DEVELOPMENT OF EIGHT SHAPED SYSTEMS FOR SLOPE STABILIZATION

By

ABOULFAZL SAFARI

THESIS SUBMITTED IN FULFILMENT OF THE REQUIRMENTS

FOR THE DEGREE OF

PhD

May 2012

AKNOWLEDGMENT

It would not have been possible to write this thesis without the help and support of many kind people around me, to only some of whom it is possible to give particular mention here.

I would like to show my great gratitude to my supervisor; Prof. Dr. Fauziah Ahmad for her supportive advises and kindly helps which provided a very good situation to handle this research.

I would like to express the greatest love to my wife; Mandana Abedini who has been my supportive accompany in my way to succeed. Her personal supports, great patience, good understanding and advices have been the best encouragement to do this research. My love also goes to my little son for his sweat smiles which helped me to concentrate on my research.

I owe my greatest gratitude to my eldest brother Hassan for all his efforts and kindly advices in all my life particularly during my PhD. My parents, parents in law, brothers and brothers in law and sisters have given me their support throughout, as always, for which my expression of thanks likewise does not suffice. My special thanks also go to dear. Pantea for all her kindly helps gave me good support to do this research..

My special and warm thanks go to Mr. Mohammad Norifard my best friend for all his kind and supportive helps. I am most grateful to my good friend Mr. Farshid Bateni for his great comments and kindly advices which helped me to finish this research. My thanks also go to all my friends and postgraduate students in Civil Engineering School for their friendly helps.

I would like to acknowledge the technical support of all technicians in civil engineering school specially geotechnical and concrete labs. Special thanks to Mrs. Zuraily Zahary, Mrs. Zaharah Wan Mohamed Khalid and all administrative office staff for their warmly helps.

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LIST OF ABBREVIATION

Abbreviation	Description
USCS	Unified Soil Classification System
WAP	Wetted After Placement
WBP	Wetted Before Placement
MTL	Maximum Tensile Load
MTS	Maximum Tensile Stress
TSt_{MTL}	Tensile Strain at Maximum Tensile Load
M	Mean value
SD	Standard deviation
El_{MTL}	Elongation at Maximum Tensile Load
MEl	Maximum Elongation
MSt	Maximum Strain
MPF	Maximum Pull-out Force
FD_{MPF}	Frontal Displacement at Maximum Tensile Load
BD_{MPF}	Back Displacement at Maximum Tensile Load
FD	Frontal Displacement
BD	Back Displacement
In	Inclinometer
PM	Pressure Meter
Pz	Piezometer
STB	Steel Bar

LIST OF SYMBOLS

Symbol	Description
D_{10}	Effective size
D_{30}	Grain diameter at 30% passing
D_{60}	Grain diameter at 60% passing
C_u	Coefficient of uniformity
C_c	Coefficient of curvature
Hi	Initial thickness
Φ	Friction angle
ϕ'	Effective friction angle
C	Cohesion intercept
c'	Effective Cohesion intercept
σ_1	Principal stress
σ_v	Normal stress
σ'_v	Effective normal stress
CD	Consolidation Drained test
SRF	Settlement ratio
BCR	Bearing capacity ratio
D_r	Relative density
P	Pull-out force
F	Pull-out resistance
f	Fraction coefficient
A	Scale effect correction factor
Le	Embedment length
C	Reinforcement effective unit parameter
K	Ratio of actual normal stress
μ	Apparent friction coefficient
α_f	Geometric factor
α_{ds}	Direct sliding efficiency
α_b	Bound efficiency coefficient
Γ	Unit weight
L_f	Length of frontal wedge
H	Height of over burden soil
W	Width of reinforcement element

K_a	Rankin's active earth pressure coefficient
G_s	Specific gravity
γ_{dmax}	Maximum dry unit weight
γ_{dmin}	Minimum dry unit weight
γ	Unit weight
$\acute{\omega}_{opt}$	Optimum moisture content
W_l	Liquid limit
W_p	Plastic limit
OC	Organic content
L	Length of 8 shaped tyre and fibreglass
B	Width of single 8 shaped tyre and fibreglass
H	Height of 8 shaped tyre and fibreglass
D	Diameter of round shaped tyre
E	Young modulus
Σ	Stress
ϵ	Strain
R^2	Coefficient of determination
O	Round shaped
8	Eight shaped
88	Double eight shaped
E_1	Primary extension
E_2	Secondary extension
E_3	Distance between sleeve and reinforcement
E_t	Total extension
V	Volume of reinforcement per m^2
N	Number of reinforced elements per m^2
V_r	Volume of single reinforcement
S_m	Surface of mobilized area

ABSTRAK

PEMBANGUNAN SISTEM BERBENTUK LAPAN BAGI PENSTABILAN CERUN

Kestabilan cerun telah menjadi topik penting dalam bidang kejuruteraan geoteknikal. Pelbagai teknik telah dikaji untuk kestabilan cerun dengan meningkatkan sifat kejuruteraan tanah. Penggunaan bahan kitar semula adalah salah satu kaedah yang baik bagi menstabilkan tanah dalam menyelesaikan masalah merangkumi semua aspek baik alam sekitar dan mahupun teknikal. Tayar kitar semula telah digunakan secara meluas untuk tujuan ini kerana sifat fizikal dan mekanikal yang sangat baik seperti bahan yang ringan, kelasakan, kekuatan tegangan yang tinggi dan kos yang sangat rendah. Bentuk tayar yang bulat dari tayar kitar semula telah dilaporkan secara umumnya boleh digunakan sebagai elemen kestabilan cerun. Walaupun, pemprosesan yang minimum diperlukan untuk bentuk ini ubahbentuk sisi yang tinggi merupakan satu perkara yang membimbangkan. Tayar berbentuk bulat menunjukkan ubahbentuk sisi yang tinggi untuk mencapai kapasiti tarik keluar yang muktamad. Jadi, ubahbentuk yang berlainan telah di gunakan untuk tayar ktiar semual. Sehubungan itu, ubah bentuk merupakan sebagai elemen tetulang mamt di penaruhi. Walau bagaimanapun, fakto ubah bentuk ini belum dikaji oleh penyelidik lagi. Oleh itu, matlamat kajian ini adalah untuk membangunkan satu sistem baru untuk penstabilan cerun dengan memberi tumpuan kepada bentuk elemen tetulang. Sistem berbentuk 8 dari tayar yang dikitar semula telah dipilih kerana pada hakikatnya bentuk ini mendorong kekuatan yang lebih tinggi dan meningkatkan keupayaan galas tanah bertetulang. Sistem berbentuk 8 dari fiberglas juga dibangunkan sebagai alternatif kepada tayar yang dikitar semula untuk

menghasilkan ubah bentuk sisi yang kecil. Bahan yang telah diuji dalam bentuk jalur dan berbentuk 8 di uji di bawah ujian ketegangan dan tarik keluar. Satu sistem tikar berbentuk 8 tayar kitar semua di bina sebagai ujian perintis , dipantau di atas tapak. Di dapati ujian terikan tegangan jalur dan betukan 8 bagi fibreglas diukur lebih rendah daripada tayar sehingga masing-masing 550% dan 105,6%. Ujian tarik-keluar menunjukkan bahawa penggunaan bentuk 8 bagi sistem tayar adalah satu kaedah yang menggalakkan dan pengurangan dapat di lihat berbanding dari ubah bentuk sisi dengan tayar bulat yang mununjukkan sehingga 127,2%. Selain itu, dengan tiada tekanan tanah beban, sistem berbentuk 8 daripada fibreglas mengalami ketegangan yang lebih rendah daripada tayar berbentuk 8 sehingga 112%. Degan keabaan tekanan beban 3.5 kPa dan 6 kPa, sistem tikar fibreglass menunjukkan ketegangan yang kurang daripada tayar sehingga 132.8%, dan 121,9% masing-masing. Keputusan pemantauan selepas pembinaan menunjukkan bahawa ubah bentuk ternormal sisi diukur pada sistem berbentuk 8 adalah berkurangan sehingga 73% lebih rendah daripada yang dilaporkan dalam sistem berbentuk bulat. Nilai ini boleh diterima dan bertoleransi dalam struktur tanah ini. Oleh itu, keputusan kerja makmal menunjukkan bahawa sistem tayar berbentuk 8 adalah berkesan dan dapat mengurangkan ubah bentuk sisi. Tambahan pula, penggunaan sistem fiberglas berbentuk 8 berbanding dengan sistem tayar berbentuk 8 boleh menghasilkan ketegangan yang lebih rendah.

ABSTRACT

DEVELOPMENT OF EIGHT SHAPED SYSTEMS FOR SLOPE STABILIZATION

Slope stability has been an important topic in the field of geotechnical engineering. The varieties of techniques were investigated to provide a stable condition for slopes by improving engineering properties of soils. Utilizing recycled materials is one the favourable methods for soil stabilization that covers all environmental and technical aspects. Recycled tyre has been widely used for this purpose due to the excellent physical and mechanical properties such as light weight, high durability, high tensile strength, and very low cost. Round shaped of recycled tyre has been reported to be generally used as slope stability elements. Despite, a minimum processing required for this shape the high lateral deformability is a matter of concern. Round shaped of recycled tyre shows a very high lateral deformation to archive ultimate pull-out capacity. To improve this property using different configuration of recycled tyre is given. Accordingly, the shape of reinforcement element seems to be influential. However, these methods were not properly investigated. Thus, the aim of this study is to develop a new system for slope stabilization by focusing on shape of reinforcement element. 8 shaped system of recycled tyre was chosen due to the fact that this shape induces higher stiffness enhancing the bearing capacity of reinforced soil. 8 shaped system of fiberglass was also developed as an alternative to recycled tyre to produce a very limited lateral deformation. The materials were tested in strip and 8 shaped under tensile and pull-out tests. The fully monitored system of recycled tyre mat was constructed for slope stabilization on a site as a pilot study. It was found that the tensile strains of strip and 8 shaped fibreglasses were measured to be lower than tyre up to 550% and 105.6% respectively. The pull-out tests indicated that using 8 shaped tyre system is a favourable method to decrease lateral deformation of round shaped up to 127.2%. Additionally, with no overburden stress, 8 shaped system of fibreglass experienced strain lower than 8 shaped tyre up to 112%. Applying overburden stress of 3.5 kPa and 6 kPa, fiberglass mat system presented a strain less than tyre up to 132.8%, and 121.9% respectively. The results of post-construction monitoring showed that the normalized lateral deformation measured for 8 shaped tyre system in this study is up to 73% lower than reported for round shaped. The values are within an acceptable deformation tolerated in earth structures. Therefore, the results of lab work showed that 8 shaped tyre system was effectively able to reduce the lateral deformation in comparison to round shaped. Furthermore, using fiberglass 8 shaped system in comparison to tyre 8 shaped leads to produce lower strain.

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Slope stabilization has been an essential subject in the field of geotechnical engineering. Numerous studies address the techniques which provide stability of slopes. Utilizing waste materials such as scrap tyre for slope stabilization is environmentally reasonable and technically favourable. Recycled tyres are mainly characterized by the excellent mechanical and physical properties such as light weight, high tensile strength, and durability which are desirable in geotechnical engineering applications specially slope stability (O'Shaughnessy and Garga, 2000, Reddy and Marella, 2001, Pierce and Blackwell, 2003, Zornberg et al., 2004b).

Zornberg et al, (2005) reported that scrap tyre can be employed as construction materials in the wide range of applications. A review of literature indicated that recycled tyres are mainly grouped in three categories, shredded, whole and bale (Zornberg et al., 2004b).

Shredded recycled tyres presented great properties such as light weight, low earth pressure, good thermal insulation, and good drainage (Humphrey, 2009). They are also the cheapest alternative in comparison to other conventional materials. Shredded tyres were subjected to many studies which showed good results where they are employed as construction materials.

Applying whole tyre in civil engineering projects is preferable due to minimum processing. Whole tyres are generally classified with their high tensile strength and great durability which are key parameters in civil engineering applications. Another aspect of using whole tyres refers to their ability to reduce vertical deformation where used as soil reinforcement element. These properties subjected to studies performed by (Yoon et al., 2004, Yoon et al., 2008, Huat et al., 2008) presenting high potential of whole tyres as construction materials.

Baled tyre is normally made by using a significant volume of recycled tyres. They are large blocks, with low compressibility, and high tensile strength and great durability. These properties in addition to very low-cost have made them a very unique material for highway application and transportation projects (Winter et al., 2005, Zornberg et al., 2004b).

High lateral deformation is a concern of using recycled tyre as constructions materials. O'Shaughnessy and Garga (2000) showed that large strain required to fully mobilize the ultimate pull-out capacity where round shaped of recycled tyre tested.

To control the high deformability, some solutions have been presented. Tyre configurations were suggested by O'Shaughnessy and Garga (2000). The shape of reinforcement element seems to be an effective parameter to decrease high deformability. Pokharel et al. (2009) reported that the bearing capacity and stiffness of the geocell-reinforced sand could be affected by the structures of geocell including its shape.

The unique properties of fibreglass have made it an attractive choice for construction purpose and a favourable alternative over other types of construction materials. Fiberglass is a composite material which is produced using high-strength, high-stiffness structural fibbers with low-cost, lightweight, environmentally resistant polymers. Combination of these materials resulted in high tensile properties, and durability (Bakis et al., 2002). Furthermore, fiberglass presents a very low strain under loading which seems to be good alternative to recycled tyre where deformation control is desirable.

1.2 Problem statement of the study

The problem which has been considered for almost 40 years is the environmental hazard of wasting millions of tyres throughout the world. The problem has been tried to turn into an opportunity by utilizing waste tyre in some applications such as civil engineering. These applications, however, can cause additional problems which need to be considered. A review of literature disclosed that one concern is the high lateral deformation of round recycled tyres when they are using for slope stability purpose. Round recycled tyres present a large strain to fully mobilize the ultimate tensile capacity. In some civil engineering projects such as retaining walls where limited amount of strain is required, the high deformability would be a point of concern. Therefore, the main problem statement of the study is the high lateral deformation characteristic of recycled tyre reinforcement elements.

Developing a new system for slope stabilization can be done by focusing on shape of reinforcement element. 8 shaped (the configuration of number eight) recycled tyre reinforcing would be helpful due to the fact that this shape induces higher stiffness enhancing the bearing capacity of reinforced soil. 8 shaped system of fiberglass can also be utilized as an alternative to recycled tyre where very limited lateral deformation is needed.

1.3 Objective of the study

The main objective of this study is to develop 8 shaped recycled tyre system for soil stabilization purpose which reduces high deformability of round shaped (the most common shape of recycled tyre reported in the literature). Additionally, fiberglass 8 shaped system has been studied as a new alternative to 8 shaped recycled tyre where a very limited value of deformation is required. Therefore, the objectives of this study can be listed as follows:

1. To determine the strength and strain properties of strip and 8 shaped samples of recycled tyre and fiberglass.
2. To investigate the soil-reinforcement interactions of recycled tyre and fiberglass under pull-out tests in different condition of overburden stress.
3. To evaluate the performance of 8 shaped recycled tyre system utilized as a slope stability retaining structure in a pilot study.

1.4 Structure of the thesis

This thesis is divided into five chapters. A brief background of study, a highlighted problem statement and objectives are given in Chapter 1. A review of literature will be presented in Chapter 2 providing a proper background of the study. Research methodology, Chapter 3, gives an overview of lab and pilot study. All methods and materials which have been employed to obtain the objectives of the study are also presented in this chapter. Data analysis and the results of lab and pilot study will be presented and discussed in Chapter 4. Finally, conclusion of the study and recommendation for further studies will be given in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The concept of earth reinforcement has been a historical issue in the field of geotechnical engineering. Many studies have been performed addressing the variety of techniques to provide stable condition for slopes and improving engineering properties of soils. Retaining structures were used for slope stabilization purpose which mostly made of reinforced concrete. Mechanically Stabilized Earth Wall (MSEW) and Reinforced Soil Slopes (RSS) are cost-effective retaining structure with ability of tolerating larger settlement than reinforced concrete walls. By placing tensile reinforcement elements (inclusions) in the soil, the strength of the soil can be improved significantly. In some cases, the inclusions can also withstand bending from shear stresses, providing additional stability to the system. The modern methods of retaining wall soil reinforcement were developed using a system in which steel strip reinforcement was used (Victor Elias and Barry, 2001).

Additionally, polymeric reinforcement materials are a consequent of recent development in civil engineering materials. Geosynthetics are planar products manufactured from polymeric materials used with soil, rock, or other geotechnical-related materials as part of a civil engineering project (Gerard, 1994). Synthetic woven and nonwoven geotextile have also found a wide application in civil engineering for soil reinforcement purpose due to their high soil fabric friction coefficient, high tensile strength (Gerard, 1994).

One of the most important issues which must be taken into account is the environmental impact of reinforcing techniques. With this regards, utilizing recycled materials have been considered as a desirable way to cover environmental concern. Application of recycled tyre in geotechnical engineering for stabilization purpose is a favourable method covering all environmental concern as well as economical and technical aspects. The excellent mechanical and physical properties such as light weight, high tensile strength, and durability have been addressed in many studies (O'Shaughnessy and Garga, 2000, Bosscher et al., 1997, Christ and Park, 2010, Edil and Bosscher, 1994, Humphery and Sandford, 1993, Humphrey, 1999, Humphrey, 2009, Humphrey and Manio, 1992, Humphrey and Tweedie, 2002, Pierce and Blackwell, 2003, Reddy, 2010, Valdes and Evans, 2008, Warith and Rao, 2006, Winter et al., 2005, Zornberg et al., 2004b, Marefat and Soltani-Jiagheh, 2011) . A review of literature indicated that recycled tyre is mainly grouped in three categories, shredded, whole and bale (Zornberg et al., 2004b). Many studies presented favourable results where utilizing shredded tyre as construction material. Bosscher et al. (1997) carried out a study to develop design procedures for utilizing shredded recycled tyre as a light-weight fill material in highway construction. Humphrey (1999) presented some projects in which tyre shreds were used as light-weight fill for highway embankment construction, bridge abutment backfill, thermal insulation, and drainage layers. Regarding to high damping capacity of rubber, Feng and Sutter (2000) presents resonant column test results for

Ottawa sand focusing on the shear modules and damping ratio of sand-rubber mixture. Humphrey and Tweedie (2002) performed a full-scale project using tyre shreds to reduce horizontal pressure in retaining walls. An experimental study on replacing sand with crumb rubber in flow able fills to produce a lightweight material performed by Pierce and Blackwell (2003). Ghazavi (2004) performed a study to present how shear strength characteristics of sand mixed with various percentages of rubber are altered. Optimizing the size of waste tyre shreds to increase shear strength parameters addressed by Ghazavi and Sakhi (2005).

Some researchers focused on improving engineering properties of clayey soil by using chip tyre. Cetin et al, (2006) presented geotechnical properties of fine and coarse grained tyre-chips mix with a cohesive soil to investigate their application as light weight fill material. Modification of clayey soil subjected to a study performed by Akbulut et al, (2007) to investigate the influence of randomly oriented waste fibber of scrap tyre on strength and dynamic behaviour of clayey soil. Tyre-chips were utilized by Ho and Chan (2010) for stabilizing a soft clay which presented high compressibility and very low strength properties. Undrained triaxial testes were carried out on clay-tyre mixture by Marefat and Soltani-Jiagheh (2011) focusing on the shear strength and consolidation behaviour of the mixture.

Many others researchers focused on the behaviour of tyre-sand mixture to present its capability in geotechnical engineering applications. Compressibility and strength behaviour of sand–tyre chip mixtures subjected to a study performed by Rao and Dutta

(2006) for utilizing this material in the highway and embankment construction. (Yoon et al, (2006) conducted an experimental study to evaluate the feasibility of using tyre shred- sand mixture as fill material in embankment construction. Tanchaisawat et al. (2009) investigated the interaction between the geogrid and the tyre chip–sand mixture. Determination of the index properties of the backfill materials, the shear strength parameters, the interaction coefficients, and the efficiency of geogrid reinforcements in tyre chip–sand backfills were investigated in this study. Christ and Park (2010) considered to the strength characteristics of frozen rubber-sand mixture by performing uniaxial compressive strength, direct-tensile strength and direct-shear tests.

Using whole tyre is preferable because less energy is required and less waste is generated. In addition, construction could be performed by using conventional techniques. Garga and O'Shaughnessy (2000) reported a construction of a 57 m high × 17 m wide instrumented test fill, by using 10,000 of whole and cut tyres. The environmental consideration of this project ,the water quality under tyre-reinforced earth fill, was investigated by O'Shaughnessy and Garga (2000). The pull-out behaviour of whole recycled tyre was subjected to another study performed by O'Shaughnessy and Garga (2000) . Yoon et al. (2004) and Yoon et al. (2008) investigated a geotechnical performance of waste tyre subjected to plate load tests to evaluate the bearing capacity and settlement behaviours of a tyre-reinforced earth fill. A study on the tensile behaviour of whole tyre as reinforcement element to repair tropical residual slope was performed by Huat et al. (2008).

The use of tyre bale is more suitable from the economical point of view as well as using significant volume of recycled tyre. Some studies presented the application of scrap bale tyre in retaining wall, transportation and highway, and port, coastal and river engineering projects (Hossain, 2000, Zornberg et al., 2004b, Winter et al., 2005, Zornberg et al., 2005, Jonsen, 2005, Winter et al., 2006, Simm et al., 2005). Mechanical properties of tyre bale as reinforcement element were also subjected to some studies performed by (LaRocque, 2005, Freilich and Zornberg, 2008)

Despite many advantages which have been reported for recycled tyre, a review of literature disclosed an important concern of using recycled tyre as soil reinforcement and slope stability element. Some studies indicated that tyre chip–soil mixtures exhibit a significant initial plastic compression under loading, and are highly compressible at normal low pressures (Bosscher et al., 1997, Edil and Bosscher, 1994, Humphrey and Manio, 1992, Rao and Dutta, 2006, Lee et al., 1999, Youwai and Bergado, 2003, Lemar, 2005, Marefat and Soltani-Jiagheh, 2011). As for scrap whole tyre, O'Shaughnessy and Garga (2000) indicated that large strain ranged from 19.6% to 44.6% required to fully mobilize the ultimate pull-out capacity. Gerscovich et al. (2004) also presented 610 mm of displacement required to achieve maximum pull-out resistance where whole cut tyre reinforcement subjected to pull-out test.

To control the high deformability, some solutions have been presented. Preloading and using optimum amount of tyre were suggested to control such a high vertical deformation in the case of chip tyre (Bosscher et al., 1997, Edil and Bosscher, 1994, Humphrey and Manio, 1992, Rao and Dutta, 2006). The tyre configurations used in field pull-out tests reported another alternative to control horizontal displacement. In fact, utilizing the same number of whole tyres reinforcement in different configuration led to different amount of frontal displacement (Gerscovich et al., 2004, O'Shaughnessy and Garga, 2000).

The shape of reinforcement element seems to be an effective parameter to control the deformation. Yoon et al. (2004, 2008) showed that using Tyrecell (8 sample) induce higher stiffness enhancing bearing capacity of soil. As a result of this study, the combination of treads and sidewalls gave the greatest improvement in the bearing capacity. Pokharel et al. (2009) reported that the bearing capacity and stiffness of the geocell-reinforced sand could be affected by the structures of geocell including its shape.

Fiberglass, In addition to very low strain, presents unique properties such as affordability, cost effectiveness, light weight, durability, high tensile strength and high corrosion resistance (Brooks et al., 1999, Kouadio, 2001, Bakis et al., 2002, Myers et al., 2007, Hollaway, 2010, Advance Fiberglass and Composite, 2010, Lawler and Polak, 2011). These behaviours seem to make fiberglass a suitable and desirable alternative to scrap whole tyre where deformation must be limited. Fibreglass has been the most common choice for reinforcement in many researches over the past 40 years (Bilida, 1971, Golestanian, 2007, Kouadio, 2001, lssa et al., 1994, Orlov and Gorin, 1999, Bakis et al., 2002, Van Den Einde et al., 2003, Timothy and Pillip, 2005, Hollaway, 2010, Khoe et al., 2011) , however, a few studies have addressed the applications of fibreglass to the field of geotechnical engineering (Oreste, 2009, Sakr et al., 2005, Timothy and Pillip, 2005, Zhu et al., 2011).

2.2 Scrap tyre as a construction material

2.2.1 Beneficial use of recycled tyre

The problem caused by recycled tyres would be turned into an opportunity and many benefits are obtained by focusing on alternative ways to utilize scrap tyres. One of the alternatives is to utilize waste tyres as a construction material. In addition to saving the environment threatened by this waste material, this option provides a very low cost construction material. The wide spread availability and high durability have resulted in the variety of applications in the field of civil engineering. According to the study performed by Zornberg et al. (2004b), recycled tyres, as construction materials, can be employed in the variety of applications grouped as follows:

a. Wall systems
b. Slope systems
c. Subgrade stabilization
d. Drainage zone in landfills
e. Soil improvement additives
f. Erosion protection
g. Blasting mats
h. Crash barriers

i. Temporary dikes and dams

j. Storm water detention systems

2.2.2 Types of recycled tyre in construction applications

Recycled tyres as construction materials can be grouped into three general categories: shredded, whole and baled tyre. The most common form of processed recycled tyres has been the use of shredded tyre mixed with soil. Apparently in the past 20 years, over a hundred of civil engineering projects had been successfully constructed in which tyre shreds utilized as material (Zornberg et al., 2005). Shredded tyres present some favourable engineering properties such as light weight (1/3 of soil), good thermal insulation (8 times better), and good drainage (10 times better) as listed by Humphrey (2009).

Using whole tyre is preferable because less energy is required and less waste is generated Huat et al. (2008). In addition, construction can be performed using conventional and simple techniques. Whole tyres also present the excellent engineering properties such as high bearing capacity, low deformability and high tensile strength. Whole tyre is also characterized by its better fire resistance when buried in soil as construction materials (Garga and O’Shaughnessy, 2000).

The practical use of whole tyre compressed into bales and placed as part of an earth embankment provides a viable alternative to shredded tyre in civil engineering applications and reduces the potential for exothermic reactions. Baled tyres also provide some economic advantages over the use of shreds in terms of production, storage, and construction costs (Zornberg et al., 2005).

According to the study performed by Zornberg et al.(2005) the potential uses of shredded, whole and baled tyres are listed Table 2.1.

Table 2.1. Reported and possible uses of shredded, whole, and tyre bales (Zornberg et al., 2005)

Possible uses	Shredded tyres	Whole Tyres	Baled tyre
Wall systems			
Residential	Feasible as fill for (GRS) Retaining Walls	Feasible with soil filler, connections, & facing	Feasible, with facing (e.g., shortcrete)
Commercial	Feasible as fill for GRS Retaining Walls	Feasible with soil filler, connections, & facing	Feasible, with facing
Sound barriers	Feasible as fill for GRS Sound Barriers	Feasible with connections & facing	Feasible, with or without facing
Small site retaining walls	Feasible as fill for GRS Retaining Walls	Feasible with connections, separation geotextile, & facing	Feasible, with or without facing
Rock fall barriers	Feasible as fill for GRS Retaining Walls	Feasible with connections & facing	Feasible, with or without facing
Culvert headwalls	No	Feasible	Feasible, with or without facing
Large building Blocks: Tyre bales encased in concrete	Feasible	Possible, but feasible	Feasible
Slopes systems			
With layered geo-synthetic reinforcement	Feasible	Feasible with connections	Feasible

Table 2.1. Reported and possible uses of shredded, whole, and tyre bales (Zornberg et al., 2005) (continued)

Repair slope failures	Feasible	Feasible with connections	Feasible
Lightweight fill Embankment constructions	Feasible	Feasible	Feasible
Lightweight fill	Feasible	Feasible with in filling	Feasible
Subgrade stabilization			
Mat for roads over very soft foundation	Feasible	Feasible with in filling	Feasible
Insulation to reduce frost action	Feasible	Feasible with in filling	Feasible
Edge drains	Feasible	Not feasible	Feasible
Other systems			
Drainage Zones in Landfills	Feasible, with separation geotextile	Feasible, with separation geotextile	Feasible, with separation geotextile
Mix with Soil to Improve Shear Strength and Reduce Unit Weight	Feasible	Feasible	Feasible as inclusions or zones in an embankment
Erosion Protection for Water Edges w/ Shortcrete	Not Applicable	Feasible, with cables	Feasible with and without shortcrete or concrete facing
Erosion Protection for Swales and Channels w/ shortcrete	Not Applicable	Feasible	Feasible
Blasting Mats	Feasible	Feasible	Feasible
Low-cost Culvert Structures	Not Applicable	Feasible, tied to form a cylinder	May be Feasible
Potential uses			
Crash Barriers	Possible	Feasible with ties	Feasible
Temporary Dikes, Dams	May be feasible	Feasible, w/geomembrane wrap	Feasible, w/geomembrane wrap
Storm Water Detention Systems	Feasible, but small storage capacity	Feasible	Feasible

2.2.3 General characteristics of recycled tyre

According to Rubber Manufacturer association (RMA., 2007), materials used to manufacture passenger and truck tyres are listed in Table 2.2.

Table 2.2. Materials used to manufacture tyre (RMA., 2007)

Materials	Value (%)	
	Passenger tyres	Truck tyres
Natural Rubber	14	27
Synthetic Rubber	27	14
Carbon Black	28	28
Steel	14-15	14-15
Fabric, fillers, accelerators	16-17	16-17

A typical weight is approximately 110 N for new automobile and 556N for new light truck tyres. The average weight of 89 N reported for scrap automobile tyres and 445 N for truck tyres.

2.2.4 Engineering properties of tyre shreds and soil-tyre shreds mixture

2.2.4 (a) Gradation

The gradation of tyre shreds obtained from three sources was determined by Humphrey et al.(1993), Tweedie et al. (1998) and Humphrey and Tweedie (2002). The tyre shreds were uniformly graded and composed primarily of gravel size particles 38 mm to 76 mm. Young et al.(2003) utilized two groups of tyre shreds, 0 mm-50 mm and 50 mm-300 mm, in an experimental study. According to the particle size distribution, for the size 0 mm- 50 mm, D_{10}, D_{30}, D_{50}, and D_{60} were calculated to be 25 mm, 36 mm, 50.5 mm, and 53 mm respectively. As for the size of 50 mm-300 mm, D_{10}, D_{30}, D_{50}, and D_{60} were determined 104 mm, 130 mm, 235 mm, and 262 mm respectively. In the other study the grain size distribution of tyre chips was reported by Thomas and Yu (2006) as shown in Figure 2.1. According to the figure, D50 of 0.2 mm was calculated and it was classified as SP according to USCS.

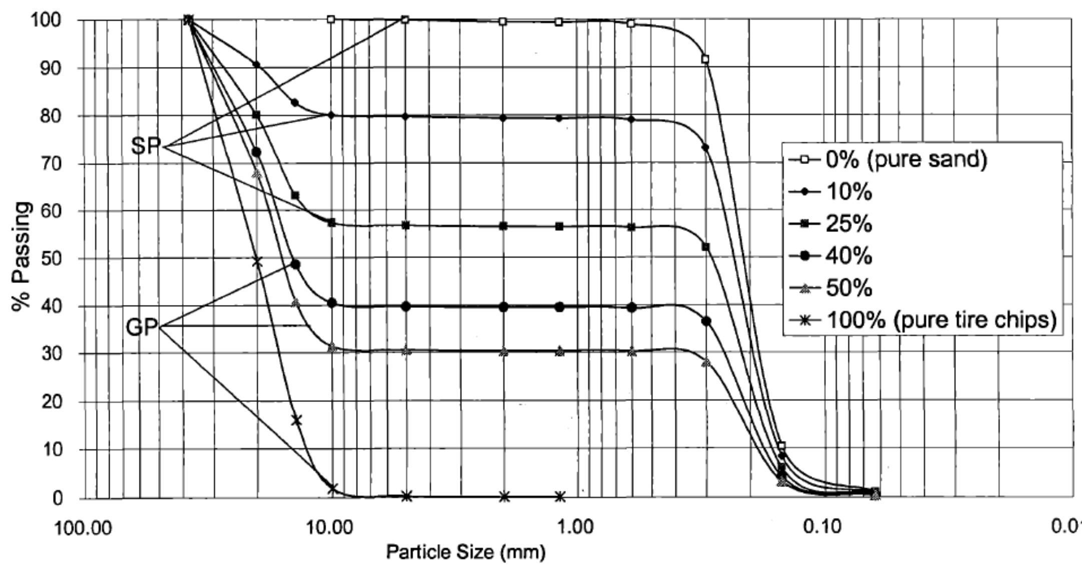

Figure 2.1. Gradation of sand, tyre chip and tyre chip-sand mixture (Thomas and Yu, 2006)

Humphrey (2009) also presented a typical gradation of tyre chips for 300 mm minus size as shown in Figure 2.2.

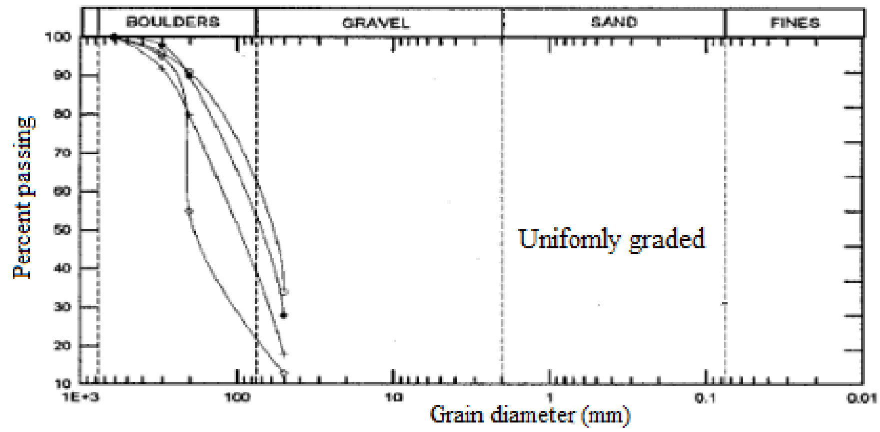

Figure 2.2. Typical gradation of tyre chips for 300 mm minus size (Humphrey, 2009)

2.2.4 (b) Unit weight

The range of unit weight reported for tyre shreds obtaind from studies profemed between 1984-1998, sumerized by Reddy and Marella (2001) as shown in Table 2.3. The loose unit weight of tyre shreds ranges from 5 kN/m^3 to 9 kN/m^3 as reported by Humphrey (2000), Young et al.(2003) , and Humphrey (2009). Tire shreds ranging from 50 mm-250 mm size presented a compacted dry unit weight in range of 6 kN/m^3 to 7.25 kN/m^3 based on modified compaction method (Young et al., 2003, Yoon et al., 2006).

The effect of mixing ratio on unit weight of tyre chips was taken into account by Youwai and Bergado (2003), the dry unit weight of tyre chips-sand mixture depending on the mixing ratio ranges from 5 kN/m^3 (100% tyre chips: 0% sand) to 16 kN/m^3 (0% tyre chips:100% sand).

Table 2.3. The unit weight of different size of tyre shreds (Reddy and Marrella., 2001)

Reference	Tire Shred Size (mm)	Dry unit weight (kN/m^3)	Specific Test Conditions
Bressette, 1984 ASTM, 1998	5-63.5	4-6	-
Humphrey et al., 1992	2-76	3.4	No compaction
Humphrey and Manion, 1992	2-76	4-5	
Manion and Humphrey, 1992 Humphrey and Sandford, 1993 ASTM, 1998	2-25.4	5	
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	12.7-5	4.7	No compaction
	12.7-25.4	5	No compaction
	12.7-25.4	5	ASTM D 4253
	12.7	4.7	ASTM D 4253
	12.7-76	6.2	50% standard – compaction energy
	12.7-25.4	6.4	
Humphrey et al., 1992	2-76	6.2	60% standard – compaction energy
Humphrey and Manion, 1992	2-50	6.2-6.4	
Manion and Humphrey, 1992 Humphrey and Sandford, 1993 ASTM, 1998	2-25.4	2.4	
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	1-25.4	6.4	Standard – compaction energy
	12.7-38	6.5	
	12.7-5	6.6	
	12.7	6.4	
Edil and Bosscher, 1992 Edil and Bosscher, 1994 ASTM, 1998	19-76	6	6 inch-diameter mould compacted by 10 lb-rammer falling 12 inches
	19-76	3.5	12 inch-diameter mould compacted by 60 lb- rammer falling 18 inches
Humphrey and Manion, 1992 Manion and Humphrey, 1992 ASTM, 1998	2-5	6.5	Modified – compaction energy
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	12.7-5	6.7	
	12.7-5	6.8	
Upton and Machan, 1993	5	3.8-5.2	Loose
		7.2	Compacted
		8.3-8.4	Surcharged with 3 feet soil, pavement & highway traffic
Newcomb and Drescher, 1994	20-46	5-5.6	
Black and Shakoor, 1994	<1-6.8	5.3	-
Duffy, 1995	5	4.8-8	-
Masad et al., 1996	4.5	6.3	
Cecich et al., 1996	5-15.2	5.6-6	ASTM D1557
Andrews and Guay, 1996	25.4-5	6.4	-
Wu et al., 1997	<2	5.3	Tested tire shreds without steel in them
	<9.4	5-6	
	<19	5.7	
	<38	6	
Tweedie et al., 1998	38	7	Full scale field tests
	76	6.9	
Chu, 1998	6.3-38	6.9	-
Reddy and Saichek, 1998	12.7-140	4.2	No compaction

The average dry unit weight of the mixed material increased linearly with increasing amounts of sand in the mixture, as shown in Figure 2. 3. The unit weight of the shredded rubber tyre–sand mixture was found to be less than that of compacted sand by about 13%–60%, depending on the mixing ratio (Youwai and Bergado, 2003).

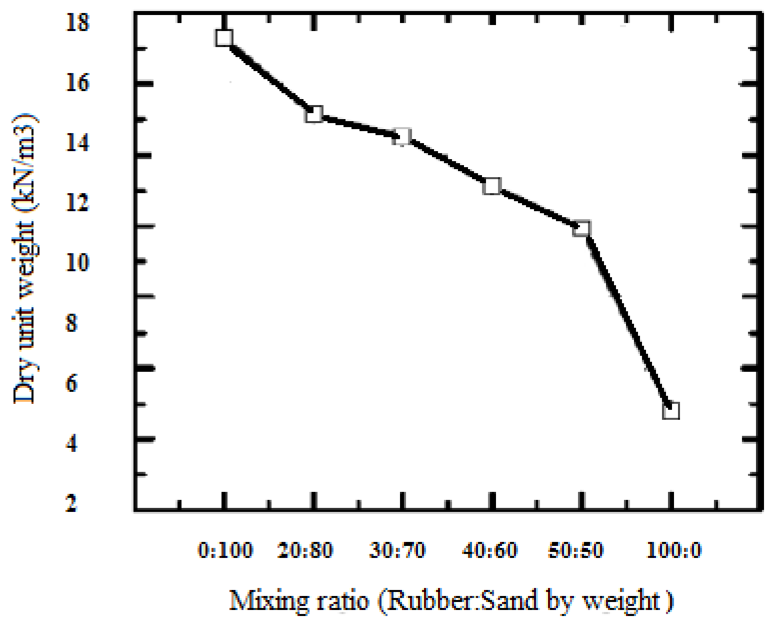

Figure 2.3. The effect of mixing ration on dry unit weight of tyre chips (Youwai and Bergado, 2003)

The unit weight of tyre chips also depends on the presence of steel belt layers. Gotteland et al. (2005) reported a study using circular chips with the average diameter of 28.1 mm and thickness of 10.4 mm. The thickness varies significantly and depends mainly on the number of steel belt layers. Tyres containing no steel belt layers generally have a smaller thickness. The unit weight of rounded pieces of tyre used in the study ranged from 11 kN/m^3 to 15.4 kN/m^3. The effect of orientation of tyre chips on different parameter comprises unit weight was conducted by Gotteland et al.(2005) and result are presented in Table 2.4. According to the results the effect of orientation on unit weight is negligible

Table 2.4. Effect of orientation of tyre chips on unit weight (Gotteland et al., 2005)

Series	Content of tyre chips (% by mass)	Orientation of tyre chips	Unit weight (kN/m3)
A	0	Na	16.7
B	15	H&V	15.5
C	14	H	15.9
D	14	V	15.9
E	14	NO	15.5
F	22	H&V	15.3
G	50	NO	11.4
H	100	H	6.8
I	100	NO	6.1

2.2.4 (c) Specific gravity

The value of specific gravity depends on the amount of steel belt. For air dried tyre chips samples, it was measured to be 1.14-1.27 (Humphery and Sandford, 1993). These values are less than half of those determined for typical soils. The specific gravity of tyre chips considering the maximum size of chips and their shapes was listed by Wu et al. (1997) as shown in Table 2.5. The effect of the tyre shred size on engineering properties was performed by Reddy and Marella (2001) with particular attention to the large-size tyre shreds (larger than 100 mm), which are economical to use as drainage material in landfill covers. The specific gravity ranged from 1.02 to 1.36, depending on the presence of glass belting or steel wire in the tyre. Tyre shreds with high specific gravity generally possess a greater proportion of shreds with steel belts. The specific gravity of soils typically ranges from 2.6 to 2.8, which is more than twice that of tyre shreds.

Table 2.5. The specific gravity of tyre chips (Wu et al., 1997)

Source	Maximum size (mm)	Particle shape	Specific gravity
Palmer shredding. Inc., Ferissberg, Vt	38	Flat	1.11
Palmer shredding. Inc., Ferissberg, Vt	19	Granular	1.08
Palmer shredding. Inc., Ferissberg, Vt	9.5	Elongated	1.18
Recycling Concepts International Ltd., Hicksville, N.Y.	9.5	Granular	1.18
The Baker Rubber Co., Chambersburg, Pa	2	Powder	1.12

The effect of size of tyre chips on specific gravity was subjected to another study done by Young et al. (2003). For the size of chips less than 50 mm, the specific gravity measured to be 1.1 and for the size rages from 50 mm-300 mm it was determined in rage of 1.06-1.1.

2.2.4 (d) Compressibility

The vertical compressibility of tyre chips was measured by (Humphery and Sandford (1993) and Bernal et al.(1996) . Three loading and unloading cycles applied on the samples and stress-strain relationship of tyre chips was investigated. According to the results, the initial section of first loading curve was very steep presenting a high compressibility. The average of vertical stress equal to 69 kPa and 276 kPa were applied on samples and vertical strain measured consequently. The vertical strain at the average of vertical stress of 69 kPa was determined in the range of 21.6% to 30.6%. Average of 276 kPa of vertical stress caused strain ranged from 35.9% to 43.8%.

Wu et al.(1997) characterized deformation behaviour of tyre chips by a high deformability. They showed that under 55 kPa of consolidation pressure tyre chips (size ranged from 2 mm-38 mm) indicated volume strain in range of 25.4%-31.6%. The relationship between deviator stress, volumetric strain and axial strain of the study is given in Figure 2.4. The results showed that tyre chips experienced a plastic deformation and a significant dilation (Wu et al., 1997, Valdes and Evans, 2008).

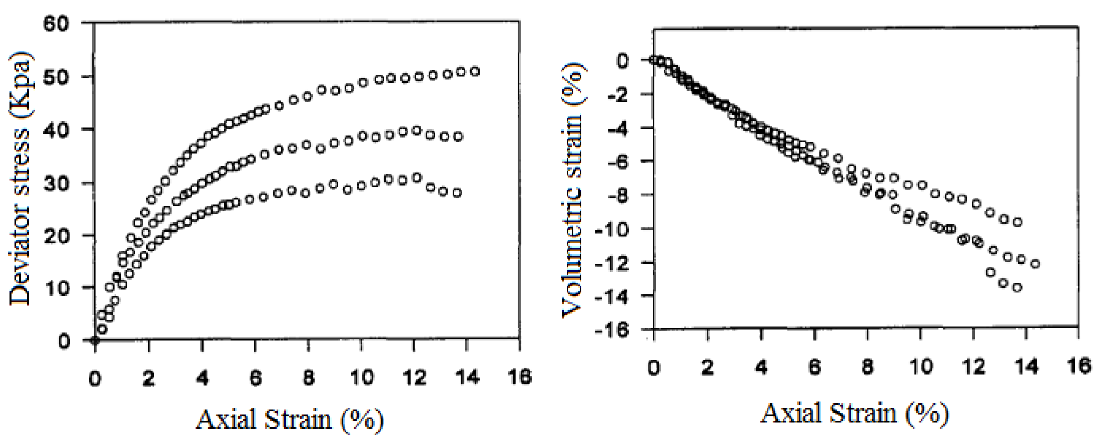

Figure 2.4. The relationship between deviator stress, volumetric strain with axial strain (Wu et al., 1997)

The volumetric and vertical strain relationship reported by Lee et al.(1999) is shown in Figure 2.5. The results showed that tyre chips presented an almost linear volumetric with axial strain. The volume strain at confined pressure equal to 28 kPa decreases linearly up to 5% of axial strain. For the confined pressure of 97 kPa, the volume strain versus axial strain is linear up to 15% of axial strain. At a confined pressure equal to 193 kPa, the volume change is linear with axial strain throughout the test.

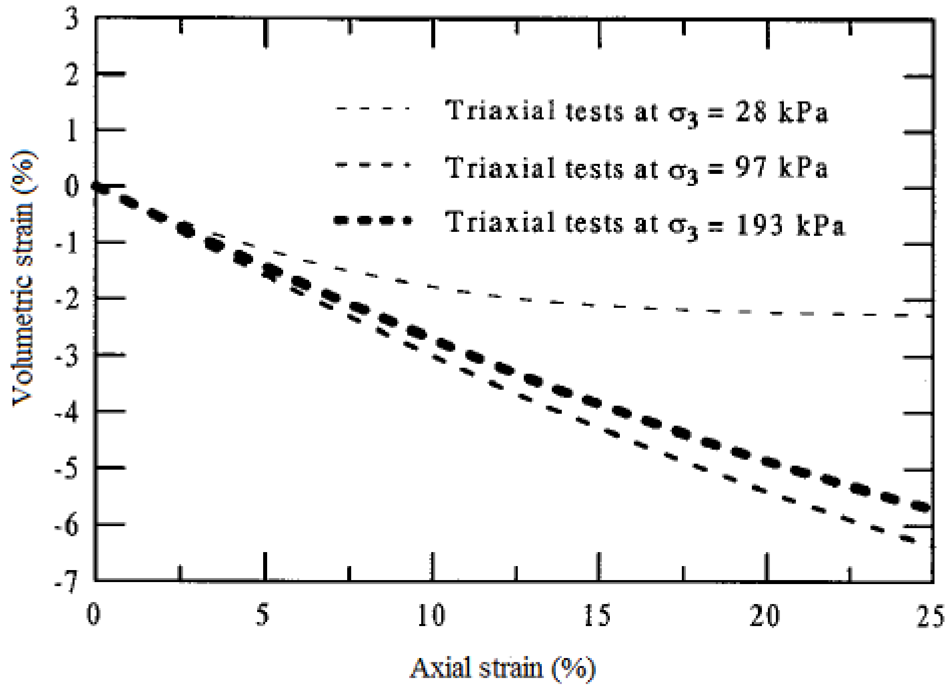

Figure 2.5. The relationship between volumetric and axial strain (Lee et al., 1999)

Reddy and Marella (2001) reported that tyre chips present high deformability because of their high porosity and high rubber content. Tyre shreds compress during a loading is due to two mechanisms: (a) rearrangement of chips by changing bending and orientation to a more compacted condition, and (b) the compression of individual tyre chips under loading (Youwai and Bergado, 2003). Reddy and Marella (2001) summarized studies from 1991-1998 which addressed to deformation of tyre chips. The result is listed in Table 2.6.