Faculty of Engineering and the Built Environment

Department of Civil Engineering

Investigation into the use of waste tyre shreds for reinforcement of sandy soils in South Africa

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A thesis submitted to the University of Cape Town in partial fulfilment of the requirement for the degree of Master of Science in Engineering

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Declaration

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Dr. Denis KALUMBA

Dedication

To my supervisors, Dr. Denis Kalumba and Ms. Faridah Chebet

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Abstract

End-of-life tyres are a disposal problem resulting from the large volumes produced worldwide every year. Waste tyres are difficult to manage because of their sheer volume and the potential impacts on human health and environment. These discarded tyres, currently stockpiled and dumped in the open, are a source of fire hazards and provide a prolific breeding ground for mosquitoes and other pests.

The use of waste tyre shreds as fill material in geotechnical applications can help to mitigate the waste tyre disposal problems. Specifically, when tyre shreds are used as lightweight fill material in the construction of highway embankments, a considerable volume of waste tyres is consumed. With regard to this, an investigation into tyre shreds mixed with sandy soils of South Africa was undertaken to assess the shear strength behaviour of the sand-tyre shred composite and to propose an alternative use of the scrap tyres produced every year.

A series of shear strength tests were performed using a large-scale direct shear box on the mixtures composed of tyre shreds with two relative sizes, i.e. 10-15 mm and 50-60 mm sizes, combined separately with Cape Flats and Klipheuwel sands. The shear strength tests started from unreinforced material (control tests) followed by those on tyre shreds-sand composites at different shred dosages such as 10, 20, 30, 40 and 50% by dry weight, ending on pure tyre shreds. The results showed that this inclusion generally improved the shear strength of sand. The angle of friction reached its maximum at 10% tyre shred content and reduced for increased shred content in the mixtures. The cohesion was improved for dosage up to 30%, then decreased at higher concentrations. Despite the shred size in the composite, a concentration of 30% by dry weight was considered as optimum shred content to reinforce granular soils of South Africa, but the long shreds showed better improvement compared to the small tyre pieces.

Based on the findings of this study, the use of lightweight tyre shreds sand composite material was recommended in the construction of road embankments and the guidelines to be followed were proposed. Because of the complexity in the preparation of the mixture based on density, the optimum shred dosage by weight was converted into volume ratio and this corresponded to 55% shred content by volume which can easily be used on site. For workability and simplicity of quantity measurements in the field, 50% tyre shred content by dry volume was suggested in the proposed guidelines to be mixed with sand in the preparation of embankment material.

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Notations

A	m^2	contact area
B	m	width of the footing
BS	-	British Standards
c'	kPa	cohesion of soil
Df	m	depth of foundation from the ground surface to the base of footing
N	kN	Normal applied load in
q	kPa	overburden pressure
q_u	kPa	ultimate bearing capacity
S	-	Sand
T	-	tyre shred
T	kPa	shear strength
σ_n	kPa	applied normal stress in
ϕ'	degree	angle of internal friction
γ	kN/m^3	unity weight of foundation soil
W_{ts}	kg	the weight of tyre shred
χ	%	the concentration of tyre shreds by mass in the mixture
Wtsc	kg	the weight of tyre shred-sand composite

CHAPTER 1 INTRODUCTION

1.1 Background

Large volumes of solid waste are generated all over the world due to population growth and the many different human and industrial activities. Much of the waste materials produced are not reused and are disposed of in the limited disposal sites available, which may be exhausted in the near future. Generally, the full hierarchy in waste management, starting with waste minimization, then proper treatment, reuse/recycling and energy recovery, is required (Hartlén, 1994). It is more desirable to minimize the need for landfill. Waste tyres which are andincreasing day by day form a part of the global waste management challenge.

The increasing number of cars all over the world results in millions of tonnes of waste tyres generated annually. This has led to major concerns about environmental problems posed by municipal solid waste that contains an ever-growing proportion of waste tyres. As depicted by Dickson et al. (2001), the United States of America generates around 270 million waste tyres each year. European Tyre Recycler Association ETRA (1998) reported 250 million used tyres in the European Union; a noticeable amount is stockpiled in the other countries, resulting in the accumulation of a billion and more used tyres per annum all over the world. These tyres have been stockpiled in the open and more are dumped illegally in the veld (in Southern Africa), mountains, valleys, etc.

South Africa is also one of the countries generating many used tyres. In 2012, 60 million scrap tyres were counted, and more than 11 million tyres are added each year [Recycling and Economic Development Initiative of South Africa’s (REDISA), 2012]. This is due to the fast-growing economy and population, contributing to the high demand for cars, which necessitates more new tyres to be manufactured in this country and then discarded at the end of their useful life. A small quantity of waste tyres is recycled for different applications such as floor-mats, insulators, various playgrounds, tarred road-making, and the manufacture of new tyres [Department of Arts, Culture, Science and Technology (DACST), 2004]. The remaining high quantity of these wastes is dumped illegally in different regions of the country. An example of waste tyres in South Africa is shown in Figure 1.1.

Figure 1.1: Waste tyre pile at a factory in Atlantis

Discarded waste tyres deposited in open spaces cause major environmental and human health problems. They are a breeding ground for mosquitoes which transmit malaria. Furthermore, when burned, waste tyres release different gases which contribute to the pollution of the atmosphere (Hoddinot, 1997). The decomposed oil from the pyrolysis and the residues can also contaminate soil, streams, channels and ground water.

Worn-out tyres in the form of shreds have been used in ground improvement. Various research projects have been conducted to assess the engineering properties of pure tyre shreds or tyre shred soil mixtures. These properties include shear strength parameters, hydraulic conductivity, compaction characteristics, etc. Some civil engineering projects have been carried out using pure tyre shreds or tyre-shred soil mixtures. An example is the highway and road embankments constructed using tyre shreds and soil in United States of America which have performed well (Yoon et al., 2006). In these projects, large numbers of waste tyres were used. The use of these wastes is not only to prevent the negative impact on human health and environment but also to reduce their disposal cost, to preserve and protect nature as well as to solve the problems associated with the soils of low shear strength.

1.2 Problem statement

In South Africa, a high number of waste tyres is added annually to the existing volume, causing major challenges in terms of their disposal. Millions of scrap tyres are generated every year and added to the existing bulk which are currently stockpiled and dumped in the open spaces in the country. Managing waste tyres in a safe way is to process them in a specific manner and use them as a substitute for conventional fill material in civil works, especially in the construction of embankments. In some countries such as the USA, waste tyres in the form of shreds have been tested in order to identify the feasibility of their being used in civil engineering applications. The results from these experiments showed that they have good properties, for instance high hydraulic conductivity, low density, good shear strength characteristics, high resistance to degradation (durability), etc. It is obvious from these results that they can be used in combination with soil to generate lightweight fill materials which can be used to construct earth structures resting on compressible soft soil (Yoon et al., 2006). Indeed, the use of these mixtures reduces the compressibility of the foundation soils.

Different techniques of ground improvement, for example dynamic compaction, stone columns, geosynthetics, etc., have been used to enhance the geotechnical properties of soils in South Africa, but no information exists on how waste tyre shreds can improve the soil or ground itself. The technique of ground improvement using waste tyres in the form of shreds is environment-friendly because it cleans the environment, and preserves and protects nature (Moo-Young et al., 2001). With this method, a high quantity of these problematic wastes can be consumed. The use of tyre shred soil mixture in the construction of earth structures such as highway embankments not only provides the alternative means of reusing tyres to address economic and environmental concerns, but also helps in solving geotechnical problems associated with low shear strength (Zornberg et al., 2004; Edincliler et al., 2010).

From the reviewed studies, tyre shreds mixed with soil were found to enhance its shear strength and reduce the weight of the composite. In addition, the contradiction in the experimental results has been noticed, for example where the addition of tyre shreds to the soil increases its shear strength (Zornberg et al., 2004) or reduces it (Cabalar, 2011). This, together with the high volume of waste tyres generated and the lack of knowledge for using them to improve the soil in South Africa, governs this study.

1.3 Justification of the study

South Africa generates many scrap tyres each year which become waste, adding to the existing volume. The volume of waste tyres recycled is less than 20% of the total generated, which indicates that the rest are dumped illegally in open space, causing threats to human health and the environment (DACST, 2004).

Various studies have been conducted to assess the feasibility of using waste materials in civil engineering applications. In this regard waste tyres have been considered to improve the engineering properties of soil in some developed countries, showing good performance. They form a substitute for conventional materials such as sand and gravels.

The studies conducted showed that the use of worn-out tyres has many advantages in civil engineering applications, particularly in the field of geotechnical engineering. According to Humphrey and Eaton (1993), tyre shreds are light in weight, possess good strength and thermal insulation as well as high drainage capacity; they are also a cost-effective material and are non-biodegradable. The use of tyre shreds in construction conserves natural aggregate resources, eliminates their disposal cost, reduces stockpiles of waste tyres which are prone to fire and health hazards, and eliminates damages to structures made of tyre shred soil mixtures (Young et al., 2003). However, when a tyre shreds/sand mixture is used as fill material, no excess pore water pressure can be built up upon loading (Humphrey and Eaton, 1993). Furthermore, the effects of tyre rubber waste on ground water and air quality are insignificant (Moo-Young et al., 2001). Tyre shreds have the additional advantage of being used as backfill material behind retaining walls since they induce small horizontal stresses (Humphrey and Eaton, 1993).

Many techniques of ground improvement have been carried out but no investigation has been conducted on waste tyres to improve the geotechnical properties of soils in South Africa. Due to all the reasons mentioned above, the investigation of the use of shredded waste tyres to improve sandy soils of South Africa is undertaken.

Furthermore, the study was limited to laboratory investigations on shear strengths based on the inclusion of tyre shreds from waste tyre materials in sand (Cape Flats sand and Klipheuwel sand). The enhancement of the shear strength will depend on the increase of cohesion and angle of internal friction.

1.4 Research objectives

This research aimed at finding the most beneficial way of reusing the waste tyres through ground improvement which will contribute to sustainable development. The study was carried out to investigate the effect of shredded waste tyres on shear strength when randomly mixed with selected sandy soils of South Africa. The specific objectives are summarized below.

- Undertake laboratory characterization of the soil and tyre shreds materials;
- Appraise the effect of varying concentration of tyre shreds on shear strength parameters of sand;
- Determine the effect of varying sizes on shear strength parameters of sand;
- Evaluate the effect of varying tyre shred content on shear strength of sand;
- Compare the overall shear strength results from the investigated tyre shred sizes.

1.5 Thesis overview

This thesis provides a literature review in Chapter 2, which initially presents the background on tyres, waste tyres and their use in different applications, and discusses the various soil reinforcement techniques. This is followed by the previous research work with soil tyre shreds composites. The mechanical properties of the research materials and the details of the experimental procedure for the large-scale direct shear tests are given in Chapter 3. All the results, their analysis and discussion are given in Chapter 4. Proposals for the practical application consisting of the use of waste tyres in civil engineering in South Africa and a proposed guideline which could be followed are presented in Chapter 5. Finally, the conclusion and recommendations for further research are given in Chapter 6.

CHAPTER 2 LITERATURE REVIEW

This chapter briefly discusses rubber tyres, their manufacture and categories, waste tyre generation and their negative impacts, management and various usages. Ground improvement, emphasizing soil reinforcement techniques, is also discussed. This is followed by the review of the previous research works on the use of waste tyres in soil improvement where the results of various experimental works are briefly presented.

2.1 Rubber Tyres

According to South Africa waste tyre regulations, the Waste Act, 2008 (Act 59 of 2008) a tyre is defined as ″a continuous pneumatic covering made of natural or synthetic rubber or a combination of the two encircling a wheel, whether new or retreaded.". Various parts of a pneumatic tyre (from Technical Guidelines 2011) are shown in Figure 2.1.

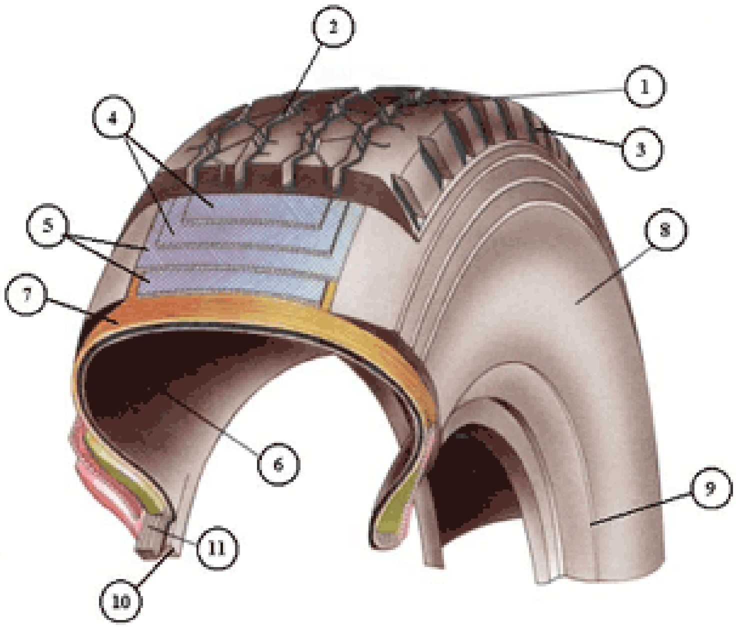

Figure 2.1: Cross-section view showing the component of a tyre (Technical Guidelines, 2011)

(1) Tread: the portion of a rubber tyre which is in contact with the road;

(2) Tread groove: the space between the adjacent ribs or blocks in the tread pattern;

(3) Sidewall: part of a rubber tyre which is between the tread and the area covered by the rim flange;

(4) & (5) Ply: a layer of rubber-coated parallel cords that plays a role of stabilization in radial tyre;

(6) Cord: the strands that form the fabric of the plies in a rubber tyre;

(7) Carcass: a part of a pneumatic tyre which supports the load when tyre is inflated;

(8) Section width: the distance between the outside of the sidewalls of an inflated rubber tyre, when fitted to the rim.

(9) Belt: a layer underneath the tread which is laid in the direction of the centre line of the tread to restrict the carcass in a circumferential direction;

(10) Bead: the part of a pneumatic tyre that fits the rim and holds the tyre on to it;

(11) Chafer: a part of pneumatic tyre which protects the carcass against chafing or abrasion by the wheel rim.

2.1.1 Manufacture of Rubber Tyres

The pneumatic tyre manufacturing process shown in Figure 2.2 starts from material preparation in which the compounds are mixed and the components of the green tyre, such as bead, tread, side wall and plies, are produced. It is followed by tyre building, where the separate components produced from material preparation are put together by building machines to generate a green tyre. In the curing process the tread and sidewall patterns are applied and the green tyre is then vulcanized, while in the final inspection, tyres are checked before shipping.

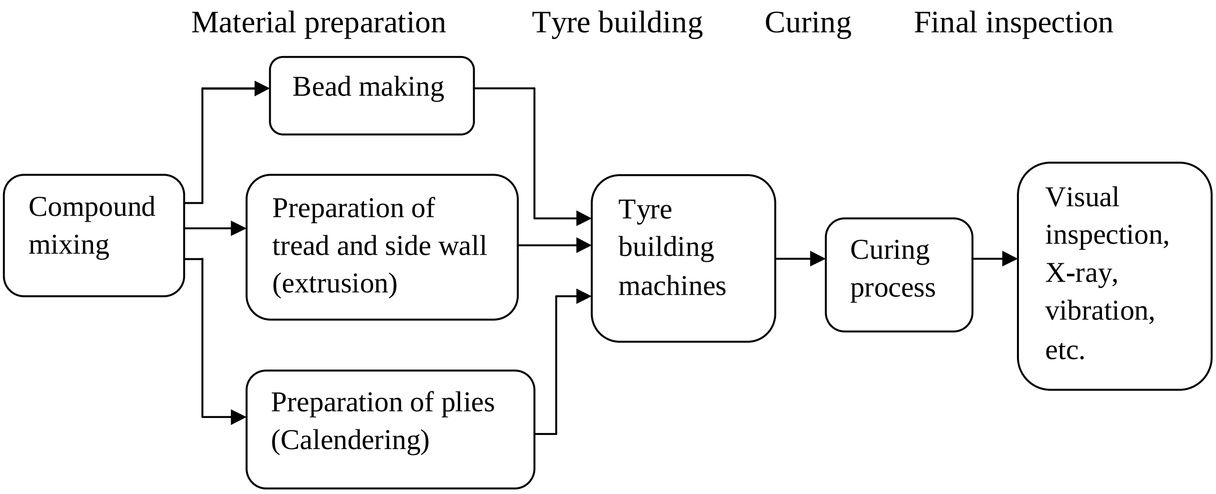

Figure 2.2: Tyre manufacturing process (Arunas, 2011)

2.1.2 Tyre categories

Based on vehicle applications, the categories of tyres as given in Department of environmental Affairs Republic of South Africa (DEA), (2012) are summarized below:

— *Passenger car and light truck tyres*

These are the tyres designed to be used on passenger vehicles to transport people and not goods. All over the world, the estimation in 2010 showed that the number of automobiles increased up to one billion compared to 500 millions in 1986 (Website: www.wikipedia). The increase in the number of automobiles requires a high number of tyres to be manufactured. There are different types of passenger car tyres, such as high-performance tyres, all-season tyres, mud and snow tyres, all-terrain tyres, spare tyres, as well as run-flat tyres.

— *Heavy duty truck tyres*

These are truck and bus tyres. These tyres are used on commercial trucks, dump trucks and passenger buses.

— *Off-the-road tyres*

These tyres are designed to use on, for example, wheel loaders, backhoes, graders, trenchers and construction vehicles.

— *Agricultural and off-road flotation tyres*

These tyres are designed to use on agricultural vehicles such as farm vehicles, tractors and harvesters.

— *Racing tyres*

These tyres are designed for competition vehicles. They last for a short period of time. This classification includes race tyres for Formula one, road racing, time attack, and more.

— *Industrial tyres*

They include non-pneumatic (airless) and pneumatic (air) tyres. These are special tyres designed for construction and industrial equipment such as skid loaders and fork-lift trucks.

— *Aircraft tyres*

These are the tyres designed for use on airplanes. They are strong enough to withstand a heavy load for a short period of time. They are inflated by helium or nitrogen to resist expansion and contraction which can arise during the temperature and pressure change while flying.

— *Motorcycle tyres*

These are the tyres designed to use on motorcycles. They include sport touring tyres, street and sport tyres and track or slick tyres.

2.1.3 Waste tyre generation, prevention and minimization

The volume of waste tyres generated depends on the number of car users and new tyres manufactured. As presented in Technical Guidelines (2005), passenger car and truck tyres represent 85% of all tyres manufactured; their composition is presented in Table 2.1.

Table 2.1: Comparison of the materials which compose passenger car and truck tyres (Technical Guidelines, 2011)

Material	**Passenger car %**	**Truck %**
Rubber	45	42
Carbon black and silica	23	24
Metal	16	25
Textile	6	-
Zinc oxide	1	2
Sulphur	1	1
Additives	8	-

The consumption stage of the tyre before its disposal should be taken into account because it has impacts on the environment (Beukering and Janssen, 2001). It was explained that in this stage, a tyre made of rubber may lose 10% of its weight; this goes into the environment, which contributes to the pollution of the atmosphere.

At the end of their life when discarded, tyres do not interact with the environment (Fuggle and Rabie, 1992). Tyres are defined as waste when they are no longer mounted on vehicles and not suitable for use as vehicle tyres due to wear, damage or deviation from the manufacturer’s original specifications. Waste tyres as defined by South Africa waste tyre regulations, the Waste Act, 2008 (Act 59 of 2008) and include ″a new, used, retreaded or unroadworthy tyre, not suitable to be retreaded, repaired or sold as a part- worn tyre and not fit for its original intended use″. When illegally dumped and burnt, waste tyres produce large volumes of black smoke and large quantities of oil which can lead to the contamination of soil, air and ground water (Neil et al., 1993). However, the legislation should emphasize tyre consumption as well as its disposal.

Waste tyres can be prevented or minimized through reuse, recycling and recovery. Used tyres can be directly reused on vehicles or be retreaded/regrooved before use on vehicles. They can also be used as a source of fuel in industries and replace other sources of energy. An example is the cement or lime kilns which use waste tyres as a second source of energy and can substitute coal as fuel. The properties of tyre rubber given in Table 2.2 show that waste tyres are good for use in civil engineering applications. These applications include, but are not limited to the construction of highway embankments over soft soils and backfill behind retaining structures.

Table 2.2: Properties of tyre rubber (CWA, 2002)

- Compacted density	- 2.3–4.8 kN/m^3 compared to soil at 15.6–19.5kN/m^3
- Durability	- non-biodegradable
- Horizontal stress on wall	- lower than that of conventional backfill
- Modulus in elastic	- range 1/10 of sand
- Permeability	- greater than 10 cm/s
- Specific gravity	- ±1.14–1.27 kg/m^3 compared to soil at 2.20–2.80 kg/m^3
- 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

2.1.4 Waste tyre problems

In South Africa, 60 million discarded tyres were counted in 2012 and 11 million tyres were added to this waste each year. It has been reported that around 80% are stockpiled or dumped across the country which can cause threats to human health and the environment. Generally the following are environmental and human health problems caused by improper management of waste tyres:

- **Human health problems**

The dumped or stockpiled waste tyres can shelter pests which carry various diseases. The stagnant water collected inside tyres also can be a breeding-site for mosquitoes. It is known that the deadly disease mostly transmitted by mosquitoes is malaria. In South America the diseases transmitted by mosquitoes are yellow fever and dengue fever, which affect a high number of the population (Technical Guidelines, 2011). The hazardous chemicals from the burned tyres like chromium, cadmium and lead can also be a danger to human health.

- **Environmental problems**

Environmental problems can be caused by burning waste tyres and are described below as water, air and soil pollutions:

- **Air pollution**

When tyres are burned, complete combustion releases carbon dioxide and sulphur dioxide into the atmosphere while incomplete combustion emits dioxins and daxious gases (Hoddinot, 1997). Other hazardous gases such as benzene, furans, arsenic, vanadium, hydrogen chloride, mercury, polynuclear aromatic hydrocarbons, polychlorinated biphenyls and chromium are released into the atmosphere (Mpanyana, 2009).

- **Soil pollution**

After burning waste tyres, the remaining residues can pollute the soil immediately by the penetration of the liquid products into soil or by the gradual leaching of ash and unburned residues (UK, Chemical Hazard Report, 2003). According to Humphrey et al. (1997), the gradual leaching of oil can also occur and together with toxic burnt tyre residues, endanger the fauna and flora. However, it can be noted that the contaminated soil takes some time to recover, otherwise remediation measures have to be taken into account.

- **Water pollution**

As a result of pyrolysis of the rubber after combustion, the decomposed oil penetrates and leaches into the ground water or can discharge into nearby ditches, streams and waterways. Groundwater may also be polluted by untreated water used to extinguish fires which carry the chemical compounds such as aromatic liquids and paraffin, and are discharged into streams or leached into the groundwater.

2.1.5 Management of used tyres in South Africa

2.1.5.1 Introduction

Generally, waste management is one way of protecting the environment. According to the CSIR (1991), the threefold paramount objectives of waste management are:

- Avoidance of waste production;
- Reduction of unavoidable wastes; and
- Disposal of residues in an environmentally acceptable and safe way.

The system of waste management in South Africa is called Integrated Solid Waste Management (ISWM). This strategy promotes clean technology and waste avoidance and promotes the resource recovery, recycling, volume reduction and processing to enhance better waste treatment as well as the reduction of the risks (Wong, 1993). The aim of ISWM was to raise the waste management to a level of decision and facilities for waste management options which conforms to the best environmental sound management.

Waste tyres are among the problematic wastes which have many negative impacts on human health and environment when unsuitably discarded. Waste tyre generation is, however, unavoidable, so there should be a sound management system to minimize their generation. The waste tyre management hierarchy is shown in Figure 2.3.

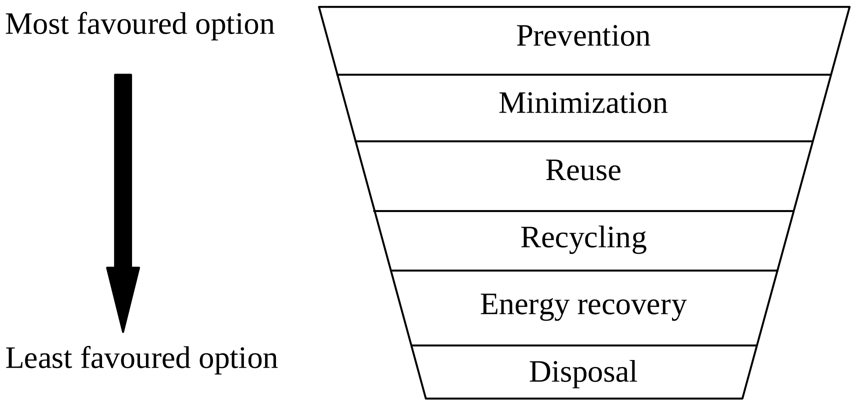

Figure 2.3: Used and waste tyre management hierarchy (Technical Guidelines, 2011)

2.1.5.2. Prevention and minimization

In South Africa, a high number of scrap tyres is generated throughout the country. As reported by Phale (2005), the great volume of such waste is generated in urban areas such as Pretoria-Witwatersrand and Vereeniging in Gauteng Province, the Cape Town metropolis in the Western Cape, Uitenhage – Port Elizabeth in the Eastern Cape and in the Durban – Pinetown area in KwaZulu-Natal. These areas face waste tyre disposal problems.

In Figure 2.3, waste prevention is the first choice of waste management. The target is to minimize the amount of waste generated entering the waste stream. Waste tyre prevention or minimization can be achieved through retreading or regrooving or direct reuse on vehicles. The reduction of the amount of waste tyre generation leads to an increase in the useful life of tyres. Through retreading/regrooving, waste tyre minimization can be achieved because it can save 80% of raw material and the necessary energy for the production of new tyres (Beukering and Janssen, 2001). According to ETRA (1998), retreading is cost-effective because the price of retreaded tyres is within 30% to 50% lower than that of the new tyres. Figure 2.4 shows the various stages in the life of a tyre.

From Figure 2.4, it can be seen that tyres can be obtained in three ways: as new tyres, retreaded tyres as well as direct re-used tyres. According to Technical Guidelines (2001) and Beukering and Janssen (2001), the used tyres can be directly reused for their original intended purpose. If they do not have the minimum remaining tread depth, they have to be retreaded or regrooved (for truck tyres only) before being reused. The minimum remaining tread depth for some countries is 1.6 mm for part-worn tyres to be sold for further use (Beukering and Janssen, 2001; Technical Guidelines, 2011). With retreading or regrooving, it is evident that tyre utilization is maximized. Around 80% of original material can be reused and if the process of regrooving is carried out correctly, the life of a truck tyre can be increased up to 30% for only 2.5% of the cost of a new tyre (Beukering and Janssen, 2001).

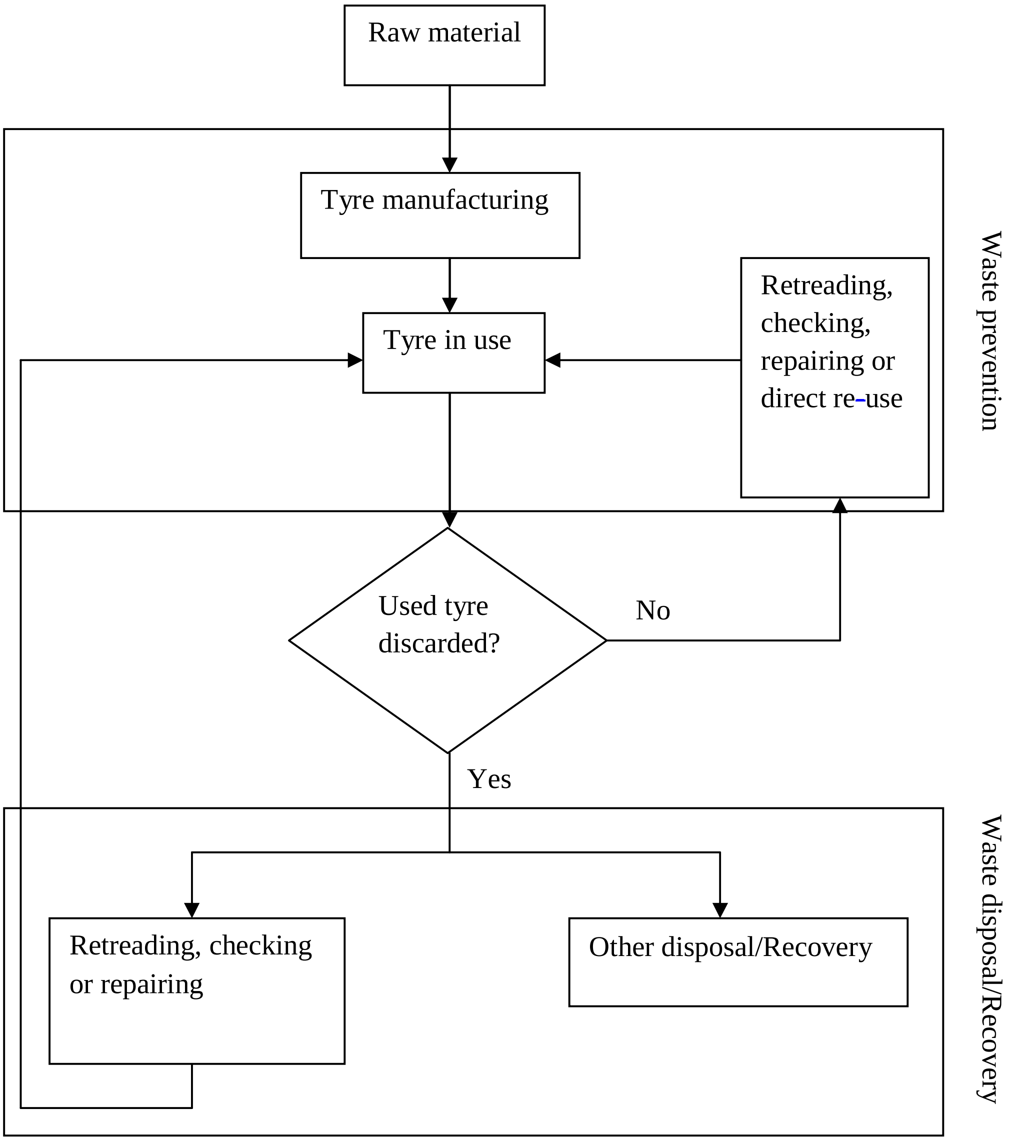

Figure 2.4: Various stages in the life of a tyre (Technical guidelines, 2011)

The importation of a large number of used tyres has some disadvantages, i.e the increase in waste load (Beukering and Janssen, 2001). This is due to the short lifetime of reusable tyres. Routine accidents while driving on worn-out tyre were also noticed. In South Africa, the number of used tyres retreaded annually is given in Table 2.3.

Table 2.3: Retreaded tyres in South Africa (SATRP, 1998)

Type of tyres	Retreaded tyres
Passenger tyres	900 000
Light delivery vehicle tyres	380 000
Truck tyres	900 000
Total	2 180 000

2.1.5.3 Recycling for material reuse and recovery

The objectives of recycling are to save the resources and reduce the impacts of wastes on the environment by reducing the amount of waste disposed of in landfills. Tyre waste may be recycled through cutting, shredding or grinding for different applications (Technical Guidelines 2011). Tyres in the form of shreds mixed with soil can be used as lightweight fill material in the construction of highway embankments resting on soft soil. The mixture can also be used as backfill material behind retaining structures which induce small horizontal stresses on these structures. Worn-out tyres as a whole can be used in the construction of, for example, field drains, erosion-control stabilization of slopes, construction of sea breakwaters, construction of road Subgrade (Ahmed 2012).

Grinding has economic and environmental advantages. As reported by Beukering and Janssen (2001), recyclable rubber, steel and textile are obtained through the grinding process. Rubber reclaim can be produced by pyrolysis of size-reduced tyres; additives are added when rubber is subjected to a thermo-mechanical process to produce the final product. Rubber reclaim can be used to manufacture new tyres. It is cheap, as its price is half that of virgin rubber cost (Beukering and Janssen 2001).

In South Africa, wealth can be created from waste tyres. As reported by Mpanyana (2009), The tyre recycling plant in Wadeville produces rubber crumbs which are exported to Europe for surface road making. He pointed out that waste tyres are used to manufacture carbon black which is sold to Botswana, Zambia, Swaziland, Lesotho and Namibia. The carbon black is intended to be used as cartridges for printer and photocopier purposes. Other waste tyres are used to manufacture products such as floor-mats, insulators, and feeding and drinking troughs for animals and so forth.

2.1.5.4 Recycling for energy recovery

Waste tyres can be used as a secondary source of fuel in the production of electricity, cement, paper, steam and steel. They can also be used in the incineration of garbage. According to Technical Guidelines (2005), the quantity of tyres burned produces an equivalent amount of energy equal to the energy produced when the same quantity of good quality of coal is burned. Despite no emission of sulfur into the environment and no solid wastes is generated when tyres are burnt, the emission of gases should be carefully controlled to protect the environment (Jones, 1997).

In the New York State Electric and Gas Corporation plant, more than 1.3 million used tyres are burned to generate power, which saves 16 000 tonnes of coal for the monthly plant consumption (Telsa, 1994). In Britain, a tyre incineration plant produces 25 megawatts of electricity per day by burning 900 000 tonnes of worn-out tyres and the rests (residues) are deposited in landfills. This plant was installed with a number of emission cleaning-up systems to minimize air pollution, and the emitted gases from tyres were equivalent to those emitted from coal (Pearce, 1993).

In 1998, nine million tyres were discarded in different provinces of South Africa (SATMC 1998). As reported by Phale (2005), Gauteng Province generated the highest amount compared to others; these wastes were treated like other kinds of solid wastes and deposited in landfills. But sometimes the landfill operators doubted or refused to accept waste tyres by demanding high fees for their disposal which led to illegal dumping or stockpiling of used tyres. Consequently waste tyres were dumped illegally in the open space. Nowadays, 200 000 tonnes of tyres become waste each year with more than 11 million tyres dumped illegally and some of them are burnt to retrieve steel wires in the tyres (DEA, 2012). Trials on the use of tyres as a source of fuel in the cement kilns were performed by Pretoria Portland Cement and Anglo-Alpha Cement institutes. The findings showed that waste tyres can be used as an alternative source of energy for cement kilns, but the challenge was the emission of harmful gases such as dioxins and furans during tyre burning.

2.1.5.5. Disposal

Waste disposal is the last option for waste management. It is economically viable to reduce waste generation, recycle it, reuse it and resource recovery (material and energy recovery). This may be a proper way of handling waste for its disposal. Waste tyres have to be reduced before their disposal, for example when used as a source of heat in the cement or lime kilns, where no solid materials remain and the ash produced can be placed in a landfill. Using tyres in the form of shreds as construction material in civil engineering applications could also be a good alternative means of disposal. In South Africa, no option of reducing waste tyres before their disposal in landfill as well as an engineering application of waste tyres which consume high volumes is in place.

2.1.6 Tyre regulations in South Africa

Regulations on waste tyres were published on 13 February 2009 by the Department of Environmental Affairs and Tourism in South Africa. The paramount objective of these regulations is to control waste tyre management by providing the regulatory mechanism. These regulations are summarized in the points below. Section 4 of these regulations requires that no person is allowed to manage waste tyres in a way opposing any of these waste regulations:

- Recycling, recovery or disposal of waste tyres must be authorized by law;
- Recovery or disposal of waste tyres which pollute the environment or cause harm to human health is prohibited;
- Waste tyres may be disposed of in a waste disposal facility only two years after the promulgation of tyre regulations. After that, tyres have to be cut into four pieces before being disposed of. Those tyre pieces may not be disposed of in landfill unless they are shredded into small pieces, but bicycle tyres and tyres with external diameter exceeding 1400 mm are not concerned.

Tyre manufacturers, waste tyre dealers, landfill site owners and tyre recyclers will be affected by these regulations. Section 6(7) of these regulations requires that the tyre producer is allowed to manufacture, import new, part-worn, retreadable casings, or supply new, part-worn, retreaded tyres after showing the approved integrated industry waste tyre management plan or an existing by the Minister.

2.1.7 The use of waste tyres in geotechnical applications

Waste tyres have been used in different projects in the field of geotechnical engineering. Some of these applications are given below.

2.1.7.1 Highway embankment applications

When constructing highway embankments with heavy-weight materials on soft ground, the compression of the soft foundation soil may occurs, leading to high settlement which may cause the instability and damage of the earth structure (Oikonomou and Mavridou, 2008). To alleviate such problems, a lightweight fill material from waste tyres such as scrap tyres, tyre shreds, tyre crumbs and tyre chips or a combination of these with soil as a substitute for heavy conventional material can be used (Zornberg et al., 2004). Humphrey et al. (1998) reported a project of two highway embankments of 10 metres high each, constructed with tyre shreds. The compressible foundation soil comprised of approximately 12 metres soft clay. These materials were selected because they were $300 000 cheaper than other lightweight fill materials. The improvement of the soft foundation soil was considered expensive; hence priority was given to the use of lightweight fill to make the embankments lighter. Figure 2.5 is the typical cross-section of one of these embankments.

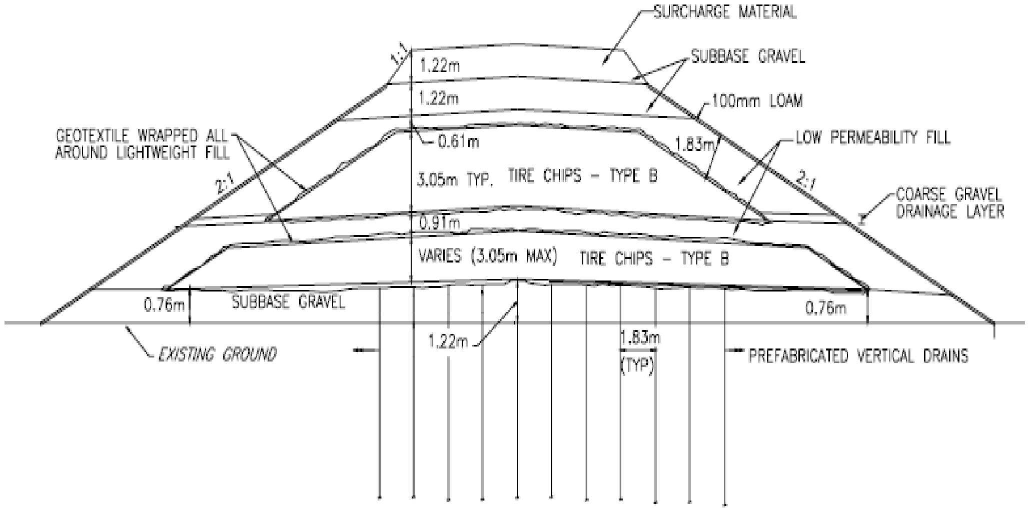

Figure 2.5: Embankment constructed with tyre shreds (Humphrey et al., 1998)

2.1.7.2 Retaining wall backfill

Backfill material comprising of tyre shreds behind a retaining walls was found to produce small horizontal stresses on the wall structures compared to conventional materials (Tweedie et al., 1998). Another reason for using tyre shreds as backfill was their hydraulic conductivity. Tyre shreds are free-draining and no excess pore water pressure can build up behind the wall. An example of where tyre shreds were used as backfill material is shown in Figure 2.6. The purpose of using these lighter materials was to reduce the horizontal pressure, vibration etc. on the wall.

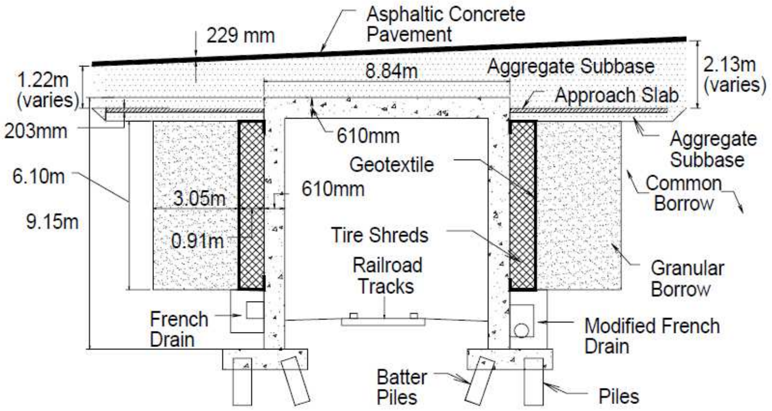

Figure 2.6: Tyre shreds backfill material for Merry Meeting rigid-frame bridge (Humphrey et al., 1998)

2.1.7.3 Drainage layer in landfill

Figure 2.7 shows the tyre shreds used as upper and lower drainage layers in a landfill site. The bottom drainage layer forms the role of leachate collection by transporting the leachate for treatment or release. As seen in the Figure 2.7, tyre shreds in contact with waste are used as a gas drainage layer while the leachate collection system below the waste and on top of sealing layer are used to prevent the pore water pressure to build up. The gas drainage system is installed in landfill to collect landfill gas which has a high potential for greenhouse effect due to its high content of methane. It can also increase the risk of landfill fire hazards.

The shreds have been found to be interesting to use as drainage material due to their high permeability (Warith et al., 2004). The properties of tyre shreds i.e drainage characteristics, durability, chemical resistant, low density and thermal characteristics, make them ideal for use in drainage system in landfill.

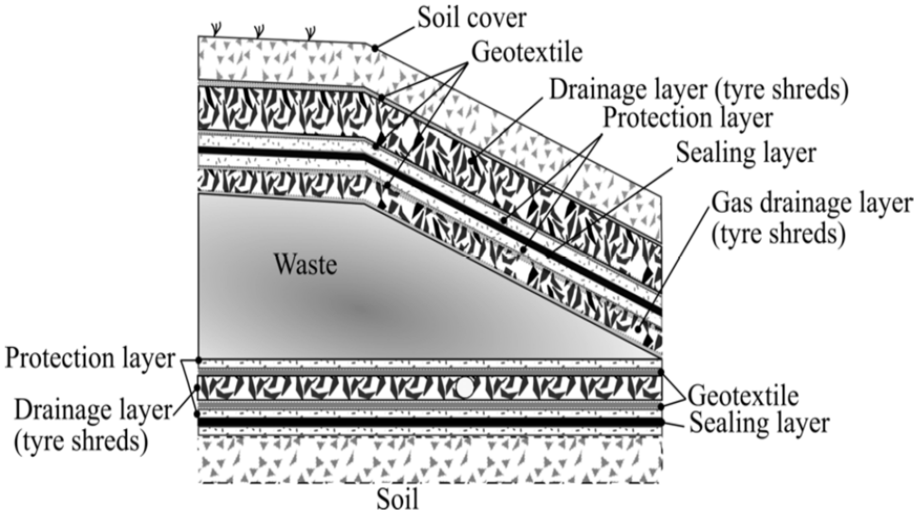

Figure 2.7: Use of tyre shreds as drainage layer in top cover, as gas drainage layer and as bottom drainage layer in landfill (Edeskar, 2006).

The suitability of tyre shred as bottom drainage layer has been studied by Reddy and Saicheck (1998), and Warith et al., (2004). They found that tyre shreds have high permeability, even at high vertical confining pressures. An example was $K=10^{-4}$m/s obtained at a stress of 1GPa and 65% compression.

2.2 Ground improvement

2.2.1 Introduction

Ground improvement is a geotechnical term applied when the soil is forced to adopt the project requirements by changing its natural state (properties) rather than changing the engineering design in response to the natural limitations of the soil. Generally the soil to be improved is that with low undrained shear strength (soft cohesive soil) and loose sand. The properties of soil which are likely to affect the cost of construction are strength and compressibility. Both can be improved by reducing the volume of the voids, decreasing settlement or by including stronger material in the soil mass.

There are numerous methods of ground improvement; all of them are grouped in different categories such as mechanical methods (vibratory compaction methods, dynamic compaction, etc.), hydraulic methods (preloading, vertical drains, etc.), chemical methods (deep soil mixing, grouting), soil reinforcement (use of geosynthetics, fibres and tyre shreds from waste tyres). One technique or another may be chosen to deal with a particular problem, for instance: increase in bearing resistance, reduction of settlement, mitigation of liquefaction, improvement of fill material, remediation of the contaminated soil, improvement of slope stability as well as the overall stability of structures. In this section, ground improvement techniques in terms of soil reinforcement are discussed.

2.2.2 Soil reinforcement

Soil reinforcement is the method used to improve the properties of soil by incorporating reinforcing materials such as fibres, geosynthetics, tyre shreds from waste tyres and so on, in soil. The objective of reinforcing soil is to increase its bearing capacity and shear strength, enhance its stability, reduce lateral deformation and reduce settlement (Hausmann, 1990; Prabakar and Sridhar, 2002; Yarbasi et al., 2007; Akbulut et al., 2007). The material to be added in the soil should be strong enough to ensure that the reinforced soil provides good strength, i.e. the shear strength characteristics, bearing capacity, improved drainage in the fine soils, and reduced weight of fill as well as the settlement of the structures when the load is applied on it. This type of ground improvement is a subject of the current study and the tyre shreds as reinforcement material from waste tyres are used. Before reinforcing soil with waste tyres, other methods of soil reinforcement took place and are briefly discussed below.

2.2.2.1 Geosynthetics materials in soil reinforcement

Geosynthetic is the general term to describe polymeric products used to solve civil engineering problems. In this method, the soil is divided into compacted layers and each layer is reinforced with geosynthetics. These products help to solve engineering problems including but not limited to erosion, slope failure, poor bearing capacity and shear strength. Conventional construction materials such as sand or gravel are considered more expensive. There are many types of geosynthetics but the commonly used for soil reinforcement include geotextiles, geogrids and geocells, as shown in Figure 2.8

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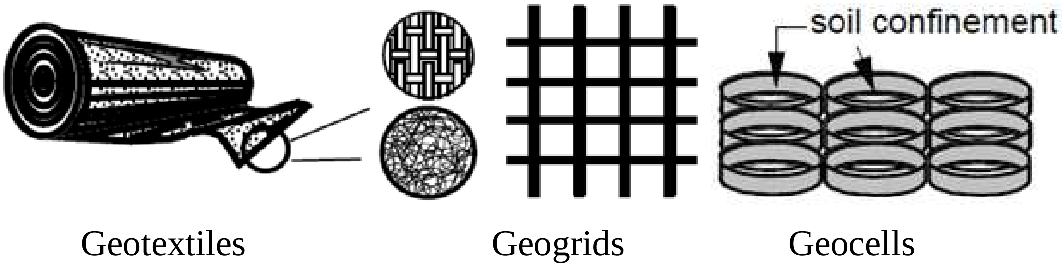


Figure 2.8: Geosynthetics commonly used for soil reinforcement (Bathurst et al., 2008)

Geosynthetic materials provide reinforcement in the form of a tensile force at each discrete layer as a function of tensile strength and pull-out resistance developed by friction and adhesion between the geosynthetic and adjacent soil (Koerner and Soong, 1998). Geosynthetics also increase bearing capacity and shear strength properties and stabilize slope. In cohesive soils, some geosynthetics act as draining material and enable the rapid dissipation of pore water pressure developed upon loading. The technique is applicable in construction of road and highway embankments, slope stabilization, commercial and office parks, residential developments, earth dams, retaining walls, etc.

Various studies were conducted on soil reinforced with geosynthetics. Triaxial tests were performed by Gray et al., (1986) on dry sand reinforced with both nonwoven and woven geotextile with different layers of reinforcement under different confining pressures. Their results showed that the fabric inclusion in sand increases its strength, changes its stress-strain behavior and limit the reduction in post peak strength loss. It was noted that the spacing between reinforcement in soil has to be well established in order to achieve the desired strength.

Apart from sand, the effect of geosynthetics on clay was evaluated. Unconfined compressive strength tests were performed by Twinkle and Sayida, (2011) on different samples of woven geosynthetics (I, II and III) with clay. Each sample was 73.5 mm in diameter. The spacing between reinforcement in clay was varied and the samples were prepared at their optimum water content and they were sheared up to 20% axial strain. The results showed that the peak strength increases as the fabrics are increased in the clay. The increase of strength in the engineered soil with four layers of reinforcement was in the order of 139%, 171% and 229% respectively.

The bearing capacity of soft clay reinforced with stone columns containing geotextiles was also investigated. According to Gray et al. (1986), the bearing capacity of soft clays can be improved by using granular piles and this in turn can be improved by internal reinforcement with oriented fabric or randomly distributed fibre layers. The improvement of the strength and bearing capacity of footing resting on clayey soil by including stone column having different fabric or randomly distributed fibre layers was studied. The results showed that the increase of both strength and bearing capacity were dependent of spacing, type and orientation of the reinforcement in samples.

2.2.2.2 Fibres in soil reinforcement

Geosynthetic reinforcing material is found to be faily expensive in soil reinforcement. According to Holtz (2001), the total cost of geosynthetics is about 20-25% of the total construction cost which leads to an increase in overall project costs. The high cost of geosynthetics motivated the development of the use of fibres. Reinforcing soil with fibres, either natural or synthetic (artificial), is a technique of ground improvement where discrete fibres or continuous filaments are mixed with soil to improve its shear strength and constrain its deformation. Fibres in soil are known to improve its bearing capacity, shear strength, reduce settlement of the structure and assist in stabilization of slopes.

For these reasons the investigation on fibre-soil composite interaction was performed by different researchers. Gray et al. (1986) performed the study on fibre (either natural or synthetic)-sand composite samples using a direct shear device and their results showed an increase in shear strength and the reduction in post peak strength loss. This reduction in post peak strength was due to the random inclusion of discrete fibres in soil. The concentration of fibres which gave the maximum strength was about 2%. Moreover, the improvement of engineering properties due to the inclusion of discrete fibres depends on fibre type, fibre length, aspect ratio, fibre content, orientation and the soil properties.

Apart from sand, the strength of clayey soil-synthetic fibre composite samples were also investigated by Akbulut et al. (2007) for unconfined compressive strength, shear strength parameters and shear modulus. Fibres used were from polypropylene and polyethylene waste materials, the size and concentration of fibres varied and the samples were compacted at their optimum moisture content. The size of the samples varied, i.e. 35 mm diameter by 70 mm in length, 50 mm diameter by 100 mm in length and 80 mm diameter by 160 mm in length. The findings showed that the addition of fibres in clayey soil increases its unconfined compressive strength and the maximum value was obtained at 0.2% content by weight for all fibre lengths. The length of fibre should be increased in proportion to the sample dimensions. The maximum cohesion and shear modulus were obtained at the same concentration of fibres and at 10 mm fibre lengths.

The bearing capacity of compressible clay reinforced with synthetic fibres (polyester) was evaluated by Kalpana et al. (2011). They concluded that the inclusion of randomly distributed fibres in clayey soil increases its ultimate bearing capacity and decreases its settlement for ultimate load.

2.2.2.3 Soil reinforcement with tyre shreds from waste tyres

2.2.2.3.1 Introduction

Another technique of soil reinforcement is the use of shredded waste tyres. In this technique the used tyres are cut into different sizes and are mixed with soil at a predetermined concentration either by weight or volume, giving the good shear strength parameters of the composite. The different sizes of tyre cuts are described in the next sub-sections.

2.2.2.3.2 Categories of waste tyre pieces (tyre cuts)

Generally, tyre cuts are available in different categories according to their sizes (Moo-Young et al., 2003). These are slit, shred, chip and granulate (ground rubber and crumb rubber). The first type of tyre pieces referred to as slits is obtained by cutting a whole tyre into halves and the sidewalls are separated from tyre treads. Slits are reduced in size to obtain the second category of tyre cut named tyre shreds ranging from 50 to 300 mm. These shreds are irregular rectangular and square in shape containing steel belts or beads. According to Moo-Young et al. (2003), tyre shreds are obtained from primary and secondary shredding processes in which the slits are loaded onto a conveyor feeding system towards a primary shredding machine and cut into 300 mm, then proceed towards secondary shredders which reduce the size to up to 50 mm depending on the requirements. Furthermore, tyre pieces called tyre chips have also irregular rectangle and square shape with size ranging from 12 mm to 50 mm and are also obtained from secondary shredding process (Moo-Young et al., 2003). These chips have the most wires removed (FHWA, 1998). The last category of tyre pieces referred to as the granulates which involve tyre crumb and ground rubber with particles ranging from 12 mm to 0.15 mm and 4.75 mm to 0.075 mm respectively are obtained from the granulator by reducing the size of tyre chip from secondary shredding (Young et al., 2003).

2.2.2.3.3 Tyre shredders

There are a number of waste tyre processers all over the world. Some of them are discussed below.

- **ZERMA**

The German Company ZERMA designed the tyre-recycling facility which produces high quality products made from recycled waste tyre. The materials produced at the end of the process are either shreds from primary and secondary shredding processes which can be used massively in the cement industry and civil engineering applications, or 5 mm size crumb rubber and powder for the other different applications.

In the primary shredding process the passenger car tyres, light truck tyres and pre-cut truck tyres are loaded onto the large conveyor towards the Shredder 1 called ZTS which reduces these materials into 300 mm to 150 mm or smaller shreds. The conveying system conveys shredded tyres from the primary to the secondary shredding process called Shredder 2 (ZTTS) which reduces the material to about 20 mm size shreds. At this stage the tyre shreds with steel are separated and shreds free from steel are fed into conveyor towards granulators called GSH where they are ground into tyre particles between 4 mm and 1 mm and less in size. At each stage the separation equipment is installed to remove metal and fibre to ensure the result of high quality. The Zig Zag Silter and screening machine 1 CS separate the tyre pieces and the material larger than 6 mm in size are returned into granulators to be ground to smaller particles, depending on the requirement. The end products of the ZERMA equipment are tyre pieces less than 1mm in size. The complete tyre shredding process is shown in Figure 2.9.

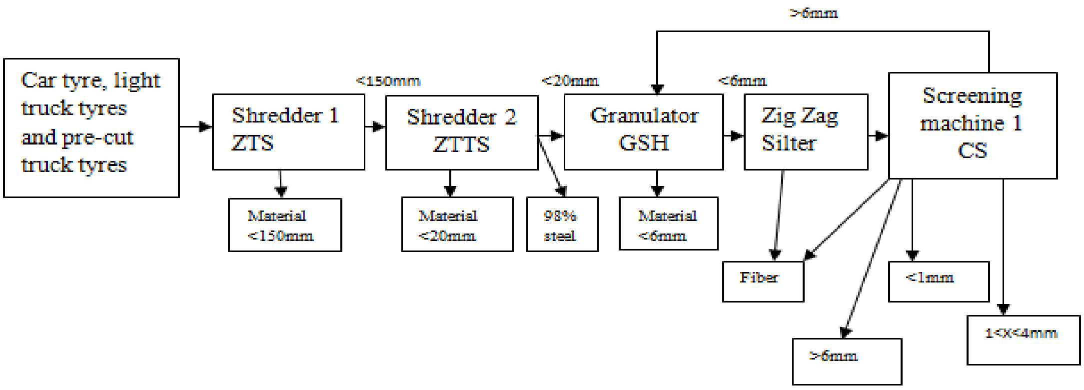


Figure 2.9: Tyre-shredding processes (Zerma Company, 2013)

- **American Tyre International Solution Inc.**

Another tyre shredder industry is Tyre International Solution in America. This industry cuts used tyres following four steps. As given in Figure 2.10, the first step is the extraction of the steel bead heel, followed by tyre shredding then granulation, and reselling and recycling come at the end.

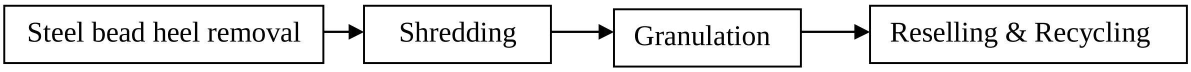


Figure 2.10: Phases of tyre shredding

The steel bead heel removal is the crucial phase of tyre recycling before the tyres are loaded into the automated plant. The extracted steel bead heels are made up of strands of 20 mm diameter. Thereafter the tyres are loaded onto the conveyor which conveys them into the shredders during the shredding phase. The shredder machines with the help of the screening system produce a minimum size of tyre shreds of 60 mm. The material from shredders continues towards granulators where they are reduced to less than 15 mm chunks. At this stage the textile fibres and steel filaments are mechanically removed by screening equipment. Under granulation phase the sub phase called refining phase reduces 15 mm tyre pieces into granules of 5 mm textile free fibres. These rubber particles are further reduced to 400 microns in the pulverization phase.

The last phase. the reselling and recycling phase, consists of reselling the extracted steel bead heels from the first phase to the steel recycling manufacturers. Furthermore, the materials from granulation phases (rubber) are recycled into various products.

- **South Africa Tyre Recyclers**

The last discussed tyre shredder is South Africa Tyre recyclers. The steps in tyre cutting in this facility start from sorting waste tyres, followed by steel removal, primary and secondary shredding, and the last is granulation to obtain the smaller rubber particles. The South Africa Tyre Recyclers products’ applications include but are used in the making athletics grounds, building insulation, playground surfaces, tarred roads and new tyre manufacturing. However, tyre shreds used in the current research were supplied by this facility because it is locally available. The shredding processes of tyres are shown in Figure 2.11. According to the South Africa Tyre Recyclers (SATR), tyre shreds are obtained through primary and secondary (granulation) stages. Further granulation is performed to generate the finished product depending on the requirements.

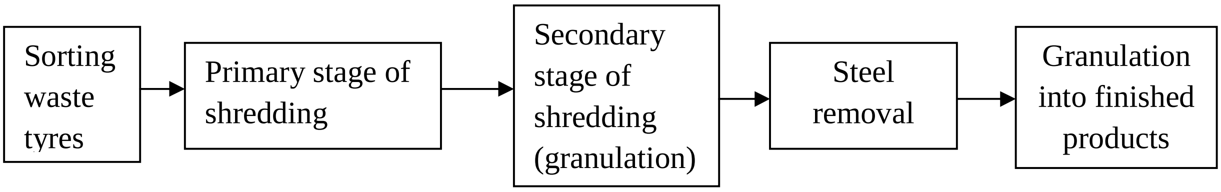


Figure 2.11: Complete processes of reducing waste tyres.

On reaching the recycling facility, the tyres are sorted by size and composition for processing. Tyres suitable for recycling are then loaded onto a large conveyor belt towards the production line. Reaching the primary stage of shredding, they are shredded into 90 to 50 mm shreds. The material from primary shredding are then fed into the secondary stage of shredding (granulator) where they are reduced into around ±18 mm size chunks and less. After secondary stage is completed, steel and fibre removal take place after which they are stored in large hoppers for the next stage. The last stage is the granulation into finished products in which the steel-free tyre granules are cut by tips and blades and pushed through sieves depending on the required product. Some pictures showing the tyre shred recycler factory are given in Figure 2.12.

Figure 2.12: Tyre recycler factory at Atlantis

2.2.2.3.4 Mechanism of reinforcing soil with tyre shreds

The mechanism of reinforcing soil with tyre shreds involves selecting appropriate sizes and optimum content of tyre shreds and mixing them with the selected soil until the mixture becomes homogeneous. Like the mechanism of reinforcement given by Gray and Al-Refaei (1986) for the randomly discrete fibres in soil shown in Figure 2.13, the randomly distributed tyre shreds in soil may have the perpendicular or inclined positions and interlock with soil material in the shear plane and resist the cut-off during shearing then increases shear resistance of the composites. This may result in an increase in friction angle and cohesion, which in turn increase the shear strength of soil.

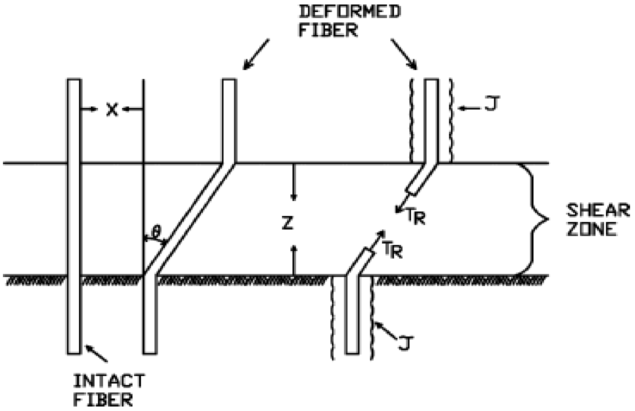


Figure 2.13: Deformation of fibres during shearing (Gray and Al-Refaei, 1986)

Where T_R: Tensile stress developed in the fibres at the shear plane; z: the thickness of the shear zone; x: horizontal shear displacement

Before the preparation of the mixture, the tyre shreds size and content must be selected. Cetin et al. (2006) give an example of compositions of mixture by weight and by volume in Table 2.4. Different samples with varying sizes and content of tyre shreds should be prepared and tested in the laboratory in order to determine the economical tyre shred size and content which give the good parameters necessary for the project design.

Humphrey (1999) reported that the use of waste tyres in the form of shreds reduces construction cost. Instead of improving soft foundation soil prior to the construction of highway embankment which would be considered expensive. The lightweight tyre shreds are cheaper than other light-weight fill material and can be used to make the embankment lighter. This alternative helps to limit the problems of settlement and the instability which can be caused by heavy weight fills placed on soft soils.

Table 2.4: Preparation of tyre shreds soil mixture, after Cetin et al. (2006)

By weight (%)	By volume (%)
Pure clay (0% fine tyre shreds)	Pure clay
10% fine tyre shreds	18% fine tyre shreds
20% fine tyre shreds	33% fine tyre shreds
30% fine tyre shreds	46% fine tyre shreds
40% fine tyre shreds	57% fine tyre shreds
50% fine tyre shreds	66% fine tyre shreds
100% fine tyre shreds	100% fine tyre shreds
10% coarse tyre shreds	25% coarse tyre shreds
20% coarse tyre shreds	42% coarse tyre shreds
30% coarse tyre shreds	55% coarse tyre shreds
40% coarse tyre shreds	66% coarse tyre shreds
50% coarse tyre shreds	74% coarse tyre shreds
100% coarse tyre shred	100% coarse tyre shreds

2.2.3 Summary of the discussed soil reinforcement techniques

Different methods of soil reinforcement were discussed in this chapter. Like other materials such as geosynthetics, etc., improving ground with tyre shreds aims at increasing shear strength, bearing capacity and reducing settlements of soft compressible soils. In South Africa no information exists on how tyre shreds materials can be used to improve soil properties. The high number of scrap tyres dumped is also a challenge for this country. However, this technique has the benefits of cleaning up these problematic wastes, being cost-effective so that able to preserve and protect nature.

2.3 Previous studies on tyre shreds in soil improvement

A comprehensive literature review was undertaken in order to understand the behaviour of tyre shreds mixed with soils. In this section, various results from laboratory works obtained by other researchers are reported.

2.3.1 Effects of tyre shreds on Atterberg limits of clayey soils

In the study conducted on tyre shreds soil mixtures, plastic limit, liquid limit and plasticity index were considered. The results from experimental works carried out by Cetin et al., (2006) following American Society of Testing and Material (ASTM) (2003) standards on clayey soil-tyre shreds composite as presented in Figure 2.14 below, showed that as the clay content of the clayey soil decreases as tyre shreds are added, no change in liquid limit occurs up to 30% content of tyre shreds, while the plastic limit remains the same up to 10% from which it starts to decrease up to 20%. It was concluded that the increase of tyre shreds in clayey (cohesive) soil decreases its Atterberg limits and clay content.

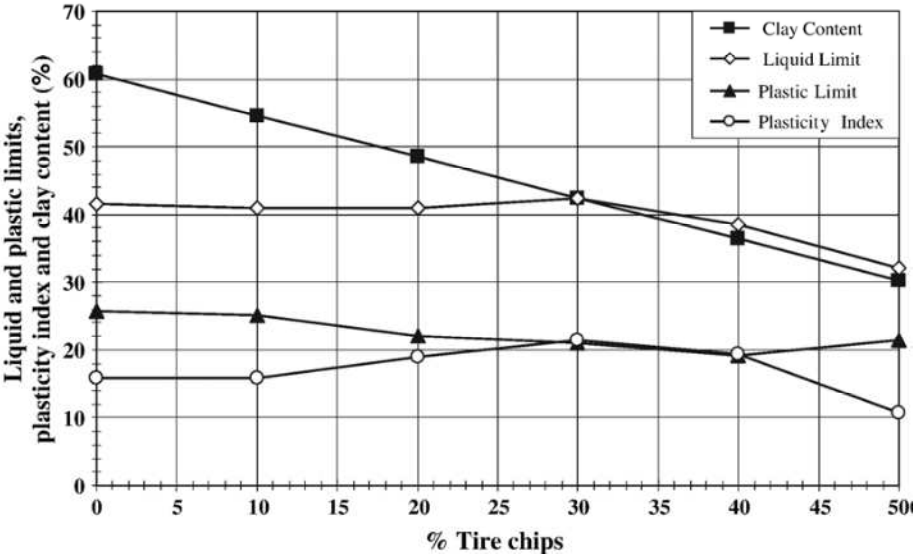


Figure 2.14: Variation of liquid limit, plastic limit and plasticity index for clay soil as the concentration of tyre-shreds increases (Cetin et al., 2006).

2.3.2 Effect of tyre shreds on permeability of soil

The permeability of soil is defined as the flow of water through the soil mass. The permeability of clayey soil is very low. When tyre shreds are mixed with low permeable soils, they act as draining material and increase in permeability. As reported by Cedergren (1989), Ahmed (1993), and Cetin et al. (2006), the draining materials minimize the development of excess pore pressure upon loading and accelerate the consolidation of foundation soil by providing shorter drainage path. As a result, the stability of the structure constructed with tyre shred-soil mixture can quickly be achieved.

The permeability of tyre shreds is influenced by tyre shred size, compaction effectiveness (initial density/void ratio), and normal stress. According to Humphrey and Sandford (1993), the value of permeability of tyre shreds size ranging from 19 mm to 76 mm at void ratio of 0.583 obtained using a permeameter is 4.8 cm/s. The hydraulic conductivity of clayey soil, fine and coarse tyre shreds and the mixture of the two at different normal pressures and different tyre shreds content were performed in consolidometer apparatus (falling head method). The results showed that the permeability of clayey soil alone and the mixture with a small percentage of tyre shreds is as low as (10^{-7}—10^{-8} cm/s) and increases as the percentage of tyre shreds increases and at a decreasing normal pressure (Cetin et al., 2006).

As shown in Figure 2.15, the hydraulic conductivity increases as the content of tyre shreds in clay increases and at low normal pressure. But this cannot prevent the pore water pressure from building up. To preclude the pore pressure development, the clay-tyre shreds mixtures cannot be used where drainage is necessary. Consequently, tyre shreds-sand or shreds-gravel mixtures are appropriate in these conditions. Clay-tyre shreds mixtures can be used in unsaturated conditions where low permeability, low weight and high strength are required in the fills resting on weak foundation soil. An example is road embankments and backfill behind retaining walls which have to be built above the water table. Cetin et al. (2006) concluded that tyre shred-clayey soil composite, when mixed with high draining material such as sands or gravels, can also be used in a saturated condition.

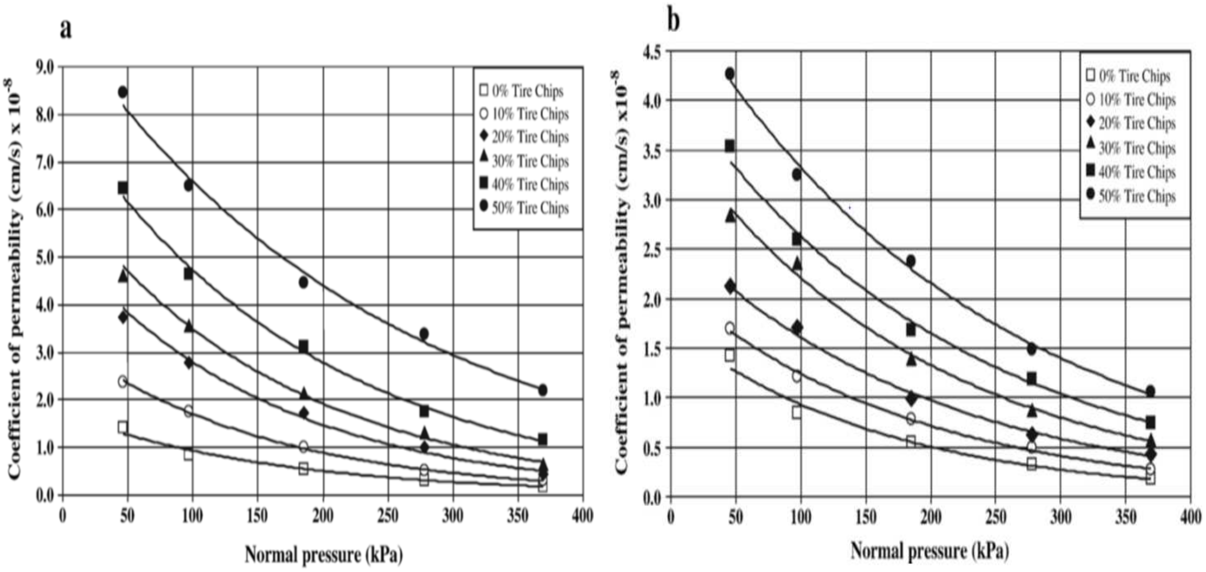


Figure 2.15: Coefficient of permeability versus normal pressure: (a) fine-grained, (b) coarse-grained tyre shreds clay mixtures (Cetin et al., 2006)

The fine and coarse tyre shreds have higher permeability which may be the same as that for sand and can increase by decreasing the normal pressure and increasing tyre shred size (Figure 2.16). Because of their high permeability, Masad et al. (1996) noted that the pure tyre shreds or tyre shreds-sand mixtures are useful materials for road embankment construction.

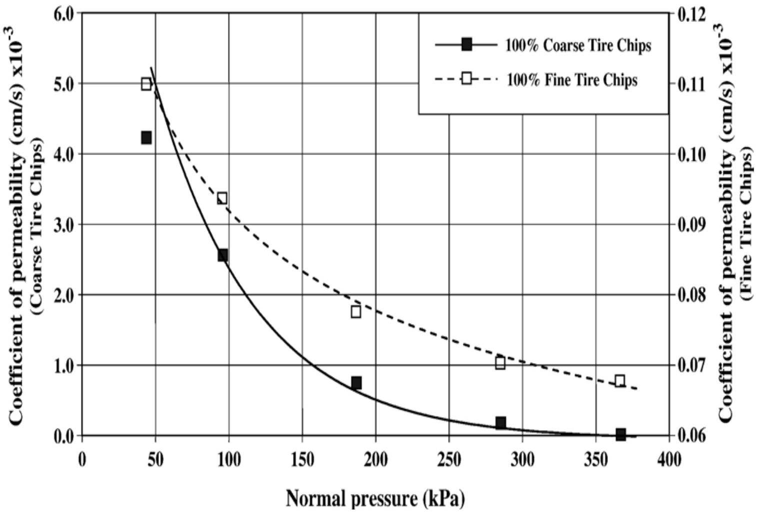


Figure 2.16: Coefficient of permeability versus normal pressure for pure fine and coarse-grained tyre shreds (Cetin et al., 2006)

2.3.3 Effect of tyre shreds on compaction

The compaction of soil is carried out to increase its density which is defined by the ratio of the mass per unit volume. The Proctor test was carried out on clayey soil, tyre shreds and tyre shreds-clay mixtures. The maximum dry densities were obtained with their corresponding moisture content. According to the results obtained by Ahmed, (1993) and Humphrey et al. (1993), the density of different compacted pure tyre shreds ranges from 225 kg/m^3 to 714 kg/m^3.

The investigations on compaction of clay and clayey soil mixed with tyre shreds were performed by Cetin et al. (2006) and their results are shown in Figure 2.17. It is clear from the Proctor curves that the maximum densities are higher for clayey soil alone and decrease as the percentage of tyre shreds increases both for fine and coarse tyre shreds soil mixtures. The same tests were performed by Oikonomou and Mavridou (2008) on sand-tyre shred mixture and they reported that dry density decreases as the percentage of rubber increases regardless of the rubber size. Thus, the values of maximum densities show the potential for using tyre shreds or tyre shred soil mixture as a lightweight fill material (Cetin et al, 2006; Oikonomou and Mavridou 2008).

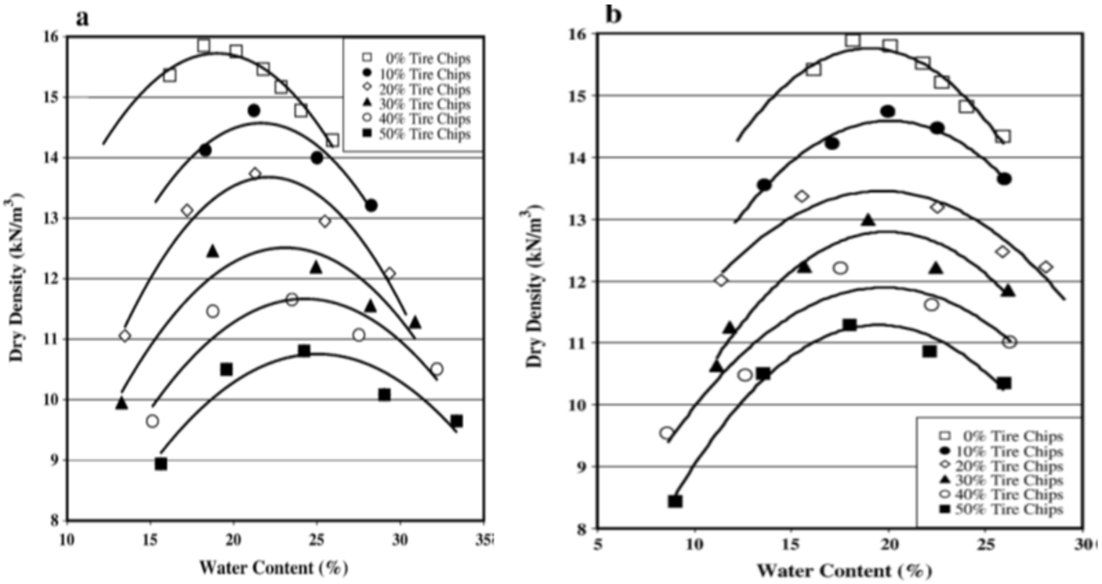


Figure 2.17: Compaction curve for fine (a) and coarse (b) grained tyre shreds mixtures (Cetin et al., 2006)

2.3.4 Shear strength of tyre shred soil composite

Shear strength of soil is defined as the maximum shear stress that a soil can sustain or internal resistance per unit area that the soil mass can offer to resist the failure and sliding along any internal plane. The resistance of soil depends on friction and how the particles are cemented or bonded together. The effective shear strength is given by equation 1:

$$\tau = c' + \sigma_n' \tan\phi' \ldots\ldots\ldots (1)$$

where:

τ: shear strength in kN/m^2

c': cohesion in $kN/m^{2`}$

σ_n': N/A: applied normal stress in kN/m^2

N: Normal applied load in kN

A: Contact area in m^2

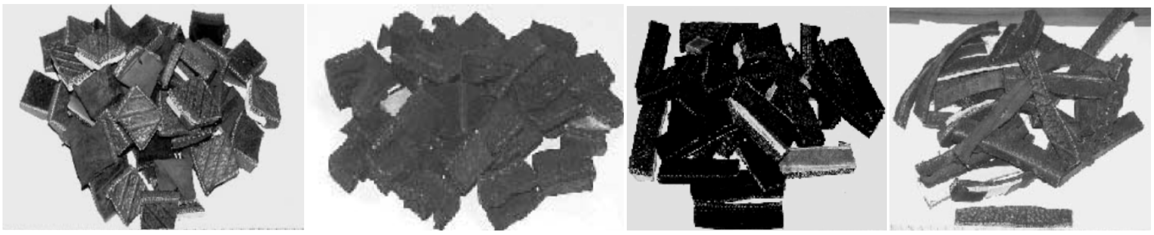
ϕ': Angle of internal friction in degree

Reinforcing soil with both geosynthetics and fibres, either natural or synthetic, was not a solution for waste tyres. These waste tyres were used in various laboratory works to assess their shear strength behaviour when mixed with soils and the results were reported as seen in the following paragraphs.

Masad et al. (1996) evaluated the shear strength of tyre shred-Ottawa sand mixtures using triaxial cell apparatus by varying sizes and concentration of shreds in the composite. They concluded that the mixture from Ottawa sand-tyre shreds is a suitable fill material for the construction of highway embankments over soft compressible soils. The same experiment was conducted by Prasad and Prasada (2009), but granular types of soils were used. The improvement of shear strength characteristics was from 36^0 to 40^0 and from 11.77 to 26.48 kN/m^2 in terms of friction angle and cohesion respectively.

Focusing on aspect ratio and the concentration of tyre shreds in the mixture, Zornberg et al. (2004) performed large-scale triaxial tests on sand-tyre shred composite. In their studies they used different concentrations of tyre shreds and aspect ratios of 1, 2, 4, and 8 shown in Figure 2.

18 (a, b, c and d). The test specimens were prepared at the relative densities of 55% and 75%. The findings showed that the addition of tyre shreds to sand enhances its shear strength. It is concluded from Figure 2.19 that the aspect ratio of shreds between 4 and 8 increased the shear strength and the higher aspect ratio affected the volume change. A high confining pressure, no influence of aspect ratio on sample volume was recorded. The maximum value of shear strength was recorded at the concentration of 35% tyre shreds by weight. This was obtained at a relative density of 55%. Therefore the increase in shear strength was independent of an increase in relative density of sand matrix. The same results were reported by Gotteland et al. (2005).



(a) (b) (c) (d)

Figure 2.18: View of tyre shreds with various lengths (Zornberg et al., 2004)

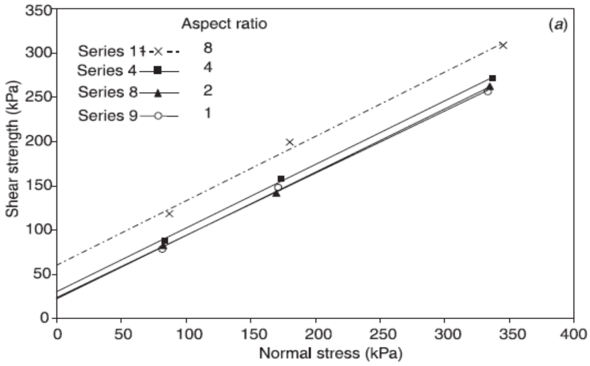


Figure 2.19: Influence of aspect ratio on shear strength (Zornberg et al., 2004)

This was in contrast to Attom (2006), who performed the tests on the same mixture but using direct shear box of 10.5 cm x 10.5 cm square and 3 cm high and varying concentrations of tyre shreds. Mousa (2006) obtained no optimum tyre shred content because the shear strength increased for all investigated concentrations of tyre shreds. He reported that shear strength increased from 0.7 kg/m^2 at 0% to 1.4 kg/m^2 at 40% content by weight of tyre shreds. The same tendency was observed in the other type of sand. Furthermore, the angle of internal friction was improved as the tyre shreds quantity increased. The author noticed that the increase of initial dry density increases shear strength of the mixture.

The shear strength behaviour of tyre shred sand mixtures was measured by Balachowski and Gotteland (2007), who performed consolidated drained triaxial compression tests. The displacement rate was controlled to 0.4 mm/min and the confining pressures used varied from 100 kPa to 300 kPa. The results obtained led to the authors' conclusion that 30% tyre shred content by dry mass is an optimum for the maximum shear strength of the composite. This value was also reported by Baleshwar and Vianot (2009), who measured the shear strength of tyre shred sand mixtures using large-scale direct shear box by varying the concentration of tyre shreds in the mixture from 10% to 50% with an interval of 10% and compacting the test specimen in the shear box to achieve nearly the maximum dry density. Baleshwar and Vianot (2011, 2013) conducted direct shear strength tests on the same mixtures, but varied the shred size and confirmed the same results.

The results above were checked from Cabalar (2011), who performed the tests on samples without any compaction. From the Figures 2.2 and 2.21 both maximum shear stress and internal angle of friction decrease as tyre shreds are added to sand up to 10% content beyond which it becomes nearly constant.

The reason for decrease in shear strength as explained by Cabalar, (2011) could be the particle size and shape of sand material. Another reason might be the small size of rubber particles used in some studies.

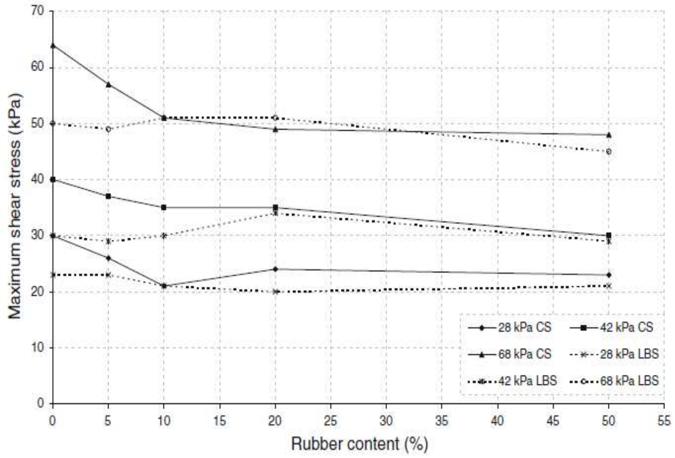


Figure 2.20: Maximum shear stress versus % of rubber content for Ceyhan (CS) and Leighton Buzzard Sands (LBS) (Cabalar, 2011)

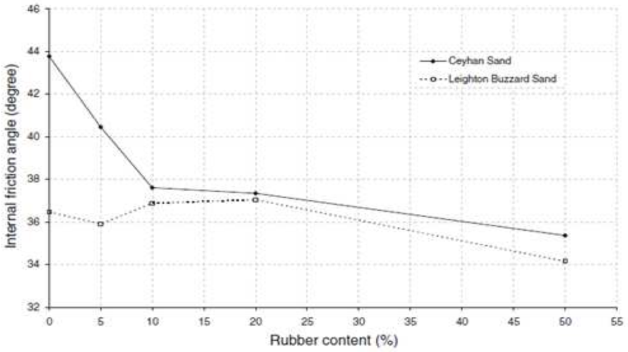


Figure 2.21: Friction angle versus rubber content for Ceyhan and Leighton Sands (Cabalar, 2011)

Tatlisoz et al. (1998) conducted large-scale direct shear tests with tyre shreds, sand, sandy silt, sand-tyre shreds and sandy silt-tyre shreds mixtures. The results showed that the shear strength of the sand-tyre shreds mixtures increases with increasing tyre shreds content up to 30% by volume. It was noted that the friction angle of the sandy silt-tyre shreds mixtures was independent of tyre shreds content. The increase in shear strength of the sandy silt-tyre shreds mixtures was primarily due to an increase in apparent cohesion. The same experiment was performed by Foose et al., (1996) and the results obtained were almost identical.

Apart from investigation on tyre shred-sand and tyre shred silts composites, Cetin et al. (2006) performed tests on tyre shreds-clayey soil mixture using small scale direct shear box. The box was seated in a pan which was filled with water and kept full during the tests. The study was carried out at different tyre shred content and sizes. It has been seen that the best mixtures which give high value of shear strength are those with 20% coarse tyre shreds (2–4.75 mm) and 30% fine tyre shreds (< 0.425 mm) when mixed with clayey soil. As shown in Figure 2.22 (a & b), cohesion increases as the tyre shreds content increases up to 40%, while the angle of internal friction decreases and vice versa beyond 40% tyre shred content.

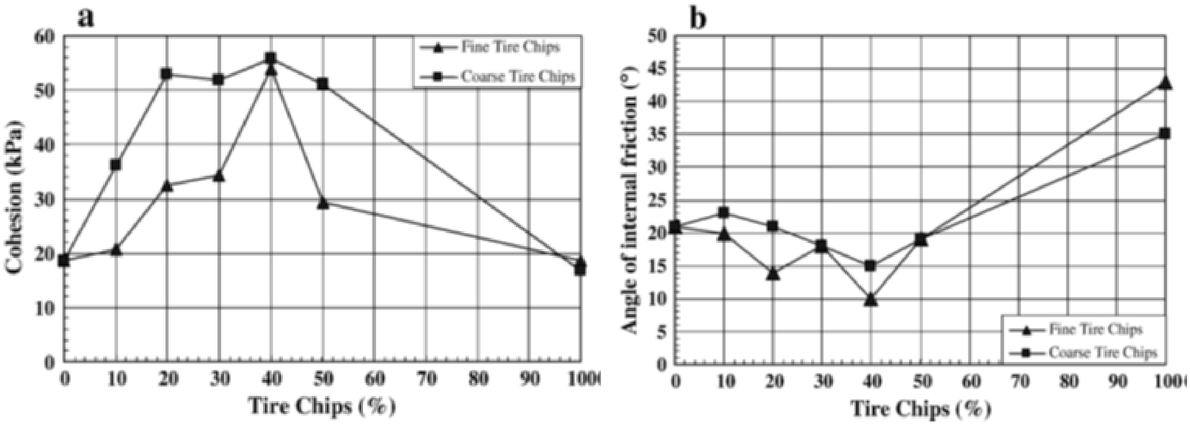


Figure 2.22: Cohesion (a) and friction (b) angle versus % tyre shreds (Cetin et al., 2006)

In contrast to Akbulut et al. (2007) who performed the test on the same soil, the maximum cohesion was obtained at 2% content and 10 mm length of shreds. Unconfined compressive strength was evaluated as well and the maximum value was obtained at the same size and content. The angle of internal friction increased in a non linear way. The summary of previous studies on shear strength of tyre shred sand mixtures is given in Table 2.5.

Table 2.5: Summary of the results from previous studies on shear strength

References	Soil type	Shred width (mm)	Shred length (mm)	Aspect ratio	Shred content (%)	Optimum Tyre shred Content (%)	Shear strength (τ)
Foose et al., 1996	Sand	-	Up to50 50-100 100-150	N/A	10 20 30	30	ϕ': 34 to 49^0
Tatlisoz et al., 1998	Sand & Sandy silt	N/A	30-110	N/A	10 20 30	30	ϕ': 30 to 53^0 c': 11 to 39 kPa
Zornberg et al., 2004	Sand	25.4 12.7 12.7 12.7	25.4 25.4 50.8 101.6	1 2 4 8	5 10 15 30 38	35	Maximum shear stress: 1.09 to 1.71 (kg/cm^2)
Mousa, 2006	Sand	N/A	N/A	N/A	10 20 30 40	40	c': 1.09 to 1.71 (kg/cm2)
Cetin et al., 2006	Clay	N/A	<0.425 2-4.75	N/A	10 20 30 40 50	40	c': 19-56kPa Friction angle: $20\text{-}15^0$
Akbulut et al.,2007	Clay	N/A	2-5 5-10 10-15	N/A	1 2 3 4 5	2	c': 94-185kPa
Cabalar, 2011	Sand	N/A	N/A	N/A	5 10 20 50	10	ϕ': $44\text{-}37.6\ ^0$
Vianot and Singh, (2009)	Sand	10	10 20 30	1 2 3	10 to 50	30	τ: Increase
Vianot and Singh, 2011	Sand	10	10 20 30	1 2 3	10 to 50	30	τ: Increase
Vianot and Singh, 2013	Sand	10	20	2	10 to 50	30	τ: Increase

N/A: Not Applicable

2.3.5 Tyre shreds in improvement of bearing capacity of soil

The bearing capacity of soil is defined as the load-carrying capacity of surface unit foundation soil or rock. It is also the pressure a soil can safely support without failure in shear. Bearing capacity controls the load from a superstructure by keeping it lower than the allowable bearing pressure in order to avoid adverse total and differential settlement which may cause damage to the structure resting on it.

When the estimate of the bearing capacity of the foundation gives a very small value, soil improvement may be required. Therefore the use of tyre shreds may be an option to improve the shear strength parameters (cohesion and friction angle) of such weak soil types. These parameters are in direct relationship with its bearing capacity.

According to Das (2007), the failure surface for the case of general shear failure due to the ultimate applied load is assumed to be similar to that shown in Figure 2.23. For equilibrium analysis Terzaghi (1943) was the first author who proposed the theory to evaluate the ultimate bearing capacity of a rough rigid continuous foundation as given in equation (2) below. The equation has been modified for other types of foundations. This equation can be used once the shear strength parameters of soil supporting the foundations are known.

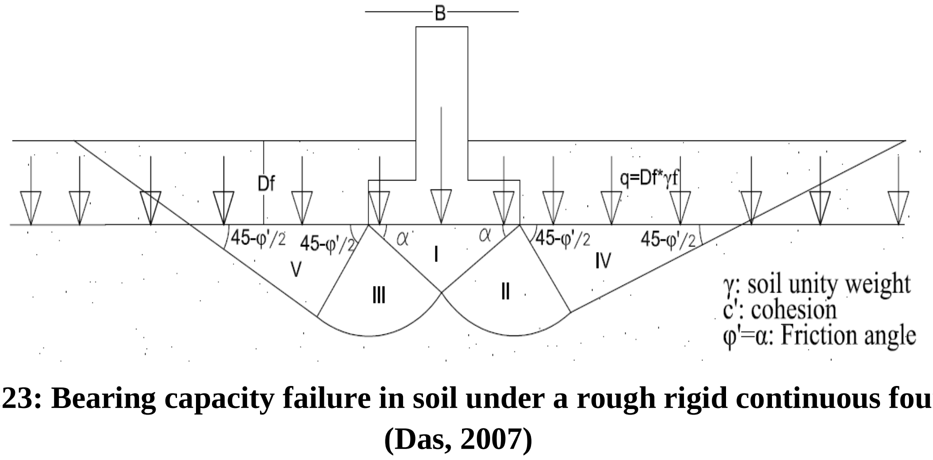


Figure 2.23: Bearing capacity failure in soil under a rough rigid continuous foundation (Das, 2007)

$$q_u = c'Nc + qNq + 0.5\ B\ \gamma\ N\gamma \ \ldots\ldots\ldots\ldots\ldots(2)$$

Nc, Nq, $N\gamma$ dimensionless bearing capacity factors which are in function related to internal friction angle (ϕ')

q_u: ultimate bearing capacity (in kPa)

c': cohesion of soil (in kPa)

B: the width of the footing (m)

γ: Unity weight of foundation soil (in kN/m^3)

q: overburden pressure = $Df*\gamma_f$ (in kPa)

γ_f: Unity weight of overburden soil (in kN/m^3)

Df: depth of foundation from the ground surface to the base of footing (in m)

Various laboratory studies were conducted to assess the improvement of the bearing capacity of soil reinforced with tyre shreds. The results of sand mixed randomly with shredded tyre obtained by Hataf and Rahimi (2005) showed that the bearing capacity ratio (ratio of bearing capacity of improved to unimproved soil) increases as tyre shreds content and aspect ratio increase. It can be noted that the equation (2) was not used to compute the bearing capacity. However, the bearing capacity was the maximum pressure applied on the sample beyond which the failure occurred. As shown in Table 2.6 below, the optimum tyre shreds content after which the bearing capacity ratio starts to decrease was found to be 40% and the optimum aspect ratio for the maximum bearing capacity ratio was 4.

Table 2.6: Bearing capacity ratio of tyre shred sand mixture (Hataf and Rahimi, 2005)

Tyre shreds content %	Size of shreds						
	2*4cm	2*6 cm	2*8 cm	2*10 cm	3*6 cm	3*9 cm	3*12 cm
10	1.17	1.46	1.46	1.56	1.56	1.73	1.83
20	1.6	2.03	2	1.97	1.9	2.13	2.2
30	2.15	2.73	2.8	2.84	2.69	2.8	3
40	-	3.2	3.4	-	-	-	3.9
50	-	2.95	3.3	-	-	-	3.9

2.3.6 Summary of the review

The inclusion of tyre shreds in soil showed an improvement of its engineering properties such as shear strength. Based on their results, many researchers derived a conclusion that soil-tyre shred mixtures is suitable for use as lightweight fill material in the construction of various earth structures such as highway and road embankments above soft compressible soils. Settlements of underlying soil caused by fill material from tyre shred-soil composites are small and no excess pore water pressures which may cause instability problems can be generated because tyre shreds are lighter in weight, possess high hydraulic conductivity and are easy to place and compact.

South Africa as a developed country contains a high volume of scrap tyres and the use of these tyres to improve soil is not undertaken. Therefore the need to utilize this type of waste for ground improvement will be beneficial in terms of waste resource recovery. It will also help to solve geotechnical problems related to low shear strength. However, there are some contradictions in the experimental findings. Zornberg et al. (2004) found that addition of tyre shreds to soil increases its shear strength while Cabalar (2011) suggested a reduction of shear strength due to tyre shreds inclusion. A decrease was observed for sand mixed with fine tyre shreds (Cabalar, 2011). To verify these findings, the study into the effect of the inclusion of tyre shreds in South African sandy soils is undertaken.

This research focused on the investigation of the optimum content of tyre shreds to achieve the highest shear strength when mixed with Cape Flats sand and Klipheuwel sand. The shred size ranges from 10 -15 mm and 50- 60 mm and dosages were 10, 20, 30, 40 and 50% by dry weight These shred sizes were obtained from the South Africa Tyre Recycling facility located at Atlantis, Cape Town. The large-scale direct shear box of 300 mm×300 mm square was chosen to test the selected tyre shred sizes.

CHAPTER 3 RESEARCH MATERIALS, EQUIPMENT AND METHODOLOGY

3.1 Introduction

In this chapter the research materials, equipment and the methods used in the investigation are discussed. The mechanical properties of the locally sourced sandy soils and tyre shreds from waste tyres were evaluated and the results presented in Section 3.2. The second part given in Section 3.3 details the equipment used while Section 3.4 which is the last component describes the methodology undertaken to achieve the objectives of this study.

3.2 Research materials

3.2.1 Soil characterization tests

The characterization of the soil materials was performed to assess their mechanical properties. Some of them were considered significant in the preparation of tyre shred-sand composites while the others were useful in the interpretation of the results. The types of sand selected for this study were Cape Flats and Klipheuwel sands. The evaluated properties as well as the methods used and standards followed are listed in Table 3.1.

Table 3.1: Experiments conducted to characterize soil

Property	Method	Test Standards
Natural Water Content	Oven drying	BS1377-2:1990, clause 3.2
Particle Density	Small Pyknometer method	BS1377-2:1990, clause 8.3
Maximum Dry Density	Standard Proctor Test	BS1377-4:1990, clause 3.3
Optimum Moisture Content	Standard Proctor Test	BS1377-4:1990, clause 3.3
Particle Grading of sands	Dry Sieve method	BS1377-2:1990, clause: 9.3
Shear Strength	Direct Shear method	ASTM D3080-2003

3.2.2 Soil materials

3.2.2.1 Cape Flats sand

Cape Flats sand used in the study was sourced from Philippi Quarry in the Cape Flats region of Cape Town, South Africa. It is a light grey fine graded, uniform sandy soil with a low percentage of fines. Based on the results of sieve analysis, the Unified soil classification system classified the soil in Figure 3.1 (a) as uniformly graded sand with particle sizes ranging from 0.063 mm to 1.18 mm. Kalumba (1998) described the Cape flats sand particle shape as rounded as observed under a microscope.

3.2.2.2 Klipheuwel sand

This sand was obtained from Kersfontein Quarry–Malmesbury area in Cape Town. It is reddish-brown in colour and classified according to Unified soil classification system as well graded sand with little fines. The sieve analysis showed that the soil particles ranged from 0.063 mm to 4.75 mm. In contrast to Cape Flats Sand, Klipheuwel sand particles were angular in shape (Kalumba, 1998). Both Cape Flats and Klipheuwel sands are shown in Figure 3.1 and their various properties are summarized in the Table 3.2. The detailed results from classification tests can be found in Appendix A.

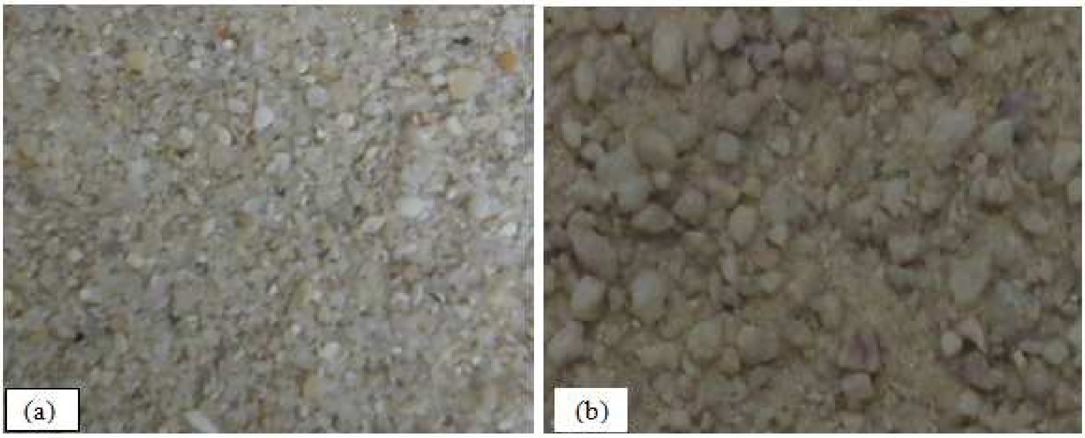


Figure 3.1: (a) Cape Flats sand (b) Klipheuwel sand

Table 3.2: Mechanical properties of the soil used in the investigation

Property	Cape Flats sand	Klipheuwel sand	Unit
	Values		
Natural moisture content	3.5	2.6	%
Specific gravity	2.62	2.62	-
Standard Proctor test results:			
— Maximum dry density	1.68	1.9	Mg/m^3
— Optimum moisture content	10.5	10	%
Vibratory compaction test results:			
— Average densest dry density	1.8	2.02	Mg/m^3
— Average loosest dry density	1.4	1.5	Mg/m^3
Particle size range	0.063 to 1.18	0.063 to 4.75	mm
Mean grain size, D_{50}	0.31	1.2	mm
Coefficient of Uniformity, C_u	1.7	7	-
Coefficient of curvature, C_c	0.95	1.5	-
Friction angle, φ	40.6	44.6	Degree
Cohesion, C	0	0	kPa

3.2.3. Tyre shreds

The tyre shreds were obtained from the South Africa Tyre Recyclers’ Factory, located in Atlantis Cape Town. The two shred sizes supplied were 10-15 mm and 50-60 mm prepared by primary and secondary shredding respectively. The primary process involved cutting waste tyres into shreds up to 50 mm, while the secondary shredder chopped the tyre shred from primary shredding into tyre particles around 15 mm. The manual separation was carried out to obtain the selected size ranging between 50-60 mm and sieve analysis for 10-15 mm tyre shreds. To obtain the smaller size, the two sieve meshes 16 mm and 9.5 mm were selected and the tyre shred particles passed through the 16 mm sieve and these retained onto the 9.5 mm sieve were taken to range between 10-15 mm.

It was difficult to obtain the single size of tyre shreds to use in this investigation. Therefore, reinforcement materials as given above were in the ranges selected from those used in previous studies and were obtained from shredding different types of tyres. The sizes of these materials are shown in Figure 3.2.

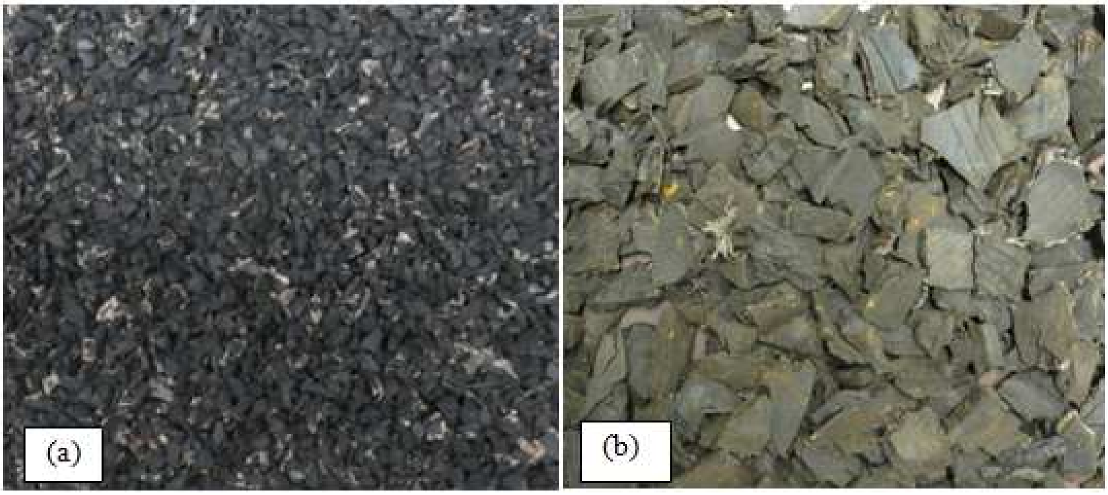


Figure 3.2: Tyre shreds (a) 10-15 mm and (b) 50-60 mm sizes

Various properties of pure tyre shred were assessed. The rubber particles used for specific gravity test passed through a 2 mm sieve and were free of steel and wires. It was decided to use the small tyre pieces because of the limited testing facilities. The BS specifications, procedure and equipment used were the same as those used for the specific gravity of the investigated sandy soils. Thus they were found to have a value of particle density of 1. This value is within 0.86 and 1.19 obtained by Baleshwar and Vianot (2009) who tested the smaller pieces. The average value of particle density for small tyre shreds was also found by Ahmed (1993) to be 1.02 and that of 50 mm tyre shreds obtained by Foose et al. (1996) was 1.21. The small variation in specific gravity can be explained by the steel belts in the long shreds. The density of tyre shreds obtained by water displacement method was 1058.5 kg/m^3 and they were found to absorb water up to 1.7%. This value is within the range of water absorption 1 and 2.5% found by Ahmed (1993) depending on the amount of exposed fibres. The friction angles found from 10-15 mm and 50-60 mm tyre shreds were 22.1^0 and 24.9^0 while the cohesions were 13.3 kPa and 19.4 kPa respectively.

3.3 Main test equipment

The shear strength of a soil material is determined using direct shear box test with various sizes of sample boxes. In the selection of the size of the box for a particular test, BS 1377-7:1990 and ASTM D3080-2003 recommend that the maximum size of sample particles must not exceed one tenth of the diameter of the sample. Therefore, due to the large size of the tyre shred material of up to 60 mm in length in this study, a large-scale direct shear box was selected for the testing regime.

According to the BS, the test was supposed to be carried out in a 600 mm square size shear box for the tested tyre shreds. But due to the limited testing facilities, the shear strength was measured using a machined brass box 305 mm square by approximately 200 mm deep, open at the top and bottom. The equipment was supplied by the Geocomp Corporation Company (www.geocomp.com). The box was horizontally divided into two halves which could be accurately fixed together by screws that passed vertically through the walls of the upper half and screwed into the lower. The box is placed in a rectangular brass container so that the bottom half of the shear box is rigidly held and prevented from moving laterally so that when a force is applied on the brass container the bottom half of the shear box slides on the upper half box attached to the ShearTrac-III frame.

The whole system as shown in Figure 3.3 is called ShearTrac-III system comprising a ShearTrac-III frame which provides and controlls vertical and horizontal loading on the sample. The vertical and horizontal loads and displacements are measured by sensors. The machine has the carriageway which houses the shear box. It has a maximum horizontal and vertical displacement of 100 mm and 90 mm respectively. Moreover the maximum capacity of the machine is 44 kN in the horizontal and vertical loading. It is capable of applying a constant rate of shear stress or displacement rate of up to 15 mm per minute, but the accurate range of the displacement rate varies from 0.00003 to 7.5 mm per minute.

The ShearTrac-III was supplied with shear software capable of running an automated direct shearing force. This software runs the test and receives the data from vertical or horizontal load and displacement sensors respectively. The shear programme collects and stores data from the test in a test file in the form of tables and graphs which can be edited to produce the new tables and graphs which are reported as the final test results.

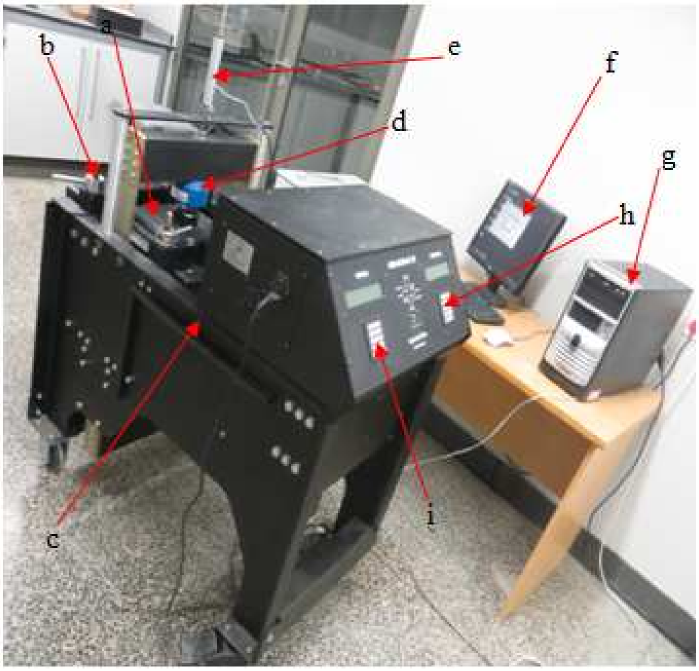


Figure 3.3: Automated large ShearTrac-III system (Various components of ShearTrac-III (a) Shear box, (b) Screws, (c) ShearTrac-III frame, (d) Vertical load cell, (f) Computer screen, (e) Vertical displacement transducer, (g) Computer monitor, (h) horizontal front panel controller and (i) Vertical front panel controllers (Geocomp Corporation, 2012)

3.4 Methodology

3.4.1 Introduction

This section presents the testing methodology undertaken in this study. Different direct shear tests were carried out on various sand tyre shred composites to assess their shear strength behaviour. Direct shear testing involved shearing a laterally restrained square soil sample along a horizontal plane. The failure occurred when the shearing resistance reached the maximum value the soil sample could sustain. For each test a set of three identical specimens were prepared and tested under three different normal pressures.

3.4.2 Sample preparation for direct shear tests

The direct shear test specimens were prepared in accordance with Section 7.5 of ASTM D3080-2003 and conducted on dried clean sand. The purpose of this was to maximize the shear strength of soil without any disturbance so that the composite can be used in unsaturated conditions. The sand was oven-dried at 105^{0}C for 24 hours to eliminate the effects of water content after which it was sealed in containers. The tyre shreds were supplied as dry material and therefore no drying was required.

3.4.2.1 Pure sand (0% tyre shreds)

The test specimen was first prepared on Klipheuwel sand. Based on its specific gravity and the volume of the shear box, a pre-estimated quantity of clean sand of about 45 kg was taken from in the container and thoroughly stirred on a tray using a scoop to produce a mixture. The two halves of shear box (Figure 4.10) were assembled using the two alignment screws and the weighed sand was poured in the assembled box. The sand was compacted in three different layers using a hand tamper having a standard weight hammer of 2.5 kg from a free fall height of 300 mm shown in Figure 3.4. Each layer was subjected to 25 tamping blows. The compacted layer boundaries were well positioned to prevent them from coinciding with the shear plane defined by the contact between the two halves of the shear box.

Figure 3.4: Hand tamper compactor

The procedure and equipment used to compact the sample in the shear box is given in ASTM 3080-2003. The standard stipulates that the test specimen can be compacted using the procedures and equipment used to determine the moisture density relationship given in ASTM D698 or D1557. These procedures were used to compact the sand material in the shear box during sample preparation. The compaction of sand was done in order to achieve the maximum dry density obtained from vibratory tests during soil characterization given in Table 3.5. The level of compaction achieved was up to 95% of the maximum dry density.

Based on the maximum dry density attained during compaction in the shear box, it was ascertained that all materials in the shear box were compacted to 95% of their maximum dry densities. The various components of the shear test are given in Figure 3.5.

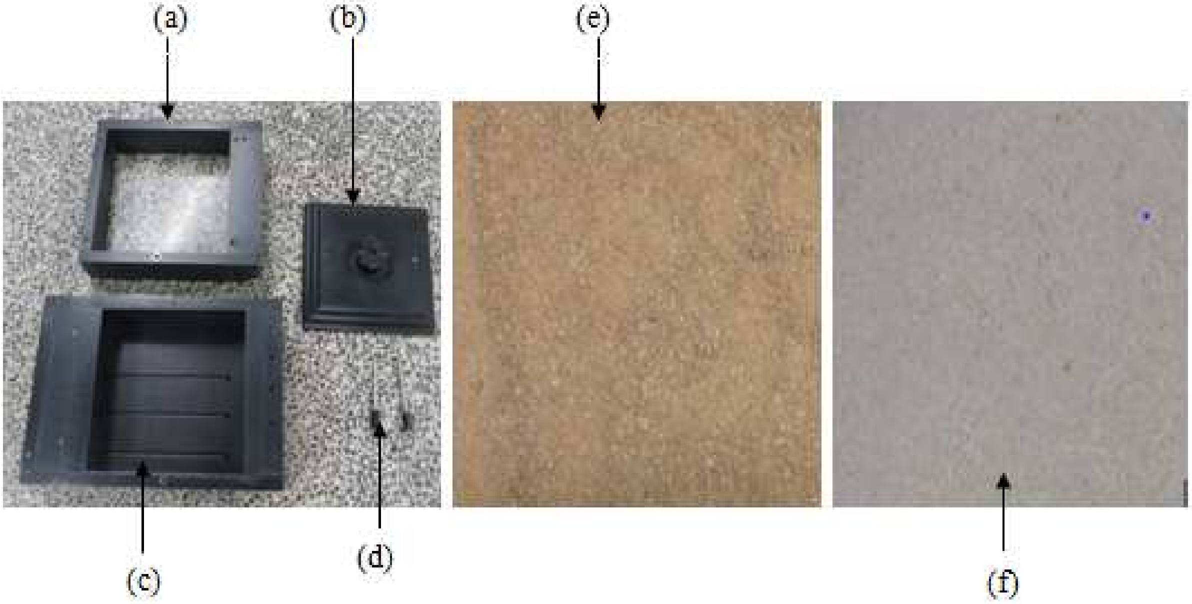


Figure 3.5: Component parts of the shear test for sand/sand: (a) top half shear box and; (b) loading plate (top cap); (c) bottom half shear box; (d) alignment screws; (e) Klipheuwel sand and (f) Cape Flats sand

After the shear box was filled with sand, a wide metal scraper was used to trim off the excess material. The sand material remaining after the test specimen preparation was weighed and subtracted from the total to get the compacted material in the shear box prior to the determination of the density achieved given in Table 4.3. A top cap was placed on top of the well-levelled sand surface for the purpose of spreading the applied normal pressure on the sample during the shear test.

A sample was also prepared for the pre-dried clean Cape Flats sand. The quantity of sand material was estimated and the procedure for sample preparation as for Klipheuwel sand was repeated. For each type of sand, three similar samples were prepared and tested at three different normal applied pressures of 50, 100 and 200 kPa. The compacted test specimen in the shear box is shown in Figure 3.6.

Figure 3.6: Prepared test specimen in shear box for pure sand (a) Klipheuwel sand, (b) Cape Flats sand and (c) the sealed sample in the shear box with top cap

3.4.2.2 Pure tyre shred (100%)

The pure tyre shreds were tested to evaluate their shear strength properties. These pieces comprised of the mixture of shreds from car tyres and truck tyres. Test specimens were prepared for 50-60 mm as well as 10-15 mm tyre shred sizes. The quantity of tyre shred to fill the shear box was estimated first for 50-60 mm shred lengths based on their particle density of a 1.21 (Foose et al., 1996) and a value of 20 kg tyre shreds was obtained. Since tyre shreds were varying in sizes, mixing these materials was required and was performed manually on a tray using a scoop after which they were placed in the direct shear box in three layers and each layer was compacted. The prepared sample in the shear box is given in Figure 3.7 (a).

The same estimate was carried out on 10-15 mm tyre shreds and the amount of 20 kg dry material was obtained. Tyre shreds taken from the container were thoroughly stirred on the tray and carefully poured into the shear box in three equal increments and compacted in the same manner as given above.

In contrast to pure sand, compacting pure tyre shred in the shear box was insignificant. Three samples were prepared to be tested at three selected vertical confining pressures. The prepared sample is shown in Figure 3.7 (b).

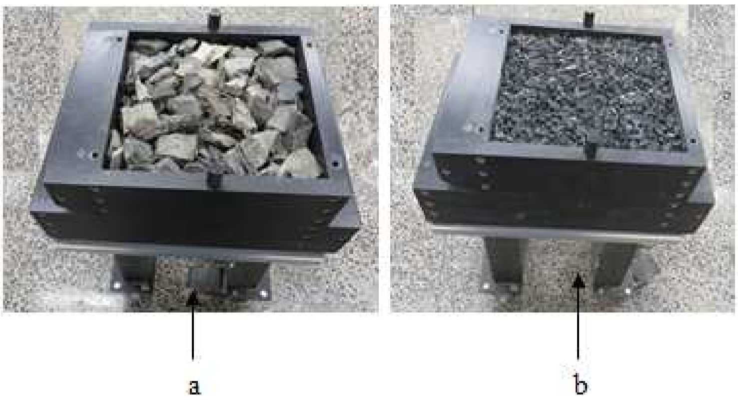


Figure 3.7: Sample preparation in the shear box for (a) 50-60 mm tyre shred and (b) 10-50 mm tyre shreds

3.4.2.3 Sand-tyre shred composite

Mix design

Before preparing the sample of any mixture it is crucial to compute the quantities required for the mixing. The equation (3) below was thus adopted during the preparation of the mixture.

$W_{ts}= \chi.W_{tsc}$ ………………………………………………(3)

Where

W_{ts}: the weight of tyre shred; χ: the concentration of tyre shreds in the mixture

W_{tsc}: the weight of tyre shred sand composite.

The concentrations of tyre shreds considered in this study were 10, 20, 30, 40 and 50 % by dry weight. Each percentage of tyre shred content was considered independently during sample preparation. The shape of tyre shreds was not considered in this study and their thickness was not uniform because of the variability in wear of the waste tyres.

Before mixing, the quantity of tyre shreds to be combined with sand was predetermined. Therefore the concentration of 10% tyre shred by dry mass was first considered for Klipheuwel sand and the size of tyre shreds was 50-60 mm. The total quantity of sand to fill the shear box was estimated following the similar procedure used in pure sand quantity calculations and 10% tyre shreds by dry mass of that sand was computed using equation (3). The weight of sand equivalent to shreds was replaced by the weight of tyre shreds. After all the necessary calculation, the quantity of each sand and tyre shreds to be used were taken from the containers and weighed using a high precision electronic scale after which they were thoroughly mixed on a tray using a scoop to obtain a well mixed sample. Care was taken during mixing to preclude the segregation of tyre shreds and sand.

The two halves shear box were assembled on the standing table using the alignment screws and the tyre shreds sand composite was carefully transferred into the box in layers. It was decided to compact tyre shred-sand composite in three layers to ensure that all the material in shear box received the same energy. Tyre shreds in the shear zone took various positions i.e. vertical, horizontal and inclined. This is evident because the thickness of the single layer was greater than the length of the longest tyre shreds. Each layer was compacted using the similar equipment used in the preparation of the pure sand sample and received the same number of blows equal to 25. The volume of the specimen in the shear box was determined and consequently its mass and then the density achieved was calculated.

Calculations based on 10% tyre shreds content were repeated for 20, 30, 40 and 50% tyre shreds content. For each mixing ratio the sample was prepared following the procedure adopted in the preparation of the test specimen for the concentration of 10% tyre shreds in the mixture.

Tests specimens were also prepared on mixtures containing Cape Flats sand and 50-60 mm tyre shred. The estimates for the quantities to be mixed were done for all the considered shred dosages. Both sand and tyre shreds were taken from the covered containers where they were stored and were blended on the tray to generate the homogeneous mixtures. The same concentrations of tyre shreds used in the preparation of tyre shreds sand composites for Klipheuwel sand were considered to evaluate the optimum percentage of tyre shred content which maximized the shear strength of Cape Flats sand. The test specimens in the shear box are shown in Figure 3.8.

Figure 3.8: Prepared test specimen in shear box for (a) Cape Flats and (b) Klipheuwel sand-shreds mixtures for 50-60 mm tyre shreds

Tyre shreds sand composite was prepared for 10-15 mm shreds size. Therefore the computation was performed to estimate the required material for sand and tyre shreds followed by mixing these quantities. Test specimens were then prepared for 10, 20, 30, 40 and 50% tyre shreds content by dry mass using the same equipment and following the procedures used to prepare the tyre shred sand composite contained 50-60 mm shreds size. The test specimens in the shear box are shown in Figure in Figure 3.9.

Figure 3.9: Prepared test specimen in shear box for (a) Cape Flats and (b) Klipheuwel sand -shred mixtures for 10-15 mm tyre shreds

3.4.3 Assembly of the apparatus

The machine was first switched on to allow the assemblage, then the shear box containing the specimen was pushed in the testing machine bed with the help of the horizontal loading system. Here, it was well positioned and tightened to the ShearTrac-III frame using various screws. The cross bar was lowered on the shear box by the vertical loading system to make careful contact between the vertical load cell and the stainless steel ball resting symmetrically on the top cap. All the necessary connections including sensors for vertical and horizontal loads and displacements were checked to allow data measurement and recording.

3.4.4 Direct shear testing (procedures)

All the required information for the test such as normal applied pressure, shear displacement rate, maximum displacement for the test, displacement interval, minimum time for consolidation were typed into the shear program (software). Shear stress was applied by maintaining a constant displacement rate of 1.3 mm/min and the maximum displacement of 50 mm was set for each test. This value of shear rate was obtained from Foose et al. (1996) for shearing tyre shreds sand mixtures. After setting the test conditions, a template file was created before running the test to store the generated data. An example of the screen shot from software is shown in Figure 3.10.

The direct shear testing was undertaken in accordance with ASTM D3080-2003. Therefore according to the ShearTrac-III machine supplier based on the said standard, the first phase of direct shear test was the consolidation by applying normal confining pressure on the sample using the vertical loading system via a vertical load cell. It was followed by the shearing phase by which a controlled constant rate of displacement to move the bottom half shear box sliding on the top fixed box was applied. Before the shear phase was commenced, the alignment screws were removed and a suitable gap ensured. This gap was controlled by the gap screws.

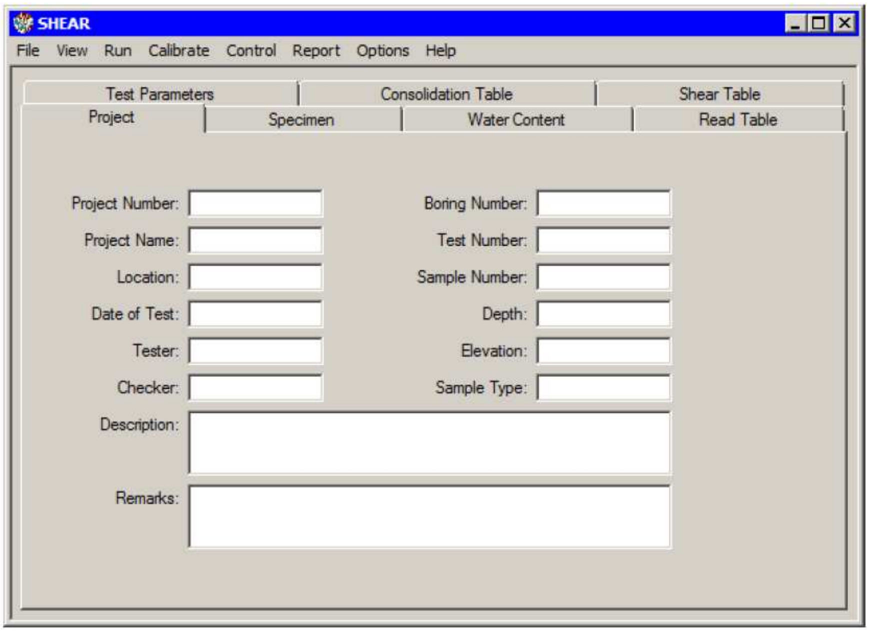


Figure 3.10: Shear control window

After the shearing had been completed, the horizontal and vertical loads were zeroed. The removal of the horizontal (shear) load from the sample was assisted by the horizontal loading system composed by motor and worm gear, whereas vertical loading was removed with the help of vertical loading system (motor combined with worm gear). The vertical load cell and cross bar were raised to facilitate the removal of the shear box from the shear box housing unit (water bath). The screws were loosened and removed, then the shear box was extracted from the ShearTrac-III machine and the sample was removed from the box after which the box was cleaned and dried prior to the preparation of the next test specimen. All steps were repeated for 75 tests performed in this study. The shear strength test in operationis shown in Figure 3.11.

Figure 3.11: Shear strength test in progress

3.4.5 Direct shear testing programme

A total of 75 tests were conducted in this investigation. As indicated by the test numbers in Table 3.3 below, three tests were conducted on both pure Cape Flats and Klipheuwel sands, six on only tyre shreds alone, thirty on Cape Flats sand-tyre shreds mixture, thirty on Klipheuwel sand-tyre shred mixture and three replicate tests performed on 30% tyre shred content mixed with Cape Flats sand. All the specimens were compacted to 95% during sample preparation.

Table 3.3: Direct shear test programme for Klipheuwel sand-tyre shred mixtures

Test	Research material			Test number	Normal pressure (kPa)
	Sand (S)	Tyre shreds (T)			
		Tyre size (mm)	Tyre shreds (%)		
Sand-Sand (SS)	Klipheuwel (K)	-	-	SS/K50	50
				SS/K100	100
				SS /K200	200
Sand-Tyre (ST)	Klipheuwel (K)	10-15	10	ST /10-15/10/K50	50
				ST /10-15/10/K100	100
				ST 10-15/10/K200	200
			20	ST /10-15/20/K50	50
				ST /10-15/20/K100	100
				ST/10-15/20/K200	200
			30	ST /10-15/30/K50	50
				ST /10-15/30/K100	100
				ST /10-15/30/K200	200
			40	ST /10-15/40/K50	50
				ST /10-15/40/K100	100
				ST /10-15/40/K200	200
			50	ST/10-15/50/K50	50
				ST/10-15/50/K100	100
				ST /10-15/50/K200	200
Tyre-Tyre (TT)	-	10-15	100	ST/10-15/100/C50	50
				ST/10-15/100/C100	100
				ST/10-15/100/C200	200
Sand-Tyre (ST)	Klipheuwel (K)	50-60	10	ST/50-60/10/K50	50
				ST/50-60/10/K100	100
				ST/50-60/10/K200	200
			20	ST/50-60/20/K50	50
				ST/50-60/20/K100	100
				ST/50-60/20/K200	200
			30	ST/50-60/30/K50	50
				ST/50-60/30/K100	100
				ST/50-60/30/K200	200
			40	ST/50-60/40/K50	50
				ST/50-60/40/K100	100
				ST/50-60/40/K200	200
			50	ST/50-60/50/K50	50
				ST/50-60/50/K100	100
				ST/50-60/50/K200	200
Tyre-Tyre (TT)	-	50-60	100	TT/50-60/100/C50	50
				TT/50-60/100/C100	100
				TT/50-60/100/C200	200

Table 3.4: Direct shear test programme for Cape Flats sand-tyre shred mixtures

Test	Research material			Test number	Normal pressure (kPa)
		Tyre shreds (T)			
	Sand (S)	Tyre size (mm)	Tyre shreds (%)		
Sand-Sand (SS)	Cape Flats (C)	-	-	SS/C25	50
				SS/C50	100
				SS/C100	200
Sand-Tyre (ST)	Cape Flats (C)	10-15	10	ST/10-15/10/C50	50
				ST/10-15/10/C100	100
				ST/10-15/10/C200	200
			20	ST/10-15/20/C50	50
				ST/10-15/20/C100	100
				ST/10-15/20/C200	200
			30	ST/10-15/30/C50	50
				ST/10-15/30/C100	100
				ST/10-15/30/C200	200
			40	ST/10-15/40/C50	50
				ST/10-15/40/C100	100
				ST/10-15/40/C200	200
			50	ST/10-15/50/C50	50
				ST/10-15/50/C100	100
				ST/10-15/50/C200	200
Tyre-Tyre (TT)	-	10-15	100	ST/10-15/100/C50	50
				ST/10-15/100/C100	100
				ST/10-15/100/C200	200
Sand-Tyre (ST)	Cape Flats (C)	50-60	10	ST/50-60/10/C50	50
				ST/50-60/10/C100	100
				ST/50-60/10/C200	200
			20	ST/50-60/20/C50	50
				ST/50-60/20/C100	100
				ST/50-60/20/C200	200
			30	ST/50-60/30/C50	50
				ST/50-60/30/C100	100
				ST/50-60/30/C200	200
			40	ST/50-60/40/C50	50
				ST/50-60/40/C100	100
				ST/50-60/40/C200	200
			50	ST/50-60/50/C50	50
				ST/50-60/50/C100	100
				ST/50-60/50/C200	200

3.4.6 Reproducibility of the data

It is crucial to produce repeatable results before carrying out any experimental works to warrant that the methods and procedures can be adopted for any investigation. In this study one vertical confining pressure of 50 kPa was selected and the three similar test specimens were prepared considering a concentration of 30% tyre shreds by dry mass in the mixture, 10-15mm tyre shred size and Cape Flats sand. The materials were thoroughly mixed to produce a homogeneous mixture, thereafter they were carefully placed in the assembled shear box and compacted using the equipment and following the method given in subsection 4.4.2 for the preparation of the test specimen for tyre shred-sand mixture. The procedures followed to run these tests were exactly the same as those given in subsection 4.4.4. The results obtained are presented and discussed in Chapter 6.

3.4.7 Data processing

Normal stress (σ_n): is defined as the vertical applied pressure on a sample and can be calculated by the following equation:

$$\sigma_n = \frac{N}{A} \qquad \text{………………………………………….. (4)}$$

N: Normal force (kN)
A: contact area which is constant throughout the test (m^2)

Shear stress (τ): Shear stress as generated automatically by the machine acts parallel to the plane being considered, and develops when applied forces tend to activate resisting forces in the tyre shred sand composite. It can be computed by the following equation:

$$\tau = \frac{F}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

F: shearing force applied to one half of the sample in a horizontal direction while the other is restrained by the screws tightening it to ShearTrac-III frame, (kN);
A: shear contact area which is the same as above (m^2).

All data were processed by ShearTrac-III software. After the test had been completed, the data from the created template file in the form of tables and figures were downloaded and the results from tables such as shear stresses, vertical and horizontal displacements were transferred into an Excel sheet where they were edited and the new graphs of shear stress versus horizontal displacement similar to those generated by ShearTrac-III software were plotted. An example of these results is given in Appendix B. All findings obtained from this investigation are presented, analyzed and discussed in Chapter 4.

CHAPTER 4 RESULTS, ANALYSIS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses all the results generated from direct shear tests from unreinforced Cape Flats and Klipheuwel sands as well as sand-tyre shred composites. It is divided into three sections: The first Section presents the evidence of repeatability while the second Section discusses the results of direct shear tests for a range of shred size mixed with sand at different dosage and the densities achieved during preparation of test specimens. The comparison of these is given in the Section three.

4.2 Repeatability of the results

Figure 4.1 shows the results of the three replicate test specimens composed of 10-15 mm tyre shred-Cape Flats sand mixture considering 30% tyre shred content by dry weight and tested at 50 kPa. The peak shear stress ranged from 60.8 kPa to 61.2 kPa with an average of 61 kPa. Therefore all the tests peaked almost at the same horizontal displacement and have the same maximum shear stress. Experiments 1, 2 and 3 exhibited the maximum shear stresses of 60.8 kPa, 61.2 kPa and 60.8 kPa respectively and peaked at horizontal displacements of 11 mm, 11.11 mm and 10.9 mm respectively. Based on these results, it was confirmed that the methods and procedures used to run the shear strength tests generated repeatable results.

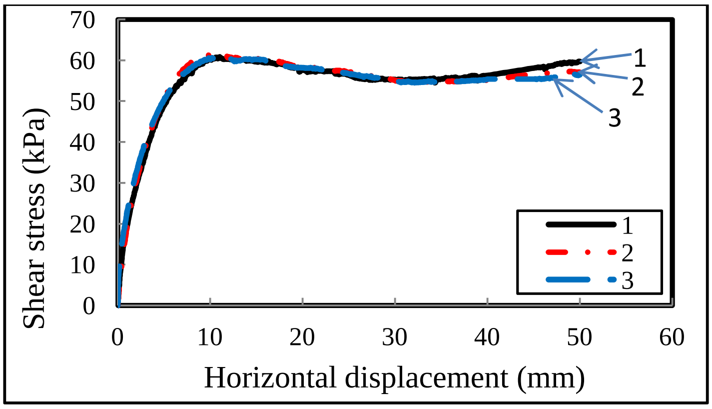


Figure 4.1: Repeatable results for three samples tested at 50 kPa

4.3 Direct shear test results of tyre shred sand mixtures

4.3.1 Shear stress horizontal displacement relationship

The relationship between shear stress and horizontal displacement for all conducted tests is shown in Figures (4.2- 4.5). Various graphs were plotted were from the data obtained from the tested Cape Flats and Klipheuwel sands reinforced with tyre shred. The concentrations of tyre shreds ranging from 10 to 50% by dry weight with an increment of 10% were considered. The composite materials, unreinforced sand (0%), and pure tyre shreds (100%) were tested at three different normal pressures of 50 kPa, 100 kPa and 200 kPa.

4.3.1.1 Shear stress-displacement response for 10-15 mm tyre shreds

Figure 4.2 (a to g) and Figure 4.3 (a to f) present the results from tyre shreds with Cape Flats sand and Klipheuwel sand composites. At all applied stresses the maximum shear stresses were recorded and presented in Table 4.1.

The shear stress development from unreinforced sands was first analyzed. It was seen from Figure 4.2 (a) and Figure 4.3 (a) (0% tyre shreds content) that Klipheuwel sand exhibited higher shear stress than Cape Flats sand. This was due to the fact that Klipheuwel sand is well-graded sand with a little fine and gravel whereas Cape Flats Sand was found to be uniformly distributed sand ranging from medium to fine. From grading curves Klipheuwel sand had a coefficient of uniformity (C_u=7) and Cape Flats sand (C_u=1.7). The results suggested that there is possibly better interlocking between Klipheuwel sand particles compared to that in Cape Flats sand which increased the shear resistance in the shear plane.

It is clear from the figures for unreinforced sand and in Table 4.1 that the increased applied vertical confining pressures resulted in the expected maximum shear stress and all the graphs showed a pronounced peak. It is possible that the increased vertical stress contributed to the increased degree of contact between sand particles, which in turn increased the shear resistance within the shear plane.

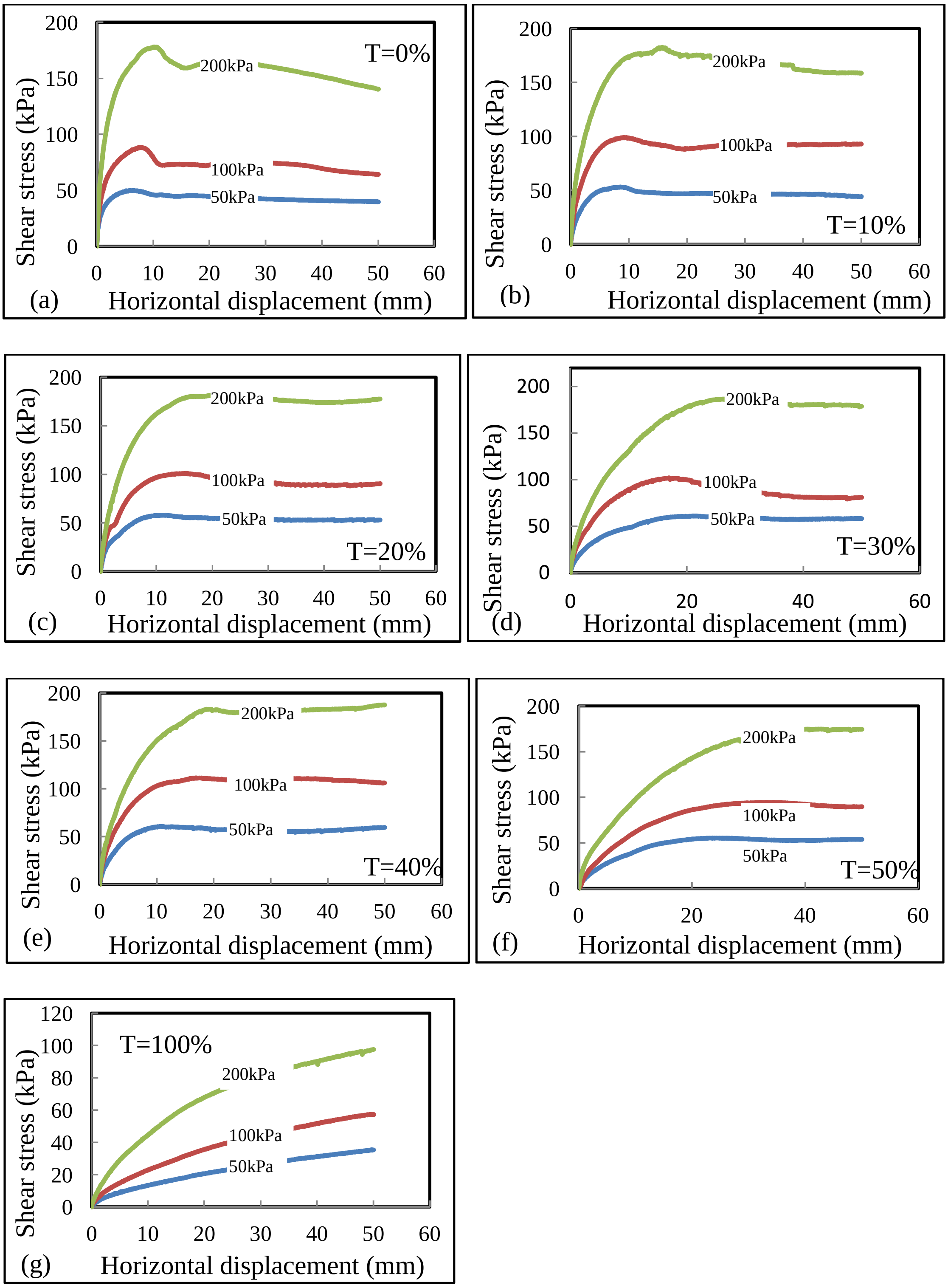


Figure 4.2: Shear stress versus horizontal displacement for Cape Flats mixed with tyre shred size of 10-15 mm at tyre shred content of (a) unreinforced sand (0%), (b) 10, (c) 20, (d) 30, (e) 40 and (f) 50% by dry weight as well as (g) pure tyre shreds (100%).

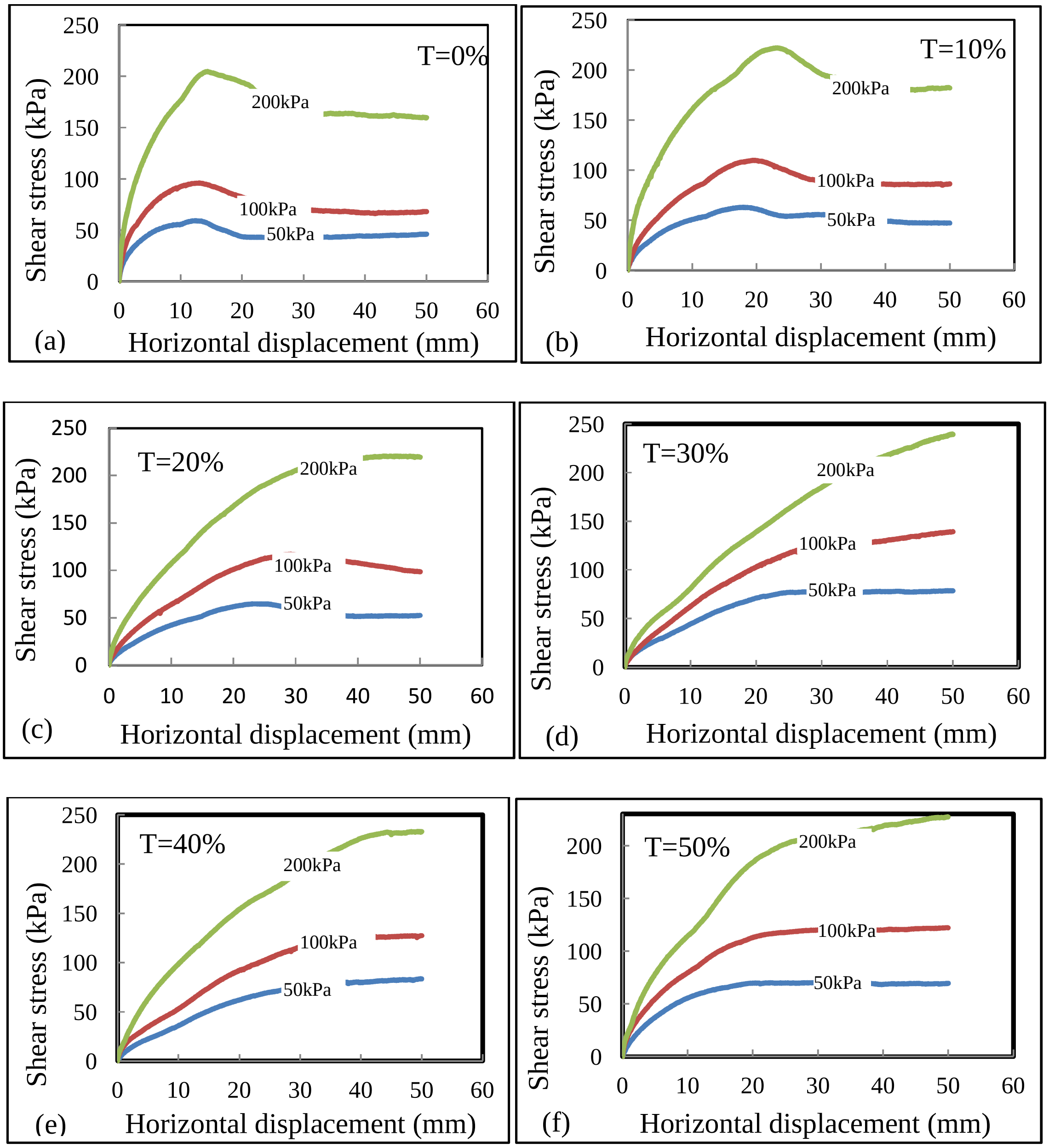


Figure 4.3: Shear stress versus horizontal displacement and vertical displacement against horizontal displacement for Klipheuwel sand mixed with tyre shred of the size 10-15 mm at tyre shreds content of (a) unreinforced sand (0%), (b) 10, (c) 20, (d) 30, (e) 40 and (f) 50% by dry weight.

Table 4.1: Peak shear stresses for 10-15 mm tyre shreds

% shreds	Peak shear stresses (kPa)					
	Cape Flats Sand			Klipheuwel Sand		
	50 kPa	100 kPa	200 kPa	50 kPa	100 kPa	200 kPa
0	49.9	88.5	177.8	59	96	204.7
10	53.2	98.9	182.6	62.9	109.8	221.8
20	57.8	100.8	181.8	63.1	111.7	216.1
30	61.1	101.9	185.9	64.7	117	220.7
40	60.8	102.6	183	65.1	108.2	205.7
50	55.3	94.5	174.9	57.9	98.8	179.2
100	33.1	54.8	94.4	33.1	54.8	94.4

The shear stress of sand was found to be influenced by the amount of tyre shreds added to sand. Generally the addition of shreds to both Cape Flats and Klipheuwel sands improved their maximum shear stress up to an optimum dosage beyond which it decreased.

Specifically, the Cape Flats sand reinforced with 10% tyre shred by dry weight showed an improvement in its shear stresses and varied also as applied normal pressures changed. The maximum shear stresses changed from 49.9 kPa to 53.2 kPa for unreinforced and reinforced sand respectively.

The continuous increase in the amount of tyre shreds in the composite resulted in a better degree of strengthening. This is evident when the maximum shear resistance of 57.8 kPa was obtained from the composite containing 20% tyre shreds and Cape Flats sand tested at the applied normal pressure of 50 kPa compared to that from 10% which was 53.2 kPa. All the maximum values of shear stresses from all tyre shred-sand composites are given in Table 4.1 for more comparison.

Some of the maximum shear stresses were obtained as the peak values. These stresses are presented as graphs in Figure 4.2 (b & c) and Figure 4.3 (b) for all normal stresses, 4.2 (d & e) and 4.3 (c) for 50 and 100 kPa vertical confining pressures respectively. Other curves in these figures did not show a pronounced peak which can be referred to as stress-hardening behaviour.

In these cases ASTM D3080-2003 standard recommends the failure to occur at the shear strain between 15 and 20%. In this study all the peak shear stress occurred at a horizontal displacement less than 40 mm. However, for the ‘no peaked’ graphs the failure was taken to correspond to 15% shear strain which corresponded to the displacement of 45 mm. These are shown in Figure 4.2 (f & g); Figure 4.2 (d & e) and 4.3 (c) for 200 kPa; Figure 4.3 (d, e & f) for all applied normal pressures.

It can be noted by increasing the tyre shreds content in the mixture, a high shear displacement was required to mobilize the peak shear stress. In all concentrations of tyre shred, the optimum tyre shred content for all applied normal pressures which gave the maximum shear stress was 30%. The same trend was observed for tyre shred-Klipheuwel sand composite and the optimum dosage was identical. Furthermore, the increased tyre shred content and normal loading enhanced the degree of interlock within the sample which contributed to the improved peak shear stress of the composite.

4.3.1.2 Shear stress-displacement response for 50-60mm tyre shreds

As with the 10-15mm tyre shreds, both Cape Flats and Klipheuwel sands were mixed with 50-60 mm tyre shreds. Pure tyre shreds and the concentrations such as 10, 20, 30, 40 and 50% were investigated and the results obtained for various applied normal pressures are depicted in Figure 4.4 (a) to (f) for Cape Flats and Figure 4.5 (a) to (e) for Klipheuwel sand.

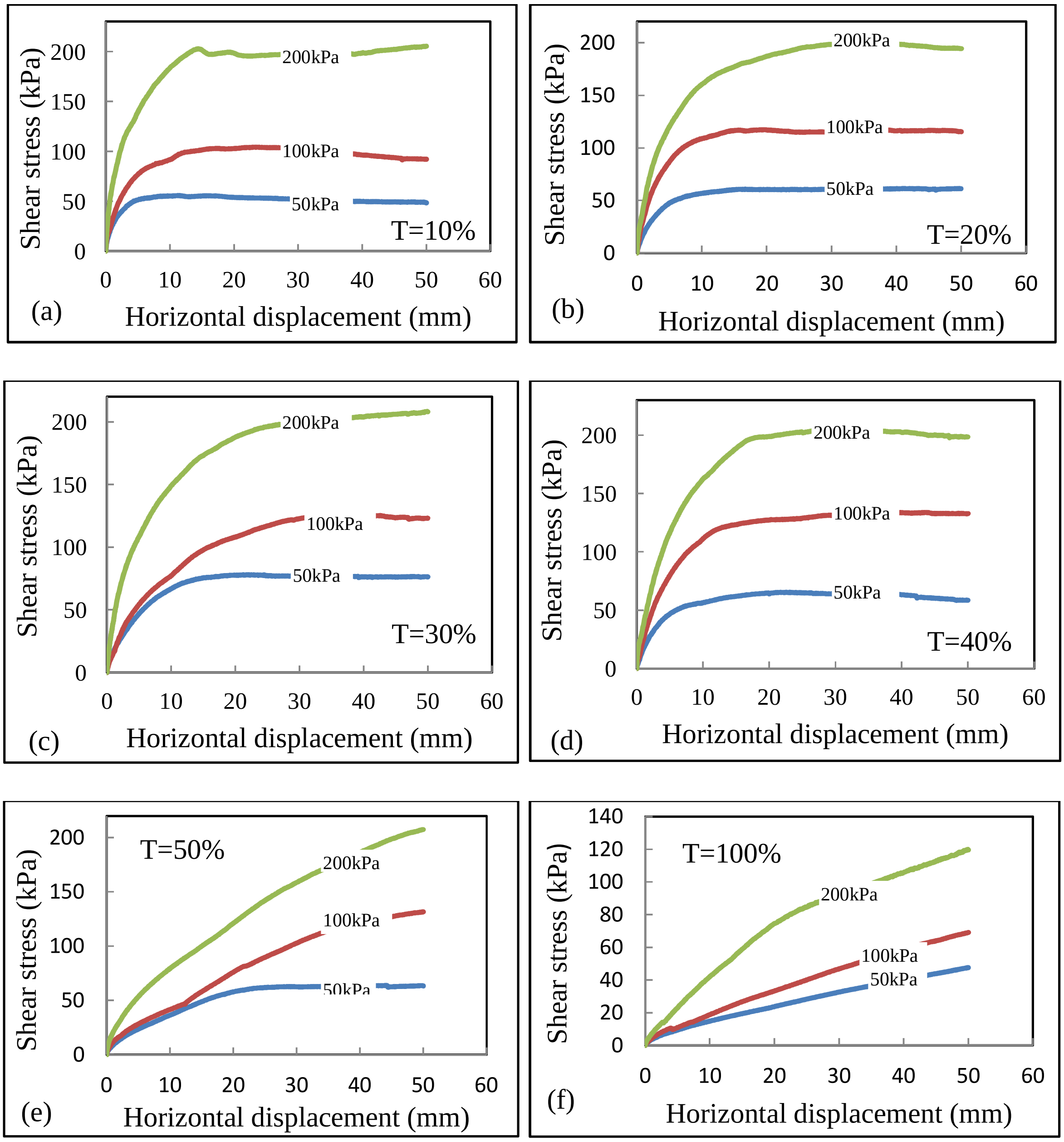


Figure 4.4: Shear stress versus horizontal displacement for Cape Flats sand mixed with tyre shred of the size 50-60 mm at tyre shreds content of (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50% by dry weight as well as (f) pure tyre shreds (100%)

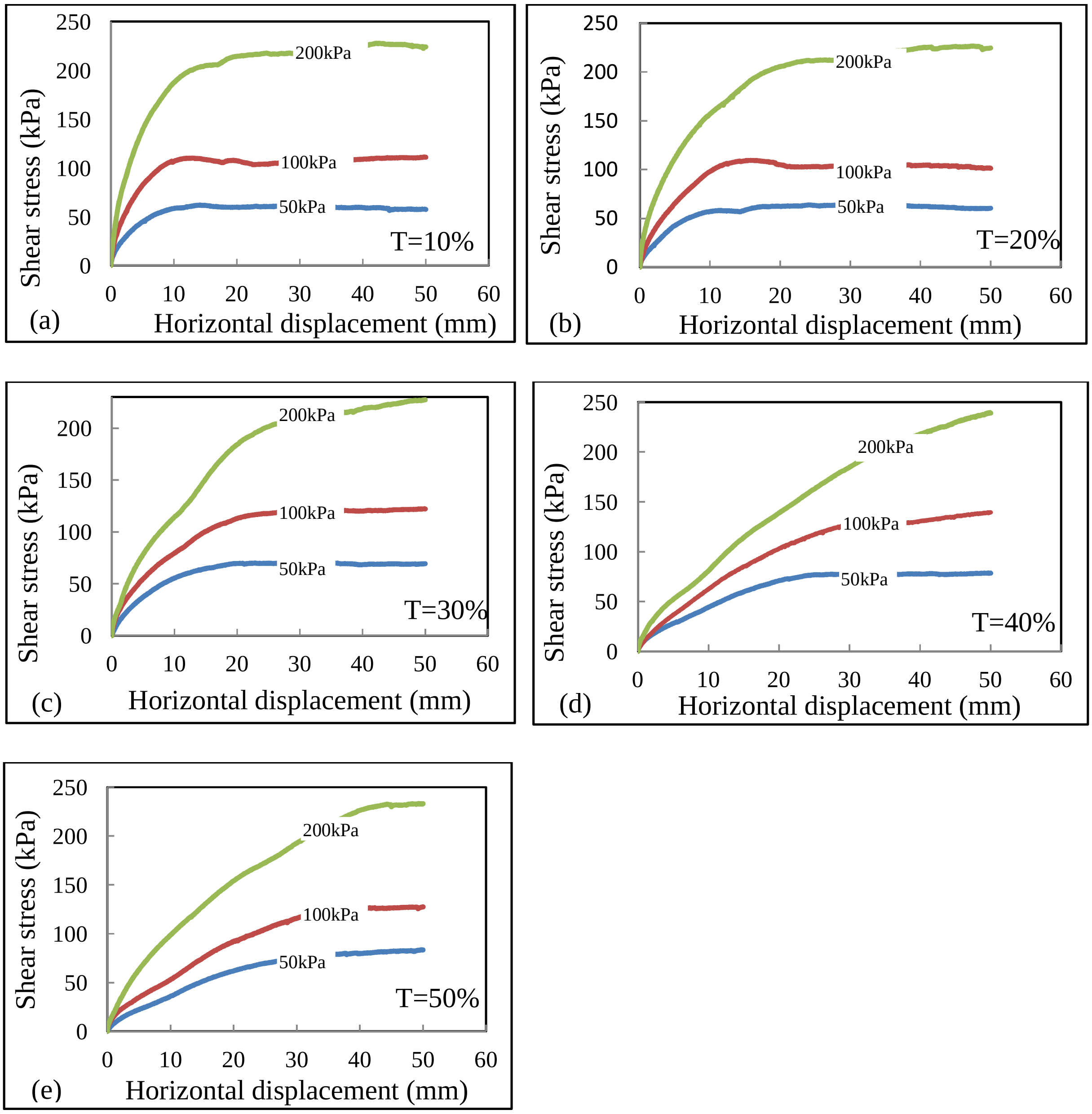


Figure 4.5: Shear stress versus horizontal displacement for Klipheuwel sand mixed with tyre shred of the size 50-60 mm at tyre shreds content of (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50% by dry weight.

Table 4.2: Maximum shear stresses for 50-60 mm tyre shreds

	Peak shear stresses (kPa)					
	Cape Flats			Klipheuwel		
% shreds	50	100	200	50	100	200
0	49.9	88.5	177.8	59.1	96	204.7
10	55.6	104.1	202.8	61.9	110	227.7
20	60.8	117	199.6	63.9	109.6	226.2
30	77.9	125.8	208.9	77.6	135.3	230
40	65.2	133.6	205.9	81.8	126.4	229.9
50	62.5	127.2	198.6	72	121.2	219
100	43.9	64.1	112.9	43.9	64.1	112.9

As observed in tyre shred-sand composites containing 10-15 mm tyre shreds, the addition of long tyre pieces to sand enhanced its shear stress. The degree of enhancement was increasing continuously reaching its maximum value as the amount of tyre shred increased up to its optimum beyond which no more increase in shear resistance was observed. These maximum shear stresses and optimum shred dosages for each applied normal pressures can be seen in Table 4.2.

The shear stress development for long tyre shreds was analyzed in comparison to that observed in small size tyre shreds sand composite. The findings presented in Table (4.1 & 4.2) showed that the shear stress development from 50-60 mm tyre shred-sand mixture is higher compared to that observed from 10-15 mm tyre shred-sand samples for the two types of sand. It can be explained that the difference in improvement was due to the long tyre shreds which had the larger contact area with sand. These long randomly distributed tyre shreds in sand acted as anchors in the shear zone and thus increased the shear resistance compared to small tyre shreds.

Examples of shear stress improvement from unreinforced sand and shreds dosage of 10, 20, 30 and 40% in Cape Flats sand at a vertical pressure of 50 kPa were 49.9 kPa, 55.6 kPa, 60.8 kPa, 77. 9 kPa and 65.2 kPa respectively. The same trend was observed in tyre shred-Klipheuwel sand composite. For more comparison, the peak shear stresses obtained from this particular size of shreds are given in Table 4.2.

The results from some experiments showed peak values in their graphs. These can be seen in Figure 4.4 (a & b) and 4.5 (a) for all vertical stresses; Figure 4.4 (c & d) and Figure 4.5 (b) for 50 and 100 kPa. However, the graphs showed stress hardening behaviour compared to those from small tyre shreds sand mixtures. The non peaked graphs for composites comprising Cape Flats sand are given in Figure 4.4 (c & d) for 200 kPa and Figure 4.4 (e & f) for all applied normal pressures. Furthermore the graphs with non-pronounced peak (stress hardening behaviour) for Klipheuwel sand are given in Figure 4.5 (b) for 200 kPa and Figure 4.5 (c, d & e) for all vertical stresses.

The observed stress hardening behaviour can be attributed to the densification of the test specimens during shearing caused by the interlocking between tyre shreds-sand or tyre shreds-tyre shreds particles as well as the applied normal pressure. Moreover, a high shear displacement especially for high concentration of tyre shreds was required to mobilize the peak shear stress compared to that of test specimens that contained 10-15 mm tyre shred. In most cases the optimum tyre shreds content which gave the maximum shear stress for all vertical confining pressures was 30%.

In all tyre shreds sand composite comprising either 10-15 mm or 50-60 mm tyre shreds, it was thought that the random inclusion of tyre shreds in sand took the various positions in the shear zone such as vertical and inclined which contributed to shear reinforcement mechanism, thus increasing the maximum resistance of sand during shear testing. This mechanism was explained by (Gray et al., 1986).

4.3.2 Vertical deformation horizontal displacement relationship

During shear testing the vertical deformations of the test specimens were recorded. These deformations described as vertical displacements are plotted against horizontal displacements in Figure (4.6 - 4.9). It is apparent from these figures that the dilatant behaviour is higher than the contractive behavior for unreinforced sand specimens and a fully contractive for the pure tyre shreds sample while tyre shred-sand composites presented intermediate response between these two.

As shown in Figure 4.6 (a) and Figure 4.7 (a), unreinforced sand (0%) exhibited a small amount of contraction at a short horizontal displacement followed by a high dilation. The amount of contraction and dilation depended only on applied normal pressure for unreinforced sand. It can be seen from 4.6 (a) and Figure 4.7 (a) that the contraction increased as vertical confining pressure increased which reduced the sample dilation.

For tyre-shred sand composites, the vertical deformation depended on both applied normal pressure and the dosage of tyre shreds in the mixture. It was observed from Figures (4.6; 4.7; 4.8 and 4.9) that the increased tyre shred content and normal pressure increased the contractive behaviour and reduced the dilatant behaviour of the test specimen. The pure tyre shred samples (100%) in Figure 4.6 (g) and Figure 4.8 (f) for 10-15 mm and 50-60 mm tyre shred size respectively exhibited a fully contractive behaviour at all applied normal pressures.

It can be noted that anomalies in vertical deformation were observed particularly in Figure 4.6 (b, c and d) and Figure 4.8 (a) which exhibited the high dilation at 100 kPa compared to that of 50 kPa and Figure 4.7 (f) which showed almost identical contractive behaviour at both 100 and 200 kPa vertical confining pressures.

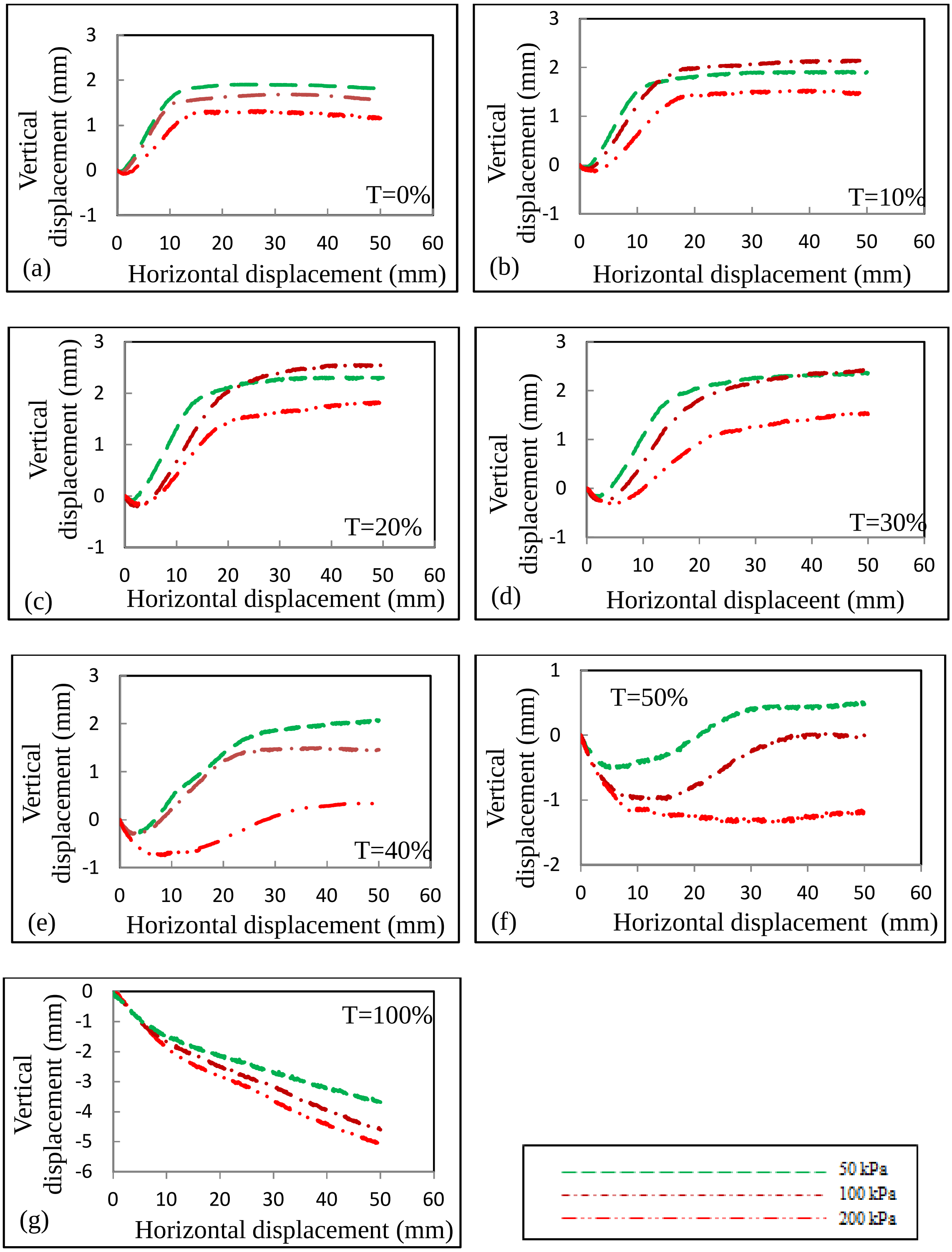


Figure 4.6: Vertical displacement versus horizontal displacement for 10-15 mm tyre shreds in Cape Flats sand (a, b, c, d, e, f and g).

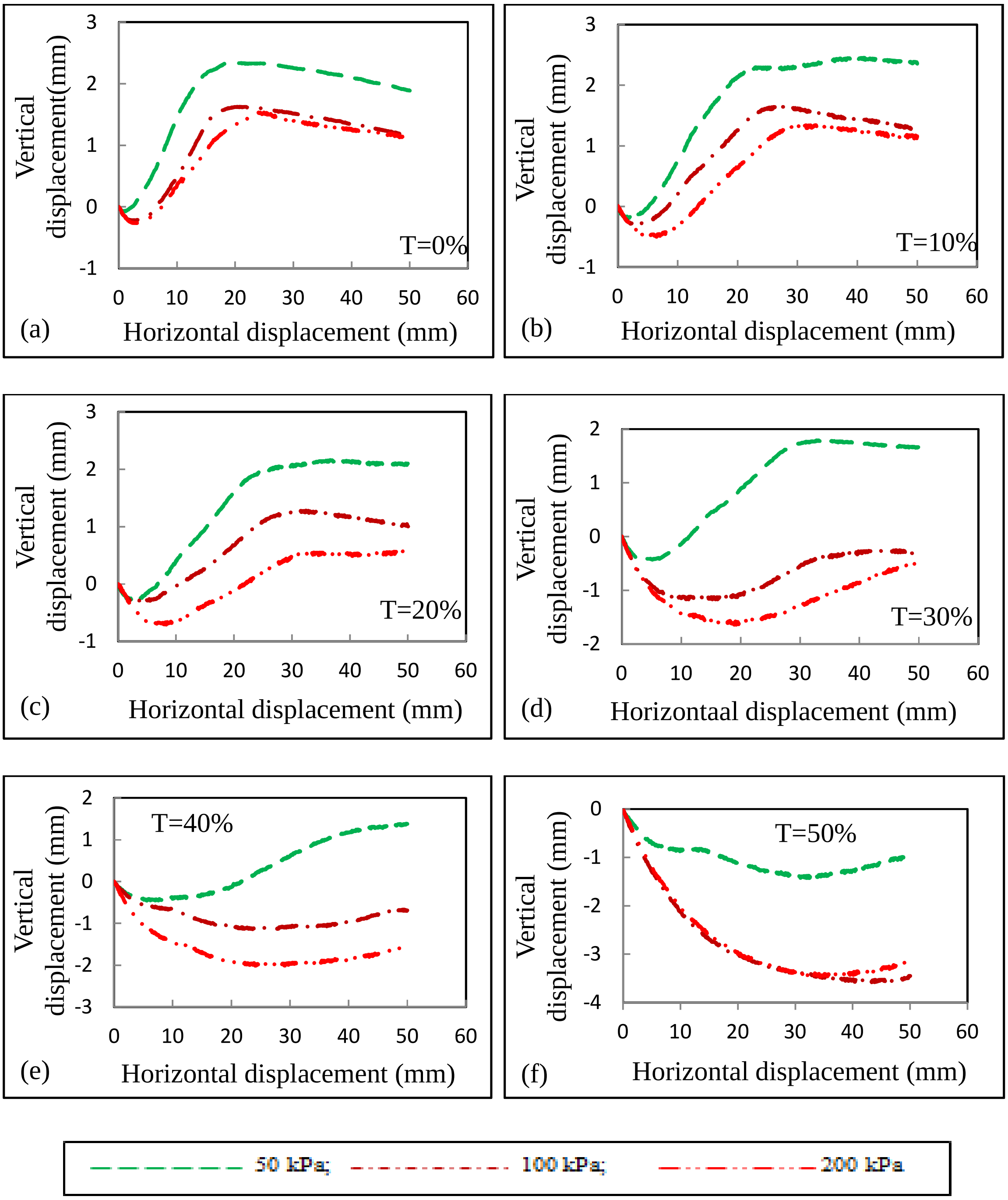


Figure 4.7: Vertical displacement versus horizontal displacement for 10-15 mm tyre shreds in Klipheuwel sand (a, b, c, d, e and f)

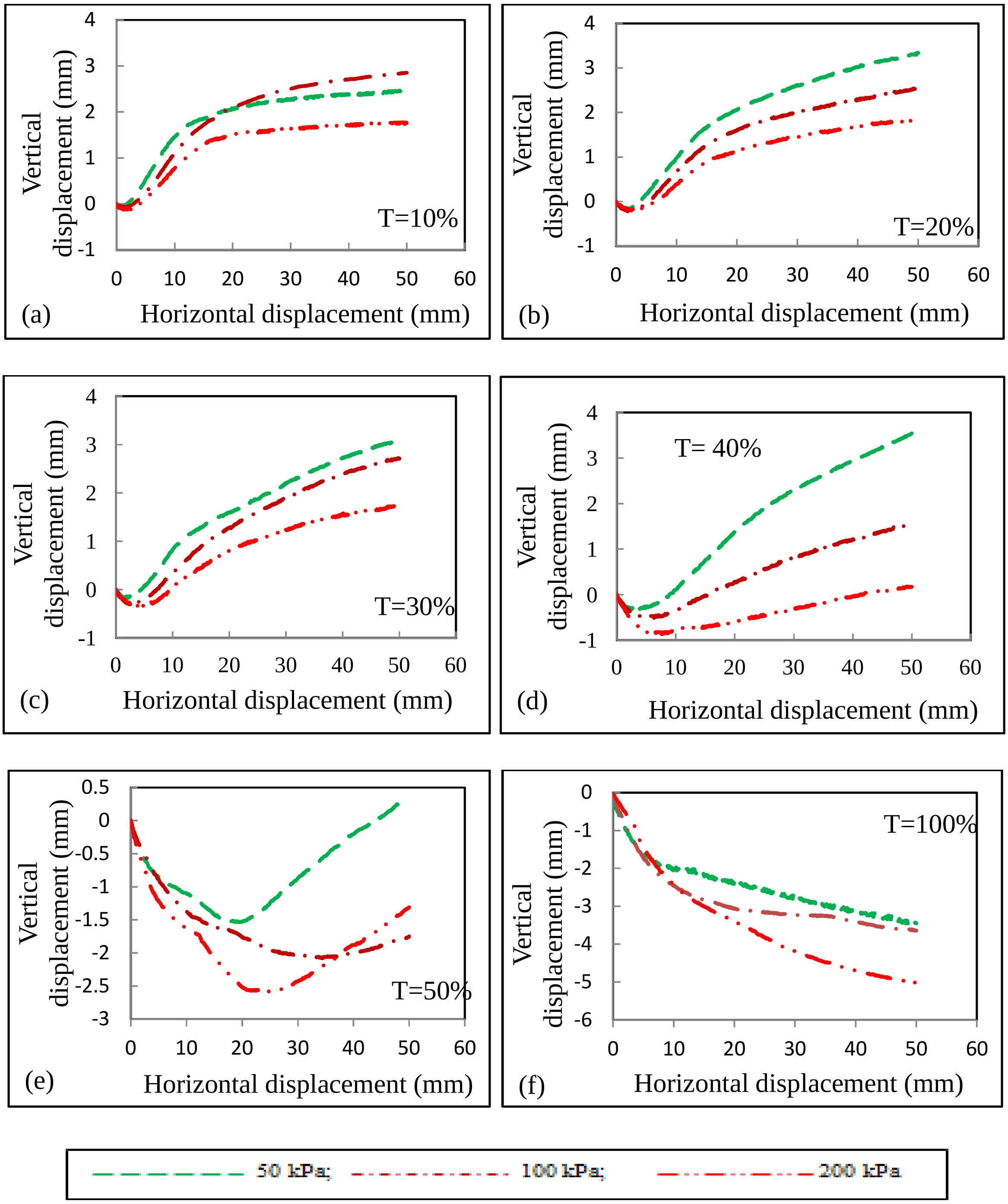


Figure 4.8: Vertical displacement versus horizontal displacement for 50-60 mm tyre shreds in Cape Flats sand (a, b, c, d, e and f)

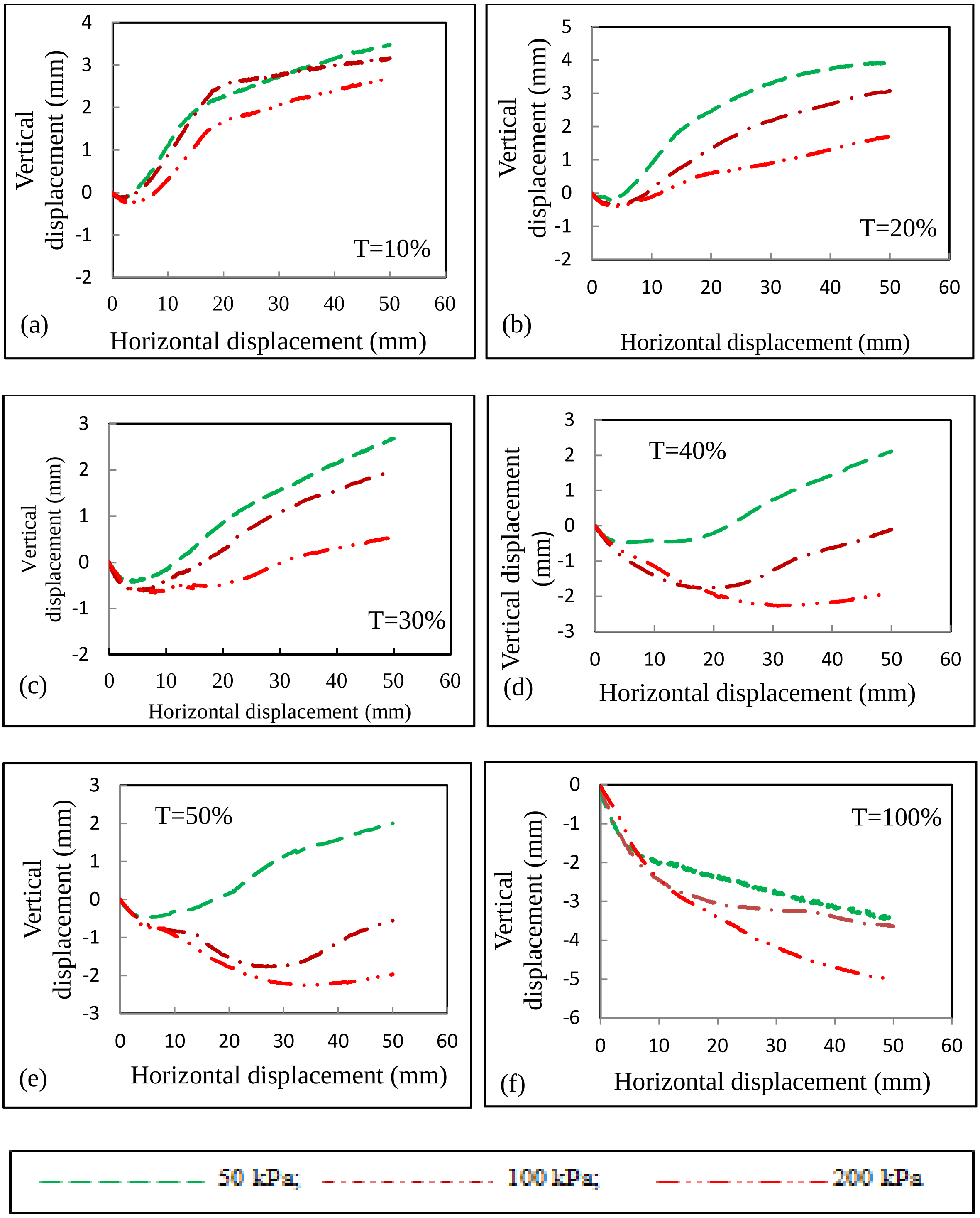


Figure 4.9: Vertical displacement versus horizontal displacement for 50-60 mm tyre shreds in Klipheuwel sand (a, b, c, d, e and f).

The increased contractive behaviour and reduced dilatant behaviour obtained during shear strength tests were explained by Baleshwar and Vianot (2011). They indicated that the inclusion of compressible tyre shreds in sand and the movement of sand particles around tyre shreds due to the increase in vertical normal pressure during shear phase result in dilatancy effect that is less than that of unreinforced sand. This increased the contraction of the mixtures. These results are generally in agreement with the results obtained by other researchers like Gotteland et al. (2005).

4.3.3 Compacted dry density

Table 4.3: The densities achieved during the preparation of test specimens

Tyre shred%	Dry density (Mg/m^3)							
	Tyre shred-Cape Flats sand composite				Tyre shred-Klipheuwel sand composite			
	10-15mm	Average	50-60 mm	Average	10-15 mm	Average	50-60 mm	Average
0	1.701 1.702 1.699	1.701	1.701 1.702 1.699	1.701	1.928 1.929 1.926	1.928	1.928 1.929 1.927	1.928
10	1.620 1.625 1.624	1.623	1.645 1.647 1.648	1.647	1.714 1.716 1.707	1.7123	1.824 1.825 1.823	1.824
20	1.554 1.552 1.553	1.553	1.559 1.555 1.561	1.558	1.627 1.620 1.618	1.622	1.725 1.721 1.723	1.723
30	1.342 1.345 1.339	1.342	1.517 1.516 1.514	1.516	1.492 1.495 1.498	1.495	1.594 1.595 1.593	1.594
40	1.259 1.256 1.254	1.256	1.353 1.355 1.357	1.355	1.327 1.330 1.331	1.329	1.426 1.423 1.423	1.424
50	1.112 1.116 1.113	1.114	1.293 1.294 1.290	1.292	1.163 1.164 1.160	1.163	1.369 1.371 1.368	1.369
100	0.541 0.541 0.541	0.541	0.515 0.517 0.516	0.516	0.541 0.541 0.541	0.541	0.516 0.518 0.516	0.517

The material was compacted in three layers each receiving 25 tampings. The results showed that the density was high for unreinforced sand and decreased as tyre dosage was increased. Example is for addition of 10% of 50-60 mm shreds in Cape Flats sand which decreased the density from 1701 kg/m^3 to 1647.2 kg/m^3. The same trend was observed for all tyre shred sizes mixed separately with Cape Flats and Klipheuwel sands. The decreased density was attributed to the continued increase of shred content in tyre shred composite. The density of compacted 10-15 mm tyre shreds was 0.541Mg/m^3 and that of 50-60 mm was 0.516 Mg/m^3. This difference was due to the high void contact in the sample with longer tyre pieces leading to the reduction in density.

Based on the densities achieved from vibratory methods in Table 3.2 and those given in Table 4.3 for unreinforced material, it can be concluded that the material in the shear box was compacted at 95%.

4.3.4 Coulomb failure envelope for tyre shreds sand mixtures

In this subsection the relationship between maximum shear stress and applied normal pressure is discussed. This relationship which is the Coulomb failure envelope was plotted based on data from the Section 4.3.1.

The three maximum shear stresses from duplicate samples tested at three different normal pressures such as 50, 100 and 200 kPa were used to plot Coulomb failure envelope line. These stresses were obtained from unreinforced and pure tyre shreds samples and tyre shred-sand specimens with different shred dosage i.e. 10, 20, 30, 40 and 50%. The maximum shear stresses were taken as ordinates and applied normal pressures as abscissa. The inclination of these lines to the horizontal axis represents the slope which gives the internal angle of friction (φ’) while the intercept on the vertical axis gives the apparent cohesion (c’).

4.3.4.1 Shear strength response for 10-15 mm shred size

Figure 4.10 presents the Coulomb failure envelopes for unreinforced sand, pure tyre shreds and tyre shred-sand composites containing 10-15 mm shred size.

The friction angle obtained from unreinforced sand (0%) was 40.6^0 and 44.6^0 for Cape Flats and Klipheuwel sands respectively. A small value of apparent cohesion was observed from these sands and it was thus neglected as cohesion of sand from direct shear test. The results showed that Klipheuwel sand had higher internal angle of friction than that of Cape Flats sand. This difference was attributed to high degree of interlocking within Klipheuwel sand particles as a result of high coefficient of uniformity of (C_u=7) compared to that of Cape Flats sand (C_u=1.7).

The friction angle obtained from pure tyre shreds was 22.1^0 and the cohesion was 13.3 kPa. The addition of tyre shred to sand influenced its cohesion and friction angle. All shred dosages considered for Cape Flats and Klipheuwel sands mixed with this category of tyre shred improved their cohesion. The friction angle was increased from 44.6^0 for pure Klipheuwel sand to 46.9^0 for tyre shred-sand mixture at 10% tyre shreds content then decreased for further increase of shred content. Any concentration of tyre shred included in Cape Flats sand decreased its friction angle. Both cohesions and friction angles from 10-15 mm shred size are presented in Table 4.4 and more details are given in subsection 4.3.5.1.

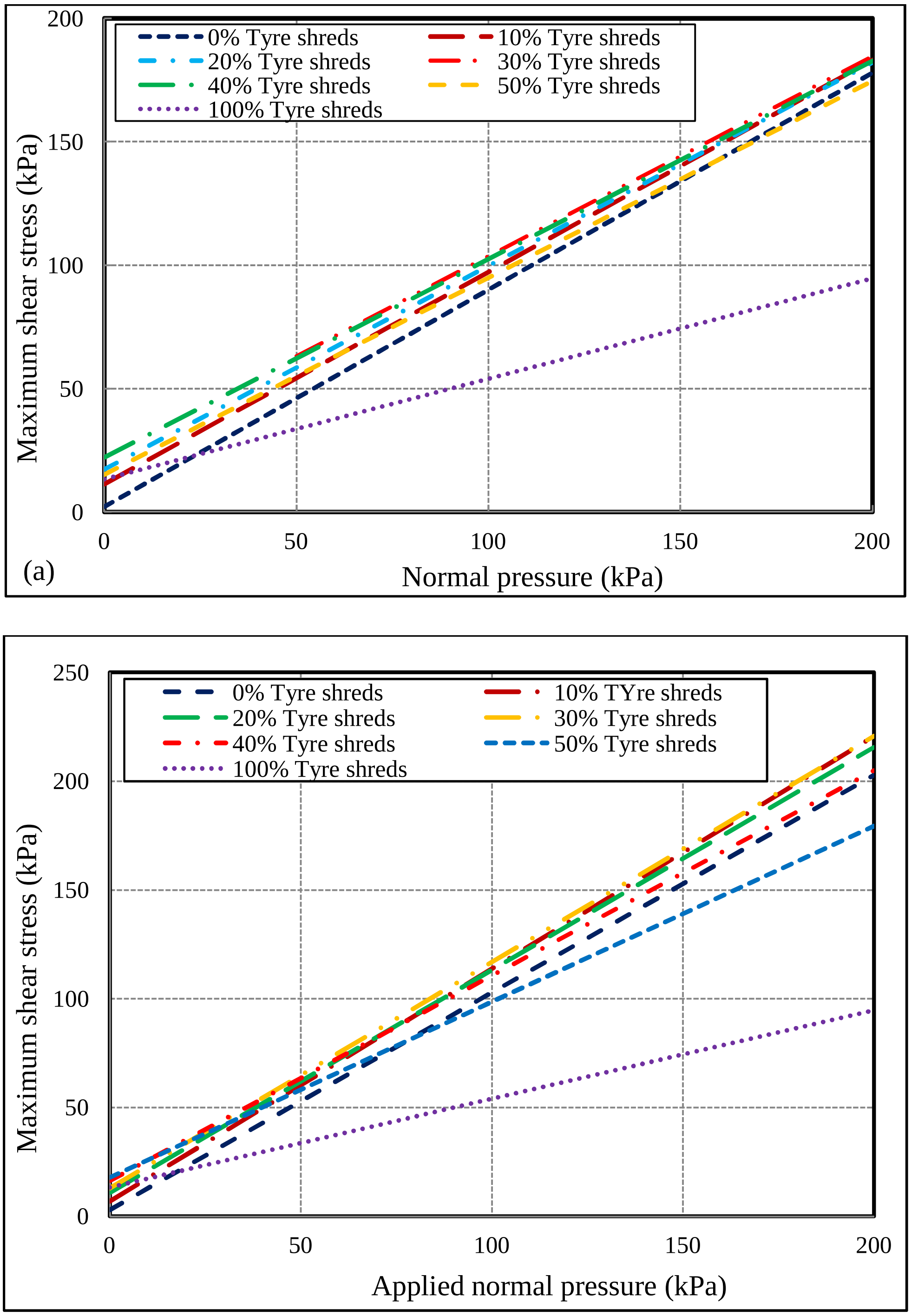


Figure 4.10: Relationship between the maximum shear stress and normal applied pressure for 10-15 mm tyre shred inclusion in (a) Cape Flats sand and (b) Klipheuwel sand

Table 4.4: Shear strength parameters (friction angle and cohesion) obtained from tyre shreds unreinforced sand and tyre shred sand composites for 10-15 mm shreds

Tyre shreds	Cape Flats		Klipheuwel	
%	c (kPa)	ϕ (º)	c (kPa)	ϕ (º)
0	0	40.6	0	44.6
10	11.3	40.7	6.7	46.9
20	17.3	39.5	10.9	45.7
30	22.5	39	12.9	46.1
40	22.1	38.7	16.3	43.3
50	15.2	38.6	17.8	38.9
100	13.3	22.1	13.3	22.1

4.3.4.2 Shear strength response for 50-60 mm shred size

Shear stress versus normal stress relationship was also plotted for 50-60 mm tyre shred inclusion in Cape Flat and Klipheuwel sands. The lines of the best fit were used to drawn to show the Coulomb failure envelopes.

The shear strength parameters found from these envelopes for pure tyre shreds and tyre shred-sand composites samples are presented in Table 4.5. The same concentrations of tyre shreds as used in 10-15 mm tyre shreds were considered. In general the friction angle and cohesion were enhanced upon adding tyre shreds to the two types of sands.

The friction angle increased when tyre shred dosage increased up to 40% for Klipheuwel sand compared to that from the control test beyond which no more improvement was observed. The maximum value was obtained at a concentration of 10% tyre shred. Contrary to the samples containing 10-15 mm tyre shreds in Cape Flats sand, the improvement of internal angle of friction was observed for the composites having 50-60 mm shreds. The dosage giving the maximum value was identified as 10%. These angles were 44. 5^0 and 48.1^0 compared to 40.6^0 and 44.6^0 from unreinforced Cape Flats and Klipheuwel sands respectively.

All dosages considered in these cohesionless materials showed improvement of apparent cohesion. The maximum values of 36.5 kPa and 30.3 kPa were reached at a shred content of 30% for each Cape Flats and Klipheuwel sand tyre shred mixture respectively. More discussion can be seen in Subsection 4.3.5.2.

The cohesion obtained was due to the nonlinear variation of maximum shear stress at failure for tyre shreds sand composites containing 10-15 mm and 50-60 mm shreds at different concentrations in both Cape Flats and Klipheuwel sands. This behaviour was reported by Foose et al. (1996) and Ahmed (2004) who investigated tyre shred sand mixtures.

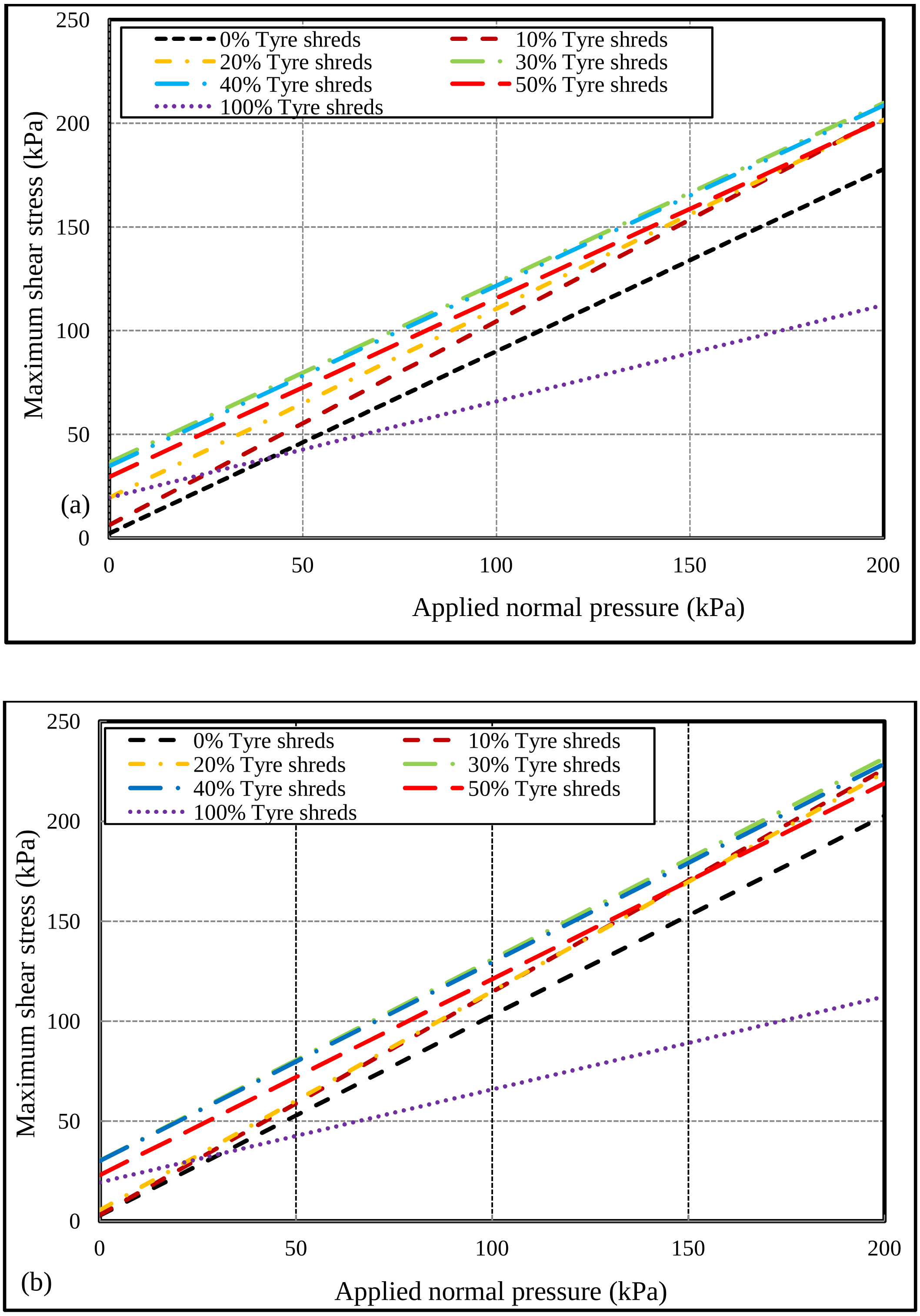


Figure 4.11: Relationship between maximum shear stress and normal applied pressure for 50-60 mm tyre shred inclusion in (a) Cape Flats sand and (b) Klipheuwel sand

Table 4.5: Shear strength parameters (friction angle and cohesion) obtained from pure tyre shreds unreinforced sands and tyre shred sand mixtures for 50-60 mm shred size

Tyre shreds	Cape Flats		Klipheuwel	
%	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)
0	0	40.6	0	44.6
10	6.3	44.5	3.1	48.1
20	19.5	42.3	5.6	47.6
30	36.5	40.9	30.3	45.2
40	34.8	41	30.1	44.8
50	29.5	40.8	23.1	44.4
100	19.4	24.9	19.5	24.9

4.3.5 Influence of tyre shreds content on cohesion and friction angle of sand

4.3.5.1 10-15 mm tyre shreds size

Figure 4.12 shows the change of cohesion and friction angles for the different tyre shred dosages. Generally mixing tyre shreds with Cape Flats and Klipheuwel sands in various proportions strengthened them and increased both their cohesion and internal angle of friction.

As presented in Figure 4.12 (a), the addition of small tyre shreds to Cape Flats sand improved its cohesion. This enhancement was obtained for all concentrations of tyre shreds in comparison to that of unreinforced sand. A concentration of 10% shreds in the mixture gave a value of 11.3 kPa. In Figure 4.12 (a) the dosages of 20, 30, 40 and 50% presented a significant improvement compared to 10% shred content. By looking at the shape of the curve in Figure 4.12 (a), it is clear from the mentioned shred contents that the maximum cohesion was achieved at a dosage of 30%. It can be mentioned that the internal angle of friction in Figure 4.12 (b) dropped for tyre shreds added to Cape Flats sand in any concentration.

The variation of friction angle for different dosages in Klipheuwel sand is given in Figure 4.12 (b). In contrast to Cape Flats sand, this composite showed an improvement in both cohesion and friction angle. Mixing it with tyre shreds at a dosage of 10% gave a friction angle of 46.9^0. It can be seen from the same figure that other shred contents, such as 20 and 30%, provided an improvement based on friction angle from unreinforced sand which was 44.6^0. Beyond these dosages the friction angle became smaller that of the control test (0% shreds). 10% was identified as an optimum which maximized the friction angle. Moreover, the cohesion as shown in Figure 4.12 (a) was improved for all concentrations in the same way as in Cape Flats sand, except the maximum value which was found at 50%.

As presented in Figure 4.12 (a), the Cape Flats sand-tyre shred composite showed the better improvement in cohesion compared to that of Klipheuwel sand-tyre shred mixtures. This was opposed to the friction angle which was increased for Klipheuwel sand-tyre shred composite and decreased for any tyre shred mixed with Cape Flat sand as shown. The relationship between friction angle and tyre shred contents is shown in Figure 4.12 (b).

The difference in improvement of shear strength parameters from these tyre shred-sand composites can be attributed to the nonlinearity in Coulomb envelopes which required the use of lines of best fit. The results suggest that the improvement of cohesion and friction angle for the cohesionless soil might be due to the interlocking effect and shear reinforcement mechanism between sand and tyre shreds particles as well as the grading of sands. The improvement of shear strength parameters was reported by Baleshwar and Vianot, (2012) who obtained the maximum friction angle at shred dosage within 10 and 20% for the tyre shred sand composite containing 10x20 mm shred size. Moreover, the observed decrease in friction was reported by Cabalar, (2011) who studied the shear strength behaviour of small tyre pieces mixed with sand.

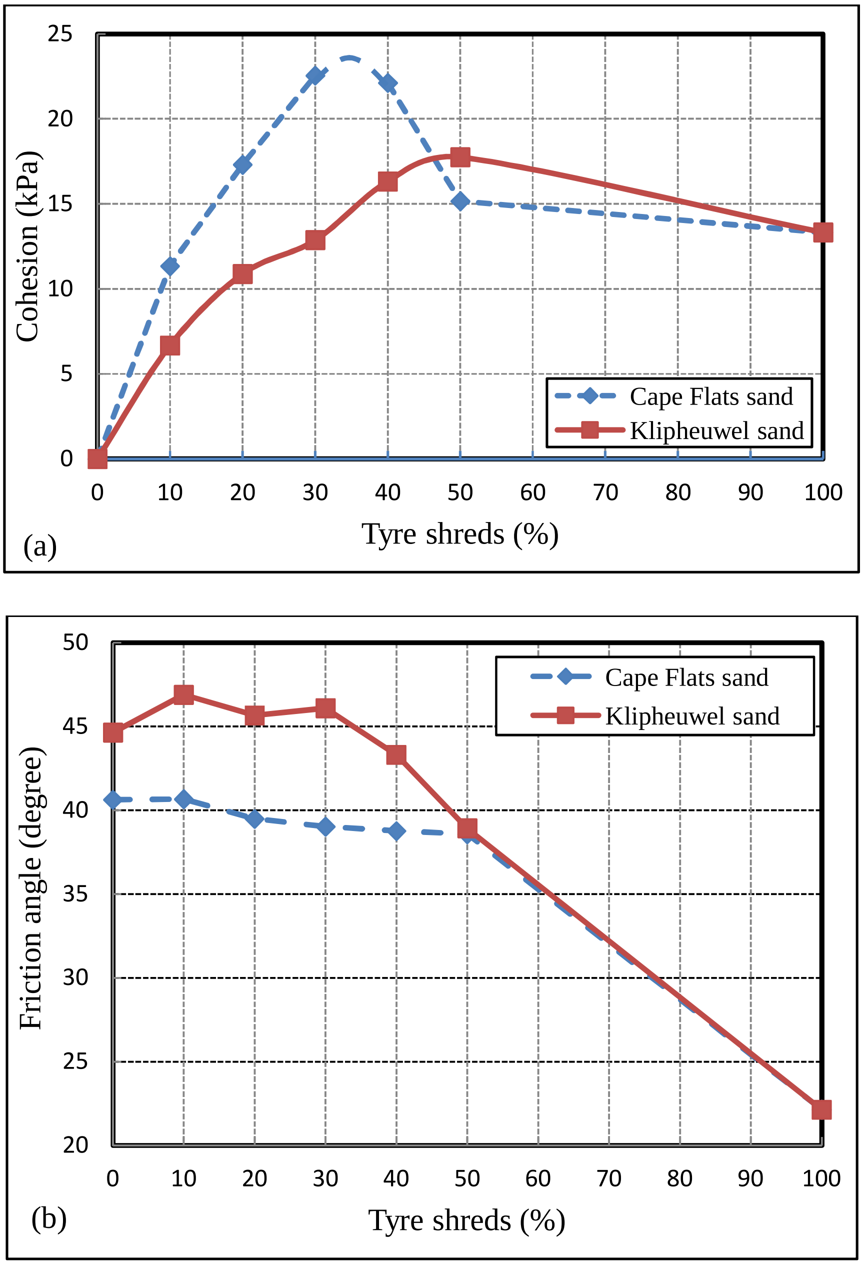


Figure 4.12: Effect of tyre shred content on (a) cohesion and (b) friction angle for Cape Flats and Klipheuwel sand contained 10-15 mm shreds

4.3.5.2 50-60 mm shred size

The relationship between internal angle of friction and cohesion with shred dosage for 50-60 mm shred size in Cape Flats and Klipheuwel sands is given in Figure 4.13 (a & b). Compared to small shreds the long tyre shreds included in Cape Flats and Klipheuwel sands generally improved both the cohesion and friction angle.

As with the small shreds, cohesion for long shred added to Cape Flats sand was increased as the shreds dosage varied. The change of cohesion with the percentage of tyre shreds provided in Figure 4.13 (a) showed that 10% in the mixture exhibited the cohesion value of 6.3 kPa. The continuous increase of tyre shreds improved progressively this parameter, reaching a maximum value of 37.5 kPa at an optimum dosage of 35% of shred and then dropped. The improved friction angle given by 10% shred in sand was 44.6^0. This value was found to be the maximum compared to the others obtained from shred contents beyond 10%.

Figure 4.13 (a & b) shows also the cohesion and friction angle for Klipheuwel sand-tyre shred mixtures. It can be seen from these figures that the improvement in shear strength parameters followed the same trend as in Cape Flats sand-shred composites. 10% dosage gave the internal angle of friction of 48.1^0 which reduced with shred quantity while the maximum cohesion of 34 kPa was identified at 35% beyond which a decrease was observed.

From the comparison point of view, the maximum improvement in friction angle was almost identical. The values of 44.5^0 and 48.1^0 were obtained from Cape Flats sand-tyre shred and Klipheuwel sand-shred composite respectively compared to 40.6^0 and 44.6^0 for unreinforced material, while the enhancement in cohesion showed a slightly different trend. The maximum values of 34 kPa and 37.5 kPa for Cape Flats sand-shred and Klipheuwel sand-shred mixtures respectively were identified both at a concentration of 35%.

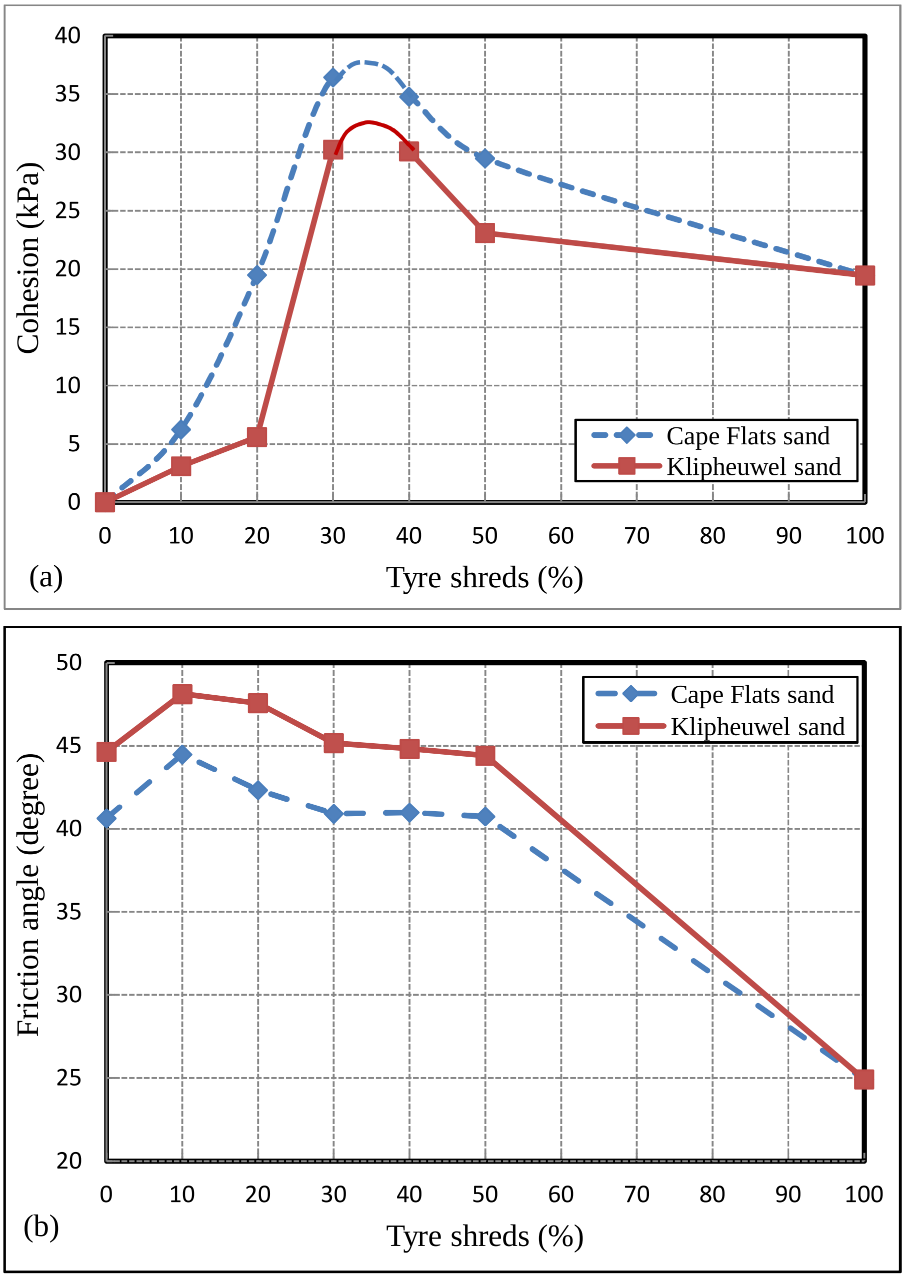


Figure 4.13: Effect of tyre shred content on (a) cohesion and (b) friction angle for Cape Flats and Klipheuwel sand contained 50-60mm shreds

The increased cohesion and friction angle for this particular size of tyre shreds can be attributed to the interlocking effects between tyre shreds and sand particles. Also, because of the long size (50-60 mm) tyre shreds they had more contact areas and acted as anchors and reinforced the shear zone, which greatly increased the shear resistance of sand compared to 10-15 mm tyre shred size. It can also be mentioned that the apparent cohesion obtained was the value of intercept from shear stress axis in the Coulomb failure strength envelope. Tatlsoz et al. (1998) and Attom (2004) reported optimum shred content in the vicinity of 30% while the shred dosage of 10% for the maximum friction angle was reported by Black and Shakoor (1994) and Ghazavi, (2004) for tyre shred-sand mixtures.

The friction angle and cohesion obtained from pure tyre shred samples were 22.1^0 and 13.3 kPa for 10-15 mm size and 24.9^0 and 19.4 kPa for 50-60 mm. These results were in agreement with those reported by Humphrey, (1993), Foose et al. (1996) and Zornberg et al. (2004).

4.3.6 Influence of tyre shreds and applied normal pressure on shear strength of sand

Based on the shear strength parameters obtained from shear strength envelopes, the overall shear strength of the investigated materials was computed by the Equation (1) given in Section 2.3.5 and is in relation with tyre shred contents as shown in Figure 4.14 (a & b), Figure 4.15 (a & b), Table 4.5 and Table 4.6.

In Figure 4.14 (a & b), the shear strength from Cape Flats sand mixed with 10-15 mm tyre shred showed that the addition of shreds in sand generally increased its shear strength. It is clear from the graphs in Figure 4.14 (a) that all tyre shred dosages considered for Cape Flats sand at all vertical stresses, improved its shear strength, taking a reference to unreinforced (0%). Overall shear strength values can be clearly seen in Table 4.5. It is seen from this table that shear strength of tyre shred-sand composite increased as the concentration of tyre shreds increased reaching 30% then started to decrease. This concentration was taken as optimum shred for this category of tyre shred in Cape Flats sand. It was noted that reinforcing Cape Flats sand with small shreds improved only cohesion and reduced its friction angle. However, the increased shear strength depended on cohesion and not on friction angle.

The shear strength of the reinforced Klipheuwel sand with 10-15 mm tyre shreds is provided in Figure 4.14 (b). As with Cape Flats sand, Klipheuwel sand was strengthened by all concentrations of tyre shreds at all vertical confining pressures. The values of shear strength are given in Table 4.5 for more comparison. From this table, the concentration giving the higher shear strength was identified as 30%. Contrary to Cape Flats sand, the shear obtained from Klipheuwel sand-tyre shred of 10-15 mm size depended on both enhanced cohesion and friction angle.

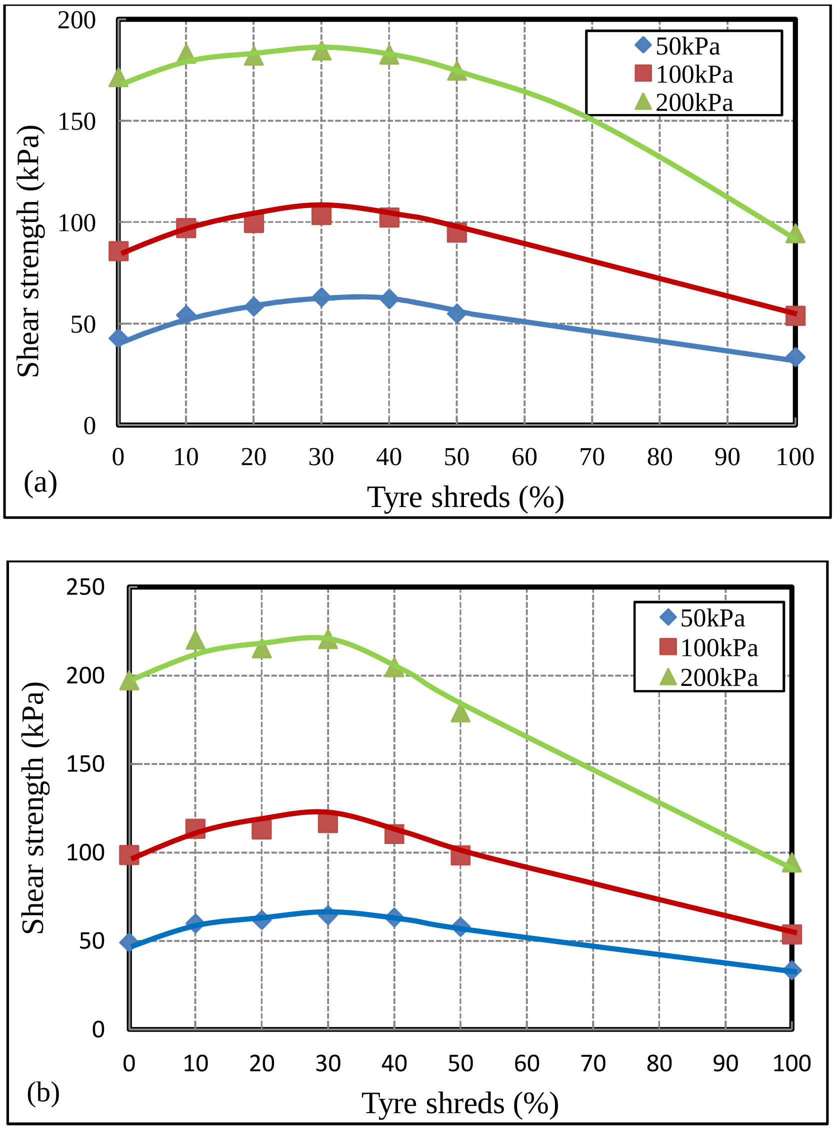


Figure 4.14: Relationship between shear strength and tyre shred content for (a) Cape Flats and (b) Klipheuwel sand for 10-15 mm

Table 4.6: Overall shear strength sand mixed with tyre shreds of the size 10-15 mm (kPa)

Shreds %	Klipheuwel sand-tyre shred mixtures			Cape Flats sand-tyre shred mixtures		
	Applied normal pressure (in kPa)					
	50	100	200	50	100	200
0	49.4	98.7	197.5	42.9	85.8	171.6
10	58	113.5	220.3	54.3	97.2	183.2
20	62.1	114	222	60	100	185
30	64	116.8	225	63.1	103.6	187
40	63.5	110.6	204.9	62.3	102.4	182.7
50	58.1	98.5	179.3	55.1	94.9	174.7
100	33.7	54	94.7	33.7	54	94.7

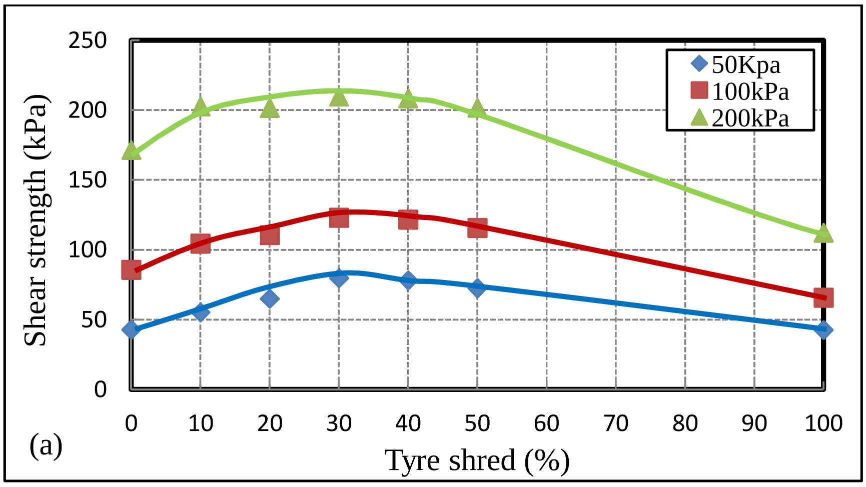
A significant increase in shear strength from the composite of 50-60 mm tyre shreds and each of Cape Flats and Klipheuwel sands was noticed. Generally all shred dosages considered for this size as shown in Figure 4.15 (a & b), strengthened these cohesionless soils compared to unreinforced material.

Figure 4.15 (a) presents the relationship between shred dosages and shear strength of Cape Flats sand-tyre shred composite containing 50-60 mm shred size. It is clear from this figure that the added tyre shred to Cape Flats sand in any concentration increased its shear strength compared to that of control tests. A progressive increase of shear strength was observed as the amount of tyre shreds added to this sand was increased up to 30% shred content beyond which it reduced. For more clarity, all shear strength values from Cape Flats sand-50-60 mm tyre shreds composites are given in Table 4.6.

Shear strengths offered by Klipheuwel sand-tyre shred composites with 50-60 mm shred size at different concentration are presented in Figure 4.6 (b). As with Cape Flats sand-tyre shred sand mixtures, an inclusion of tyre shreds in Klipheuwel sand in any concentration increased its shear strength. A progressive increase in shear strength was noted as shred dosages were increased and levelled off at 30% shred content which was taken as optimum shred dosage for this type of sand.

The applied normal pressures were also found to affect the shear strength of tyre shred sand mixtures. An example was the percentage improvement of shear strength calculated using the shear strengths from control test and those from Klipheuwel sand-50-60 mm tyre shred composite with shred dosage of 30% at 50 and 100 kPa applied normal pressures given in Table 4.6. The calculation showed that the improvement reduced from 34.9% to 21.6% for 50 to 100 kPa respectively. It is obvious from these values that the degree of enhancement of shear strength of the mixture was influenced by applied normal pressures. The same trend was observed in other samples taking reference from pure sand samples.

Even though the friction angle and cohesion maximized at shred dosage of 10 and 35% respectively, it was concluded that the shred content of 30% by dry mass in the composite was an optimum which maximized the overall shear strength of Cape Flats and Klipheuwel sands, considering the two tyre shred sizes mixed separately with these soils. The identical optimum tyre shred content to reinforce the granular soil was reported by Balachowski and Gotteland (2007); Tanchaisawat et al. (2008); Baleshwar and Vianot (2009, 2011 and 2013).



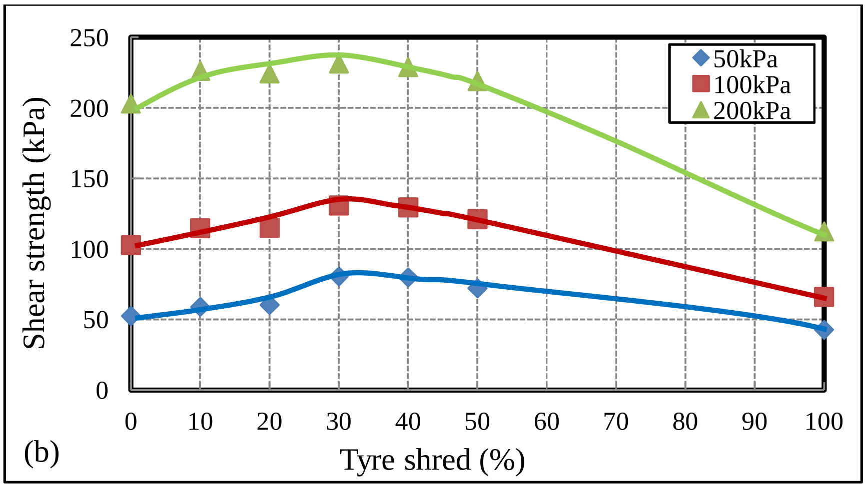


Figure 4.15: Relationship between shear strength and tyre shred content for (a) Cape Flats and (b) Klipheuwel sand for 50-60 mm shred size

Table 4.6: Overall shear strength of sand mixed with tyre shred of the size 50-60 mm (in kPa)

Shreds %	Klipheuwel sand-tyre shred mixtures			Cape Flats sand-tyre shreds mixtures		
	Applied normal pressure (kPa)					
	50	100	200	50	100	200
0	52.4	102.6	203.0	42.9	85.8	171.7
10	58.9	114.6	226.2	55.4	104.5	202.7
20	65	119	228	70	112	205
30	80.6	130.9	231.5	79.8	123.1	209.9
40	79.8	129.5	228.9	78.2	121.7	208.6
50	72.1	121.1	219.	72.6	115.7	201.8
100	42.7	65.9	112.4	42.7	65.9	112.4

4.4 Comparison of the results

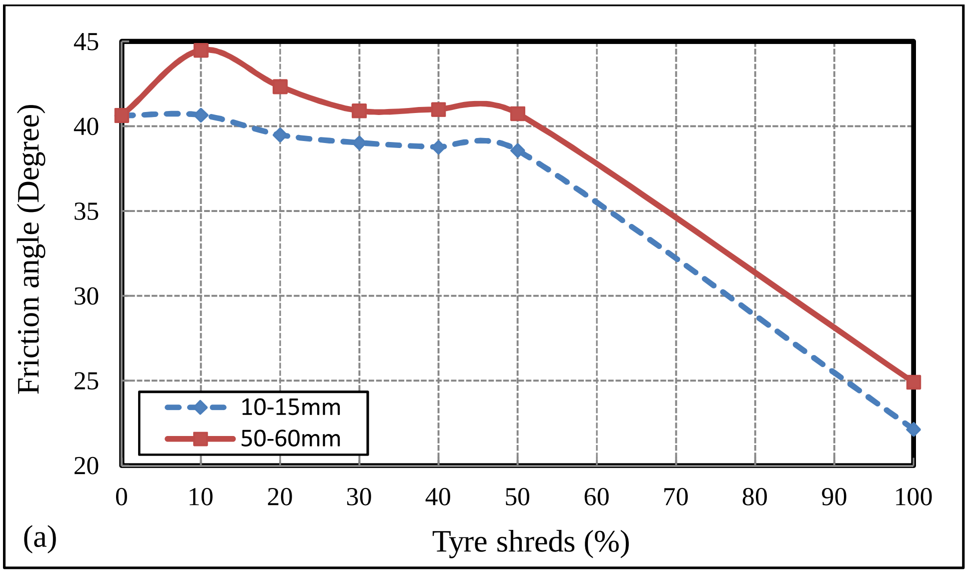
The comparison given herein was between tyre shreds composite containing 10-15 mm and 50-60 mm tyre shreds. This was assessed based on shear strength parameters and the overall shear strength from these mixtures.

4.4.1 Friction angle and cohesion for 10-15mm and 50-60mm tyre shreds

The comparison of internal angle of friction and cohesion for the sand mixed with 10-15 mm and 50-60 mm tyre shreds is given in Figures 4.16 (a & b) and 4.17 and Figures (a & b) for Cape Flats and Klipheuwel sands.

It is clear from Figure 4.16 (a) that the friction angle from Cape Flats sand containing 50-60 mm tyre shreds kept above that of unreinforced sand up to 40% shred content while the addition of 10-15 mm tyre shreds to the same soil decreased its friction angle. It can be said that the addition of longer tyre shreds to this type of sand enhanced its friction angle and that the smaller tyre pieces reduced it. Contrary to friction angle, improved cohesion was obtained for all shred sizes at all shred dosages, but the degree of improvement was different. The maximum value of cohesion obtained from the mixture that contained 50-60 mm tyre shreds was 37.5 kPa at a concentration of around 35% compared to that of 10-15 mm tyre shreds, which was 24 kPa at the same tyre shred content. The percentage difference in improvement was 37% higher for 50-60 mm.

The comparison of internal angle of friction and cohesion from Klipheuwel sand for both 10-15 mm and 50-60 mm tyre shreds sizes was also evaluated. The improvement shown in Figure 4.17 (a) proved that the addition of tyre shred (both smaller and larger sizes) to Klipheuwel sand enhanced its friction angle, but the level of improvement was not the same. The maximum value from 10-15 mm was 46.9^0 and that from 50-60 mm was 48.1^0. Hence 2.5% difference in degree of improvement was attained. Except 10-15 mm shred in Cape Flats sand, 10% shred dosage was optimum giving the maximum value of friction angle.



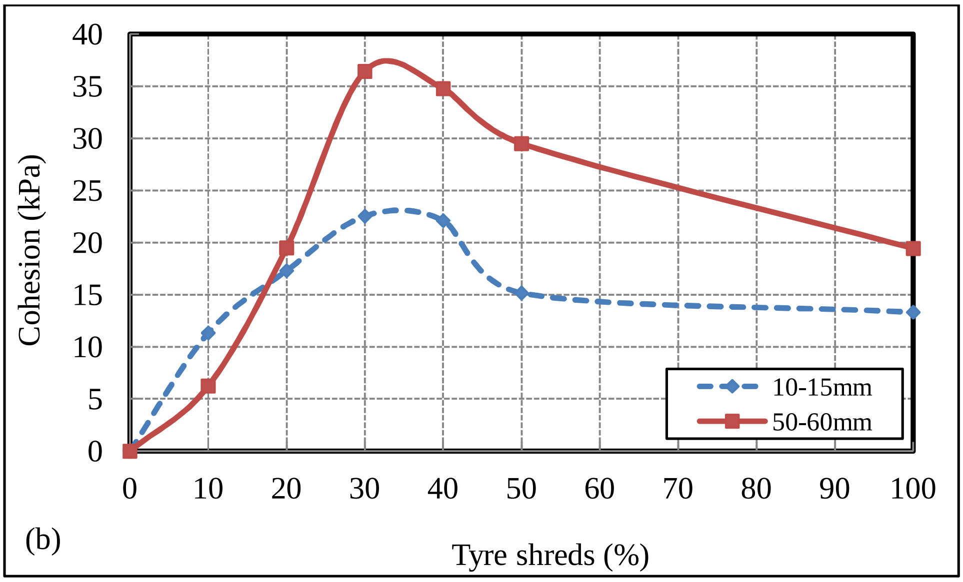


Figure 4.16: Comparison of (a) friction angle and (b) cohesion from 10-15 mm and 50-60 mm tyre shreds Cape Flats sand

In Figure 4.17 (b) the cohesion from the reinforced Klipheuwel sand with the two shreds sizes was improved and the maximum values of 17.7 kPa and 34 kPa kPa from the composite containing 10-15 mm and 50-60 mm were achieved at around a concentration of 50% and 35% tyre shreds respectively. However, the degree of enhancement in cohesion was different with a percentage difference of 47.9%.

Based on the degree of improvement it was confirmed that the addition of tyre shreds to Cape Flats and Klipheuwel sands improved cohesion and marginally increased the friction angle for longer tyre pieces.

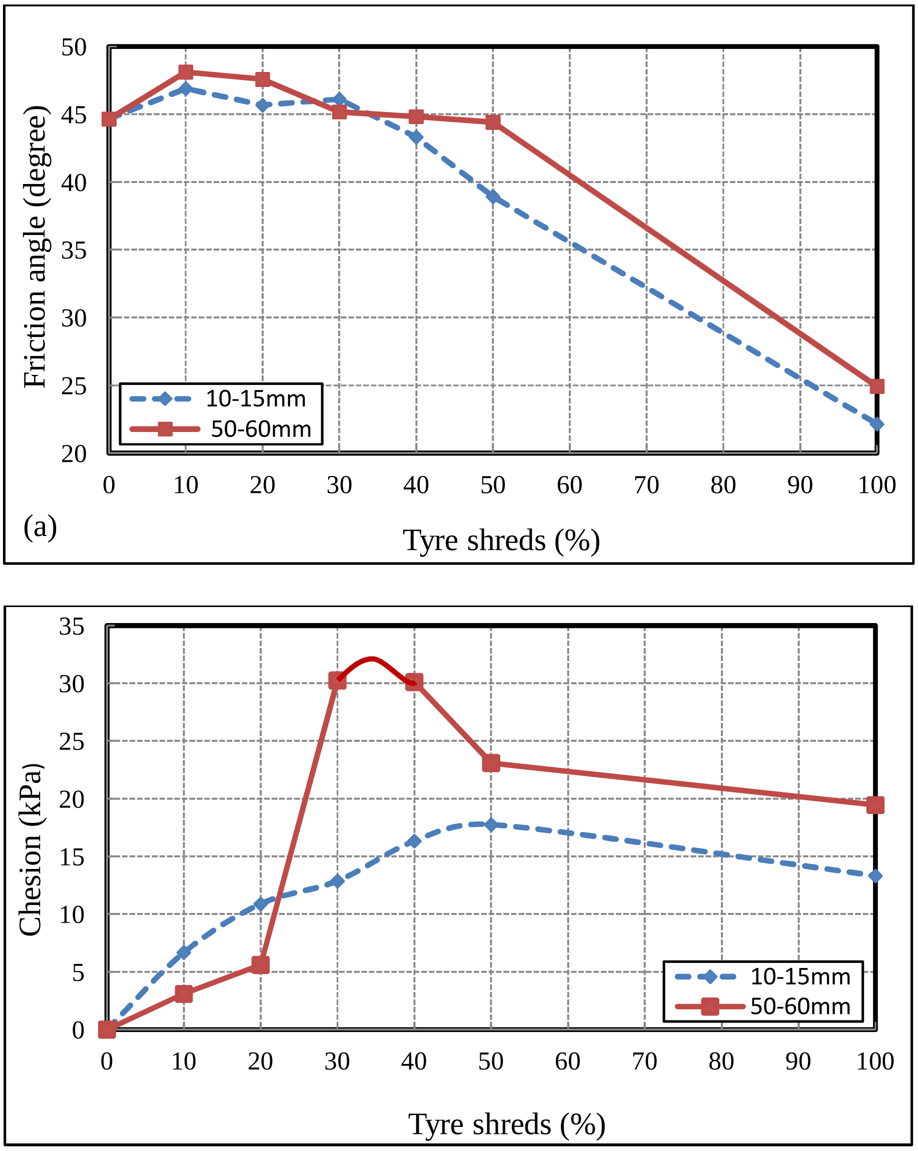


Figure 4.17: Comparison of (a) friction angle and (b) cohesion from 10-15 mm and 50-60 mm tyre shreds Klipheuwel sand

4.4.2 Shear strength of 10-15 mm and 50-60 mm tyre shreds in sand

The plot of shear strength with the variation of tyre shred sizes and contents as well as applied normal pressures is shown in Figure 4.18 (a & b). It is evident from these figures that the shear strength for the 10-15 mm and 50-60 mm tyre shreds included in Cape Flats sand increased with increasing concentration of tyre shreds. For more clarification, shear strength from Cape Flats sand-shred and Klipheuwel sand-shred composites are given in Table 4.7 and Table 4.8 respectively. Thus the improvement depended on size and content of shredded tyres.

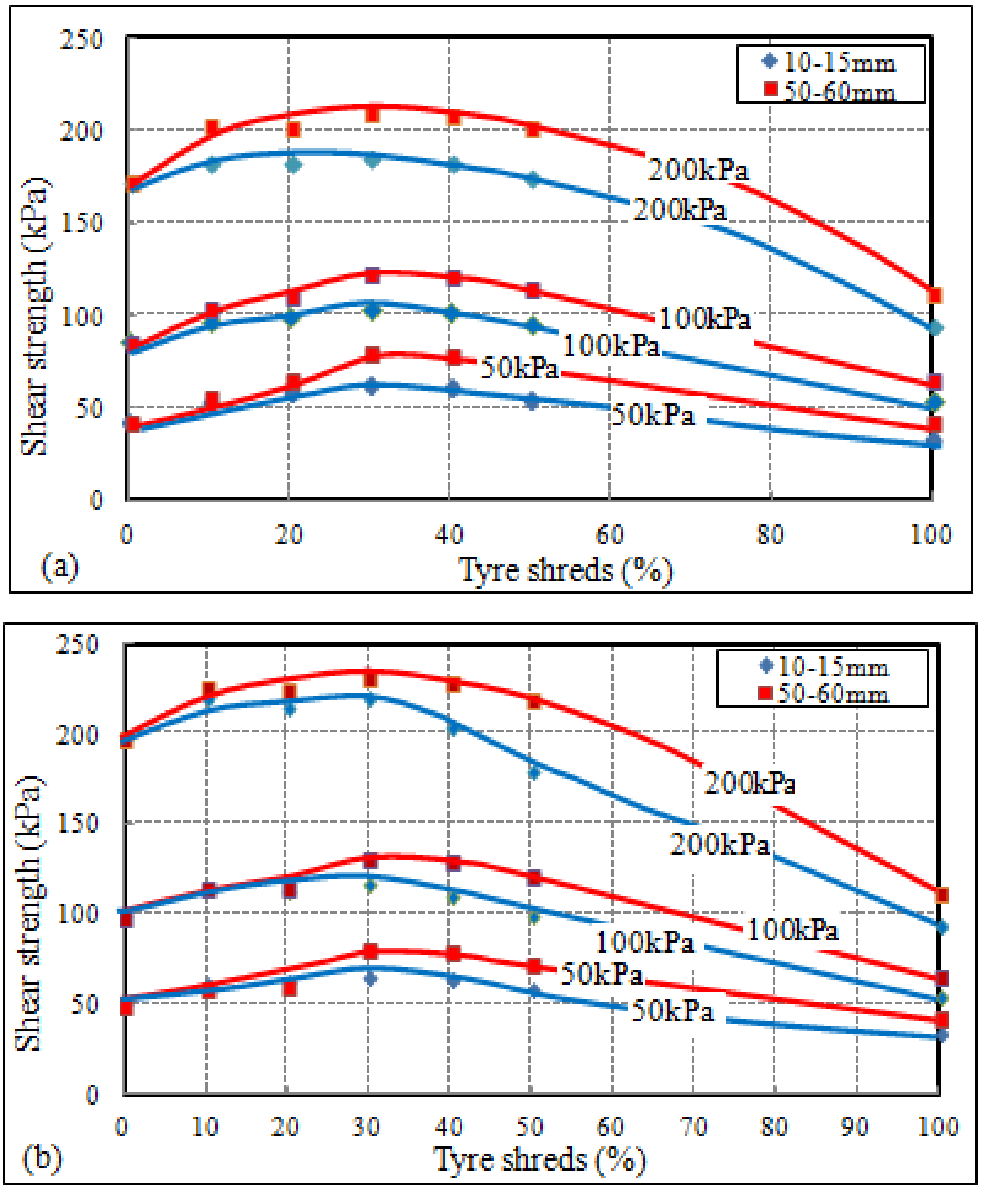


Figure 4.18: Comparison of shear strength for the investigated sizes and the applied normal pressures for (a) Cape Flats sand and (b) Klipheuwel sand

Table 4.7: Comparison of shear strength from two sizes of tyre shreds mixed with Cape Flats sand

Shreds %	10-15 mm			50-60 mm		
	Normal stresses Strength (kPa)					
	50	100	200	50	100	200
0	42.9	85.8	171.6	42.9	85.8	171.7
10	54.3	97.2	183.2	55.4	104.5	202.7
20	60	100	185	70	112	205
30	63.1	103.6	187	79.8	123.1	209.9
40	62.3	102.4	182.7	78.2	121.7	208.6
50	55.1	94.9	174.7	72.6	115.7	201.8
100	33.7	54	94.7	42.7	65.9	112.4

Table 4.8: Comparison of shear strength from two sizes of tyre shreds mixed with Klipheuwel sand

Shreds %	10-15mm			50-60 mm		
	Normal stresses (kPa)					
	50	100	200	50	100	200
0	49.4	98.7	197.5	52.4	102.6	203.0
10	58	113.5	220.3	58.9	114.6	226.2
20	62.1	114	222	65	119	228
30	64	116.8	225	80.6	130.9	231.5
40	63.5	110.6	204.9	79.8	129.5	228.9
50	58.1	98.5	179.3	72.1	121.1	219.
100	33.7	54	94.7	42.7	65.9	112.4

An example of the improvement can be picked from Table 4.7 at 30% tyre shreds from 10-15 mm to 50-60 mm at a normal pressure of 50 kPa. The percentage difference was calculated as

20.9% higher for 50-60 mm than 10-15 mm shred sizes. The same trend was observed in other shred dosages and normal stresses for this type of sand. It was also the same for Klipheuwel sand-tyre shred composites given in Table 4.8. The difference in the improvement can be attributed to more contact surface area between the large shreds and sand.

With the exception of 10-15 mm tyre shreds included in Cape Flats sand which decreased its friction angle, the inclusion of random tyre shreds in sand generally improved its cohesion and friction angle as well as its overall shear strength. Based on the results obtained, it can be concluded that the longer tyre shreds mixed with South African sand soils increased their shear strength in comparison to small tyre shred sizes. The addition of 30% shred content was better than all other shred dosage. It can also be mentioned that mixing may have significant influence, especially when using excessively long tyre shreds as it is difficult to produce a well mixed tyre shred-sand with theses tyre pieces.

CHAPTER 5 CIVIL ENGINEERING APPLICATION OF WASTE TYRES IN SOUTH AFRICA

South Africa produces a high volume of waste tyres and therefore the need for the utilization of a great quantity of these wastes is essential. There are potentially several civil engineering applications where shredded waste tyres could be utilized. Some of these include lightweight road embankments construction, retaining structures backfill and as selected drainage systems in landfill covers, etc. The construction of road embankment activities may consume a reasonable quantity of waste tyres. The evidence was a full-scale test embankment constructed by Yoon et al. (2006) which consumed a great quantity of waste tyres. However, the objective of this chapter was to propose the application of shreds and granular soils of South Africa based on the experimental results and the guidelines which can be followed during the execution of the project.

5.1 Highway embankment application

The suggested application herein proposes the use of blended tyre-shred granular soils as lightweight fill material in the construction of road embankments. When mixed with soil, tyre shreds reduce its weight and improve its shear strength, which in turn stabilize the embankment in terms of settlement reduction and the improvement of slope stability when used as fill materials. The results obtained from the current study suggest that the long tyre shreds could be mixed with sandy soils of South Africa, i.e. Cape Flats sand or Klipheuwel sand and use as lightweight fill material in construction of road embankments in this country. These results can be seen in Chapter 4.

Based on available guidelines, the constructed embankment and experimental results from the current study, guidelines for the use of tyre shreds sand mixture in the construction of road embankments in South Africa are proposed and discussed in Section 5.2. These include design and construction procedures to be followed.

5.2 The proposed guidelines

These provisional guidelines were based on the previous constructed tyre shreds and tyre shreds soil embankments, available guidelines and the results from current research.

5.2.1 Material description

The test embankment constructed by Yoon et al. (2006) in the USA using tyre shred-sand composites performed well. In their study, tyre shreds ranging from 36 mm to 76 mm were used. According to South Africa Tyre Recyclers, categories of tyre pieces which can be used in the construction of road embankments range from 90 mm to 50 mm and ±18 mm produced by primary and secondary shredding processes respectively. ASTM D6270-2008 recommends that for tyre shreds layer thickness between 1-3 mm, the maximum of 50% by weight must pass through 75 mm screens, 25% through 38 mm and 1% through 4.75 mm. Besides that, the current study conducted on tyre shred-sand composites proved that the tyre pieces ranging between 50-60 mm are better to reinforce cohesionless soils compared to 10-15 mm shred sizes. Based on these results, local tyre shredder specifications as well as other information indicated above, shreds ranging from 30 to 80 mm mixed with granular soils could be used in the construction of road embankments in South Africa. These shreds should fulfill the following requirements as given in ASTM D6270-2008:

- Tyre shreds must be free of contaminants such as oil, grease, gasoline, diesel, etc., that can create a fire hazard.
- Shredded tyres that have been subjected to fires are not permitted in the fill.
- Tyre aggregates must be free of fibrous organic matter (wood fragment and wood chips).
- They must have less than 1% by weight of metal fragments not encased in rubber.
- Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tyre aggregates on 75 % of the pieces (by weight) and no more than 50 mm on 90 % of the pieces (by weight).

5.2.2 Design consideration

Design consideration as part of the proposed guidelines discusses the mix and structural design.

- **Mix design**

The blended tyre shreds and soil has a low density compared to that of soil alone. The tyre shred-sand composite should meet the technical requirements such as having good shear strength, workability (good mixture), reduced weight of the fill material, etc.

This study showed that 30% tyre shreds content by dry weight is optimum to reinforce the selected granular soils of South Africa. To simplify blending activities in the field, the mixing ratio could be prepared on volumetric basis. The optimum shred dosage by weight from laboratory study was thus converted into the volume basis and 55% shred content by volume was obtained which would simply be a used in the field. However, for workability and simplification of quantity measurement a ratio of 50:50 (tyre shred:soil) by volume is recommended in the preparation of embankment fill material. In most cases, this mixing ratio is a maximum and could not be exceeded (FHWA, 2012).

- **Structural design**

The principal design consideration for a tyre shred-sand composite in embankment construction comprises the composite mixture confinement, the particle size distribution of tyre shreds and sand, type of belts and the required compacted density of the mixture. The following should be taken into account during the design of the embankment constructed from tyre shred.

- The mixture should be enclosed in geotextiles fabric to ensure the necessary containment.
- 2:1 embankment side slope (Horizontal:Vertical) is recommended.
- At least 0.9 mm thickness of soil cover should be placed between the top of enclosed tyre shred-soil fill and the base of pavement to minimize differential settlement.
- The thickness of tyre shred-soil composite shall not exceed 3 m (Salgado et al., 2003). Where the required height becomes greater than that, it should be split into different layers having the maximum thickness of 3 m each separated by soil thickness in between.

- The allowable settlement of the embankment due to itself weight and traffic could not exceed the range of 0.3 m to 0.6 m provided they are uniform (FHWA, 2012). Before placing soil cover and surcharge, the compacted thickness of tyre shred-soil mixture equal to the predicted settlement should be provided to avoid the drop of required height of tyre shred-sand composite.
- For the anticipated heavy wheel loading, 0.6 m or higher uncompacted soil surcharge could be placed and removed by the authorization of the engineer. This should be done to accelerate the settlement before starting pavement activities.

5.2.3 Construction procedures

- **Material Handling**

Tyre shreds to be used should reflect the number of cubic metres of tyre shreds obtained based on the ratio of the composite and the compacted volume of the embankment.

- **Site preparation**

The site for tyre shred-granular soil embankment could be prepared in a similar manner as that of earthen fill material. In terms of a high water table or swampy area which occurs at the base of the embankment, a granular aggregate drainage blanket could be constructed in order to drain out the raised water in order to prevent tyre shreds to be in contact with groundwater. A provision should be made to pipe the runoff beneath the embankment for the natural runoff passing through the embankment area (FHWA, 2012).

- **Mixing**

Mixing materials should be performed at the construction site and blended on volumetric basis using bucket loads from a front-end loader and blending the materials together as well as possible with the bucket by following the specified mixing proportion. This is to avoid the loss of expected strength and reduction in volume of waste tyres to be used.

- **Placing and compaction**

After the preparation of the embankment base, geotextiles fabric which encloses tyre shred-granular soil composites should be laid transversally on top of the aggregate base of 150 mm thick. A bulldozer should be used to spread the mixture across geotextiles in such a way that the segregation of the materials will not occur.

Yoon et al. (2006) suggested six passes of a D6 10 ton bulldozer to compact 300 mm thick pre-mixed material and at each layer, transverse splices of geotextile can be pinned on the side slope of the embankment to provide additional reinforcement of the slope. They recommend the compacted height of fill to not exceed 3 m. If the fill required exceeds such height, it should be divided into different layers not greater than that and be separated from one another by soil layer in between. A 0.9 m soil thickness encasement material should be placed on side slope and compacted at the same time the tyre and soil lift was placed. The same soil thickness should be placed and compacted on top of tyre shred-soil mixtures. The cover soil on side slopes should be covered by top soil and seeded to protect slopes against erosion.

- **Quality control**

Beside the a sufficient number of passes of the bulldozer on tyre shred sand layer during construction, the settlement and differential settlement of tyre shred-soil embankment can be performed using settlement plates and inclinometers installed along slopes of the embankment and within or adjacent to the roadway (FHWA, 2012). These devices may help to monitor the post-construction settlements. The reading from these settlement devices should be taken periodically for the purpose of comparing the actual to the predicted settlements.

The effect of tyre shreds-soil embankment on the environment should be evaluated. This is mainly based on fire hazard and groundwater quality assessment. Occurrence of fire may be observed in the embankment constructed with tyre shreds alone or tyre shred-soil fill material. However, the variation in temperature should be monitored by placing a thermometer at the centre of the embankment.

The groundwater quality underneath the tyre shred-soil embankment should be monitored using installed well points. The results should comply with the standard limits recommended for secondary drinking water (EPA 2002) and the maximum contaminant-level standard for drinking water (IDEM 2000).

It is concluded that long tyre shreds mixed with selected granular soils could be used in the preparation of embankment fill materials in South Africa because of their good performance and relatively low cost. This is because the smaller tyre pieces require too much energy during the different processes as well as the low level of improvement of soil properties compared to long tyre shreds. As suggested above, the material could be prepared at a shred dosage of 50% by dry volume. This could facilitate the ease of quantities measurement throughout field works. The geotechnical aspects of the tyre shred-sand embankment project are given in Figure 5.2.

As a great quantity of tyre shred-soil is used in embankment, if the demolition or level of the road embankments or other tyre shred-soil structures is likely to happen for other purposes, the disposal of these materials may be a big challenge to environmentalists. They should not be used in any other structures (temporary road embankment for example), the choice should be permanent structures (road embankment, retaining walls, etc.) which last longer and not temporary ones as tyre rubber materials are non-biodegradable. In this research, a suggestion is to use tyre shred-sand mixtures in motor ways and national road embankments in South Africa which last longer. If levelling is to be done for the purpose of extending the structure (road embankment) either increasing its height or the number of lanes, other fill materials should be placed following the proposed guidelines.

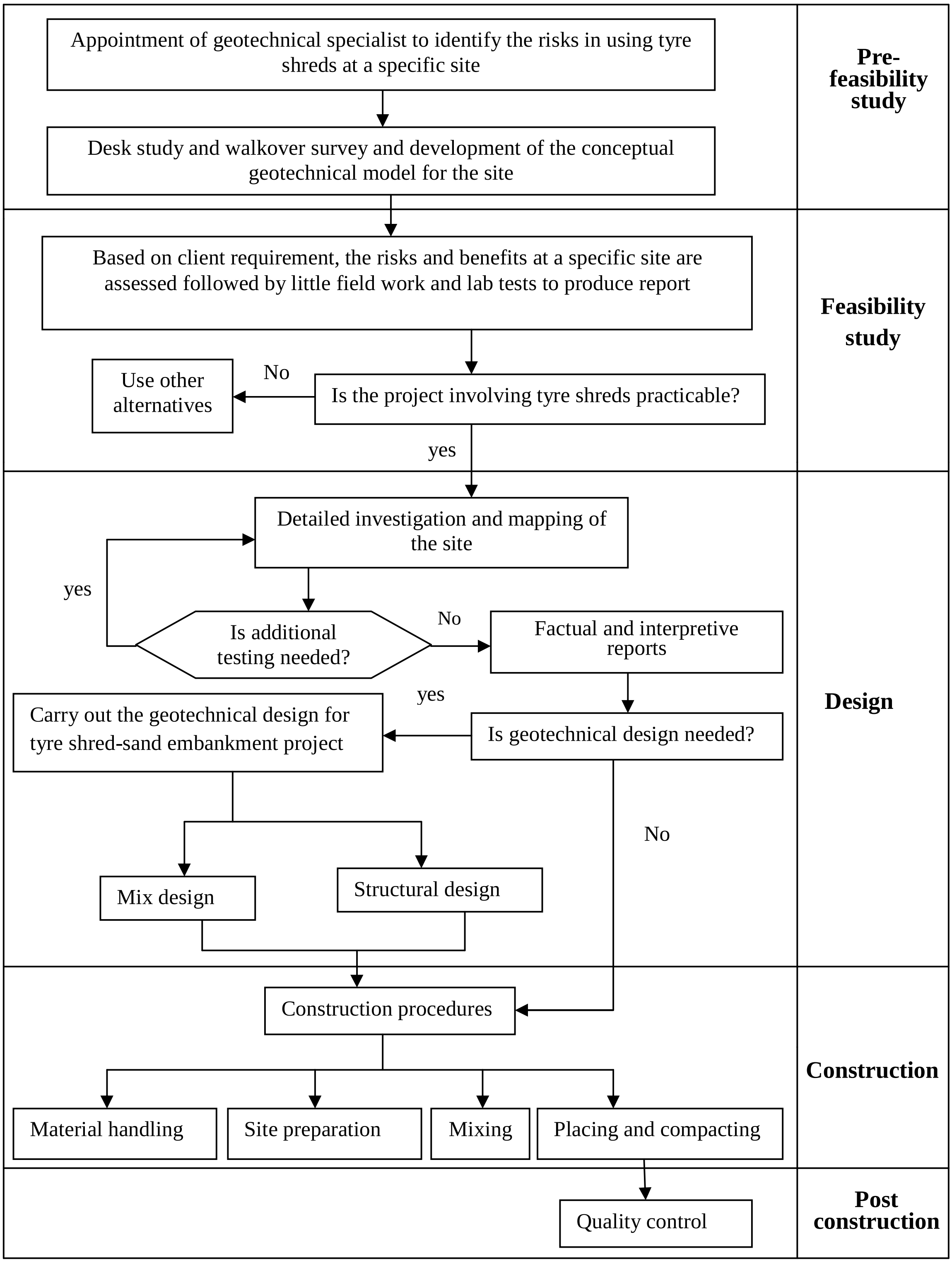


Figure 5.2: Geotechnical aspects of the tyre shred-sand composite embankment project for a particular site

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This study investigated the shear strength behaviour of tyre shred and selected granular soil composites. Two types of sands, i.e. Cape Flats and Klipheuwel sands, were used. They were selected because of their local availability. These soils are a common source of fill material used in the construction of road embankments. The study was conducted to appraise the compatibility of tyre shreds and granular soils in order to produce a suitable lightweight embankment fill material as an alternative means of recycling high volumes of the waste tyres stockpiled in South Africa. Waste tyre shreds were mixed with sands in various proportions such as 10, 20, 30, 40 and 50% by dry mass and the composites were tested using a large-scale direct shear box. The summary of the findings as well as recommendations are given in the following sections.

6.1.1 Summary of the findings

The shear strength test results from different tyre shreds sand composites generally showed that the shear strength parameters as well as the overall shear strength of sand soils were improved for the increased tyre shred dosage.

The results showed that the addition of tyre shreds of 50 to 60 mm size to Cape Flats and Klipheuwel sands improved their friction angle at a shred dosage of 10% by dry mass. A suitable increase in cohesion was observed as shreds were added to these soils. This cohesion was obtained from Coulomb shear strength envelopes and reached its maximum value for both sands at a shred dosage of 30% by dry mass. The same trend was observed for small tyre shreds (10-15 mm) incorporation in these selected granular soils and the respective shred contents. The exception was the slight reduction in internal angle of friction for all tyre shred Cape Flats sand composites.

The effect of varying tyre shred sizes with regards to shear strength parameters was analyzed. The results showed that the long tyre shreds for both of the selected sands showed better improvement compared to small shreds. Klipheuwel sand 50-60 mm tyre shred composites showed 41.6% of cohesion and a 2.5% higher friction angle than that for the composite samples with small tyre shreds. The difference in degree of improvement in cohesion for Cape Flats sand rubber composite was 37.2%. The results suggested that the high improvement of cohesion from Klipheuwel sand was due to the better interparticle interaction between the materials compared to that of Cape Flats sand shred composite.

The overall shear strength of sand was found to be influenced by the variation of tyre shred dosages. It was noted that the addition of tyre shred to both Cape Flats and Klipheuwel sands enhanced their shear strength up to a certain dosage then levelled off. The highest values from all categories of composites were reached at shred content of 30% by dry mass. This dosage was found to be an optimum tyre shred dosage to reinforce selected granular soils of South Africa.

The analogy in the enhancement of the overall shear strength from the two shred sizes mixed with sands was evaluated. The discrepancies in improvement were 20.9% and 19.6% higher and were obtained from Cape Flats and Klipheuwel sands each combined with 50-60 mm tyre shred in comparison to the composites contained 10-15 mm shred size. These values were obtained at the lowest normal pressure considered during shearing.

6.2 Recommendations

From the literature, the use of shredded waste tyres in highway embankment construction has performed successfully in the past. These applications consume large quantities of waste tyres and offer technical, economical and environmental benefits. Based on these, together with the results obtained from this study, mixing Cape Flats and Klipheuwel sands with tyre shreds to generate the lightweight fill material for the construction of an embankment project is highly recommended as an alternative option.

Further investigations including but not limited to compaction characteristics and permeability of the tyre shreds sand composites, chemical tests on tyre shreds for potential leaching problems, compressibility study on the use of tyre shreds to modify the geotechnical properties of other types of soils of South Africa such as clays or silts are recommended. The construction of a full-scale field test embankments made of tyre shreds and selected granular soils is recommended to evaluate its performance and strengthen the proposed guidelines which can be followed during the execution of tyre shreds soil embankment project.

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Appendices

A. Characterization tests results

A.1 Natural water content

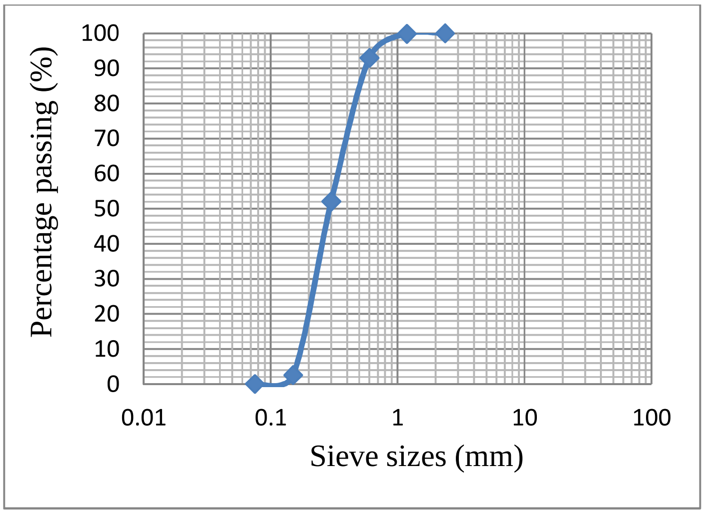
Klipheuwel sand

Can No	1	2	3
Mass of can (g)	100.2	108.4	100.4
Mass of wet soil + can (g)	400.3	408.5	400.5
Mass of dry soil + can (g)	392.8	401.0	392.9
Mass of dry soil (g)	292.6	292.6	292.5
Mass of water (g)	7.5	7.5	7.6
Water content (%)	2.56	2.56	2.6
Average water content (%)	2.57		

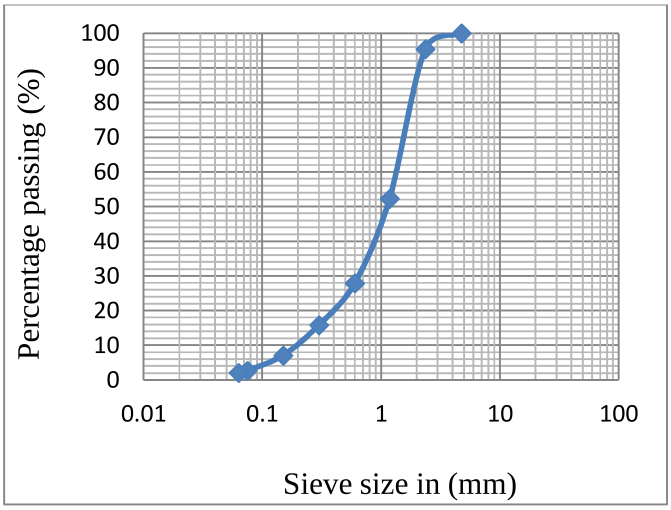
Cape Flats sands

Can No	1	2	3
Mass of can (g)	93	123.5	109.8
Mass of wet soil + can (g)	393.1	423.6	409.8
Mass of dry soil + can (g)	382.8	413.3	399.8
Mass of dry soil (g)	289.8	289.8	290
Mass of water (g)	10.3	10.3	10
Water content (%)	3.55	3.55	3.35
Average water content (%)	3.5		

A.2 Sieve analysis

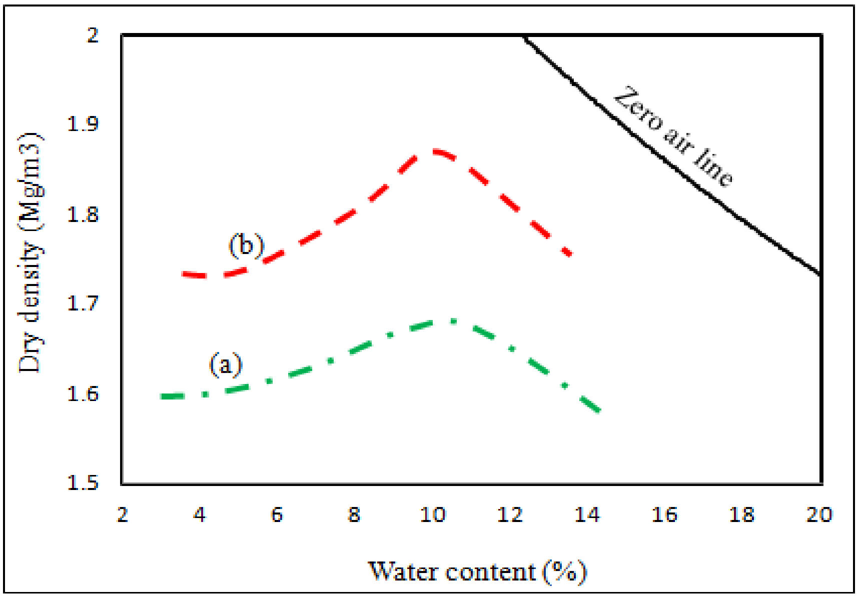


Particle grading curve for Cape Flats sand



Particle grading curve for Klipheuwel sand

A.3 Standard proctor test results



Compaction curve for (a) Cape Flats sand and (b) Klipheuwel sand

A.4 Particle density

Cape Flats sand

Test No	1	2	3
mass of bottle + soil + water m3 (g)	87.242	87.932	91.610
mass of bottle + soil m2 (g)	40.204	39.340	41.685
mass of bottle full of water m4 (g)	83.360	84.490	87.432
mass of bottle m1 (g)	33.852	33.791	34.984
mass of soil m2 - m1 (g)	6.352	5.549	6.701
mass of water in full bottle m4 - m1 (g)	49.508	50.699	52.448
mass of water used m3 - m2 (g)	47.038	48.592	49.925
volume of soil particles (m4 - m1) - (m3 - m2) mL	2.47	2.107	2.523
particle density ρs = ρL*(m2 - m1)/((m4-m1)-(m3-m2)) (Mg/m3)	2.61	2.63	2.62
Average value of particle density, ρs (Mg/m3)	2.62		

Klipheuwel

Test No	1	2	3
mass of bottle + soil + water m3 (g)	93.162	89.552	89.496
mass of bottle + soil m2 (g)	44.898	43.850	42.502
mass of bottle full of water m4 (g)	87.273	83.345	84.695
mass of bottle m1 (g)	35.339	33.850	34.707
mass of soil (m2 - m1) (g)	9.559	10	7.807
mass of water in full bottle (m4 - m1) (g)	51.934	49.495	49.988
mass of water used (m3 - m2) (g)	48.264	45.702	46.994
volume of soil particles (m4 - m1) - (m3 - m2) mL	3.67	3.793	2.994
particle density ρs = ρL*(m2 - m1)/((m4-m1)-(m3-m2)) (Mg/m3)	2.605	2.64	2.61
Average value of particle density, ρs (Mg/m3)	2.62		

Tyre shreds passing 2 mm test sieves

Test No	1	2	3
mass of bottle + shreds+ water m3 (g)	88.356	84.859	88.179
mass of bottle + shreds m2 (g)	43.447	39.858	43.355
mass of bottle full of water m4 (g)	88.673	84.859	88.179
mass of bottle m1 (g)	36.595	34.703	36.825
mass of shreds m2 - m1 (g)	6.852	5.155	6.53
mass of water in full bottle m4 - m1 (g)	52.078	50.156	51.354
mass of water used m3 - m2 (g)	44.909	45.001	44.824
volume of shreds particles (m4 - m1) - (m3 - m2) mL	7.169	5.155	6.53
particle density ρs = ρL*(m2 - m1)/((m4-m1)-(m3-m2)) (Mg/m3)	0.96	1	1
Average value of particle density, ρs (Mg/m3)	1		

A.5 Limiting densities

Maximum dry density (densest state) from vibratory compaction

Klipheuwel

No	1	2	3
Volume of mould m^3	0.002314	0.002314	0.002314
Mass of mould (kg)	15.96	15.96	15.96
Mass of mould +soil (kg)	20.64	20.64	20.64
Mass of soil (kg)	4.68	4.68	4.68
Density (kg/m^3)	2022.5	2022.5	2022.5
Average maximum density(kg/m^3)	2022.5		

Cape Flats

No	1	2	3
Volume of mould	0.0022266	0.0022266	0.0022266
Mass of mould (kg)	15.95	15.95	15.95
Mass of mould +soil (kg)	20.06	20.02	20.045
Mass of soil (kg)	4.11	4.07	4.095
Density (kg/m^3)	1845.86	1827.9	1839.1
Average maximum density(kg/m^3)	1837.6		

Loose density (loosest state)

Cape Flats

No	1	2	3
Volume of mould	0.000946597m^3	0.000946597m^3	0.000946597m^3
Mass of mould (kg)	4.440	4.440	4.440
Mass of mould +soil (kg)	5.791	5.787	5.783
Mass of soil (kg)	1.351	1.347	1343
Density (kg/m^3)	1461.76	1423	1418.76
Average maximum density(kg/m^3)	1434.5		

Klipheuwel

No	1	2	3
Volume of mould	0.000946597	0.000946597	0.000946597
Mass of mould (kg)	4.440	4.440	4.440
Mass of mould +soil (kg)	5.891	5.887	5.896
Mass of soil (kg)	1.451	1.447	1.456
Density (kg/m^3)	1532.9	1528.6	1538.1
Average maximum density(kg/m^3)	1533.2		

B. Shear strength test (example)

The format of shear stress data as obtained from the software for unreinforced Cape Flats sand for vertical pressure of 50 kPa

No	Elapsed Time (min)	Vertical Stress (kPa)	Vertical Displace (mm)	Horizontal Stress kPa	Cumulative Displace (mm)	correct stress kPa
1	0	50.05	0.5105	0.2521	0	0
2	0.08	49.86	0.5184	1.668	0.01077	1.4159
3	0.1	49.8	0.5215	3.084	0.02001	2.8319
4	0.11	49.86	0.5231	4.693	0.03079	4.4409
5	0.13	49.58	0.5246	6.128	0.04002	5.8759
6	0.15	49.57	0.5246	7.447	0.05387	7.1949
7	0.2	49.7	0.5278	10.86	0.1016	10.6079
8	0.3	49.8	0.5325	15.75	0.2016	15.4979
9	0.39	49.9	0.5356	19.12	0.3002	18.8679
10	0.47	49.9	0.5372	21.82	0.4002	21.5679
11	0.55	50.01	0.5356	24.16	0.5018	23.9079
12	0.64	50.21	0.5419	26.39	0.6019	26.1379
13	0.72	50.09	0.5356	27.97	0.7034	27.7179
14	0.79	50.13	0.5293	29.42	0.802	29.1679
15	0.87	50.25	0.5246	30.87	0.902	30.6179
16	0.96	50.19	0.5231	32.17	1.004	31.9179
17	1.04	50.15	0.5168	33.26	1.101	33.0079
18	1.12	50.15	0.5074	34.38	1.202	34.1279
19	1.2	50.07	0.4949	35.22	1.305	34.9679
20	1.27	50.11	0.487	36.05	1.402	35.7979
21	1.35	50.07	0.4667	36.83	1.504	36.5779
22	1.42	50.07	0.451	37.56	1.601	37.3079
23	1.51	50.07	0.4416	38.38	1.706	38.1279
24	1.59	50.46	0.415	39.21	1.802	38.9579
25	1.67	50.32	0.404	39.8	1.906	39.5479
26	1.75	50.23	0.3868	40.38	2.009	40.1279
27	1.84	50.15	0.3727	40.88	2.104	40.6279
28	1.91	50.09	0.3586	41.35	2.206	41.0979
29	1.98	50.09	0.3461	41.83	2.304	41.5779
30	2.05	50.01	0.3304	42.22	2.401	41.9679
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