (e.g., nitrosamines), carbon oxides (CO, CO_2), acrid fumes, and flammable hydrocarbons may be liberated due to thermal decomposition/combustion.

7.2.4 *Landscape and visual quality*

Landscape and visual quality can be adversely affected by storage or construction activities involving tyres or tyre-derived materials, where these are stored or used in an unsightly and uncontrolled way. Poorly designed and/or controlled construction works can also break down and leave whole or part tyres lying around in an unsightly fashion.

7.3 ESTIMATION OF THE MAGNITUDE OF CONSEQUENCES

7.3.1 *Fire*

Tyre fires are difficult to extinguish, are persistent underground, can contaminate ground and water receptors with compounds and chemicals, and pollute the air with black acrid smoke and noxious fumes harmful to human health. Thus, where a tyre fire occurs, the magnitude of consequences in terms of physical damage and potential impact on human health from smoke and other products of ignition is estimated to be *severe*.

7.3.2 *Leachates*

Leachate laboratory and field studies indicate that for all regulated metals and organics the results for used tyres are well below regulatory levels. Substances which could potentially leach from post-consumer tyre materials are already present at low levels in groundwater in developed areas. Studies suggest that leachate levels for the majority of determinants fall below acceptable regulatory limits and have negligible impacts on the general quality of water in close proximity to tyres (Westerberg and Màcsik, *op.cit)*.

Benzothiazole and its derivatives have to be present in very high concentrations (>1000□g l^{-1}) to be toxic. From the evidence, one could conclude that in an open aquatic system (relevant to the natural environment around most storage or construction works), the flushing rate will be high and benzothiazole toxicity would not be a problem.

The magnitude of consequences is estimated to be *negligible*, except where slow or stationary waters are the receptor where it might be estimated to be *mild*.

7.3.3 *Health and safety*

In an uncontrolled (i.e. illegal) environment the magnitude of health and safety consequences may be assessed overall as *mild*.

7.3.4 Landscape and visual quality

The magnitude of the impact on landscape and visual quality overall of uncontrolled construction or storage activities may be assessed as *mild*, although locally the consequences might be *moderate*.

7.4 PROBABILITY OF THE CONSEQUENCES

The magnitude of the consequences has been assessed as a combination of the probabilities of the hazard occurring, of the receptors being exposed to the hazard and of harm resulting from exposure to the hazard.

7.4.1 Fire

Although the probability of a fire hazard occurring might be viewed as low, the probability of receptors, especially humans and the natural environment, being exposed to the hazard is high and the probability of harm resulting is medium. Hence, overall the probability of the consequences of fire hazard is assessed as *medium.*

7.4.2 Leachates

Although the probability of a leachate hazard occurring might be viewed as medium, the probability of receptors, especially humans and the natural environment, being exposed to any hazard is low and the probability of harm resulting is negligible. Hence, overall the probability of the consequences of leachates is assessed as *low.*

7.4.3 Health and safety

The probability of a health and safety hazard occurring, the probability of humans being exposed to any hazard and the probability of harm resulting are all assessed as medium. Hence, overall the probability of the consequences of health and safety hazards in an uncontrolled environment is assessed as *medium.*

7.4.4 Landscape and visual quality

The probability of a landscape and visual quality hazard occurring, the probability of humans being exposed to any hazard and the probability of harm resulting are all assessed as medium. Hence, overall the probability of the consequences of landscape and visual quality hazards in an uncontrolled environment is assessed as *medium.*

7.5 EVALUATION OF THE SIGNIFICANCE OF THE RISK

The overall risk of damage to the environment and human health is assessed to be *medium*, but is expected to be reduced to *low* to *near zero* by appropriate controls, including those already in place under existing regulation and legislation. The significance of the subsidiary components of risk has been assessed as:

- Fire: *High*
- Leachates: *Near zero*; *low* in slow or stationary receiving waters,
- Health and safety: *Low*
- Landscape and visual quality *Low*

7.6 RISK MANAGEMENT

7.6.1 Fire

The risk of tyre fires started by arson are significantly diminished with the proper consideration and application of security provisions wherever stocks of tyres, tyre bales, casings etc are easily accessible. Registering of exemptions could be made conditional on a commitment to provision of adequate security.

7.6.2 Leachates

The fact that tyres are durable is one of the main advantages for their use. Provided that applications are appropriately and properly designed and engineered there should be no environmental liability. Higher levels of some leachates may arise within closed aquatic systems that form part of some construction works, but planning permission for such works could be made subject to appropriate control provisions and ongoing monitoring.

7.6.3 Health and safety

Risks to health and safety are generally reduced to low under normal operating conditions in factories and on construction sites, where existing regulatory and best practice provisions are in force

Normal protective wear (steel reinforced boots, eye, ear and head protection, protective gloves and dust masks) together with long sleeves and trousers has proven sufficient against any potential irritations from the handling of tyres and tyre based rubber materials, should they arise.

7.6.4 Landscape and visual quality

The requirement to obtain planning permission and the subsequent enforcement of planning and building controls has already been proposed by Defra for a new paragraph 19 2(b) of Schedule 3 of the Waste Management Licensing Regulations (see Appendix 11). This limits the issuing of exemptions for construction works to those situations "where the carrying out of the relevant work requires planning permission for the purposes of the Town and Country Planning Act 1990, that permission is in force at the time the work is carried out and the waste is used in accordance with that permission."[6] The effect of the controls imposed by this amendment should ensure that the impact on landscape and visual quality is kept to between low and near zero.

7.7 MONITORING

Exemptions are subject to 'appropriate periodic inspections' as required by the Waste Framework Directive. As well as conducting appropriate periodic inspections the EA will respond to any complaints or allegations about exempt activities.

[6] "Proposals for amendments to the Waste Management Licensing Regulations 1994 (as amended) - A consultation paper". Defra, June 2003. See http://www.defra.gov.uk/corporate/consult/wastemanlicence/index.htm

7.8 CONSTRUCTION PROJECT FIELD STUDIES ON LEACHATES

There is a growing amount of available scientific data arising from construction projects and studies around the world relating to tyre leachates and effects on receptors.

In July 1998 tyre modules and concrete control modules were deployed alongside an existing cement stabilised coal ash reef study site in 12m of water off the South Coast of England near Poole in Dorset. Five hundred scrap tyres were used in various configurations.

Organisms sampled from both the concrete units and the tyres were routinely analysed for heavy metals and organic compounds. No evidence of significant uptake of zinc was detected ((Roenelle 1999); (Rayner 2001)). Benzothiazoles (Collins, Jensen et al. 2001) or PAHs (Rayner 2001) were not detected in the reef epibiota.

The lack of effect on the development of the artificial reef organisms can be explained by the limited release of leachates from the tyres. Tyres in the stable pH conditions of seawater and away from the deleterious effects of UV in sunlight, are very stable and leaching is confined to a 2mm surface layer. This leaching decreases exponentially with a time scale of days. The toxicity studies reviewed by Evans (1997) show decreasing effect with time of immersion. In a coastal environment, leachates are quickly dispersed by tidal currents. Malek and Stevenson (1986) examined tyres recovered from a World War II wreck off Scotland after 42 years immersion, finding them to be in excellent physical condition.

In 1997 a 200m wall of lorry tyres was built along the shore of Copperas Wood Farm, Wrabness in a north Essex estuary to stop erosion of the clay cliffs. This was formed of stacks of tyres four high and two deep, tied together with polypropylene rope and filled with stone and soil (see Box 5.1.4). Seaweed (*Fucus vesiculosus*) was sampled (27.2.03) from the tyre wall along with control specimens growing on stones and concrete blocks 50m further along the beach. No difference in levels of zinc were found between the two populations.

In November 2002, some 350 tyre bales (each containing 100 car tyres compressed to form a block 150 x 125 x 75cm) were placed in a beach at Pevensey Bay in the South East of England and surrounded by a number of sampling wells to monitor water quality in the shingle (See Figure 7.1 and Figure A8.14). Water inundation is restricted to tide induced percolation through the beach. Whilst the base of the tyres are at the level of mean neap tide high water, the limited permeability of the beach material only allows sea water to reach the base of the tyre bales during the higher spring tides.

Detailed monitoring of this trial demonstrated that levels of zinc leachates in beach interstitial water were below EQS levels and declined with time. It was possible to model the levels of zinc observed within the tyre bales. In addition, no evidence of cadmium contamination was found even within the tyre bales (Collins *et al*, 2004) (a full account of the monitoring is given in Appendix 8, Section 8.2.4).

Figure 7.1 Water samples being drawn at Pevensey for chemical analysis

Large numbers of tyres are used in the USA for road construction as shred ((Eldin and Senouci 1992); (Stotz and Krauth 1994); (Hossain, Funk et al. 1995)) in the basal layers or incorporated into the surface asphalt layer (Vashisth, Lee et al. 1998). Humphrey, Katz et al. (1997) have examined the use of tyre chips in bulk fill applications, comparing water quality from wells in tyre chips above groundwater table, to control wells used to distinguish substances naturally present in groundwater from those leached from tyre chips. There was no evidence that tyre chips increased levels of substances that have a primary drinking water standard. Two sets of samples were tested for organic compounds with results below the drinking water test method detection limits.

For an experimental tyre-reinforced embankment in Ottawa, Canada using 10,000 whole or half tyres packed with sand and earth, O'Shaughnessy and Garga (2000), analysed eighteen samples of leachate taken over 2 years and for a range of inorganic elements and organic compounds. The values for zinc ranged from 440 – 8I g l^{-1} (average 90I g l^{-1}, compared with background levels of <40I g l^{-1}, U.S. EPA regulatory allowable limit of 5mg/l)[7]. Levels of cadmium were typically below the detection limit of 0.5I g l^{-1}. Benzothiazole, and 2(3H)-Benzothiazolone were found above their detection limit of 1I g l^{-1} Similarly 4-(2-benzothiazolythio) morpholine was not detected in 16 out of 18 samples. No regulatory limits are set for these organic compounds.

[7] Φg g^{-1} or mg l^{-1} = 1ppm (part per million), Φg l^{-1} = 1ppb (part per billion)

In 2003/2004 a flood defence embankment on the River Witham near Lincoln UK was reconstructed using tyre bales as the bulk fill material (see Box 5.2.4 and Appendix 8 for details). The scheme used the largest number of tyres known thus far in the UK for this type of application – 10,000 bales (> 1 million tyres).

Surface and river waters were sampled for submission to a suite of analyses routinely undertaken by the Environment Agency (see Figure A8.4 for sampling locations) including dissolved ions, biological oxygen demand, nutrients, heavy metals and PAHs. Monitoring results indicate that other than temporarily elevated levels of zinc and cadmium at the site during the construction phase, overall there was no evidence for any elevation of the downstream river levels of any constituents. (A summary account of this monitoring can be found in Appendix 8, Section A8.1.5.)

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Conventions

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European Directives and Regulations

Assessment of the Effects of Certain Public and Private Projects on the Environment Directive (97/11/EC)
Dangerous Substances Directive (76/464/EEC)
EC Regulation (259/93) on the International Movement of Waste
End of Life Vehicle Directive (2000/53/EC)
Framework Directive on Waste (75/442/EEC as amended by 91/156/EEC and 91/692/EEC)
Groundwater Directive (80/68/EEC)
Habitats and Species Directive (92/43/EEC)
Landfill Directive (1999/31/EC)
Shellfish Waters Directive (79/923/EC)
Water Framework Directive (2000/60/EC)

UK National Legislation

Ancient Monuments and Archaeological Areas Act 1979 (England, Wales and Scotland)
Burials Act 1857 (England and Wales)
Clean Air Act 1993
Coast Protection Act 1949
Control of Pollution Act 1974 (and amendments)
Control of Pollution (Amendment) Act 1989
    Registration of carriers of controlled waste
Control of Pollution Act 1974 (COPA) Part III (provisions to allow local authorities to impose requirements on work at construction sites relating to noise.
Countryside and Rights of Way (CROW) Act 2000
Environment Act 1995
Environmental Protection Act 1990 Part II
    Controlled waste and duty of care (Section 34)
    Waste management licensing (Section 33)
Environmental Protection Act 1990 Part III
    Statutory nuisance includes ‘any accumulation or deposit’ which is prejudicial to health or a nuisance [8]
The Environmental Protection Act 1990 (as amended by The Environment Act 1995)
Flood prevention (Scotland) Act 1961
Food and Environmental Protection Act 1985 (FEPA)[9]

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[8] Common Law (an individual can seek an injunction under common law, as noise is recognised as a nuisance)

[9] Licensing Authorities in the UK have a statutory duty to control the deposit of articles or materials in the sea and/or in tidal waters. The Food and Environment Protection Act 1985 requires that a license be obtained from the relevant department in order that the placement of structures and materials at sea or in tidal waters (below Mean High Water Springs) can take

Health & Safety at Work etc. Act 1974
Land Drainage Act 1991
Merchant Shipping Act 1894 (England, Wales and Northern Ireland)
Protection of Military Remains Act 1986 (England, Wales and Scotland)
Protection of Wrecks Act 1973 (England, Wales and Northern Ireland)
Salmon and Freshwater Fisheries Act 1975
The Planning (Listed Buildings and Conservation Areas) Act 1990 (England and Wales)
Town and Country Planning Act 1990 (England and Wales)
Water Act 1989
Water Resources Act 1991
Wildlife and Countryside Act 1981

UK Regulations

Construction Plant and Equipment (Harmonisation of Noise Emission Standards) Regulations 1985 and 1998
Contaminated Land (England) Regulations 2000
Contaminated Land (Northern Ireland) Order 1997 Part III
Contaminated Land (Scotland) Regulations 2000
Control of Major Accident Hazards Regulations 1999
Controlled Waste (Registration of Carriers and Seizure of Vehicles) Regulations 1991
Duty of Care Regulations 1991 (Section 34 of the EPA 1990)
Groundwater Regulations 1998
Landfill (England and Wales) Regulations 2002
Lifting operations and lifting equipment regulations 1998
Management of Health & Safety at Work Regulations 1992
Noise at Work Regulations 1989
Provision and use of work equipment regulations 1998
The Conservation (Natural Habitats &c) Regulations 1994 (as amended) and the Conservation (Natural Habitats, &c) Regulations (Northern Ireland) 1995
Waste Management Licensing Regulations 1994.
Waste Management Regulations 1996

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place. This includes materials used during construction (eg for new harbours, offshore structures etc), and for “soft engineering” purposes (eg beach nourishment, groynes etc).

Appendices