Analysing the Behaviour of Soil Reinforced with Polyethylene Terephthalate (PET) Plastic Waste.

By

John Groover Luwalaga (17188040)

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Supervisor: Dr Marius De Wet

Senior Lecturer, Civil Engineering, Stellenbosch University

Co-Supervisor: Dr P. V. Vijay

Assistant Professor, Civil & Environmental Engineering, West Virginia University

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ABSTRACT

Environmental issue effects like natural resource depletion, climatic change and global warming have significantly influenced the innovations in material science and technology with the aim of attaining sustainable materials to avert calamities. Conservation and sustainability of quality natural materials in the civil engineering field is a challenge currently due to their scarcity brought about by increased population, rapid development of cities and continued depletion of such materials. On the other hand, currently there is a boom in the plastic industry as most of the sectors like agriculture, automotive, education, government, health, marketing and advertising, transportation, to mention but a few use plastic products. Due to the wear and tear of the plastic products there is a challenge in handling the non-biodegradable plastic waste by the solid waste management field.

This research has been conducted to mitigate the challenges faced by the civil engineering field and the solid waste management field by analysing sand-PET (Polyethylene Terephthalate) plastic waste composite. The research was conducted at Stellenbosch University (SUN), using materials like PET plastic waste flakes from the Kaytech factory and sand of medium dense, clean quartz uniformly graded with round shaped particles which is predominant in Western Cape region, South Africa.

Furthermore, the aim of this research was achieved through the experimental work which included particle size distribution testing, compaction testing, California Bearing Ratio (CBR) testing, and direct shear box testing. Sand was reinforced with randomly mixed PET plastic waste flakes of different varying percentages of 12.5%, 22.5% and 32.5%, and tests were performed on unreinforced sand and sand-PET plastic waste composite specimens. It was established that sand reinforced with 22.5% of PET plastic waste flakes gave an optimum value of PET plastic waste giving a maximum percentage increase in friction angle of 15.32%, hence the highest shear strength with an angle of friction equal to 44.4^{o}. Furthermore, the optimum maximum dry density of $1547 kg/m^3$ resulted into a maximum friction angle of 44.4^{o}. It was concluded that the appropriate percentage of PET plastic waste to use while reinforcing sandy soil used in this study is 22.5%.

Therefore, it was established that reinforcing soil with 22.5% PET plastic waste can improve its bearing capacity and CBR. The soil-22.5% PET plastic waste composite can be applicable in civil engineering applications like as material for foundation bearing strata, light road sub-base or subgrade, and as backfill materials for foundations and retaining walls. Additionally, the study has established that reinforcing soil with 22.5% PET plastic waste is sustainable, hence mitigating the social, economic and environmental impacts by reducing need for natural resources, no land filling of PET plastic waste, and increased utilisation of poor quality construction soils like sand. Furthermore, calculations where done and found out that reinforcing sand with 22.5% reduced the width of the foundation by 3% which made it more economical compared to unreinforced sand.

OPSOMMING

Omgewings verwante probleme soos die vermindering van natuurlike hulpbronne, klimaatsverandering en globale verwarming het die materiaal wetenskap en tegnologie beïnvloed wat verwant hou met die gebruik van volhoubare materiale om natuurrampe te voorkom. Beskerming en die volhoubaarheid van kwaliteit natuurlike van materiale in siviele ingenieurswese is tans ŉ uitdaging weens die skaarsheid asevolvan toenemende bevolking, vinnige ontwikkeling van stede en toenemende gebruik materiale verwant aan die bedryf. Daar is ook ŉ geweldige groei in die plastiek industrie. Meeste van die sektore soos die landbou, motorindustrie, onderwys, regeringsinstansies, gesondheid, bemarking en advertensies, vervoer en vele andere gebruik plastiek. As gevolg van die gebruik van plastiekprodukte is daar ŉ uitdaging in die hantering van nie-afbreekbare plastiek afval deur die vasteafvalindustrie.

Die navorsing was gedoen om van die uitdagings te verlig in die siviele ingenieurs en vaste afval industrie. Die uitwerking van versterkde sand met Polyethylene Terephthalate (PET) plastiek afval was geanaliseer. Die navorsing was gedoen by Universiteit Stellenbosch (US), deur gebruik te maak van materiale soos PET plastiekafvalvlokkies vanaf die Kaytech fabriek en medium digte sand, was skoon uniforme gegradueerde kwarts met ronde gevormde partikels is wat volop is in die Wes Kaap provinsie, Suid Afrika.

Die resultate van die navorsing was verkry deur eksperimentele werk wat insluit toetse soos; partikel grootte verspreiding -, kompaksie -, Kaliforniese Dravermoë-Verhouding (KDV) -, en direkte skuifkas toetse. Sand was versterk met willekeurige gemengde PET plastiekvlokkies van verskillende persentasies van onder andere 12.5%, 22.5% en 32.5%, en toetse was gedoen op onversterkte sand en sand-PET plastiek-afval kombinasie. Dit was vasgestel dat sand versterk met 22.5% PET plastiekvlokkies die optimale waarde gegee het met ŉ verhoging in die wrywingshoek van 15.32% wat gevolglik lei tot die hoogste sterkte met ŉ wrywingshoek van 44.4^o. Optimale maksimum droë digtheid van 1547 kg/m^3 het gelei tot ŉ maksimum wrywingshoek van 44.4^o. ŉ Gevolgtrekking was gemaak dat die gepaste persentasie van PET plastiekafval om te gebruik tesame met die versterking van sanderige grond in die studie 22.5% is.

Deur grond te versterk met 22.5% PET plastiek afval kan dit die grond se dravermoë en KDV verbeter. Die grond-22.5% PET plastiek kombinasie kan toegepas word in siviele ingenieurs toepassings soos materiaal vir funderingslaag, ligte pad sub-basis of en as opvul materiaal vir fondasies en keermure. Die studie het ook getoon dat deur grond met 22.5% PET plastiek afval te versterk volhoubaar is. Dit is volhoubaar in so opsig dat die druk verminder op sosiale, ekonomiese en omgewings impakte deur die vraag na natuurlike hulpbronne te verminder, die nodigheid van PET plastiek afval op vullisstostingsterreine uitskakel, en die verhoogde gebruik van swak gehalte konstruksie materiaal soos sand.

DECLARATION

By submitting this thesis electronically, I, John Groover Luwalaga, with Stellenbosch University student number 17188040, hereby "declare that the entirety of the work contained therein is my own original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification."

Date: March 2016

DEDICATION

This research is dedicated to advocates of sustainability in civil engineering field.

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More so, I owe a heartfelt note of gratitude to all my loved ones – my wife, children, parents, siblings, in-laws, relatives and friends for all your patience and support. Special thanks to my wife who sacrificed so much to see me accomplish this research project. Lastly but not least, I thank the Almighty God for the good health, wisdom, knowledge, support and protection. From far you have brought me and far you are taking me. May the Glory and Honour be unto You.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND NOTATIONS

AASHTO	American Association of State Highway and Transportation Officials
B	Pad width
BS	British Standard
CBR	California Bearing Ratio
C_c	Coefficient of curvature
C_u	Uniformity coefficient
d	Pad depth
D	Pad depth
D_{10}	10% of the sample is finer for the particle size diameter
D_{30}	30% of the sample is finer for the particle size diameter
D_{60}	60% of the sample is finer for the particle size diameter
DEA	Department of Environment Affairs
e	Eccentricity
EC	European Commission
γ_c	Unit weight of concrete
GEO	Geotechnical Actions
γ_G	Geotechnical (unfavourable) partial factor
γ_Q	Geotechnical (unfavourable) partial factor
G_{vk}	Permanent vertical load
h	height of load (Q_h)

HDPE	High Density Polyethylene
ID	Identification
i_γ	Loading inclination factor for self-weight of soil
i_q	Load inclination factor for overburden pressure
ITS	Indirect tensile strength
LDPE	Low Density Polyethylene
M_d	Design moment
MDD	Maximum dry density
MSW	Municipal Solid Waste
N_γ	Bearing capacity factor for self-weight of soil
N_q	Bearing capacity factor for overburden pressure
OMC	Optimum moisture content
OPC	Ordinary Portland cement
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
Q_{hd}	Total horizontal load
Q_{hk}	Variable horizontal load
Q_{vk}	Variable vertical load
R_{vd}	Design drained bearing resistance ()

SA	South Africa
SABS	South African Bureau of Standards
SANS	South African National Standards
SEM	Scanning electron microscopy
S_γ	Shape factor for self-weight of soil
SPI	Plastic Industry Trade Association
S_q	Shape factor for overburden pressure
STR	Structural Resistance Actions
STR-P	Structural Resistance Permanent Actions
SUN	Stellenbosch University
TMH	Technical Methods for Highways
UCS	Unconfined compressive strength
UCT	University of Cape Town
UKDT	United Kingdom Department of Transport
UN	United Nations
USCS	Unified soil Classification System
USMSW	United States Municipal Solid Waste
V_d	Total vertical design load

CHAPTER 1: RESEARCH INTRODUCTION AND BACKGROUND

1.1 Introduction and Background of the Thesis.

Worldwide, waste management is still a challenge brought about by urbanisation, population increase, and industrial growth. The conventional methods of disposing of solid wastes are landfill, incineration and recycling. However, landfill spaces are reducing, incineration process emits hazardous gases, and recycling seem to be expensive and laborious (Sobhee 2010; Williamson 2012; Schaffler 2011).

The current sustainable approach is 'reduce, reuse and recycle.' However, it does not address properly the abandoned waste which pollutes the environment.

Research and advanced technology in the current knowledge economy have enhanced technological innovations in material science. This has led to the increase in the manufacture of various products like plastic. (SPI 2014) classifies plastic as follow:

1. Polyethylene Terephthalate (PET),
2. High-Density Polyethylene (HDPE),
3. Polyvinyl Chloride (PVC),
4. Low-Density Polyethylene (LDPE),
5. Polypropylene (PP),
6. Polystyrene (PS), and
7. Others (like polyester, polyamides, and polycarbonate).

Sectors that use plastic are packaging, automotive, agriculture, furniture, sport, electrical and electronics, health and safety, building and construction, and consumer and household appliances (EC 2011, SPI 2014, Barendse 2012, PlasticsEurope 2015). Increase in plastic products has resulted in an increase in plastic waste, which is a challenge to waste management authorities. Statistics on plastic manufacture is indicated in Figure 1.1.

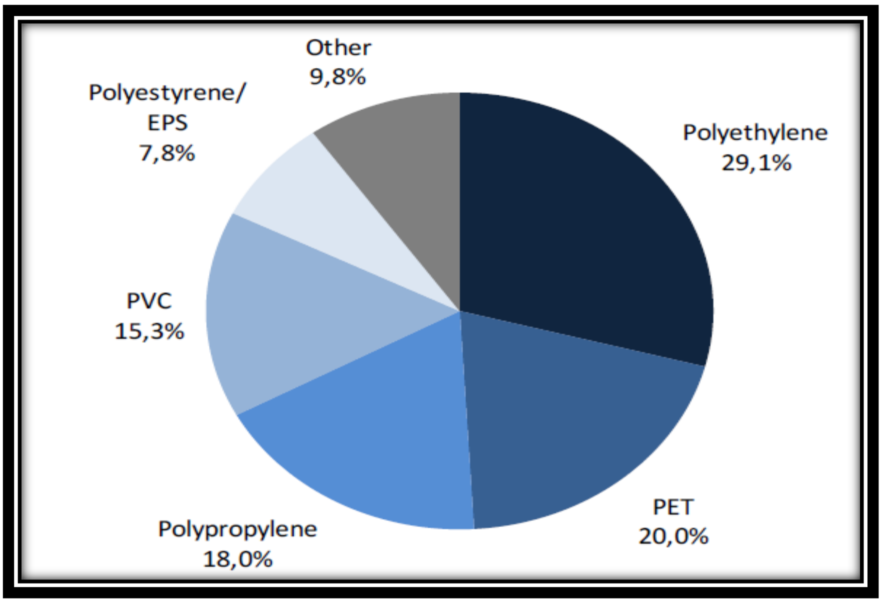


Figure 1.1: Global plastic capacity in 2008 (EC 2011)

PET plastic waste recycling benefits the society, economy and environment (Urban Earth 2013, Greenwald 2013). In South Africa, PET plastic waste is recycled into fibre for making bedcovers, cushions, fleece coats, automotive parts, insulation, geotextiles and new PET plastic bottles (Amanda 2012).

However, EC, (2011) highlights the demerit of plastic waste as being non-bio-degradable, pose a health risk, and difficult to reuse or recycle in practice.

Figure 1.2: a) PET plastic bottles and b) PET plastic waste flakes (primary source)

Civil engineering structures transfer their loads through foundations onto the soil. The structures need to be erected on the soil of good strength to ensure their serviceability. Due to urbanisation and modernity, civil engineering structures like roads, railways, dams, retaining walls, tunnels, embankments, and buildings are on demand. The demand for good quality soil and other building materials is high. In some places, good quality natural soil is depleted and importing it from long distances is costly and time-consuming.

Social, economic, and environmental challenges have stimulated researchers to find techniques to improve the quality of geotechnical materials. Research has shown that, reinforcing poor quality soil with fibre materials like PET plastic waste, greatly improves its performance and durability (Consoli et al. 2009). However, this technique has received little acceptance in the civil engineering field.

1.2 Research Questions

This research analysed the engineering behaviour of soil reinforced with PET plastic waste. Research questions pertaining to the study included but not limited to the following:

i) Does soil-PET plastic waste composite improve soil quality and performance?
ii) What percentage of PET plastic waste (by weight of soil) is optimum to improve the performance and durability of the proposed sandy soil?
iii) What laboratory experiments are required/carried out on soil, water, and PET plastic waste?
iv) What laboratory experiments are required/carried out on soil-PET plastic waste composite?
v) What are the applications of soil reinforced with PET plastic wastes in the civil engineering field?
vi) How is soil-PET plastic waste composite sustainable?

1.3 Research Objectives

As previously mentioned, the subject of reinforcing soil with PET plastic waste has been tackled by a number of researchers. Various theoretical and laboratory-based approaches have been developed to acquire an understanding of the subject. However, according to the published literature, the knowledge gap is still wide as far as reinforcing soil with PET plastic waste is concerned. This, therefore, provided a solid basis to conduct this study.

The main objective of the research was to analyse the engineering behaviour of soil reinforced with PET plastic waste. However, the following were the specific objectives formulated with the goal of achieving the main objective:

i) To evaluate the mechanical properties by carrying out laboratory experiments on soil reinforced with PET plastic waste. Such laboratory experiments included particle size distribution test, compaction test, direct shear box test, and California Bearing Ratio (CBR).
ii) To propose applications of soil reinforced with PET plastic waste in the civil engineering field particularly in the geotechnical engineering field.
iii) To discuss the social, economic, and environmental impact of soil reinforced with PET plastic waste.

1.4 Problem Statement

PET plastic wastes are harmful to the economy, society and environment in such a way that: incineration (during energy recovery) releases toxic gases, makes land infertile, pollutes water bodies, blocks the drainage channels, and littered PET plastic wastes make the landscape look unpleasant. However, the demand and supply of PET plastic products is on the rise. Furthermore, poor quality soil exhibits low strength, high permeability, and high compressibility, which are a nightmare to every civil engineer as such leads to the collapse of structures.

Soil reinforcement is the process of integrating oriented or randomly distributed discrete fibres, like shredded plastics, tyre shreds, and metal pieces in the soil (Anagnostopoulos et al. 2013). The importance of reinforcing soil is to increase bearing capacity and stability, and reduce lateral deformation and settlement of the poor quality geotechnical soil (Zaimoglu & Yetimoglu 2011). However, this technique is barely used in improving the performance and durability of geotechnical soil of poor quality (Tang et al. 2006).

(Gray & Ohashi 1983, Gray & Al-Refeai 1986, Ranjan et al. 1994, Benson & Khire 1994, Consoli et al. 2002, Yetimoglu & Salbas 2003, Park & Tan 2005, Tang et al. 2006, Akbulut et al. 2007, Sadek et al. 2010, Consoli et al. 2010, Babu & Chouksey 2011, Acharyya et al. 2013, Anagnostopoulos et al. 2013, Kalumba & Chebet 2013) researched on reinforcing soil with plastic waste. In their findings, it was noted that reinforcing soil with plastic waste:

i) Increases the strength of the soil,
ii) Improves California Bearing Ratio of the soil,
iii) Reduces the compressibility of the soil,
iv) Decreases the coefficient of permeability, and
v) Changes brittle cemented soil to a ductile state.

This research was inspired by the increased demand and supplies of plastic products which results into enormous unmanaged plastic waste having a negative impact on the environment, society and economy. Furthermore, the rapid increase in population leading to increased demand of infrastructures yet there is a decrease in the good quality of civil engineering construction materials like sand.

As mentioned earlier in Chapter 1.1, the seven (7) classifications of plastics are: Polyethylene Terephthalate (PET), High-Density polyethylene (HDPE), Polyvinyl chloride (PVC), Low-Density polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and Others (like polyester, polyamides, and polycarbonate). Many researchers have explored the possibilities of reinforcing soil with different types of plastics as provided in Table 1.1.

Table 1.1: Soil and plastic types different researchers have used.

Researcher	**Soil type**	**Plastic type**
Gray & Ohashi (1983)	Sand	Polyvinyl chloride (PVC)
Benson & Khire (1994)	Sand	High density polyethylene (HDPE)
Yetimoglu & Salbas (2003)	Sand	Polypropylene (PP)
Park & Tan (2005)	Sandy silt	Polypropylene (PP)
Akbulut et al. (2007)	Clay	Polyethylene & Polypropylene (PP)
Consoli et al. (2010)	Sand	Polypropylene (PP)
Acharyya et al. (2013)	Clay and sand	Polyethylene Terephthalate (PET)
Anagnostopoulos et al. (2013)	Sandy silt	Polypropylene (PP)
Kalumba & Chebet (2013)	Sand	High density polyethylene (HDPE)

However, this research focused on the analysis of engineering behaviour of soil reinforced with Polyethylene Terephthalate (PET) plastic waste (Athanasopoulos 1993). This was because PET plastics are stiffer and stronger, making it suitable as a reinforcement material to poor quality soils. Basing on the analysis of the research results, suggestions to the applications of soil reinforced with PET plastic waste in the civil engineering field have been drawn.

Furthermore, the research focused on the sustainability of PET plastic waste management by reinforcing soil with up to 32.5% (by weight of dry soil) of PET plastic waste. Sustainability according to UN is defined as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Johann et al. 1987). Sustainability encompasses approaches like economic, environmental and social development or social (Johann et al. 1987, Ciegis et al. 2015). Reinforcing soil with PET plastic waste is another way of ensuring that human and other forms of life on earth flourishes forever. This research aimed at mitigating the challenges faced by civil engineering and waste management fields, which meets the sustainability criteria as seen in Figure 1.3. The sustainability issue has not been the focus of the previous researchers, and there exists a knowledge gap on reinforcing soil with PET plastic waste.

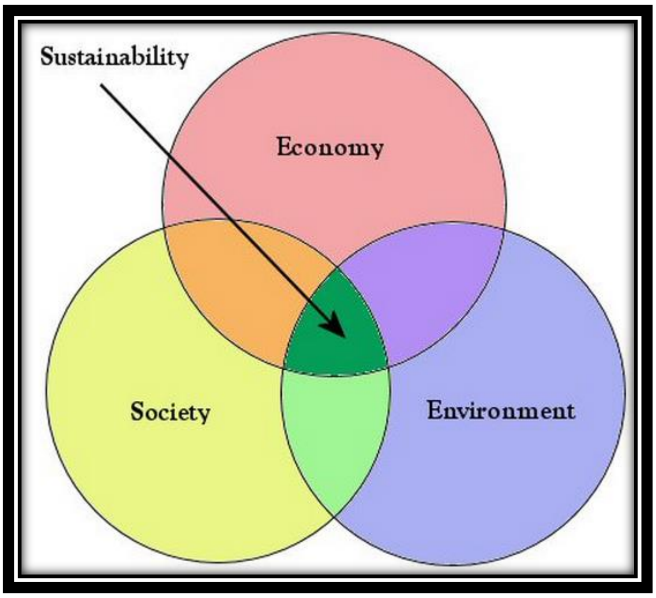


Figure 1.3: UN sustainability model (Johann et al. 1987)

1.5 Significance of the Thesis

Findings of the research study have expanded on the literature and data regarding reinforcing soil with PET plastic waste. Furthermore, mitigating the challenges faced by waste management and civil engineering fields. The sectors to benefit from this research include but are not limited to:

i) Waste management field will benefit by the reduction of PET plastic waste which is normally taken to landfills if not recycled or littered around and hinders the proper flow of water which leads to poor drainage.

ii) Civil engineering field will benefit by the improvement of the performance and durability of poor quality soil which can be used in the construction of civil engineering structures like roads, railways, dams, retaining walls, tunnels, slopes, embankments, and buildings.

1.6 Research Scope

This research considered a laboratory analysis of the engineering behaviour of soil reinforced with PET plastic waste. The research scope included the following:

i) Local fine sand from Stellenbosch, South Africa, was used as a representative of geotechnical soil.

ii) PET plastic waste flakes from Keytech factory located in Atlantis, South Africa were used in varying proportions.

iii) Laboratory experiments on the sand and sand-PET plastic waste composite specimens have been carried out to determine their engineering physical properties. These tests include particle size distribution, compaction, CBR and direct shear box tests. Only particle size distribution tests on PET plastic flakes was carried out.

1.7 Research Limitations

The research has not tackled the theoretical aspects of recycled plastic waste management, soil stabilisation, and type and purity of water. Some of the experiments on PET flakes (like tensile modulus, tensile strength at break, elongation at break, flexural strength, flexural modulus, heat deflection, and melting point) were not conducted due to lack of laboratory equipment, available published data on the index and mechanical properties of PET fibres has been quoted. Also, water used during the laboratory experiment program was assumed to be potable water suitable to be used while mixing soil and soil-PET plastic waste composites, hence no tests was conducted on it. Also, field reinforcement of soil has not been handled.

Furthermore, since the soil type adopted for this research was cohesionless soil, some of the tests could not be performed on soil specimens and soil-PET plastic waste specimens. Such tests included indirect tensile strength (ITS), unconfined compressive strength (UCS), triaxial shear test, and others. During laboratory experimenting, some specimens of soil and soil-PET plastic waste were stabilised with 3%, 6% and 9% OPC cement and some tests were performed on it for comparison purposes. Since cement stabilisation of soil and soil-PET plastic waste was not part of this research scope the results are provided in the Appendix for related research in the future.

1.8 Layout of the Thesis

Chapter 1: Research Introduction and Background

The first chapter describes the general background of soil reinforced with PET plastic waste. The chapter highlights what has been covered on the subject and identifies the knowledge gap. It also outlines the research background, problem statement, research questions, and research objectives, significance of the research, research scope, and limitations among others.

Chapter 2: Literature Review

The second chapter presents a summary of published literature on soil reinforced with PET plastic waste. It further exhibits theoretical and laboratory-based approaches developed by various researchers.

Chapter 3: Research Materials; Apparatus; and Methodology

The adopted research methods and the laboratory investigation program are outlined in this chapter. Standard tests conducted to characterise research materials are presented. Moreover, different procedures followed while conducting this research are presented in this chapter.

Chapter 4: Presentation of Test Results and Discussion

The test results and discussion of research findings are presented in this chapter.

Chapter 5: Research Practical Significance

The practical applications of soil reinforced with PET plastic waste are presented in this chapter. Also in this chapter, the social, economic and environmental impact of the research are discussed.

Chapter 6: Conclusions and Recommendations

Last but not least, the sixth chapter brings out the general conclusions of the study and provides recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter looks at previous publications of different researchers on the subject matter. More so, this chapter presents an overview of plastics, PET, fibre-reinforced soil, and case studies of fibre-reinforced soils. Furthermore, the chapter highlights the behaviour of soil-PET plastic waste composite and potential applications of soil reinforced with PET plastic waste in civil engineering. Lastly, a summary and conclusions discussed in this chapter are listed.

2.2 Plastics

2.2.1 Introduction to plastics

Plastics are resins or polymers that have been synthesised from petroleum or natural gas derivatives (EPA 1990). The term 'plastics' encompasses a wide variety of resins each offering unique properties and functions. In addition, the properties of each resin can be modified by additives (EPA 1990). Different combinations of resins and additives have allowed the creation of a wide range of products meeting a wide variety of specifications (Randall 1991; EPA 1990).

Polymers are chemically inert large molecules made up of repeating chemical units (monomers) that bind together to form long chains or polymers (Crawford 2007, EC 2011). Polymers are pure materials formed by the process of polymerisation, though cannot be used on their own, but additives are added to form plastics (Crawford 2007). These additives include: antistatic agents, coupling agents, fillers, flame retardants, lubricants, pigments, plasticisers, reinforcements, and stabilisers (Harper 2006). Pure polymer may include silk, bitumen, wool, shellac, leather, rubber, wood, cotton and cellulose (Crawford 2007, Stephen 2009).

Randall (1991) and EPA (1990), argues that plastic production and use has grown because of the many advantages plastics offer over other more traditional materials. A few of the desirable intrinsic properties of plastics include (EPA 1990):

i) Design flexibility – plastics can be modified for a wide variety of end uses,
ii) High resistance to corrosion,
iii) Low weight, and
iv) Shatter resistance.

2.2.2 Categories of plastic

The Plastic Industry Trade Association (SPI), identifies plastic into seven (7) broad categories and Table 2.1 summarises their detailed identification and respective applications.

Table 2.1: Plastic identification and applications (EC 2007; Jill 2014; SPI 2014; Kaytech 2014; GangaRao et al. 2006)

Plastic ID #	Plastic ID code	Plastic	Applications
1	1 PET	Polyethylene Terephthalate	• Make bottles for water, beverage, oil, vinegar, medicine products, peanut butter, cleaning products, and lubricants. • Make pouch films for sauces, dried soups, and cooked meals; lidding films for heat sealing. Also, blisters, ropes, and combs. • PET plastic waste can be recycled into tote bags, carpets, fleece jackets, luggage, clothing, erosion blankets, bidim, geomesh,
2	2 HDPE	High Density Polyethylene	• Make bottles for dairy products, juice, sauces, lubricants, detergents, bleaches, shampoos, and conditioners. • Make caps and closures of bottles, jars, pots, and cartons. • Make carrier bags and garbage bags. • HDPE plastic waste can be recycled into plastic crates, plastic lumber, buckets, picnic tables, recycling containers, benches, pens, dog houses, flower pots and floor tiles.
3	3 PVC	Polyvinyl Chloride	• Make bottles for oil, vinegar, lubricants, shampoos, and detergents. Also, plumbing pipes and tiles. • Make caps and closures of bottles, jars, pots, cartons. • Make trays for salads, desserts, confectionery, meat, and poultry. Also, blisters. • PVC plastic waste can be recycled into mobile homes, gutters, mats, garden hose, binders, cassette trays, electrical boxes, floor tiles, cables, traffic cones.
4	4	Low Density Polyethylene	• Make caps and closures of bottles, jars, pots, and cartons. • Make squeezable bottles. • Make carrier bags, garbage bags, and sandwich bags. • Make plastic cling stretch wrap film for food.

	LDPE		• LDPE plastic waste can be recycled into garbage cans, lumber furniture, floor tiles, shipping envelopes, and landscape boards.
5	**PP**	Polypropylene	• Make bottles for syrup, juice, and sauces. Also, pouch films for wrapping sauces, dried soups, and cooked meals. • Make films for wrapping, packets, and sachets. • Make trays for vegetables, dairy products, and soups. • Make cups, pots, plastic diapers, Tupper ware, margarine containers, yogurt boxes, and tubs. • PP plastic waste can be recycled into ice scrapers, bins, oil funnels, battery cables, brooms, brushes, trays, and automobile battery cases.
6	**PS**	Polystyrene	• Make trays for confectionery and dairy products. • Make disposable coffee cups, plastic food boxes, pots, tubs, plastic cutlery, packaging foam and packaging peanuts. • PS plastic waste can be recycled into thermal insulation, light switch plates, thermometers, egg cartons, vents, cups, desk trays, license plate frames and rulers.
7	**O**	Others like: Polyester, Polyamides, Polycarbonate,	• Polycarbonate plastic is used to make baby bottles, water tanks, compact discs and medical storage containers. • Polycarbonate plastic waste can be recycled into plastic lumber.

2.2.3 Applications of plastic in civil engineering field

Plastic has numerous applications in the different sectors like: construction, packaging, automotive, furniture, sports, electrical and electronics, health and safety, consumer and household appliances. In the civil engineering field, plastic is used as components in the construction of bridges, buildings, roads and highways, ports and terminals, railroads, landscaping, landfills, water retaining structures; etcetera (McLaren 2003). The plastic components that are used in the construction industry include: sound barriers, guide rails/guard rails, piles, piers, railroad ties, pallets, curbs/wheel stops, bulk heads, docks, board walks and walkways, bicycle racks, foundation backfills, erosion control, and construction materials separations.

In civil engineering for a material to qualify as a good construction material it should be durable, strong, ductile, easy to install, fire resistant, and inexpensive. However, Table 2.2 shows the characteristics of plastic compared with other construction materials, and since this research focused on reinforced soil with Polyethylene Terephthalate (PET) plastic waste, its properties are outlined in Table 2.3. Furthermore, the following are the qualities of construction plastics (BPF 2011).

i) Plastics are strong, and can resist knocking and scratching.
ii) Plastics are durable, making them withstand harsh weather.
iii) Plastics are easy to install and move around.
iv) Plastics offer design freedom in that it can be turned into any shape, and plastic products can be coloured, opaque, or transparent, rigid or flexible.
v) Plastics promote energy efficiency in buildings since they are low conductors of heat, and can achieve a tight seal.
vi) Plastic products have low maintenance cost and do not need painting.
vii) Plastic building products can be recycled with low energy input and can as well be turned into energy.
viii) Constructing using plastic products is cost effective since plastic is durable, of good quality, have low maintenance cost and saves labour.

Table 2.2: Characteristics of plastic compared with other construction materials (McLaren 2003).

	Plastic	**Steel**	**Concrete**	**Wood**
Ultraviolet resistance	Excellent (with stabilisers)	Excellent	Excellent	Excellent
Abrasion resistance	Excellent	Excellent	Good	Poor
Chemical resistance	Excellent	Fair	Good	Good
Fabrication	Workable with standard woodworking tools.	Specialised equipment	Formwork	Hand tools
Ozone resistance	Excellent	Excellent	Excellent	Excellent
Fire resistance	Requires frame source	Non-combustible	Non-combustible	Combustible
Stress crack performance	Excellent	Excellent	Poor	Poor
Electrical conductivity	None –conductive	Conductive	Conductive through reinforcement	Conductivity increases with moisture content
Decay potential	Non-Biodegradable	Will corrode	Degrades	Biodegradable
Resistance to marine borers	Excellent	Excellent	Excellent	Poor
Fastening materials	Metal fasteners (withdraw resistance increase with time)	Bolts/welds	Casting/inserts	Metal fasteners

2.2.4 Management of plastic wastes

"Solid waste management refers to all activities pertaining to the control of generation, storage, collection, transfer and transport, treatment and processing, and disposal of solid wastes in accordance with the best principles of public health, economics, engineering, conservation, aesthetic, and other environmental considerations" (Filemon 2008, McDougall et al. 2008).

Waste is an item (plastic, food, paper, and etcetera) rejected for being of no use or value to the owner after its intended application. McDougall et al. (2008), classify waste as follows:

i) Physical state (like solid, liquid and gaseous)
ii) Origin (like agriculture, mining, quarrying, manufacturing, industrial, construction, household, commercial, etcetera)
iii) Physical properties (combustible, compostable, and recyclable)
iv) Safety level (like hazardous, and non-hazardous)
v) Material type (like plastic, glass, metal, paper, food, etcetera)
vi) Usage (like packaging waste, food waste, etcetera)

All wastes excluding liquid and gases are termed as solid waste. Commercial solid wastes and household solid wastes together form the municipal solid waste (MSW). The MSW include plastics, organic, metals, papers, glass. MSW are usually mixed together, hence it is laborious to manage while disposing of. Solid waste management is the process of safely disposing of MSW through recycling, incineration, and landfill to avert polluting humans and environment. For this section of the chapter, attention is geared towards plastic waste management.

Most of the post-consumer plastic waste is landfilled along with municipal solid waste (EPA 1990). Plastic waste account for a large and growing portion of the municipal solid waste stream (EPA 1990). Plastics are about 7% (by weight) of municipal solid waste and a large percentage by volume estimated to be in the range of 14 to 21 percent of the waste stream (EPA 1990). Considering the trend, this amount of plastic waste is predicted to increase.

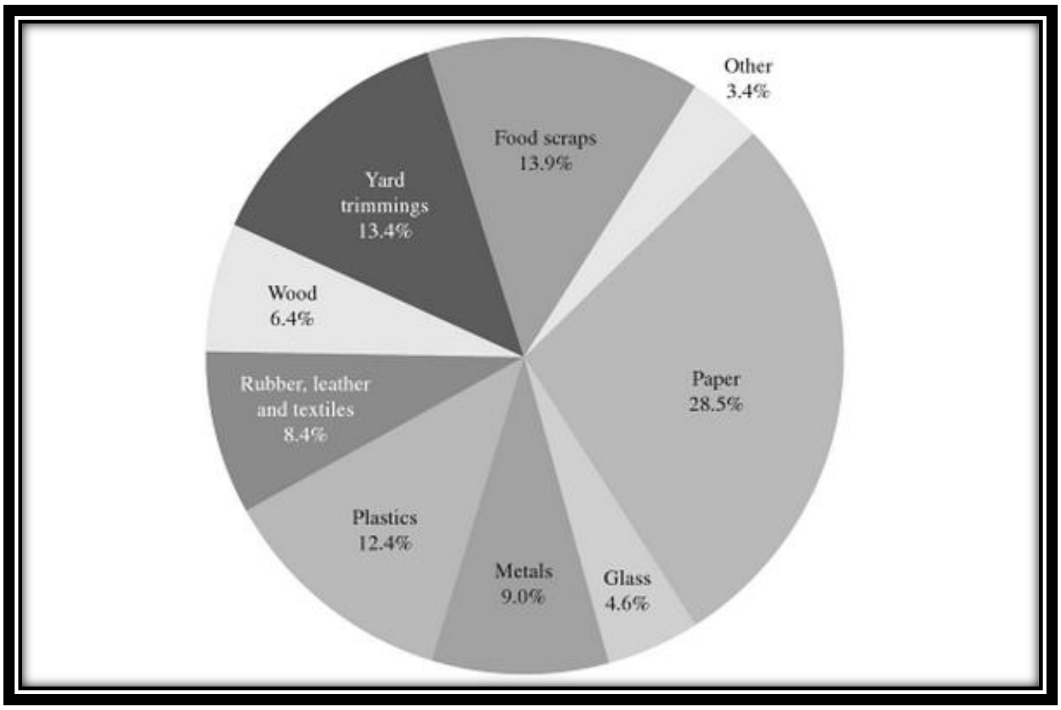


Figure 2.1: The composition of the USMSW stream of 250 million tons generated in the year 2010. Source (Andrady 2015)

Management of plastics in a landfill

Plastics are non-degradable and do not affect the structural integrity of a landfill. However, plastic wastes do affect the landfill capacity due to their large numbers and continued plastics production.

Management of plastics in an incinerator

Plastics contribute significantly to the heating value of municipal solid waste, with a heating value of three times that of typical municipal waste (Randall 1991; EPA 1990). Controversy exists regarding whether halogenated plastics (e.g., polyvinyl chloride) contribute to emission from municipal waste incinerators (EPA 1990). Analysis should be done for the emission of toxic acid gases and dioxin/furan (EPA 1990). Furthermore, investigation should be done on lead and cadmium (plastic additives) as they may contain heavy metals leading to toxicity of incinerator ash (Randall 1991; EPA 1990).

Methods for reducing impacts of plastic wastes

Source Reduction

Source reduction aims at reducing generated plastic waste amount or toxicity (EPA 1990). However, source reduction should target at reducing the entire waste stream as it becomes difficult to only reduce the amount or toxicity of a single component of waste (EPA 1990). Concentrating on reducing only one waste component say plastic waste, may escalate the amount and toxicity of the entire waste stream (EPA 1990). Therefore, waste management teams should plan on how to eliminate the entire waste stream before it degrades the environment. Source reduction processes are as follows (EPA 1990):

i) Modifying design of product or package to decrease the amount of material used,
ii) Utilising economies of scale with large size packages,
iii) Utilising economies of scale with product concentrates,
iv) Making materials more durable so that it may be reused, and
v) Substitute away from toxic constituents in products and packaging.

Recycling

Recycling is the process of converting waste materials into reusable products, and it is important to say that plastic recycling is in its infancy stage. Despite the seven (7) SPI plastic identifications (Table 2.1), most of the recycling companies or individuals concentrate on PET and HDPE plastic waste (EPA 1990). These plastic wastes makes only 5% of the post-consumer plastic waste stream and the rest is either incinerated or put in landfill or abandoned in open space (EPA 1990; Andrady 2015). EPA (1990), explains below the single homogeneous resins or a mixture of plastic resins recycling technologies:

1) Recycling PET and HDPE plastic waste is an example of homogenous resin, which yields to products similar in quality to those of virgin resins. PET and HDPE plastic waste can be recycled over and over again, hence reducing the need for PET and HDPE disposal (EPA 1990; Randall 1991).
2) Considering plastic identification according to SPI and as seen in Table 2.1, in this case plastic wastes can be mixed and recycled into new low cost construction building materials which can compete with wood and concrete (EPA 1990). In this case, the recycling process becomes simple as sorting of different types of plastic waste is

eliminated (EPA 1990). However, these recycled products can't be recycled again as in the previous scenario. Therefore, this process may delay the ultimate disposal of these plastic waste through recycling once but not over and over again (EPA 1990; Randall 1991).

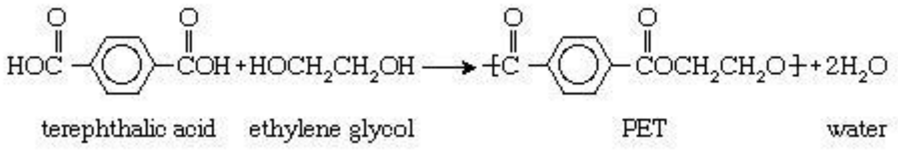
Factors limiting recycling

1) Collection and supply: one of the limiting factors of recycling is the collection and supply of single resins or a mixture of resins (EPA 1990). The single resins are affected most due to the complex composition of plastic wastes. As in most cases plastic wastes consist of a variety of different type of plastic types. Collection of plastic waste can be done by "bottle container deposit, road curb side collection, drop-off centres, and buy-back centres" (EPA 1990; Randall 1991).
2) Markets: PET and HDPE plastic waste recycled products market is available on a large scale (EPA 1990). Though, it should be noted that markets for mixed plastic waste recycled products is hard to get and the production of such products is still at its infancy (EPA 1990; Randall 1991).

2.3 Polyethylene Terephthalate (PET)

2.3.1 Manufacture of PET

Polyethylene Terephthalate (PET or PETE), is a strong, stiff synthetic fibre and resin. PET is a member of the polyester family of polymers. PET is produced by the polymerisation of ethylene glycol and terephthalic acid. Ethylene glycol is a colourless liquid and a product of ethylene, and terephthalic acid is a crystalline solid which is a product of xylene. Once ethylene glycol and terephthalic acid are heated together under the influence of chemical catalysts, it results into a molten viscous PET. This molten PET can be turned into fibres directly, or solidified in order to be processed into plastic at a later stage (Britannica 2015). Chemically, ethylene glycol is a diol, an alcohol with a molecular structure that contains two hydroxyl (OH) groups (Britannica 2015). Terephthalic acid is a dicarboxylic aromatic acid with a molecular structure that contains a large six-sided carbon or aromatic ring and two carboxyl (CO_2H) groups (Britannica 2015). Under the influence of heat and catalysts, the hydroxyl and carboxyl groups react to form ester (CO-O) groups, which serve as the chemical links joining multiple PET units together into long-chain polymers. Water is also produced as a by-product. The chemical reaction is as below (Britannica 2015):



2.3.2 General uses and properties of PET

Polyethylene Terephthalate (PET) is usually stiff and strong, which makes it applicable in various sectors. PET can be made into high-strength textile fibres, which are used in durable-press blends with other fibres like rayon, wool, and cotton; reinforcing the inherent properties of those fibres while restraining them from wrinkling. Also PET can be used in the manufacture of fibre filling for insulated clothing; and for furniture and pillows. Artificial silk and carpets are also made from small and large PET filament fibres respectively.

Furthermore, PET can be used in automobile tyre yarns, conveyor belts and drive belts, reinforcement for fire and garden hoses, seat belts (GangaRao et al. 2006). Also PET can be used in the manufacture of geotextiles for stabilising drainage ditches, culverts, and railroad beds. Also diaper top sheets and disposable medical garments, magnetic recording tapes and photographic films, liquid and gas containers, water and beverage bottles.

Table 2.3: Typical PET property values (PP 2015; GangaRao et al. 2006)

Item	Description	ASTM Test Method	Units	PET value
1	**Physical properties**			
i)	Density	D792	lbs/cu in^3	0.0499
ii)	Water absorption	D570	%	0.10
2	**Mechanical properties**			
i)	Specific gravity	D792	g/cu cm^3	1.38
ii)	Tensile strength at break	D638	psi	11,500
iii)	Tensile modulus	D638	psi	4x10^5
iv)	Elongation at break	D638	%	70
v)	Flexural strength	D790	psi	15,000
vi)	Flexural modulus	D790	psi	4x10^5
vii)	Izod impact strength, Notched	D256	ft-lbs/in	0.7

viii)	Rock well hardness	D785	-	R117
ix)	Coefficient of friction	-	Static/dynamic	0.19/0.25
3	**Thermal properties**			
i)	Heat deflection	D648	^{o}F	175
ii)	Melting point	-	^{o}F	490
iii)	Coefficient of linear thermal expansion	D696	Iin./in./ ^{o}F	$3.9x10^{-5}$
iv)	Applicable temperature range for thermal expansion	-	^{o}F	50-250
v)	Maximum serving temperature for long term	-	^{o}F	230
vi)	Flammability	UL94	-	HB
4	**Electrical properties**			
i)	Volume resistivity	D257	ohm-cm	10^{16}
ii)	Dielectric constant	D150	-	3.4
iii)	Dissipation factor	D150	-	0.002
iv)	Dielectric strength	D140	v/mil	400

2.4 Fibre-Reinforced soil

Due to rapid urbanisation worldwide and increased rural-urban migration, coupled with increase in the world population estimated to be 7 billion people, there has been increase in the creation of cities to accommodate for the demand of houses and better infrastructures. This has led to, shortage of quality building materials and suitable sites with proper soil properties for proposed buildings and any other civil engineering projects.

In civil engineering a site for a project, say for a building, or any other civil engineering construction project is key in the project's existence. This determines whether the project will be able to be established on that site or not. The first step in the determination of the suitability of the site for any construction or civil engineering project is to carry out a site investigation. This helps in determining the properties of the soil and water level, history of the site, and the existing services available on or near the site.

2.4.1 Soil improvement

Soil improvement is a process carried out to achieve improved geotechnical properties (and engineering response) of a soil (or earth material) at a site (Nicholson 2014). Hausmann (1990), asserts that, the process can be achieved by methods like:

Mechanical modification.

In this technique, external mechanical forces are used to increase soil density, including soil compaction by using methods like static compaction, dynamic compaction, and deep compaction by heavy tamping (Hausmann 1990, Nicholson 2014).

Hydraulic modification.

In this technique pore-water is forced out of the ground through drains or wells. Lowering the groundwater level by pumping from trenches or boreholes can be applied for coarse-grained or cohesion-less soils. However, for fine-grained or cohesive soils, application of the long-term of external pressure (preloading) or electrical loads (electrokinetic stabilisation) is used (Nicholson 2014).

Physical and chemical modification.

One example of this method is soil stabilisation by physically mixing/blending additives with top layers at depth. Additives can be natural soils, industrial by-products or waste materials; and other chemical materials that can react with the soil or ground. Other applications are soil/ground modification by grouting and thermal modifications (Nicholson 2014, Hausmann 1990).

Modification by inclusions and confinement.

This technique is considered as strengthening soil by materials such as meshes, bars, strips, fibres, and fabrics corresponding to the tensile strengths. Confining a site with steel, or fabric elements can also form stable-earth retaining structures (Hausmann 1990). Soil reinforcement method falls under this category and it's further elaborated in the next section.

2.4.2 Site Investigation

Site investigation involves collection of information concerning the proposed site and its environs whether is suitable for the proposed civil engineering project (Simons et al. 2002, Nicholson 2014). Simons et al., (2002) further highlights the objectives carrying out site investigation as seen below:

i) To determine whether the proposed site and its surrounding environment is suitable for the proposed project.
ii) To help in achieving adequate and economic design of the entire proposed project including design of temporary works, proposing methods of soil improvements, and ground water management.
iii) To come up with construction methods, and identify possible future challenges which may hinder the completion of the proposed project.
iv) To counteract any failures which may occur during the execution of the proposed project by coming up with remedial designs.
v) To assess the suitability of locally available construction materials.
vi) To assess the safety of the existing infrastructures like dams and buildings.
vii) To assess the environmental impact of the proposed project.

However, as stressed earlier, not all proposed sites, once investigated turn out to be suitable sites with desirable soil properties. Nicholson, (2014) proposes possible alternative solutions to solve unsuitable proposed sites that are listed below:

1) Abandon the project: This might be considered a practical solution only when another suitable site can be found and no compelling commitments require the project to remain at the location in question, or when the cost estimates are considered to be impractical.
2) Excavate and replace the existing “poor” soil. This method was common practice for many years, but has declined in use due to cost restraints for materials and hauling, availability and cost of selected materials, and environmental issues.
3) Redesign the project or design (often including structural members) to accommodate the soil and site conditions. A common example is the use of driven piles and drilled shafts to bypass soft, weak, and compressible soils by transferring substantial applied loads to suitable bearing strata.

4) Modify the soil (rock) to improve its properties and/or behaviour through the use of available ground improvement technologies. Ground improvement methods have been used to address and solve many ground/soil condition problems and improve desired engineering properties of existing or available soils. In addition, ground/soil improvement has often provided economical and environmentally responsible alternatives to more traditional approaches.

Soil reinforcement as one of the ground/soil improvement techniques, is a process of using synthetic or natural additive materials to improve the soil/ground characteristics or properties (Hausmann 1990). Soil reinforcement with randomly distributed fibres can be done by using either natural fibres or synthetic fibres. Natural fibres can be obtained from coconut, sisal, palm, jute, flax, barely straw, bamboo, and cane or sugarcane. Whereas, synthetic or man-made fibres are obtained from polypropylene, polyester, PET, polyethylene, glass, nylon, steel, and polyvinyl alcohol.

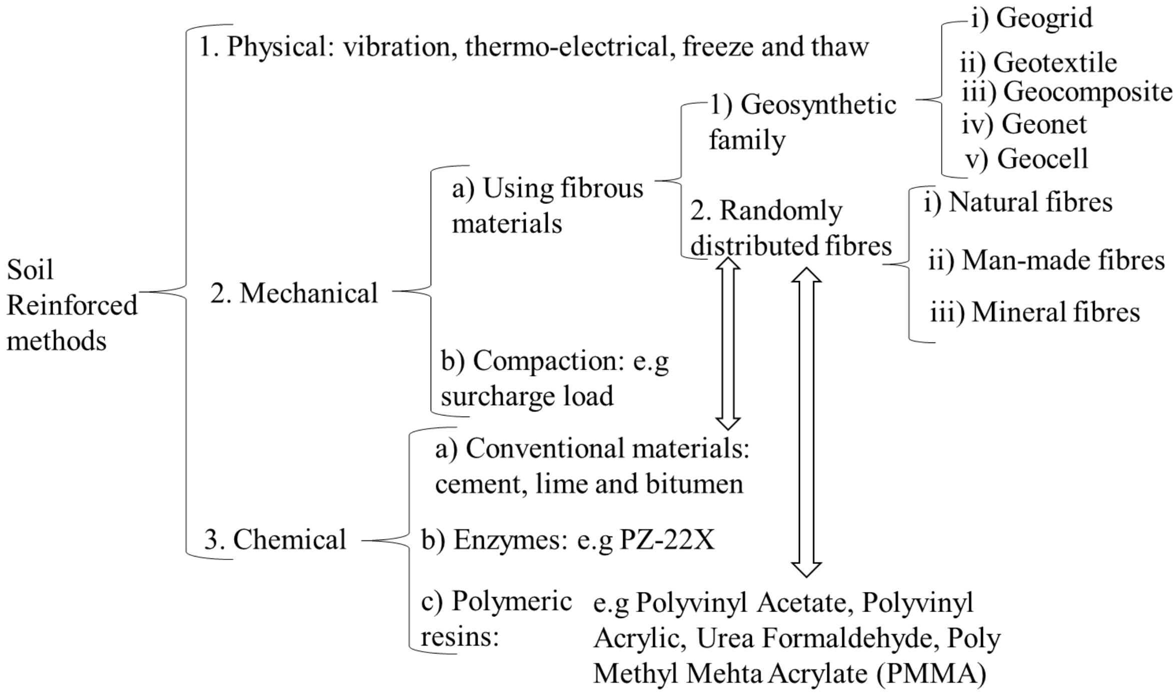


Figure 2.2: Methods of soil reinforcement (Hejazi et al. 2012).

The standard soil-PET plastic waste composite is defined by Li, (2005) as the composite with randomly distributed, discrete elements of PET plastic flakes, which improve the mechanical behaviour of the composite. Soil reinforced with PET plastic waste flakes are homogeneously embedded in a matrix of soil (Hejazi et al. 2012). Shear stresses in the soil mobilises tensile resistance in the PET plastic waste flakes, which in turn imparts greater strength to the soil (Li 2005).

2.4.3 Case studies of fibre-reinforced soil

There has been an evolution in the inclusion of fibres in soil for reinforcement purposes. Various researchers have conducted studies on fibre-reinforced soil and this section summarises some of the published research.

2.4.3.1 Shear strength increase of the soil-fibre composite

Gray & Ohashi (1983), researched about mechanics of fibre reinforcement in sand, where direct shear tests were performed on dry sand reinforced with natural fibres, synthetic fibres and metal wires. The reinforcements included common basket reeds, PVC plastics, Palmyra (a tough fibre obtained from the African Palmyra palm), and copper wire. The diameter of the fibres used ranged from 1 to 2mm with lengths ranging from 2 – 25 cm; and 0.25 – 0.5% fibre inclusion in the dry sand was used (Gray & Ohashi 1983). The results showed an increase in the shear resistance that was directly proportional to the fibres that were oriented at 60^o to the shear surface. The research findings were found to be relevant in solving diverse problems like stabilising of sandy, coarse textured soils in granitic slopes, dune and beach stabilisation by pioneer plants, tillage in root permeated soils, and soil stabilisation with low modulus.

Yetimoglu & Salbas (2003), conducted a study on shear strength of sand reinforced with randomly distributed discrete fibres. Sand and polypropylene fibres of diameter 0.05mm and length of 20mm were used in the proportion of 0.10%, 0.25%, 0.50% and 1.00% by weight of sand. Direct shear, specific gravity and compaction tests were performed on sand alone and sand-fibre composite to determine the impact of fibres on the shear strength of the soil. Laboratory test results of the study showed that reinforced sand with polypropylene fibres does not affect the peak shear strength and initial stiffness (Yetimoglu & Salbas 2003).

Park & Tan (2005), investigated the suitability of soil-polypropylene plastic composite wall. The study was carried out using materials of sandy silt (SM) soil, and polypropylene fibres of 60mm in length and fibre inclusion of 0.2% by weight of the soil. Soil physical tests like specific gravity, liquid limit, plasticity limit, and grain size distribution, and compaction tests (OMC and MDD) were performed to establish the soil properties. Also, specific gravity, tensile strength, melting point and Young's modulus tests were carried out to determine the physical properties of polypropylene fibres. Furthermore, full-scale physical model tests were conducted on the reinforced soil wall. It was observed that, soil-polypropylene plastic composite improved the stability of the wall and reduced earth pressure and wall settlement (Park & Tan 2005). It was also noted that short fibre reinforced soil used in conjunction with geo-grids can result into economic embankments.

Consoli et al. (2010), carried out research on the mechanics of sand reinforced with fibres, by using uniformly graded quarzitic sand; and polypropylene of diameter 0.023mm, length of 24mm, and fibre inclusion of 0.05% by weight of dry sand. Physical properties of sand were determined by carrying out specific gravity, and particle size distribution tests. Furthermore, isotropic compression and triaxial compression tests were performed on both sand and sand-fibre composite. Research findings were that, the peak strength of the sand-fibre composite does not seem to be linked to volume change, and is reduced at low confining pressure and very little dilation (Consoli et al. 2010).

Babu and Chouksey, (2011), investigated the stress-strain response of plastic waste-soil composite, with fibre inclusion percentage ranging from 0% - 1.0%. In this research, red soil and sand having particles ranging from 425µm to 75µm were mixed together with plastic fibres of length 12mm, and width of 4mm. Carried out tests like Atterberg limit, specific gravity, and compaction to determine soil properties. Furthermore, unconfined compression, consolidated undrained, triaxial compression tests, and one dimensional compression test were performed on the fibre-soil composite to determine their stress-strain responses. It was concluded that in the unconfined compression test results, there was a 73.8% increase in unconfined strength for 1% plastic waste mixed with soil compared to unreinforced soil (Babu & Chouksey 2011).

Acharyya et al. (2013), investigated the improvement of undrained shear strength of clayey soil with PET bottle strips. The clayey soils were mixed with 10% and 20% of sand; and PET shreds had a length ranging from 5mm to 15mm, with a width of 5mm, and fibre inclusion of 0.5% - 2% by weight of soil. Atterberg limit, compaction, unconfined compressive strength and direct shear tests were carried out for physical properties determination of soil and soil-fibre composite. Tests carried to achieve the properties of PET plastic strips included width, thickness, tensile, and density. Unconfined compressive strength of soil-fibre composite increased as percentage of PET inclusion increased up to 1% (Acharyya et al. 2013) as the results revealed.

Anagnostopoulos et al. (2013), investigated the engineering behaviour of soil reinforced with Polypropylene. Sandy silt and clay soils were reinforced with polypropylene fibre with their inclusion of 0.3% and 1.1%. Polypropylene fibres were tested and tests included: diameter, length, density, tensile strength, elongation at break, elastic modulus, and aspect ratio were determined. Also, Atterberg limit, particle size distribution, specific gravity tests were carried out on study soils to establish their properties. Furthermore, direct shear box tests were performed on soil-fibre composite. In conclusion, it was noted that fibre inclusion of up to 0.5% of sandy silt soil and 0.9% of silty clay soils improved the peak shear stress by 59% and 24% respectively (Anagnostopoulos et al. 2013).

Kalumba & Chebet, (2013), investigated the engineering behaviour of soil reinforced with polyethylene plastic waste. Sandy soils of Klipheuwel sands and Cape flats sands were used; and High Density Polyethylene (HDPE) plastic waste of length (15mm – 45mm), width (6mm – 18mm) at an increment of fibre (0.1%, 0.2%, 0.3%) were used. Engineering physical properties of sand were determined by carrying out specific gravity, particle size distribution, and direct shear box tests. Also index and mechanical fibre properties such as density, tensile modulus, and tensile strength were determined. Furthermore, direct shear box tests for fibre-soil composite were performed for normal stresses of 25kPa, 50kPa, and 100kPa at a shear loading rate of 1.2mm/min (Kalumba & Chebet 2013). In conclusion, fibre addition of 0.1% to the soil resulted in an improvement of peak friction angle from 38.5^0 to 44.5^0, also fibre increment of 0.1% to the soil caused an improvement in the friction angle, but fibre increment of 0.2% and 0.3% caused a decrease in the friction angle.

Akbulut et al. (2007), modified clayey soils by using scrap tire rubber and synthetic fibres. This was achieved by reinforcing clayey soil with 2% by weight scrap tire rubber; and 0.2% by weight of polyethylene and polypropylene fibres with diameter of 1mm and length ranging from 5mm to 60mm. Tests on clay, scrap tire rubber, polyethylene and polypropylene in order to establish their engineering properties. Furthermore, unconfined compression, direct shear box, and resonant frequency tests on unreinforced and reinforced soil were carried out to determine their strength and dynamic properties (Akbulut et al. 2007). Research findings showed that the strength and dynamic behaviour of clayey soils greatly improved after reinforcing it with fibres.

2.4.3.2 California Bearing Ratio (CBR) increase of soil-fibre composite

Benson & Khire (1994), used strips of reclaimed High Density Polyethylene (HDPE) as reinforcing fibre in sand; with fibre contents ranging from 1% to 4%. California Bearing Ratio (CBR); resilient modulus and direct shear tests were the main experimental laboratory tests carried out in this research. Test results showed that reinforcing sand with strips of reclaimed HDPE does not only enhance its resistance to deformation but also increases its strength (Benson & Khire 1994). The study suggests that sand reinforced with strips of reclaimed HDPE may be useful in highway and light-duty geotechnical applications.

2.4.3.3 Ductility increase of soil-fibre composite

Consoli et al. (2002), studied the engineering behaviour of sand reinforced with plastic waste. The materials used in the study included uniform fine sand; Polyethylene Terephthalate (PET) fibres of length up to 36mm and content up to 0.9% by weight of sand; and rapid hardening Portland cement with content ranging from 0% to 7% by weight of sand. Unconfined compression tests, splitting tensile tests, saturated drained triaxial compression tests with local strain measurement were carried to evaluate the benefit of utilising randomly distributed PET fibres alone or combined with rapid hardening Portland cement to improve the engineering behaviour of a uniform sand (Consoli et al. 2002). Test results showed that PET fibre reinforcement improved the peak and ultimate strength of both cemented and uncemented soil, and reduced the brittleness of the cemented sand.

Tang et al. (2006), analysed the strength and mechanical behaviour of short polypropylene (PP) fibres reinforced and cement stabilised clayey soil. The research centred on materials like clayey soil, polypropylene (PP) fibres added in quantities of 0.05%, 0.15% and 0.25% by weight of soil, and cement added in quantity of 5%, and 8% by weight of soil. Various tests were conducted on soil, chemical composition and physical properties of cement, and index and strength parameters of PP fibres. Furthermore, unconfined compression, direct shear, and scanning electron microscopy (SEM) tests were carried out on the soil mixture. Finally the test results indicated that the inclusion of fibre reinforcement within uncemented and cemented soil caused an increase in the unconfined compressive strength (UCS), shear strength and axial strain at failure, decreased the stiffness and the loss of post-peak strength, and changed the cemented soil's brittle behaviour to a more ductile one (Tang et al. 2006).

Sadek et al., (2010), investigated the shear strength of fibre reinforced sand, by mixing coarse or fine sand with nylon fishing wires as reinforcement fibres. The fibres were of diameter 0.18mm and 0.7mm, of length ranging from 7mm to 27mm, and fibre content inclusion ranging from 0% to 1.5% by weight of dry sand. Specific gravity and particle size distribution tests were carried out to determine the physical properties of sand. Whereas, nylon fishing fibre properties like length, diameter, Young's modulus, tensile strength, and specific gravity were determined. Furthermore, 150 direct shear tests were performed on the fibre-sand composite at normal stress levels of 100, 150 and 200 kN/m^2 (Sadek et al. 2010). Results showed that, the addition of 1% by dry sand weight of nylon fibres with an aspect ratio of 150 and fibre length of 27mm, prepared at a relative density of 55% increased the shear strength and ductility of the composite by 37% for coarse sand and 46.8% for fine sand.

2.4.3.4 Bearing capacity increase of soil-fibre composite

Gray & Al-Refeai (1986), researched on the behaviour of fabric versus fibre-reinforced sand. The researchers considered materials like uniformly graded medium-grained clean sand, and geotextiles like woven polypropylene multifilament, woven polypropylene tap, nonwoven polypropylene multifilament and woven glass yarn monofilament. Particle size distribution, specific gravity, and triaxial tests were carried out to determine the properties of sand. Tensile strength, elongation, mullen burst, and secant modulus tests were carried out to determine the mechanical properties of geotextiles. Diameter, specific gravity, tensile strength and tensile modulus tests were carried out to determine the fibre properties. Fibre content in the range of 1% to 2% by sand weight was used, and a fibre reinforced composite specimens were subjected to triaxial compression tests. Test results showed that both types of reinforcement improved strength, increased the axial strain at failure, and in most cases reduced post-peak loss of strength (Gray & Al-Refeai 1986). The research findings are suitable for increasing the bearing capacity of a strip footing placed on the soil.

Ranjan et al (1994), studied the behaviour of plastic fibre reinforced sand composite. This was done by mixing poorly graded fine sand (SP-SM) together with randomly distributed discrete plastic fibres in the range of 1% to 4% (by weight) fibre content. Particle size distribution, specific gravity and triaxial compression tests were carried out to determine the properties of fine sand. Diameter, specific gravity, tensile strength and tensile modulus tests were carried out to determine the properties of plastic fibres. Triaxial compression tests were analysed to study the stress-deformation and failure behaviour of plastic fibre reinforced sand mixture. Results indicated that the magnitude of the critical confining stress decreases with increase in aspect ratio of the plastic fibre, and the shear strength of plastic fibre reinforced sand mixture increased with increase in fibre content and aspect ratio (Ranjan et al. 1994). The practical significance of the findings recommended were ground improvement of embankments and subgrade.

2.5 Summary of Literature Review

Table 2.4: Summary of research literature published.

#	Author	Material used			Fibre dimensions			% of fibre inclusion (%)	Tests carried out			Conclusion
		Soil type	Binder	Fibre	Length (mm)	Width (mm)	Diameter (mm)		Physical properties of soil	Index and mechanical properties of fibre	Soil-fibre composite	
Shear strength increase of soil-fibre composite												
1	Gray & Ohashi (1983)	Sand		Basket reeds, PVC plastics, Palmyra, copper wire	20 to 250		1 to 2	0.25 to 0.5	Particle size distribution, direct shear box		Direct shear box	Improved shear strength
2	Yetimoglu & Salbas (2003)	Sand		Polypropylene	20		0.05	0.1 to 1.0	Specific gravity, compaction, direct shear box		Compaction, direct shear box	Shear strength increase.
3	Park & Tan (2005)	Sandy-silt		Polypropylene, geogrids	60			0.2	Specific gravity, Atterberg limit, compaction	Specific gravity, tensile strength, melting point, young's modulus	Full-scale physical model	Wall stability increased; earth pressures and displacement reduced.
4	Akbulut et al. (2007)	Clay		Scrap tire rubber, polyethylene, polypropylene	5 to 60		1	0.2 and 2			Unconfined compression, direct shear box, resonant frequency	Improvement of strength and dynamic behaviour of soil-fibre composite.
5	Consoli et al. (2010)	Quartzitic sand		Polypropylene	24		0.023	0.05	Specific gravity, particle size distribution, isotropic compression, triaxial compression		Isotropic compression, triaxial compression	Peak strength is not linked to volume change
6	Babu and Chouksey, (2011)	Red soil and sand		Plastic	12	4	0.425 to 0.075	Up to 1.o	Atterberg limits, specific gravity, compaction, unconfined compression		Unconfined compression, consolidated undrained, triaxial compression	Shear strength increased
7	Acharyya et al. (2013)	Clay and sand		PET	5 to 15	5		0.5 to 2	Atterberg limit, compaction, unconfined compression strength, direct shear box	Width, thickness, tensile, density	Compaction, unconfined compression strength, direct shear box	Strength increased
8	Anagnostop	Sandy		Polypropylene				0.3 to 1.1	Atterberg limit,	Specific gravity,	Direct shear box	Peak shear increased

	oulos et al. (2013)	silt							particle size distribution, specific gravity	tensile strength, melting point,		
9	Kalumba & Chebet, (2013)	Sand		HDPE	15 to 45	6 to 8	1.18 to 0.075	0.1 to 0.3	Atterberg limit, particle size distribution, specific gravity	Specific gravity, tensile strength, melting point,	Direct shear box	Shear strength increased
California Bearing Ratio (CBR) increase of soil-fibre composite												
1	Benson & Khire (1994)	Sand		HDPE				1 to 4	California Bearing Ratio (CBR), direct shear box		California Bearing Ratio (CBR), direct shear box	Useful in highway and light-duty geotechnical applications.
Ductility increase of soil-fibre composite												
1	Consoli et al. (2002)	Sand	Cemen t	PET				0.9			Unconfined compression, splitting tensile, saturated drained triaxal compression	Peak and ultimate strength improved; brittleness of the cemented sand reduced
2	Tang et al. (2006)	Clay	Cemen t (5% & 8%)	Polypropylene (PP)				0.05, 0.15, 0.25			Unconfined compression, direct shear box, scanning electron microscopy (SEM)	Increases strength; brittle cemented soil changed to ductile soil.
3	Sadek et al., (2010)	Sand		Nylon fishing wire	7 to 27		0.18 to 0.7	1 to 1.5	Specific gravity, particle size distribution, direct shear box	Length, diameter, young's modulus, tensile strength, specific gravity	Direct shear box	Ductility and shear strength increased
Bearing capacity increase of soil-fibre composite												
1	Gray & Al-Refeai (1986)	Sand		Geotextiles				1 to 2	Particle size distribution, specific gravity, triaxial compression	Tensile strength, elongation, mullen burst, secant modulus, tensile modulus	Triaxial compression	Shear strength improved, can increase bearing capacity of a strip footing placed on soil.
2	Ranjan et al (1994)	Sand		Randomly distributed discrete plastic				1 to 4	Particle size distribution, specific gravity, triaxial compression	Specific gravity, tensile strength, tensile modulus	Triaxial compression	Shear strength increased, recommended for ground improvement of embankments and subgrades

From the reviewed literature published, it can be summarised that materials used were soil ranging from sand to clay, Ordinary Portland Cement (OPC) used as stabiliser, and fibres as reinforcements like basket reeds, PVC, Palmyra, copper wire, geotextiles, HDPE, PET, polypropylene, polyethylene, scrape tire rubber, and nylon fishing wires. The length of fibres ranged from 5mm to 250mm, fibre width ranged from 4mm to 8mm, fibre diameter ranged from 0.023mm to 2mm, and fibre inclusion ranged from 0.05% to 4% of the dry soil weight.

Furthermore, tests carried out to determine the engineering physical properties of soil and soil-fibre composite included particle size distribution, specific gravity, Atterberg limits, compaction, CBR, direct shear, triaxial compression, unconfined compression, isotropic compression, and full-scale physical model tests. Also, tests carried out to determine the index and mechanical properties of fibres included tensile strength, specific gravity, secant modulus, tensile modulus, melting point, Young's modulus, and density tests. In their conclusions, researchers established that, reinforcing soil with fibres increases the shear strength, increases the bearing capacity, and cemented soil-fibre composite changes from brittle to ductile.

From the literature review, percentage of fibre used in the reinforcing of soil ranged from 0.05% to 4% of the dry soil weight. But, reinforcing soil with higher percentages of PET plastic waste fibres ranging from 12.5% to 32.5% can be used in civil engineering applications such as construction of roads, railways, dams, retaining walls, tunnels, embankments, and as shallow foundation strata. However some of the civil engineering applications such as construction of heavy duty roads, railways, dams, retaining walls, and tunnels may not benefit beyond PET plastic waste fibre inclusion of 22.5%. However, removal of higher percentages of PET plastic waste of 32.5% will bring a reduction in the general plastic waste channelled into the landfills. Therefore, use of higher percentage of PET plastic waste to reinforce soil is seen as a mitigation measure to solve the challenges facing civil engineering and waste management fields.

Furthermore, the published literature did not tackle the social, economic, and environmental effects of reinforcing soil with PET plastic waste. The social, economic, and environmental effects are core in the sustainability of PET plastic waste management. Due to this gap in the published literature, this research discussed the social, economic and environmental effects of reinforcing soil with PET plastic waste in Chapter 5. With sustainability of PET plastic waste management, challenges faced with civil engineering and waste management fields will be mitigated.

CHAPTER 3: RESEARCH MATERIALS, APPARATUS, AND METHODOLOGY

3.1 Introduction

The content in this Chapter evolve around the laboratory experimental work carried out to achieve the aims of the study. This Chapter first elaborates on the research materials used to conduct this research. Thereafter, it describes the laboratory experiments carried out on soil, PET plastic waste flakes, and soil-PET plastic waste composite. Furthermore, it gives an insight on test introduction, test method, sample preparation, apparatus used, test procedure, and data processing of each test carried out to achieve the aims of this research.

3.2 Research Materials

The materials used in this research included: soil, water, and PET plastic waste flakes.

3.2.1 Soil

The soil material (sand) used in this research was obtained from Stellenbosch. The sand was medium dense, clean quartz sand, round shaped particles ranging between 0.075mm to 1.18mm. Tests carried out on the research soil included particle size distribution, compaction, California Bearing Ratio (CBR), and direct shear box.

3.2.2 PET plastic waste flakes

Plastic waste flakes of the type of Polyethylene Terephthalate (PET) were used as reinforcing material in the present investigation Figure 3.1. These were obtained from Kaytech factory located in Atlantis, South Africa, a factory that uses recycled PET plastic bottle flakes to manufacture geosynthetics products like geotextiles. The PET plastic waste flakes were of assorted colours and their sizes ranged between less than 10mm to greater than 1.18mm. The physical properties of the PET plastic waste, like particle size distribution analysis are given in Chapter 4 and other index and mechanical properties of PET plastic have been assumed on the basis of published data (PP 2015) given in Table 2.3

Figure 3.1: PET plastic waste flakes.

3.2.3 Water

Water used was de-ionised water and purified tap water (potable water) which was obtained within the laboratory of the Department of Civil Engineering, Faculty of Engineering, Stellenbosch University (SUN).

3.3 Laboratory Experiments carried out on Soil, PET Plastic Waste, and Soil-PET Plastic Waste Composite

Table 3.1: Laboratory tests with their methods and references.

#	Research material	Tests carried out	Method used	Reference
1	Unreinforced sand	Particle size distribution	Dry sieving	BS 1377: Part 2: 1990
		Compaction	Modified AASHTO	BS 1377: Part 4: 1990 TMH 1: Method A7: 1986
		CBR	Three point	BS 1377: Part 4: 1990; TMH 1: Method A8: 1986
		Direct shear box		BS 1377: Part 7: 1990
2	PET	Particle size distribution	Dry sieving	BS 1377: Part 2: 1990
		Compaction	Modified AASHTO	BS 1377: Part 4: 1990 TMH 1: Method A8: 1986
		CBR	Three point	BS 1377: Part 4: 1990;

3	Sand-PET plastic waste composite			TMH 1: Method A7: 1986
		Direct shear box	Small direct shear box	BS 1377: Part 7: 1990

3.3.2 Particle size distribution test

Soil is an aggregate of mineral particles consisting of discrete particles of various shapes and sizes ranging from greater than 200mm to less than 0.002mm (Das 2013). Soil can be categorised as boulders, cobbles, gravel, sand, silt, and clay as seen in Figure 3.2. Das (2012), defines particle size distribution as the determination of the size ranges of particles present in a soil, expressed as a percentage of the total dry weight (mass). Therefore, particle size distribution test aims at grouping various particles into separate ranges of sizes, and so determine the relative proportions, by dry mass of each size range.

Two methods are used to determine particle size distribution of soil i.e., sieve analysis (dry or wet) – for soils like gravel and sand having particles larger than 0.075mm in diameter, and sedimentation analysis (pipette or hydrometer) – for soils like silt and clay having particles smaller than 0.075mm in diameter (Das 2012). A particle size analysis is a necessary classification test for soils especially coarse soils, in that it presents the relative proportions of different sizes of particles. From this it is possible to determine whether the soil consists of predominantly gravel, sand, silt, or clay sizes and to a limited extent, which of the size ranges is likely to control the engineering properties of the soil. This section of the Chapter is based on the particle size distribution analysis of soil and PET plastic waste by the dry sieving method as stipulated in BS 1377: Part 2: 1990.

Various apparatus were used in carrying out this experiment and these included but not limited to test sieves of sizes 10mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.425mm, 0.212mm, 0.15mm, 0.075mm. Also lid and receiver, balance, oven, metal trays, scoop, sieve brushes, and mechanical sieve shaker. The dry sieve analysis test of both sand and PET plastic waste flakes representative specimens each weighing 500g, were separately subjected to dry sieve analysis method carried in accordance with BS 1377: Part 2: 1990. Thereafter, particles retained on each sieve were weighed and calculations aiming at determining the cumulative percentages passing as seen in Table 4.1 were done in accordance with BS 1377: Part 2: 1990. Figure 3.2 and Figure 3.3, were used in classifying the research materials used in accordance with USCS.

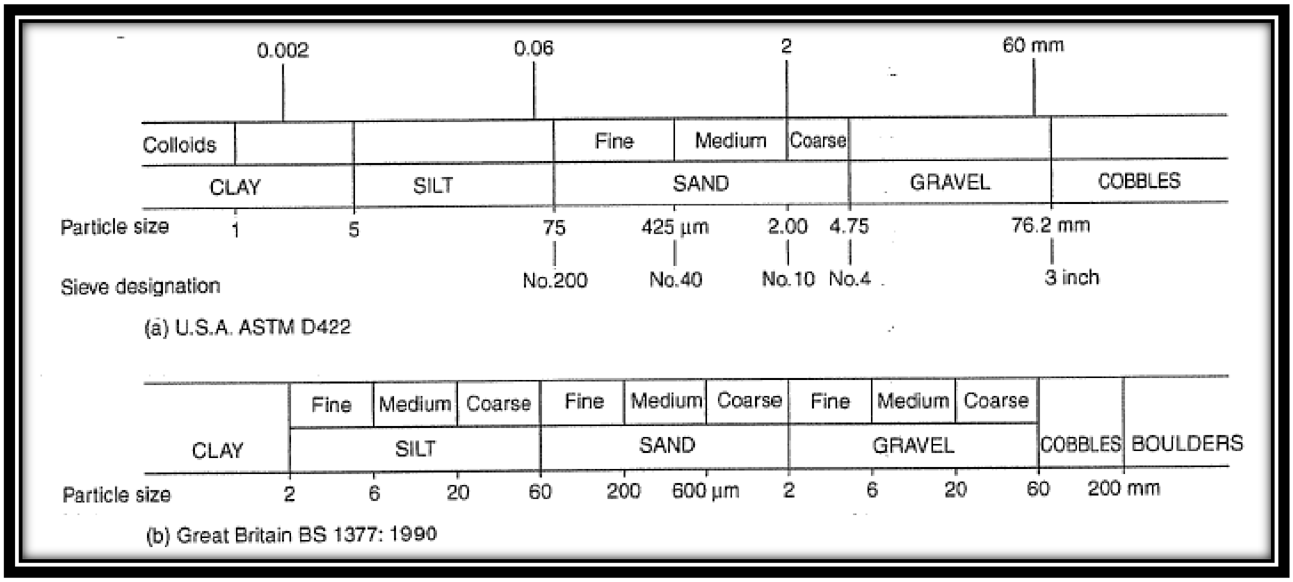


Figure 3.2: Comparison of systems for classifying particle size ranges of soils (Head 1994).

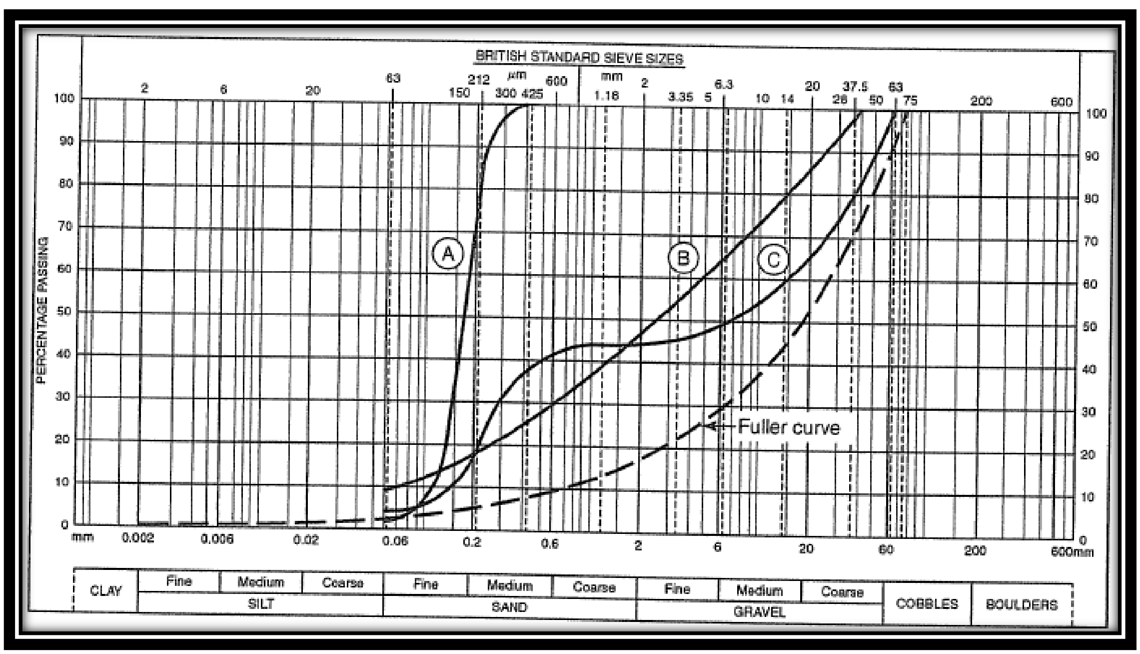


Figure 3.3: Particle size curves for sand and gravel (BS1377 1990).

3.3.3 Compaction test

Engineering fill materials need to be compacted to a dense state in order to obtain satisfactory engineering properties that would not be achieved with loosely placed materials. Compaction in the field is usually effected by mechanical means such as rolling, ramming, or vibrating, and needs to be controlled using the laboratory compaction in order to achieve a satisfactory result at a reasonable cost. The laboratory compaction provides values of optimum moisture content (OMC) and maximum dry density (MDD) from the relationship between dry density and moisture content for a given degree of compactive effort, Table 3.2 shows typical values of OMC and MDD. Some of the terms used are defined below (Head 1994, Das 2013, Look 2014):

i) Compaction: the process of packing soil particles more closely together, usually by rolling or other mechanical means, thus increasing the dry density of the soil.

ii) Optimum moisture content (OMC): the moisture content of a soil at which a specified amount of compaction will produce the maximum dry density.

iii) Maximum dry density (MDD): the dry density obtained using a specified amount of compaction at the optimum moisture content.

iv) Dry density-moisture content relationship: the relationship between dry density and moisture content of a soil when a specified amount of compaction is applied. Figure 3.4 shows a typical dry density-moisture content relationship.

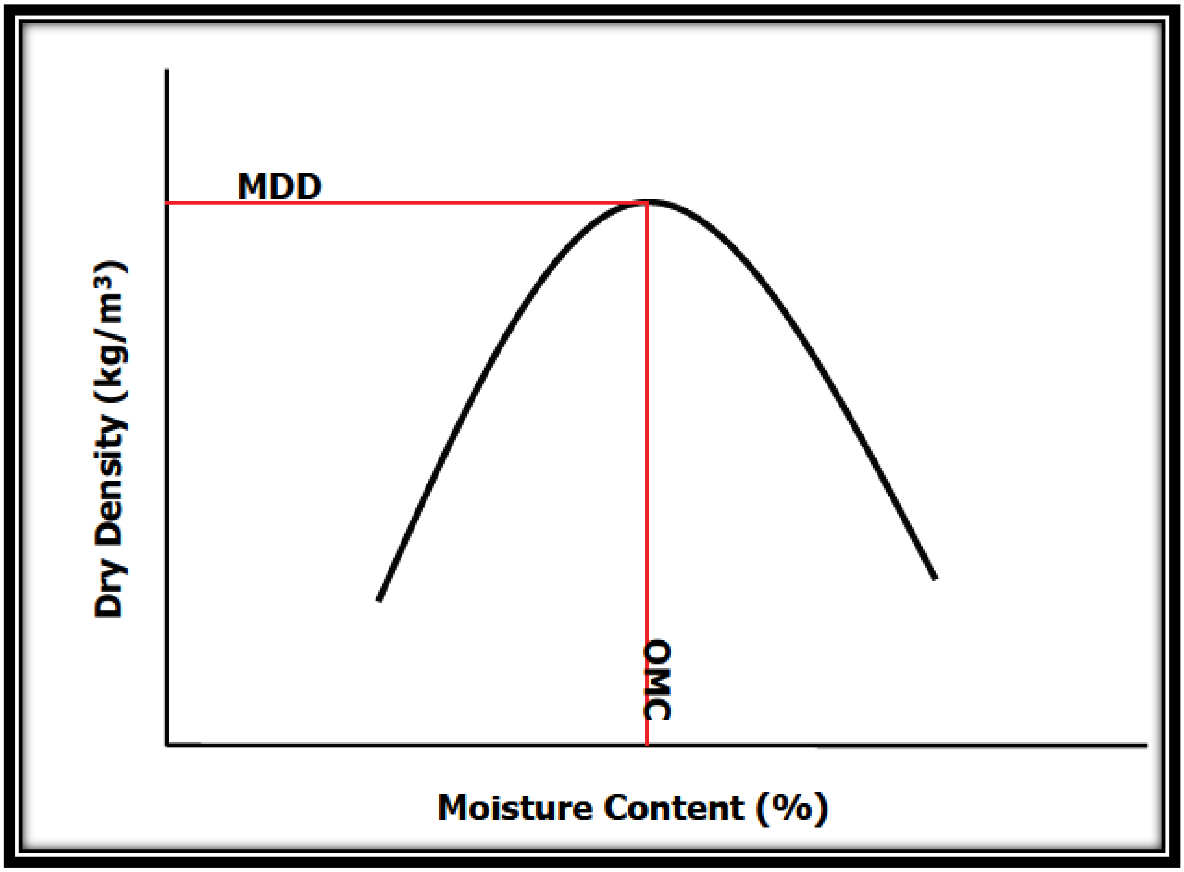


Figure 3.4: The dry density-moisture content relationship (Head 1994, Das 2009).

Table 3.2: Typical compaction test results (Look, 2014 after Hoerner, 1990)

Material	Type of compaction test	Optimum moisture content OMC (%)	Maximum dry density MDD (kg/m^3)
Heavy clay	Standard (2.5kg Hammer)	26	1470
	Modified (4.5kg Hammer)	18	1870
Silty clay	Standard (2.5kg Hammer)	21	1570
	Modified (4.5kg Hammer)	12	1940
Sandy clay	Standard (2.5kg Hammer)	13	1870
	Modified (4.5kg Hammer)	11	2050
Silty gravelly clay	Standard (2.5kg Hammer)	17	1740
	Modified (4.5kg Hammer)	11	1920
Uniform sand	Standard (2.5kg Hammer)	17	1690
	Modified (4.5kg Hammer)	12	1840
Gravelly sand/sandy gravel	Standard (2.5kg Hammer)	8	2060

	Modified (4.5kg Hammer)	8	2150
	Vibrating hammer	6	2250
Clayey sandy gravel	Standard (2.5kg Hammer)	11	1900
	Vibrating hammer	9	2000
Pulverised fuel ash	Standard (2.5kg Hammer)	25	1280
Chalk	Standard (2.5kg Hammer)	20	1560
Slag	Standard (2.5kg Hammer)	6	2140
Burnt shale	Standard (2.5kg Hammer)	17	1700
	Modified (4.5kg Hammer)	14	1790

A series of equipment were used during compaction testing like a cylindrical compaction mould with internal diameter of 152mm and internal height of 152mm, 4.5kg metal rammer, electric compactor, balance, steel straight edge strip, mixing pan, electric mixer, measuring cylinder, and oven (BS1377 1990; TMH1 1986, Head 1994). Compaction laboratory experiment was performed in accordance with BS 1377: Part 4: 1990, and TMH 1: Method A7: 1986 with the modified AASHTO compaction effort at different moisture contents, with the aim of obtaining relationships between compacted dry density and soil moisture content. Figure 3.5 shows the compacted sand-PET plastic waste composite.

Figure 3.5: Compacted sand-PET plastic waste composite

3.3.4 California Bearing Ratio (CBR) test

California Bearing Ratio (CBR) or Bearing Ratio, is the ratio of the force required to penetrate a circular piston of 1935mm^2 cross-section into soil in a mould at a rate of 1.27 mm per minute, to that required for similar penetration into a standard sample of compacted crushed rock. CBR is determined at penetration of 2.5mm and 5.0mm; and the higher value is used (Head 1994, O'Flaherty 2002).

$$CBR = \frac{\text{Measured force}}{\text{Standard force}} * 100\% \quad \text{...Eqn 3.1}$$

The CBR test is a constant rate of penetration shear test in which a standard plunger is pushed into the soil at a constant rate and the force required to maintain that rate is measured at suitable intervals. The load-penetration relationship is drawn as a graph from which the loads corresponding to standard penetrations are read off and expressed as ratios (percent) of standard loads (Head 1994, O'Flaherty 2002). The accepted percentage is known as the California Bearing Ratio or CBR value of the soil in the condition at which it was tested. The CBR value can be regarded as an indirect measure of the shear strength of the soil, but it cannot be related directly to shear strength parameters. An assumed mechanism of failure of the soil beneath the plunger (Black 1961) is indicated in figure 3.1.

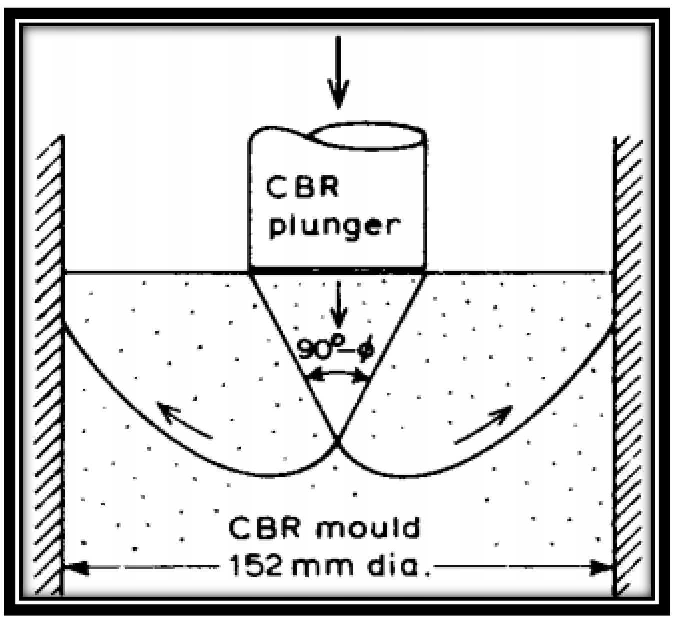


Figure 3.6: Assumed mechanism of failure beneath CBR plunger (Black 1961).

CBR can be carried out on most types of soil ranging from heavy clay to medium gravel soils. The test can be used on the sub-grade, sub-base and base course materials and the results obtained enable maximum utilisation to be made of low cost materials where better quality material is not available. It should also be noted that the CBR test can be used to provide a rational method of design for flexible pavements (such as macadam or asphalt), rigid (concrete) pavements, and granular base courses. Hence, CBR test data are applicable to the design of airfield runways and roads. Furthermore, CBR values enable a suitable thickness of sub-base construction to be determined to withstand the anticipated traffic conditions (vehicles or aircraft), in terms of axle loadings and traffic frequency, over the design life-span of the pavement (Head 1994).

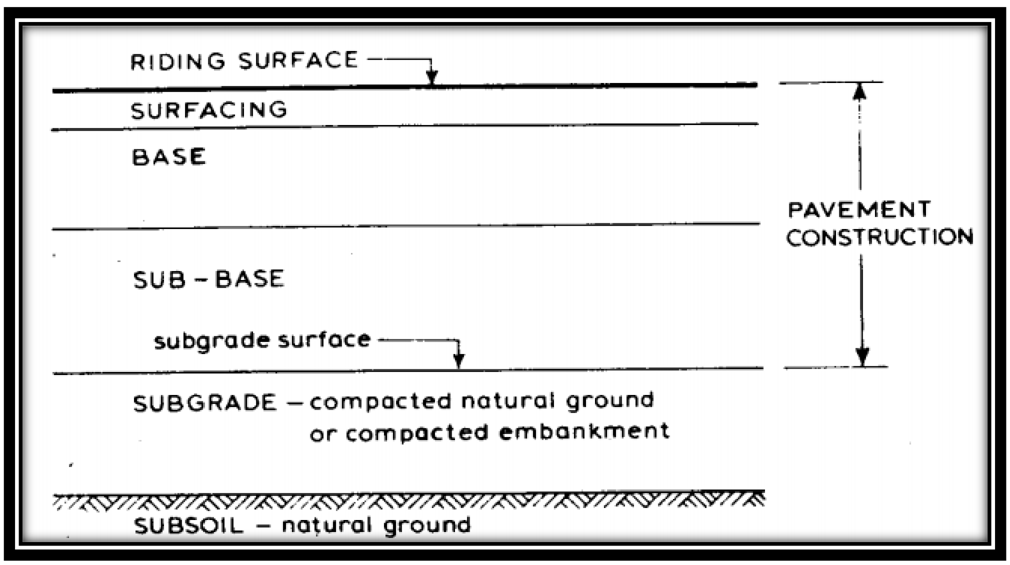


Figure 3.7: Some terms used in pavement construction (Head 1994).

Table 3.3: Typical ranges of CBR (%) values for compacted soils (O'Flaherty 2002)

Type of soil	**Plasticity**	**Range of CBR (%) values**
Clay	CH	1.5 to 2.5
	CI	1.5 to 3.5
Silty clay	CL	2.5 to 6
Sandy clay	PI = 20	2.5 to 8
	PI = 10	2.5 to 8 or more

Silt	-	1 to 2
Sand – poorly graded	-	20
Sand – well graded	-	40
Sandy gravel – well graded	-	60

3.3.4.2 CBR laboratory experiment

CBR laboratory experiment covers the laboratory determination of the CBR of a compacted sample of soil – three point method; which is the prescribed method in the pavement and materials design manual (TMH1 1986). The table below shows the testing schedule for the CBR test program.

A series of equipment were used in the determination of CBR test like CBR metal moulds, rammer, steel rod, steel straight edge, balance, oven, filter papers, mixer, and dial gauge. Furthermore, soaking tank, surcharge disks, cylindrical metal plunger, CBR compression machine, loading ring, and stop watch (TMH1 1986; BS1377 1990; Head 1994).

The particle sizes of soil and PET plastic waste used in this research were less than 20mm, hence there was no need to first pass the samples through a test sieve of 20mm. About 20kg of dry soil was weighed after getting its representative sample by the quartering method. For the soil-PET plastic waste composite specimens, 3 different samples of 20kg each were weighed separately, together with their respective PET plastic waste fibres inclusions of 12.5%, 22.5% and 32.5% by dry soil weight. Furthermore, each test sample was mixed with the optimum moisture content (OMC) which had been earlier determined in the compaction test.

A set of CBR tests were carried out on sand and sand-fibre composite materials, at varying percentage fibre inclusion of 12.5%, 22.5% and 32.5%., the effects of PET plastic waste content on the CBR value of the sandy soil was the main purpose of carrying out this test. The CBR tests were performed in the Civil Engineering laboratory of Stellenbosch University. Specimens were moulded in a steel CBR mould with an inside diameter of 152mm and internal height of 152mm. The specimens to be tested were prepared with optimum moisture contents (OMC) obtained from previously conducted compaction tests as per BS 1377: Part 4: 1990 and

TMH 1: Method A7: 1986 (Edinçliler & Cagatay 2013). An electric mixer was used to mix sand and sand-fibre composite specimens until a homogeneous state was attained.

There were four (4) specimens to be tested and each specimen needed three (3) CBR moulds, and compaction was done using an automated mechanical compactor. The first specimen was compacted in such a way that, in the first mould, five (5) layers of soil were subjected to 55 blows per layers using a 4.5kg rammer; second mould, five (5) layers of soil were subjected to 25 blows per layer using 4.5kg rammer; and third mould, three (3) layers of soil were subjected to 55 blows per layer using 2.5kg rammer. The subsequent specimens were compacted in the same manner as for the first sample; and as per BS 1377: Part 4: 1990 and TMH 1: Method A8: 1986.

After compaction, the specimens were soaked in a curing tank for four (4) days and swelling readings were taken at the beginning and end of the soaking period using the dial gauge. The specimens were penetrated using a standard CBR machine with a penetration speed of 1.27mm per minute as described in BS 1377: Part 4: 1990 and TMH 1: Method A8: 1986; and procedures described in these standards were employed.

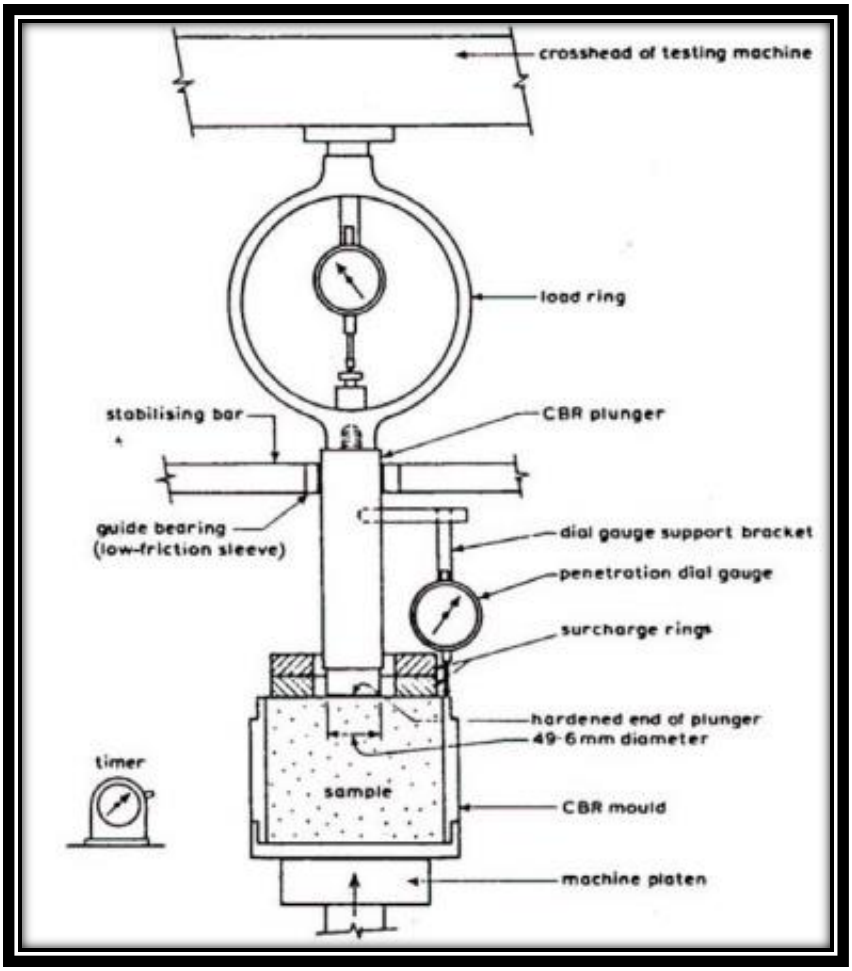


Figure 3.8: CBR machine setup (Head 1994).

3.3.5 Direct shear box test

3.3.5.1 Shear strength introduction

Venkatramaiah, (2006), defines shear strength as the resistance to shearing stresses and a consequent tendency for shear deformation. Soils derives its shearing strength from resistance due to the interlocking of particles, frictional resistance between the individual soil grains, and adhesion between soil particles or cohesion (Venkatramaiah 2006). Every building or structure which is founded in or on the earth imposes loads on the soil which supports the foundations. Head (1994) suggests that, the stresses set up in the soil can cause deformations of the soil, in three (3) ways namely:-

i) By the elastic deformation of the soil particles.

ii) By the change in volume of the soil, resulting from the expulsion of fluid (water and/or gas) from the voids between the solid particles; and this is known a consolidation.

iii) By the slippage of soil particles, one on another, this may lead to the sliding of one body of soil relative to the surrounding mass. This is known as shear failure and occurs when shear stresses set up in the soil mass exceed the maximum shear resistance which the soil can offer, i.e. its shear strength.

The form of expressing functional relationship between normal stress and shear stress on a failure plane is presented in Equation 3.2 (Das 2009).

$$\tau_f = f(\sigma) \qquad \text{Eqn 3.2}$$

Where τ_f = shear stress on failure envelope

$f(\sigma)$ = normal stress on the failure envelope.

Das (2009), further concludes that the failure envelop defined by Equation 3.2 is a curved line. Therefore, Das (2009) recommends Mohr-Coulomb's friction law which suggests that for most soil mechanics problems, it's sufficient to approximate the shear stress on the failure plane as a linear function of the normal stress. The linear function (Equation 3.3) below is the Mohr-Coulomb failure criterion (Das 2009). Table 3.4 shows the estimated strength parameters of soil and rock.

$$\tau_f = c + \sigma tan(\varphi) \qquad \text{Eqn 3.3}$$

Where

τ_f = shear strength

c = cohesion

σ = normal stress on the failure plane

φ = angle of internal friction

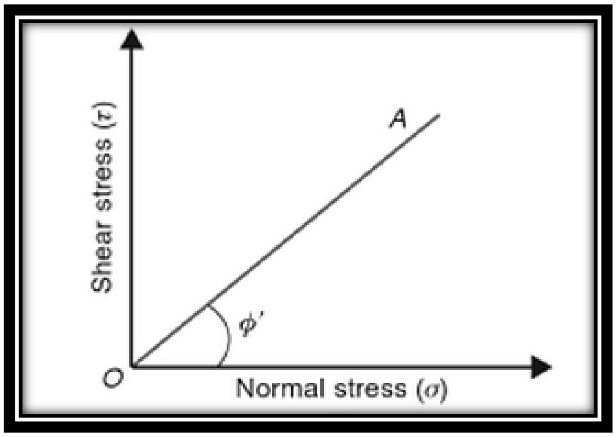


Figure 3.9: Relationship between normal stress and shear stress on a failure plane (Das 2013)

Table 3.4: Soil and rock estimated strength parameters (Look 2014).

Item	Soil classification	Cohesion, c (kPa)	Angle of internal friction, φ (degree)
1	**Sand**		
	Very loose		< 30
	Loose		30-35
	Medium dense		35-40
	Dense		40-45
	Very dense		>45
2	**Clay**		
	Very soft	0-12	
	Soft	12-25	
	Firm	25-50	
	Stiff	50-100	
	Very stiff	100-200	
	Hard	>200	
3	Gravels, cobbles, boulders		35 or >40
4	Rock	25 or >50	>30

Several laboratory methods used to determine the shear strength parameter of the soil specimens include direct shear box test (small shear box and large shear box), triaxial test, direct simple shear test, plane strain triaxial test, and torsional ring shear test (Das 2009). This section of the chapter deals with the measurement of the shear strength of soils in the laboratory by small direct shear box method. This method involves the sliding of one portion of soil on another causing relative movement of two halves of a square block of soil along a horizontal surface.

The shear box allows a direct shear test to be made by relating to the shear stress at failure to the applied normal stress. The objective of the test is to determine the effective shear strength parameters of the soil, the cohesion (c') and the angle of internal friction φ'. These shear strength parameters of the soil are important aspects in many foundation engineering problems like bearing capacity of shallow foundations and piles, the stability of the slopes of dams and embankments, and lateral earth pressure on retaining walls (Das 2013).

3.3.5.1.1 Advantages of direct shear test

i) The test is relatively simple to carry out.
ii) The basic principle is easily understood.
iii) Preparation of recompacted test specimens is not difficult.
iv) Consolidation is relatively rapid due to the small thickness of the test specimen.
v) The principle can be extended to gravelly soils and other materials containing large particles, which would be more expensive to test by other means.
vi) Friction between rocks and the angle of friction between soils and many other engineering materials can be measured.
vii) In addition to the determination of the peak strength at failure, the apparatus can be used for the measurement of residual shear strength by the multi-reversal process.

3.3.5.1.2 Disadvantages of direct shear test

i) The specimen is constrained to fail along a predetermined plane of shear.
ii) The distribution of stresses on this surface is not uniform.
iii) The actual stress pattern is complex and the directions of the planes of principal stresses rotate as the shear strain is increased.
iv) No control can be exercised over drainage, except by varying the rate of shear displacement.
v) Pore-water pressures cannot be measure.

vi) The deformation which can be applied to the soil is limited by the maximum length of travel of the apparatus.

3.3.5.2 Direct shear laboratory experiment

The direct shear device or direct shear apparatus was used to carry out tests on soil and soil-PET plastic waste composite specimens of 100mm square and 30mm high divided horizontally into two halves as seen in Figure 3.10 below.

The inner side or diameter of the shear box was measured and its area determined. Care was taken to see that the top and bottom halves of the shear box were in contact and fixed together. The weight of the soil, or soil-PET plastic waste composite measured to 150g per specimen. The specimen was homogeneously mixed well with the corresponding optimum water content of the specimen which was got during the compaction test. Using the funnel the saturated soil or soil-PET plastic waste composite was placed in the shear box in three (3) layers and each layer compacted 15 blows using a hand tamper. Care was taken to make sure that the top of the soil or soil-PET plastic waste composite in the shear box was covered before being transferred to the direct shear box machine (digishear).

After compaction, the loose particles were removed and the fully levelled compacted soil or soil-PET plastic waste composite in the shear box was covered with perforated and porous plates. During this process the two halves of the shear box were tightened with screws and care was taken for shear box not to lose shape. The shear box containing the specimen to be tested was placed into the digishear machine as seen in Figure 3.11. Furthermore, the tests were conducted at three (3) normal stresses of 100kPa, 200kPa, and 300kPa. Also, before the digishear machine was started, it was first set at a speed of 0.05556mm per minute, in the forward direction, with a time limit of 180 minutes and stroke was limited to 10.0mm. In order determine the cohesion and angle of friction, a graph of total stress (kPa) against normal stress (kPa) was plotted. Having known the normal stress, total stress values were got dividing the resisting shear force with the corresponding area of the specimen. The test and necessary calculations were performed in accordance with BS 1377: Part 7: 1990.

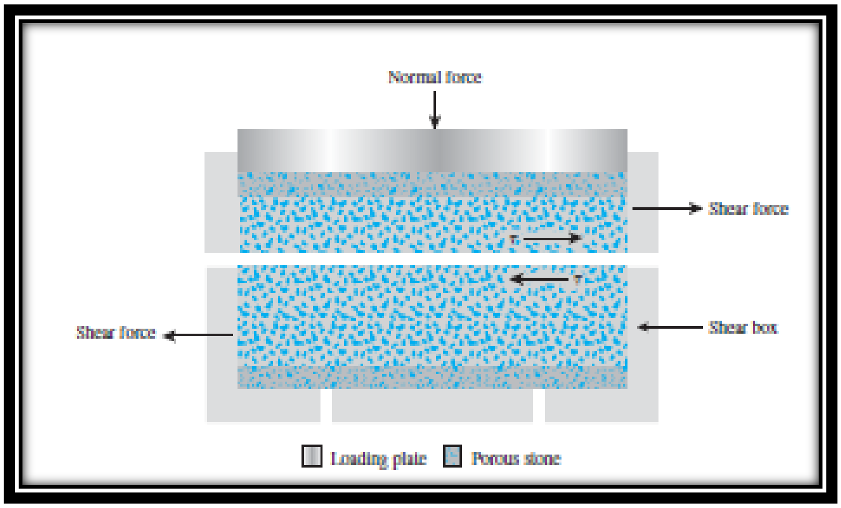


Figure 3.10: Direct shear box principle (Das 2009)

Figure 3.11: Digishear apparatus used during research.

CHAPTER 4: TEST RESULTS AND DISCUSSION

4.1 Introduction

The engineering behaviour of the soil-PET plastic waste composite was examined by focusing on the influence of percentage inclusion of PET plastic waste to the soil. Basing on the various experiments elaborated in Chapter 3, this Chapter presents the test results, analysis and discussions. Indicator tests, compaction test, California Bearing Ratio (CBR) test, and direct shear box test performed on soil and soil-PET plastic waste are all presented in this Chapter. Most of the tests were performed on both reinforced and unreinforced soil. The unreinforced soil served as reference to evaluate the effect of PET plastic waste on studied soil.

4.2 Results and Discussion Pertaining to Indicator Tests

As stated in Chapter three (3), this research was conducted using materials such as sandy soil, water and PET plastic waste. The indicator tests like specific gravity, particle size distribution, and Atterberg limits are used to classify soil. For the current research, particle size distribution was carried out on sandy soil and PET plastic waste flakes and results are given in Section 4.2.1 below. The Atterberg limit tests revealed that the soil specimen was non-plastic. Specific gravity value of 2.66 for the sandy soil specimen was adopted from Kalumba & Chebet, (2013) since researched on the similar sandy soils within Western Cape region. Properties of PET plastic waste used were adopted from Table 2.3.

4.2.1 Particle Size Distribution Test

As defined earlier in Chapter 3.3.2, particle size distribution as being the determination of the size ranges of particles present in a soil (Das 2012), expressed as a percentage of the total dry weight (mass). As emphasised earlier in Chapter 3.3.2, particle size distribution analysis (dry or wet) is carried out on cohesionless (gravel and sandy) soils, whereas sedimentation analysis is carried out on cohesive (silt and clay) soils. Particle size distribution analysis as an index test for soils like sand is important to carry out, as it presents the relative proportions of different sizes of particles. This helps in determining whether a soil specimen consists of predominantly gravel, sand, silt or clay and roughly tells which of the soil type is likely to control the engineering properties. Table 4.1 and Figure 4.1 present the particle size distribution test of both sandy soil and PET plastic waste flakes.

Table 4.1: Particle size distribution test results

#	Property	Soil	PET plastic waste
1	Specific gravity	2.66	1.38
2	**Consistency limits**		
a)	Liquid limit (%)	0	
b)	Plastic limit (%)	0	
c)	Plasticity index (%)	0	
3	**Particle size analysis**		
a)	Particle size distribution (%)		
	10	100	100
	4.75	100	56.41
	2.36	100	12.27
	1.18	98.59	5.94
	0.6	81.57	
	0.425	63.78	
	0.212	17.94	
	0.15	5.39	
	0.075	0.21	
b)	Gravel (%)	0	
c)	Sand (%)	99.79	
d)	Silt (%)	0.21	
e)	Clay	0	
f)	Mean particle size $_{D50}$	0.354	
g)	D_{60} (mm)	0.405	
h)	D_{30} (mm)	0.265	
i)	D_{10} (mm)	0.175	
j)	Coefficient of uniformity, C_u	2.314	
k)	Coefficient of curvature, C_c	0.99	

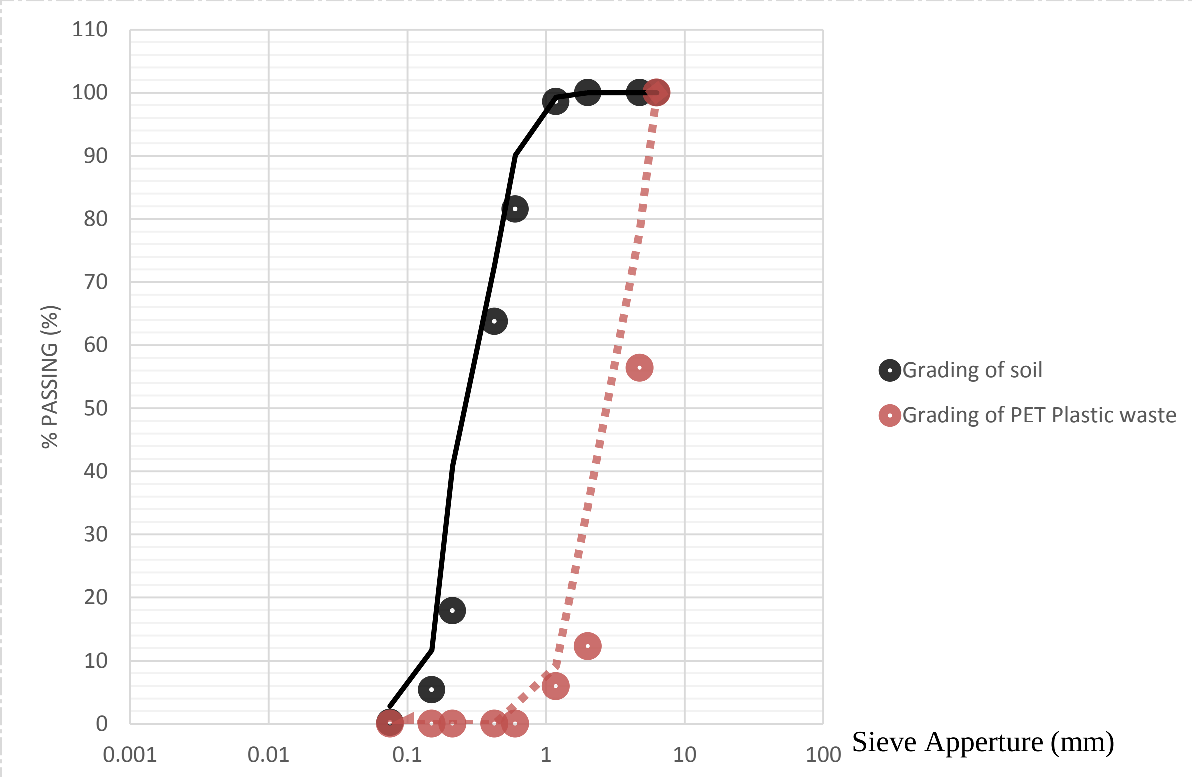


Figure 4.1: Results of particle size distribution of sand and PET plastic waste flakes.

Figure 4.1 shows the particle size distribution curves of soil and PET plastic waste flakes specimens. Particle sizes of soil specimens ranged from 1.18mm to 0.075mm, with gravel percentage of 0%, sand percentage of 99.79%, silt percentage of 0.21% and clay percentage of 0%. As seen in Table 4.1, the soil specimen has a mean particle size D_{50} of 0.354mm, D_{60} of 0.405, D_{30} of 0.265mm, and D_{10} of 0.175mm.

These resulted into coefficient of uniformity C_u of 2.314 and coefficient of curvature C_c of 0.99. Classifying the soil specimen using Unified Soil Classification system (USCS) - Great Britain BS 1377:1990 (Figure 3.3), together with Figure 3.4, it can be concluded that the soil specimen used in the research is uniformly graded fine sand (SPu) (Head 1994, BS1377 1990). Kalumba & Chebet (2013), carried out particle size distribution test on a similar sand specimen which is within the region of Western Cape, got similar results and classified it as “Cape Flats sand of medium dense light grey, clean quartz sand with round shaped particles.”

Furthermore, from Figure 4.1 and Table 4.1, the specific gravity of PET plastic waste is 1.38 and particle sizes are in the range of 10mm – 0.6mm, it can be concluded that PET plastic waste is uniformly graded according to USCS. In civil engineering, field materials of good quality used on various projects should be well graded. It was observed and as seen in Figure 3.1, that the PET plastic waste contains smooth and flaky particles, this became a challenge while mixing it with sandy soils as it was difficult to get a perfect bond. It was also be noted that a mixture of sand and PET plastic waste resulted into a uniformly graded composite as the mixture lacked fines.

4.3 Results and Discussion Pertaining to Compaction Test of Soil and Soil-PET Plastic Waste Composite.

As mentioned in Chapter 3.3.3, compaction is the process of packing soil particles more closely together, usually by rolling or other mechanical means, thus increasing the dry density of the soil. Soil compaction results into increased bearing capacity, shear strength and dry density. Properly compacted soils decreases its voids ratio, permeability and settlements. The results are used in the study of the stability of earth structures like earth dams, embankments, roads, and airfields (Kumar et al. 2007).

For this research, the compaction test was performed in accordance with BS 1377: Part 4: 1990, and TMH 1: Method A7: 1986 as elaborated in Chapter 3.3.3. The relationship between dry density and moisture content was established by plotting a graph as seen in Figure 4.2, MDD and OMC were read off and recorded (Table 4.2). The typical results of various soil types are given by Look, (2014) after Hoerner, (1990) in Table 3.2. Results of the compaction tests performed on sand and sand-PET plastic waste composite are given in Table 4.2.

Table 4.2: Results obtained during compaction testing program.

#	PET plastic waste (%)	OMC (%)	MDD (kg/m^3)
1	0	12.2	1740
2	12.5	12.2	1630
3	22.5	11.2	1547
4	32.5	13.2	1490

4.3.1 Relationship between MDD and OMC

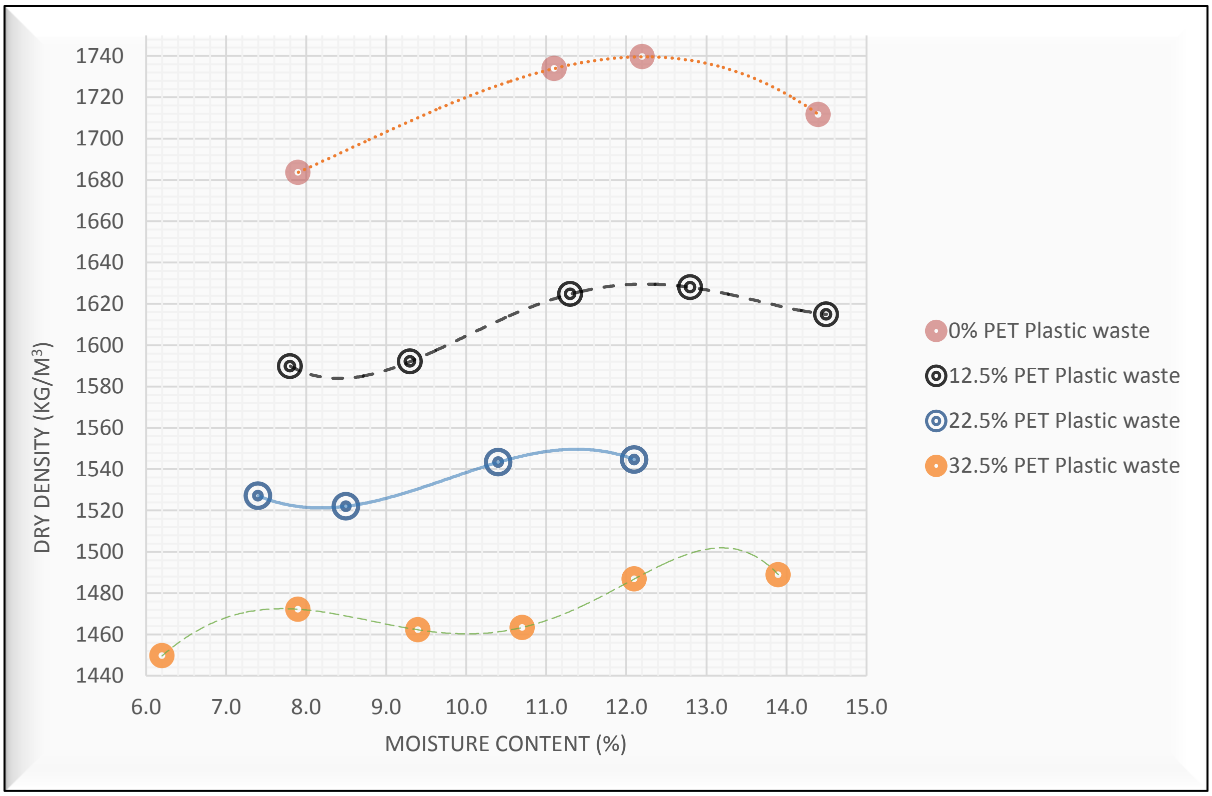


Figure 4.2: Dry density-moisture content relationships of sand and sand-PET plastic waste composites.

Figure 4.2 demonstrates the dry density – moisture content relationships of sand and sand-PET plastic waste composites. Compacted unreinforced sand yielded to a 12.2 % optimum moisture content (OMC) and 1740 kg/m^3 maximum dry density (MDD). The calculated values are equivalent to those of modified compacted sand as seen in Table 3.2.

When sand was reinforced with PET plastic waste, the compacted sand-PET plastic waste composite yielded to a 12.2% of OMC and 1630 kg/m^3 MDD. It can been noticed that there was no difference in the OMC of unreinforced sand and sand- PET plastic waste reinforced with 12.5% PET plastic waste. Furthermore, there was a decrease of 6.75% of the MDD values of unreinforced sand and sand-PET plastic waste composite reinforced with 12.5% PET plastic waste. This shows that though the amount of water used to attain MDD remained constant, sand-12.5% PET plastic waste composite became lighter.

Furthermore, from Figure 4.2 when the sand was reinforced with 22.5% PET plastic waste, the sand-22.5% PET plastic waste composite yielded to 11.2% OMC and 1547 kg/m^3 MDD. Comparing unreinforced sand with sand-22.5% PET plastic waste composite, there was a reduction of 8.9% of the OMC and a reduction of 12.5% of the MDD. When sand-22.5% PET plastic waste composite is compared with sand-12.5% PET plastic waste composite, there is a reduction of 8.9% of the OMC and a reduction of 6.75% of the MDD. This implies that addition of addition of 22.5% PET plastic waste made the sand-22.5% PET plastic waste lighter. This benefits both the civil engineering field and waste management field as 22.5% PET plastic waste which can’t be recycled is withdrawn from the environment and utilised to civil engineering structures where lighter structures are needed.

Lastly but not least, from Figure 4.3 when the sand was reinforced with 32.5% PET plastic waste, the sand-32.5% PET plastic waste composite yielded to 13.2% OMC and 1490 kg/m^3 MDD. Comparing unreinforced sand with 32.5% PET plastic waste there is an increase of 7.6% of the OMC and a decrease of 16.8% of the MDD. Comparing sand-32.5% PET plastic composite and sand-22.5% PET plastic waste composite, there is an increase of 15% of OMC and a decrease of 3.8% of MDD. This shows that during the compaction of sand-32.5% PET plastic waste composite, more water was used. This could be because percentage PET plastic waste was exceeded and that the more PET waste plastic is added the more water is required and it becomes difficult to compact the composite specimen, which leads to lower values of MDD, shear strength and CBR, which is a negative effect.

4.3.2 Relationship between MDD and PET plastic waste

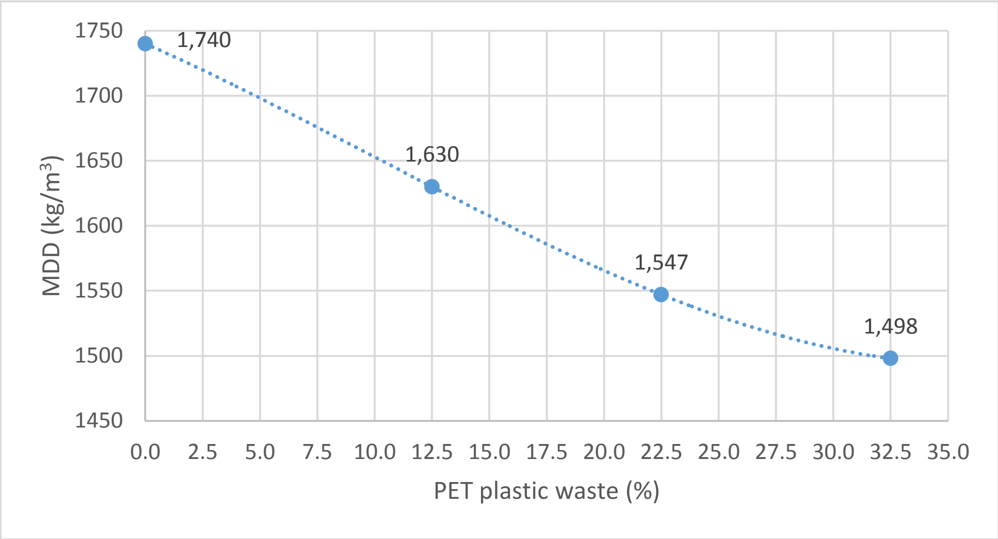


Figure 4.3: Relationship between MDD and PET plastic waste.

Figure 4.3 shows the relationship between MDD and PET plastic waste, generally an increase in PET plastic waster percentage inclusion in the sand, reduces the MDD of sand-PET plastic composite. This is attributed by the fact that sand particles are denser than PET plastic waste. As more PET plastic waste is added in the sand-PET plastic waste composite, the composite becomes lighter and such composite can be used in projects that require lower MDD.

4.4 Results and Discussion Pertaining to California Bearing Ratio (CBR) Test of Soil and Soil-PET Plastic Waste Composite.

CBR values are used as index of soil strength and bearing capacity in the design of base and sub-base of a pavement. CBR tests were carried out in the laboratory with the aim of determining the relationship between force and penetration when a cylindrical plunger of a standard cross-sectional area was made to penetrate the compacted sandy soil and sand-PET plastic waste composite specimens at a given rate (Eqn 3.1). Table 3.3 gives typical ranges of CBR (%) values for compacted soils.

The research results from the tests are appended in Appendix B and summarised in Table 4.3. The CBR (%) value of the specimens were calculated by the ratio of measured penetration force (kN) to a standard force and expressed as a percentage. Thereafter, the final phase of the CBR testing program was the plotting of CBR curves where by the calculated load (kN) was plotted on the y-axis against the depth of penetration (mm) on the x-axis. The measured force (kN) for each of the three specimens were recorded at 2.5mm and 5.0mm depth penetration points as summarised in Table 4.3 below.

Table 4.3: Summary of California Bearing Ratio test results

Material	%PET plastic waste inclusion (%)	Test no.	2.5mm depth penetration		CBR (%) at 2.5mm depth penetration	5.0mm depth penetration		CBR (%) at 5.0mm depth penetration	Actual CBR value (%)	Average CBR (%)
			Measured force (kN)	Standard force (kN)		Measured force	Standard force			
Sand	0	1	1.64	13.2	12.4	0	20	0.0	12	12
	0	2	1.12	13.2	8.5	1.6	20	8.0	9	
	0	3	1.98	13.2	15.0	2.36	20	11.8	15	
Sand-PET plastic waste composite	12.5	1	1.08	13.2	8.2	1.76	20	8.8	9	12
	12.5	2	0.96	13.2	7.3	2.2	20	11.0	11	
	12.5	3	2.08	13.2	15.8	0	20	0.0	16	
Sand-PET plastic waste composite	22.5	1	2.2	13.2	16.7	5.8	20	29.0	29	21
	22.5	2	1.8	13.2	13.6	4	20	20.0	20	
	22.5	3	1.7	13.2	12.9	3.05	20	15.3	15	
Sand-PET plastic waste composite	32.5	1	1.9	13.2	14.4	4.5	20	22.5	23	22
	32.5	2	1.9	13.2	14.4	4.2	20	21.0	21	
	32.5	3	2.2	13.2	16.7	4.35	20	21.8	22	

Table 4.3 shows the CBR values of the four (4) tested specimens compacted at their respective optimum moisture content (Table 4.2 above). The test was executed in accordance with BS 1377: Part 4: 1990 and TMH 1: Method A8: 1986 as elaborated in Chapter 3.3.4. The inclusion of PET plastic waste of 0%, 12.5%, 22.5% and 32.5% to reinforce poorly graded uniform sand resulted in CBR values of 12%, 12%, 21% and 22% respectively. The analysis of these results is elaborated below.

4.4.1 Relationship between PET plastic waste (%) and CBR (%)

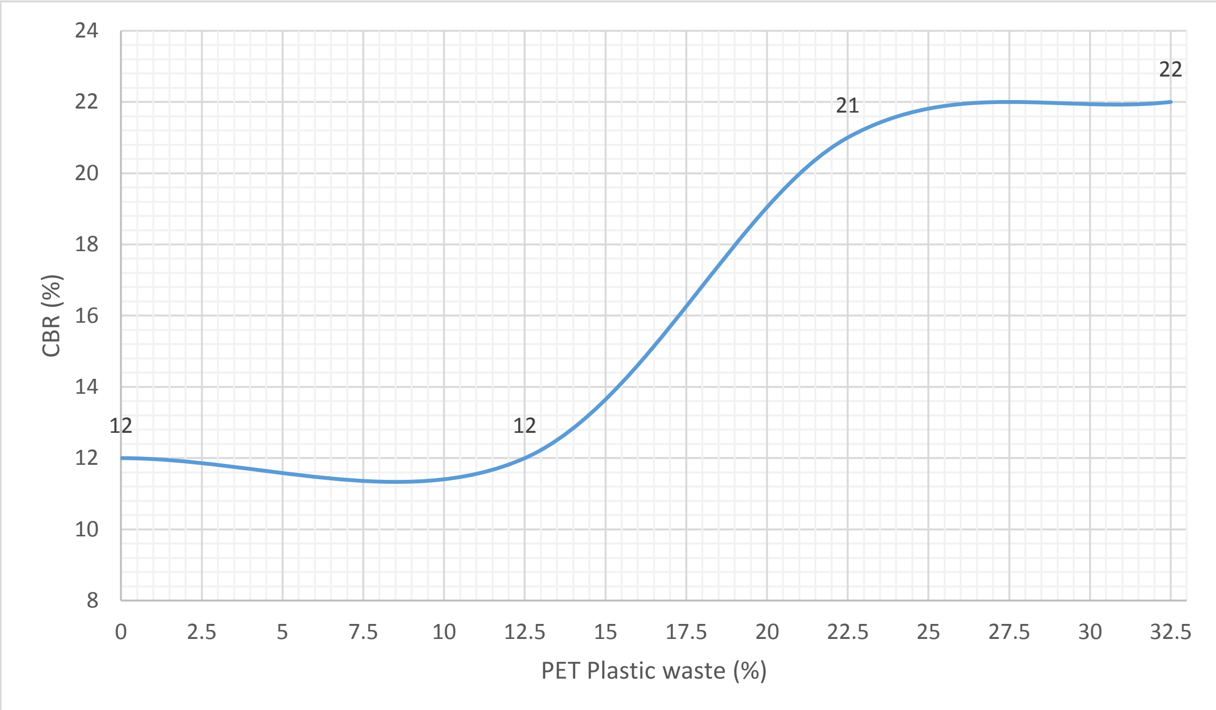


Figure 4.4: Relationship between PET plastic waste (%) and CBR (%)

Figure 4.4 above shows the relationship between CBR (%) and PET plastic waste (%) which was used to reinforce the poorly graded uniform sand soils during the laboratory experiment. It is noted that, when the sand is unreinforced it possesses a CBR value of 12% which is equivalent to sand-PET plastic waste composite specimen reinforced with 12.5% PET plastic waste. It implies that reinforcing poorly graded uniform sand with 12.5% PET plastic doesn't cause a change in CBR values. This may have been attributed by lack of fines in the sand-PET plastic waste composite, and the flaky PET plastic waste flakes causing low bondage between sand particles and the PET plastic waste flakes.

Furthermore, it should be noted that an increase in PET plastic waste in the sand-PET plastic waste composite generally resulted in an increase in CBR value. Though Figure 4.4

suggests that an increase of PET plastic waste beyond 25% of PET plastic waste may not result in an increase in the CBR value as for this case it remained constant.

4.5 Results and Discussion Pertaining to Direct Shear Box Test of Soil and Soil-PET Plastic Waste Composite.

Shear strength as defined earlier in Chapter 3.3.5.1, as the resistance to shearing stresses and a consequent tendency for shear deformation. This section elaborates on the results of shear stresses obtained from the direct shear tests of unreinforced sand and sand-PET plastic waste composites recorded and plotted against their respective applied normal stresses to determine the friction angles (φ) and cohesion values (c). The detailed explanation of the testing program is as provided in Chapter 3.3.5 and done in accordance with BS 1377: Part 7: 1990. The results here presented in Table 4.4 and Figure 4.5, were performed on unreinforced sand specimens and sand-PET plastic waste composite specimens.

Table 4.4: Direct Shear box test results

PET plastic waste (%)	**Shear Stress, τ (KN/m^2 or kpa)**	**Normal Stress, σ (kN/m^2 or kpa)**
0	88	100
0	171	200
0	246	300
12.5	133	100
12.5	222	200
12.5	303	300
22.5	129	100
22.5	226	200
22.5	324	300
32.5	125	100
32.5	238	200
32.5	300	300

4.5.1 Relationship between Shear stress (kPa) and normal stress (kPa)

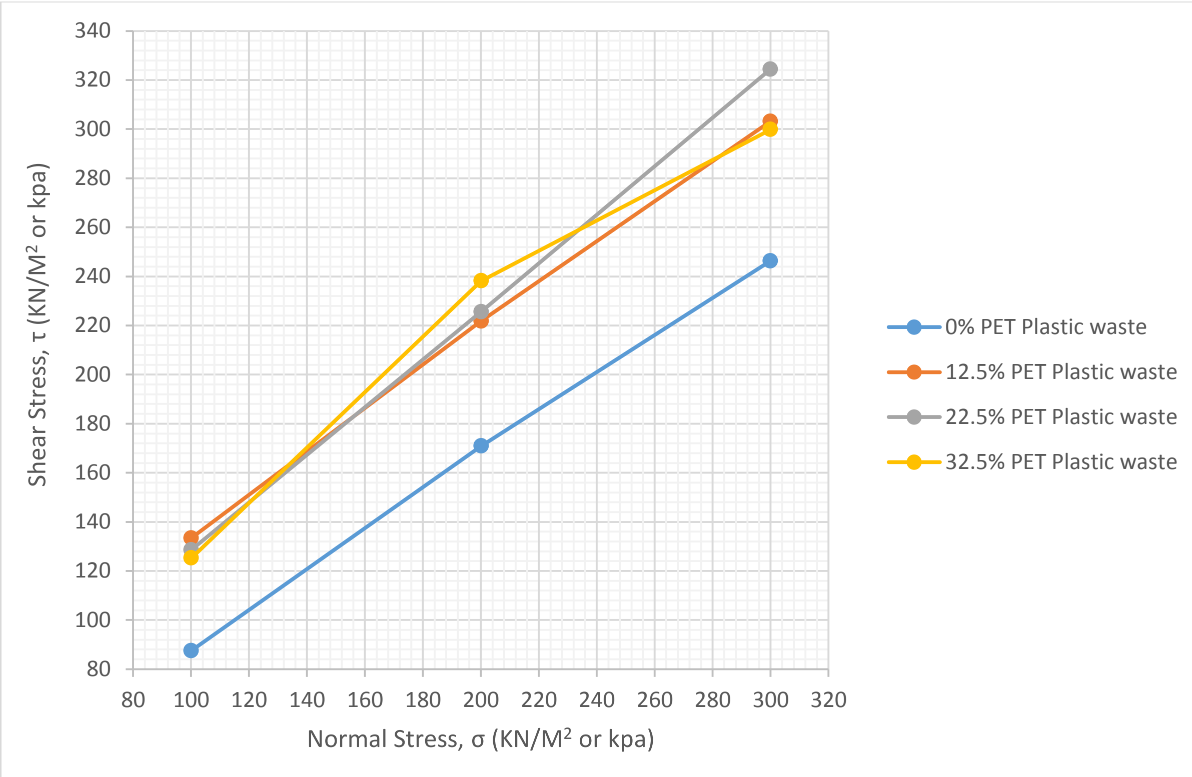


Figure 4.5: Relationship between shear stress and normal stress

Figure 4.5 shows the relationship between shear stress and normal stress for both unreinforced sand and sand-PET plastic waste composite specimens.

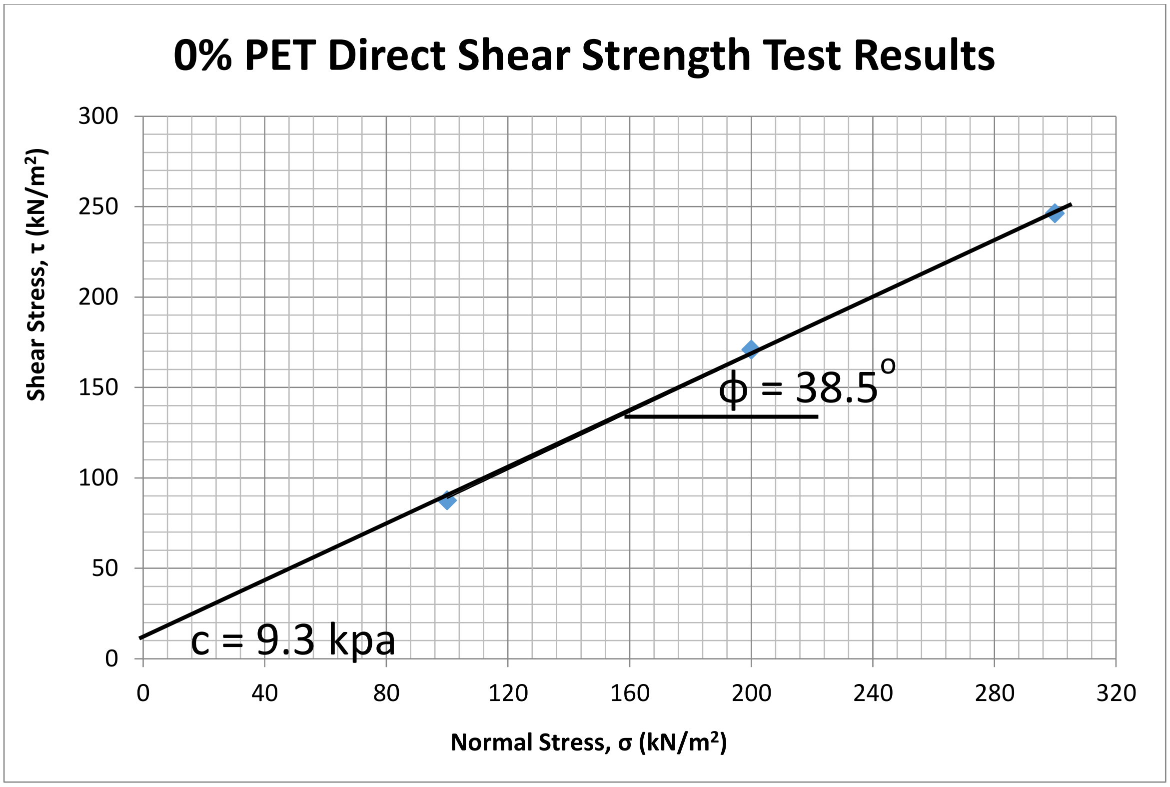


Figure 4.6: 0% PET plastic waste composite direct shear test result

Figure 4.6 above shows the direct shear test result of unreinforced sand, the shear stress was plotted on the y-axis and the normal stress was plotted on the x-axis. The results shows that shear strength is proportional to the normal load. The angle of friction determined was 38.5^o, this result is consistent with results obtained by Kalumba & Chebet (2013), of 38.5^o when similar sand specimen from the Western Cape region was tested. Kalumba & Chebet (2013), classified this type of sand as "Cape Flats sand of medium dense light grey, clean quartz sand with round shaped particles which is predominant in Western Cape region, South Africa." Also considering the estimated values of angle of friction given in Table 3.4 by Look (2014), the angle of friction obtained during this research falls between 35^o-40^o. However, the angle of friction would have been higher if there was chemical and increased physical bonding of the sand particles. This would have increased the interlocking of particles and the friction between them when subjected to normal effective stress. Cohesion of 9.3kPa of the 0% PET sand is negligible.

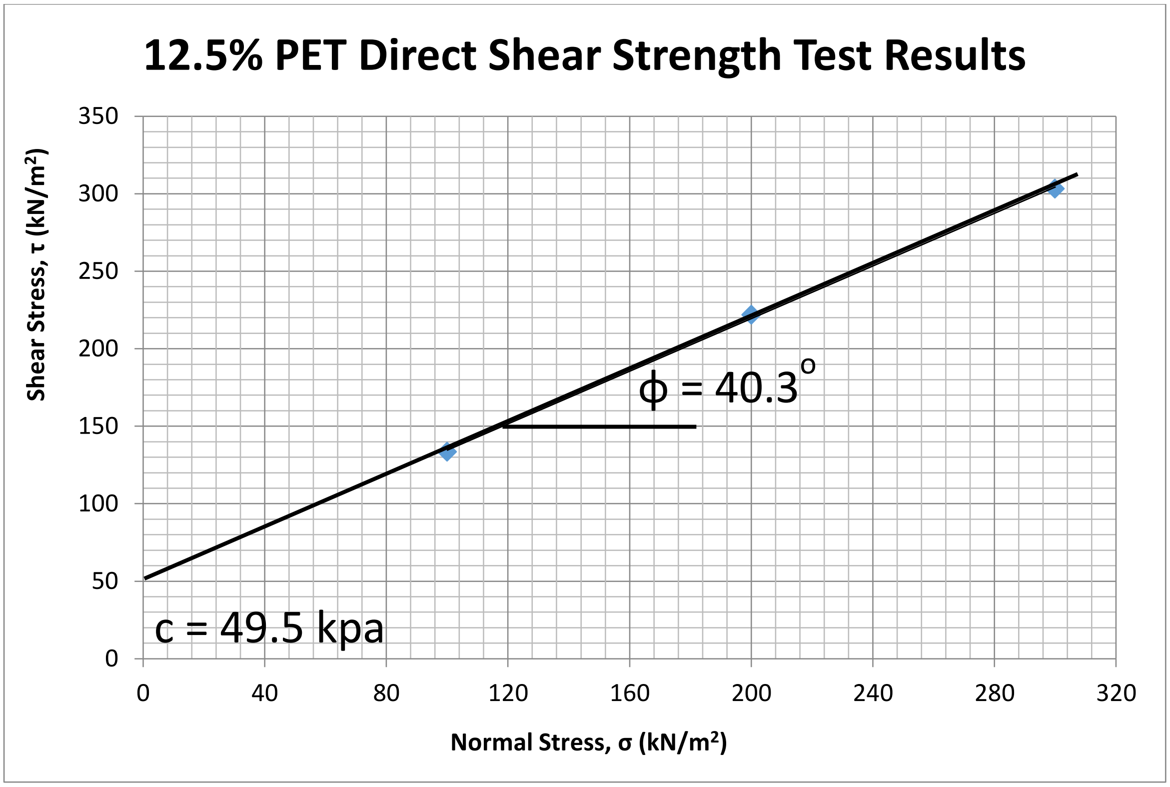


Figure 4.7: 12.5% PET plastic waste composite direct shear test result.

Figure 4.7 above shows the direct shear test result of sand reinforced with 12.5% of PET plastic waste (by dry weight of sand). The sand-PET plastic waste composite has an angle of friction of 40.3° and cohesion of 49.5kPa. There was an increase of the friction angle from 38.5° to 40.3°, when 12.5% of PET plastic waste was added to the sand. This translated into a 4.5% increase in the angle of friction when sand was reinforced with 12.5% of PET plastic waste. The increase in angle of friction could have been caused by the improved sand-12.5% PET plastic waste composite structure where by the improved packing and compaction of the soil in addition to higher roughness of PET plastic waste particles, thus causing an increase in shear strength. From Table 3.4, the angle of friction of 40.3° falls under dense sand, or gravels, or cobbles, or boulders, or rock.

Furthermore, Figure 4.7 above shows that sand reinforced with 12.5% PET plastic waste resulted in a cohesion of 40.3kPa. Much as sand alone produces negligible cohesion value, addition of 12.5% PET plastic waste improved the internal forces by holding the sand-PET plastic waste composite particles together in a solid mass. Basing on the cohesion values in Table 3.4, the sand-PET plastic composite is providing cohesion values similar to that of firm clay soil or a rocky material (Table 3.4).

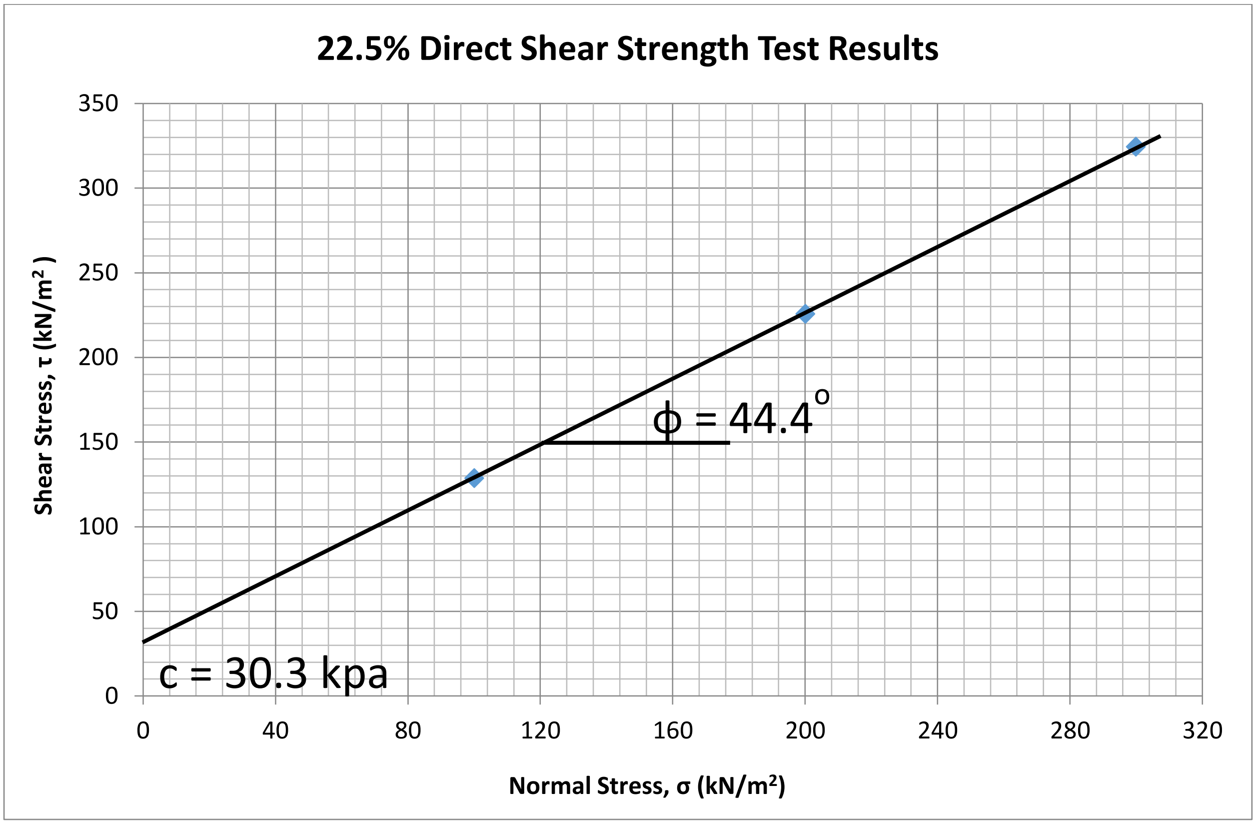


Figure 4.8: 22.5% PET plastic waste composite direct shear test result

Figure 4.8 shows direct shear strength test results of sand reinforced with 22.5% PET plastic waste (by dry sand weight). The shear strength is proportional to the normal stress. The sand-22.5% PET plastic waste composite has an angle of friction of 44.4^{o} and cohesion value of 30.3kPa. Comparing angle of friction of sand only (38.5^{o}) and sand-22.5% PET plastic waste composite (44.4^{o}), there was a 13.3% angle of friction increase. The increase in strength indicates that 22.5% or more PET plastic waste could be nearly the optimum PET plastic waste needed to reinforce sand. The increase in the shear strength was due to the increase in roughness.

Also, comparing angle of friction of sand-12.5% PET plastic waste composite (40.3^{o}) and sand-22.5% PET plastic waste composite (44.4^{o}), there was a 9.2% angle of friction increase. This increase was due to the rougher surface texture between the soil and PET plastic waste particles. There was proper physical bond between the particles, which could have reduced the friction between the particles when subjected to the normal stresses. From Table 3.4, it can be noted that sand-22.5% PET plastic waste with 44.4^{o} angle of friction can be termed as dense sand, or gravels, or cobbles, or boulders, or rock (Table 3.4).

Due to the dense packing of the sand-22.5% PET plastic waste, there was low void ratio. As the sand-22.5% PET plastic waste composite specimen was sheared along a plane, there was no distortion or crushing of individual sand or PET plastic waste particles. The particles lying just above the upper half of the shear box were forced to ride up and over those lying just below the lower halve of the shear box when relative movement occurred. This was noted during the testing process by observing the shear box, whereby, the expansion of the particles caused an upward movement of the top surface of the sand-22.5% PET plastic waste composite specimen, Das (2013) and Head (1994) term this as dilation.

The cohesion of 30.3kPa indicates that due to the good physical bond, there was internal forces that held the soil-22.5% PET plastic waste composite particles together in a solid mass. From Table 3.4, it can be noted that sand-22.5% PET plastic waste with 30.3kPa cohesion can be termed as having cohesion similar to that of firm clay soil or rock.

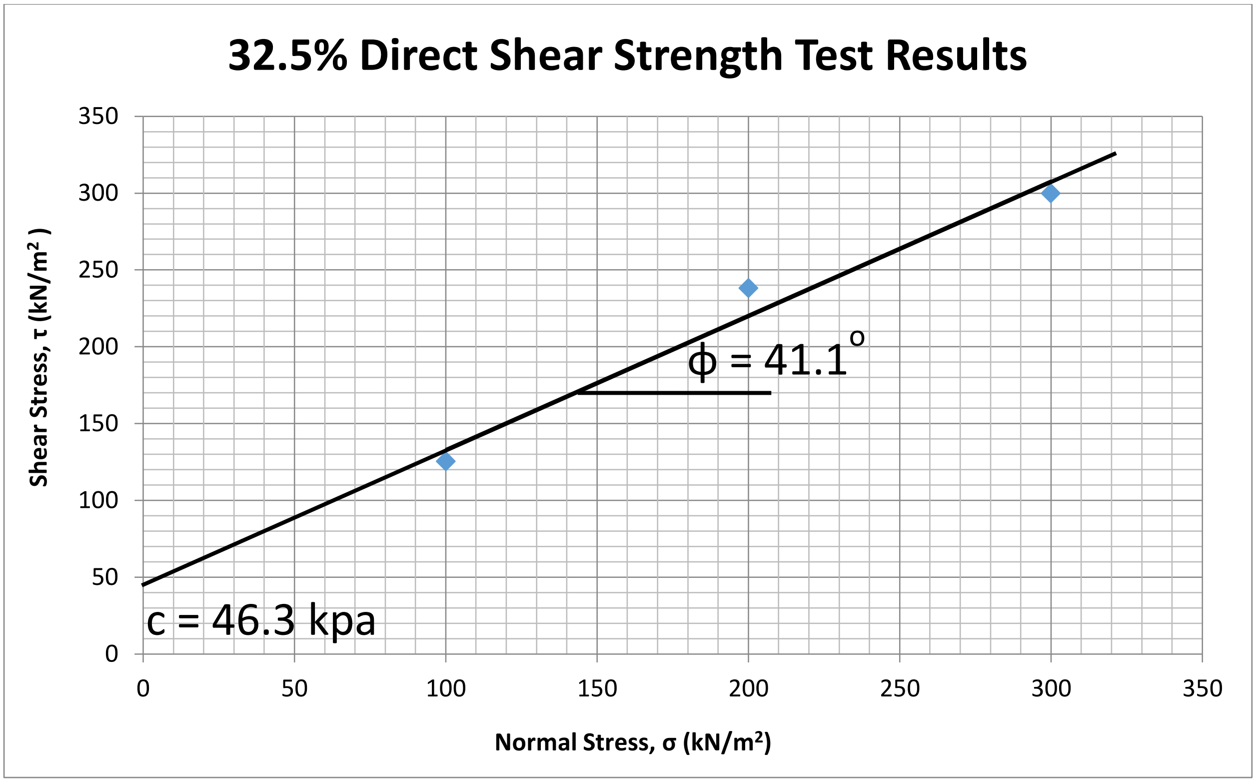


Figure 4.9: 32.5% PET plastic waste composite direct shear test results

Furthermore, Figure 4.9, shows the direct shear strength of sand reinforced with 32.5% of PET plastic waste (by dry sand weight). The shear strength is proportional to the normal stress. The sand-32.5% PET plastic waste composite has an angle of friction of 41.1^o and cohesion value of 46.3kPa. These values obtained are similar to those of dense sand, firm clay soil, gravel, cobble, boulders and rock as seen in Table 3.4. Comparing angle of friction of sand only (38.5^o) and sand-32.5% PET plastic waste composite (41.1^o), there was a 6.3% angle of friction increase. The increase in the angle of friction could have been caused by reinforcing sandy soil with 32.5%, which could also be due to improved interlocking of sand-32.5% PET plastic waste composite particles.

However, it should be noted that there was a decrease of 7.4% between sand-22.5% PET plastic waste composite (44.4^o) and sand-32.5% PET plastic waste composite (41.1^o). The decrease could have been due to the higher presence of PET plastic waste in the sand-32.5% PET plastic waste composite beyond the optimum PET plastic that can be added to reinforce soil. This could have reduced the bonding properties of the composite thereby decreasing the friction angle, hence reducing the shearing strength of the composite. Another suggestion is the smooth surface of the PET plastic waste flakes which could have reduced the interaction with sand particle during compaction. Also it may be suggested that since the sandy soil and PET plastic particles are uniformly graded, there is lack of finer particles to fill the voids that exist in the sand-32.5% PET plastic waste composite.

4.5.2 Relationship between percentage increase in friction angle (%) and Polyethylene Terephthalate (PET) plastic waste (%)

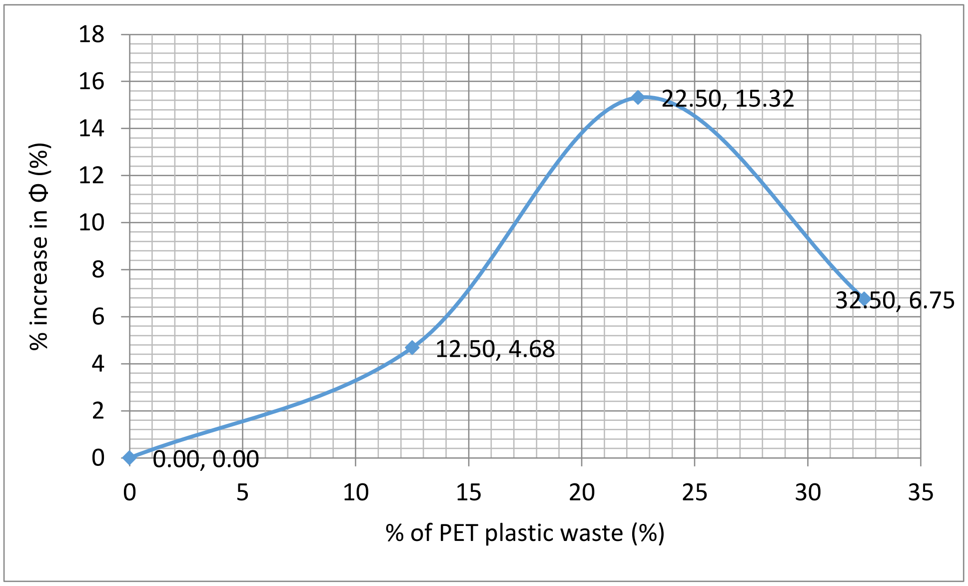


Figure 4.10: Relationship % increase in angle of friction (%) and PET plastic waste (%)

Figure 4.10 shows the relationship between percentage increase in friction angle (%) and PET plastic waste (%). From the figure, it can be deduced that as a small amount of 4% PET plastic waste is used to reinforce sandy soil, there seem to be a percentage decrease in the angle of friction of about 2%. This suggests that there is a decrease in the shear strength of sand-4% PET plastic waste composite. This could have been due to lack of interaction between sand and 4% PET plastic waste particles. Though Acharyya et al. (2013), used up to 5% of PET plastic waste to reinforce soil and registered a percentage increase in the angle of friction hence increased shear strength, the soil used was a mixture of sand and clay.

Furthermore, inclusion of PET plastic waste of about 12.5% in uniformly poorly graded sand, results in a sharp percentage increase in the angle of friction say of 4.68%. The trend can even be seen as more 22.5% PET plastic waste is used to reinforce sand, the percentage increase in friction angle of 15.32% is registered. As more PET plastic waste is added, an optimum PET plastic waste is reached (25%) which gives the maximum percentage increase in friction angle of 16%. This implies that the sand-PET plastic composite possesses low voids ratio as the composite is compacted making it denser. As the composite is sheared, the particles just lying above the upper halve of the shear box apparatus were forced to ride up and over those lying just below when relative movement occurred. This was noted by observing the shear box apparatus when movement occurred during the testing period. Expansion of the particles caused an upward movement of the top surface of the composite.

After this point as more PET plastic waste is added, the percentage increase in the angle of friction reduces. Like for the case of 32.5% PET plastic waste yielding to percentage increase in angle of friction of 6.75%. This shows that higher percentages of PET plastic waste more than 25% reduces a denser sand-PET plastic waste composite to a loose state and form voids in the composite. In this case shearing of the composite particles in a loose state results in a collapse as the particles move downwards into void spaces, which cause a volume decrease (contraction). In the laboratory, during the carrying out of the testing was noticed by the downward movement of the top surface of the shear box apparatus hence, low shear strength is registered.

4.5.3 Relationship between angle of friction and maximum dry density (MDD)

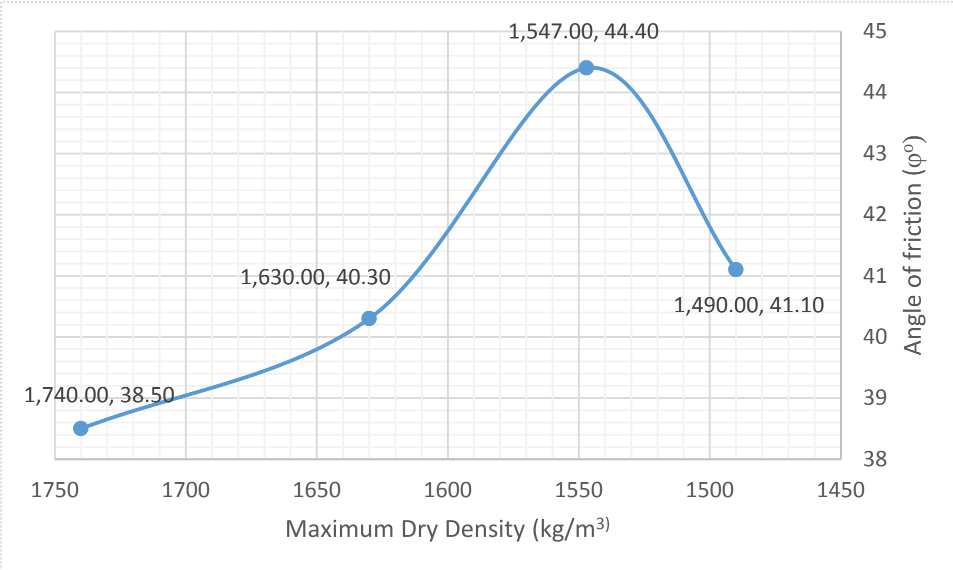


Figure 4.11: Relationship between angle of friction (ϕ°) and maximum dry density (kg/m^3)

Figure 4.11 shows the relationship between angle of friction and maximum dry density, and it resembles Figure 4.10 (relationship between percentage increase in angle of friction (%) and PET plastic waste (%). For this case, the highest angle of friction (44.4°) was attained when the maximum dry density is 1547 kg/m^3.

4.5.4 Shear efficiency

The increase in shear strength achieved by adding PET plastic waste content to sand can be described in terms of shear efficiency, E_t, which is defined by Vinot and Singh (2010) as

$$E_t = \frac{\tau_{st}}{\tau_s}$$

τ_{st}= shear strength of the sand-PET plastic waste composite

τ_s = shear strength of the sand (Vinot & Singh 2010).

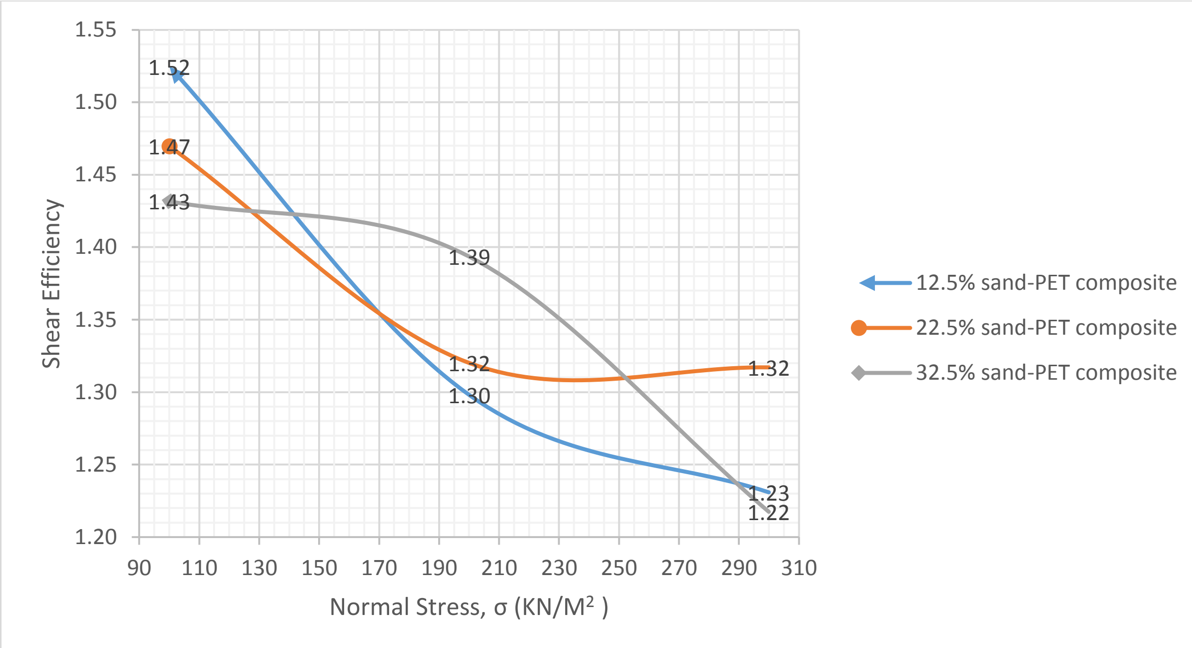


Figure 4.12: Variation of shear efficiency with Normal stress.

Figure 4.12 shows the variation of shear efficiency with normal stress. An increase of normal stress leads to considerable decrease of the shear efficiency at a PET plastic waste content higher than 22.5% due to less dilatancy. As the normal stress is increased, the efficiency decreases and asymptotically approaches 1.3 for 12.5% PET plastic waste content.

CHAPTER 5: RESEARCH PRACTICAL SIGNIFICANCE

5.1 Bearing Capacity of Sand-PET Plastic Waste Composite.

Most of the civil engineering structures have contact with the earth's crust, and whatever depth these structures are placed within the earth's crust require quality soil materials which are strong enough to counteract the applied loads. The earth crust is about 10 to 60km in thickness (Attewell & Farmer 2012) and constitutes of igneous rocks, metamorphic rocks and sedimentary rocks (Zawada 1994; Faquan 2013). The mechanical, chemical and biological weathering of igneous rocks or metamorphic rocks results in sedimentary rocks (Zawada 1994). The sedimentary rocks can further be transformed into soils with different particle sizes. The strength of soils (like gravel, sand, sand and clay) which lays within top 1km (Xiao 2015) of the earth crust is key to geotechnical engineers, as it supports most of the substructures. Any poor quality soils or slight movement of soil may cause large deflections in the structure or even collapse of the entire structure causing fatalities and economic loss. It's with this background that the bearing capacity of sand-PET plastic waste composite of this research is determined in this section.

Therefore, geotechnical designers need to determine the bearing capacity of soil such that, the strength of the foundation bearing strata (for the case of this research 'sand-PET plastic waste composite') is known before structural loads are imposed on it (Day 2013). Das (2013) defines bearing capacity of the soil as the ability of the soil to resist applied stress/force. For many years design philosophies have evolved when it comes to verifying the strength of soil, due to the uncertainties (Dithinde 2007) of the foundation bearing strata (BSI 1995, Bond & Harris 2008). These design philosophies are experience based design, working stress design and limit state design (Dithinde 2007) and the latter is elaborated below, including using it to assess the bearing capacity of sand-PET plastic waste. The design philosophy used in this section is the limit state design as seen below.

This research has demonstrated the application of direct shear box and compaction tests results in the determination of the bearing capacity of unreinforced sand and sand-PET plastic waste composite. These values were then used to calculate the foundation width using the limit state design (STR, STR-P, and GEO limit state design conforming to SANS 10160) as seen in Appendix F. The relationship between PET plastic waste, foundation width and angle of friction is summarised in Table 5.1 and Figure 5.1 below.

Table 5.1: Summary of PET plastic waste, angle of friction and foundation width

PET plastic waste (%)	Foundation width, B (m)	Angle of friction (degree)
0	3.323	38.5
12.5	3.298	40.3
22.5	3.230	44.4
32.5	3.297	41.1

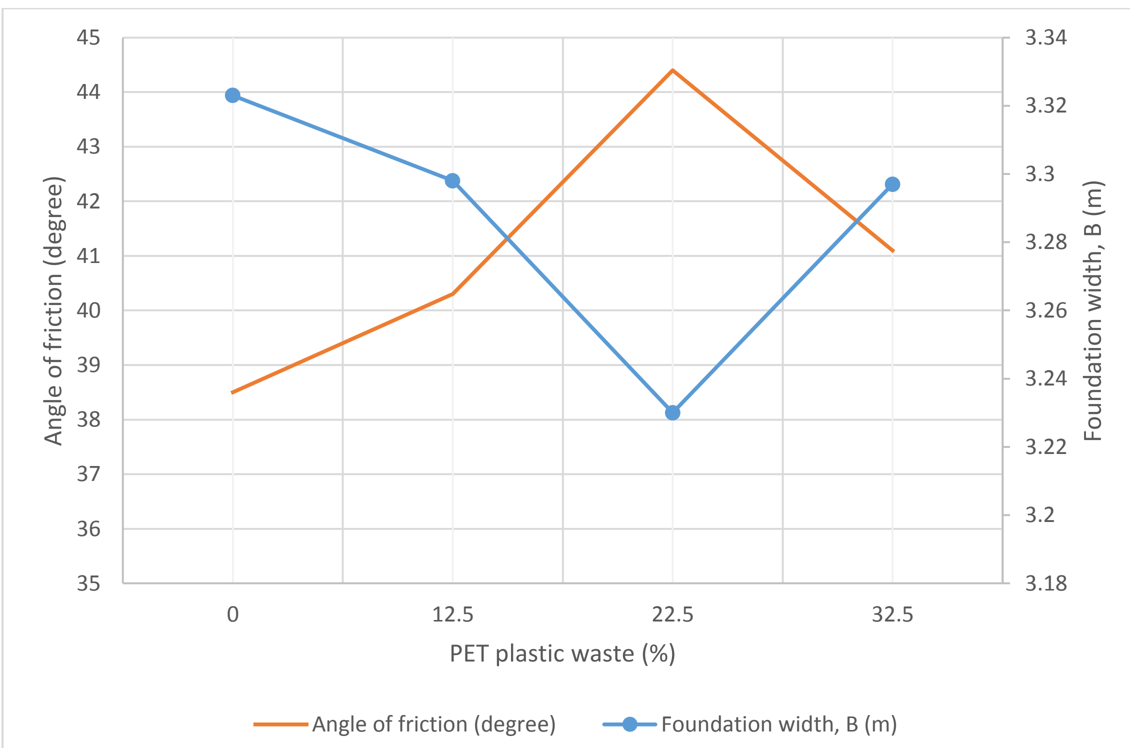


Figure 5.1: Relationship between PET plastic waste, angle of friction and foundation width.

Figure 5.1 shows the relationship between PET plastic waste, angle of friction and foundation width. As the percentage inclusion of PET plastic waste flakes is increased, the value of the angle of friction increases and the width of the foundation decreases. This indicates that the presence of PET plastic waste in the sand specimen increases the shear strength of the composite leading to an increase in the bearing capacity of the strata, which finally lowers the foundation width, hence making it economical. For this research the trend continues up to the 22.5% PET plastic waste flakes inclusion into the composite. This leads to the maximum angle of friction of 44.4^o and the minimum foundation width B of 3.23m which in this case is seen as the optimum foundation width.

Furthermore, as sand is reinforced with more PET plastic waste say of 32.5%, the angle of friction decreases to 41.1^o, and in the foundation width increases to 3.297m compared to the previously when reinforced with 22.5%. This implies that as more PET plastic waste is increased, the shear strength of the sand-PET plastic composite reduces hence leading to an increase in the foundation width and making it costly (Gray & Ohashi 1983).

Therefore, reinforcing sand with 22.5% PET plastic waste flakes can improve its bearing capacity that translates into decreased foundation width of about 3%. This lowers the cost of the project compared to the unreinforced sand. Though 3% decrease in the width of the foundation seem to be little when angle of friction changes from 38.5^o to 44.4^o, sand-PET plastic waste composite has shown potential of improving the bearing capacity of the sandy soil. More so, the mere fact that 22.5% PET plastic waste is reused and prevented from endangering the environment, and lowering the plastic wastes taken to landfill can be seen as an achievement. This may lead to a sustainable way of handling plastic waste, and preventing its negative impact globally.

Lastly but not least, with improved grading of this composite's particles and/or stabilising it may improve its shear strength. Also, investigating its ability as a construction material like bricks/blocks may open new doors for its application in the civil engineering field.

5.2 Pavement Design – Foundation Design Using Sand-PET Plastic Waste Composite

Foundations are vital in pavement, as its purpose is to transfer applied loads (both the live and dead loads) and distribute it to the different pavement layers (surface, base, sub-base, subgrade as seen in Figure 3.7) up to the formation layer (subsoil) with no or minimum distress (DMRB 2011). A lot of emphasis is usually placed on the design of pavement, though it should be noted that even a cycleway or footway need to be designed and constructed with appropriate materials to avoid distress of their foundation when loads are applied. In order to achieve the main objective of this research which is analysing the behaviour of soil reinforced with Polyethylene Terephthalate (PET) plastic waste, California Bearing Ratio (CBR) test was determined. CBR is nothing other than an indirect measure of soil strength based on resistance to penetration. This section looks at the possibility of using sand-PET plastic waste composite material in the flexible pavement, cycleway or footway design.

The subgrade material is compacted in a subgrade layer which is usually below the subbase layer as seen in Figure 3.7. Subgrade strength is usually assessed using CBR (%) values obtained in-situ or from laboratory test results as elaborated in Chapter 3.3.4 and Chapter 4.4. DMRB (2011), estimates CBR (%) values of poorly graded sandy soils to be in the range of 10% to 20% for subgrade layer and that of well graded sandy soils to be in the range of 15% to 40% for subgrade layer.

Therefore, using the CBR (%) results of sand-PET plastic waste of this research finding in Table 4.3 and the BS standard estimates, it can be concluded as follows:

- The unreinforced sand with 12% CBR value is suitable for the category of poorly graded sandy soil if material is to be used in the subgrade layer.
- The 12.5% sand-PET plastic waste composite with 12% CBR value is suitable for the category of poorly graded sandy soil if the composite is to be used in the subgrade layer.

- The 22.5% sand-PET plastic waste composite with 21% CBR value is suitable for the category of poorly graded sandy soil and also well graded sandy soil if the composite is to be used in the subgrade layer.
- The 32.5% sand-PET plastic waste composite with 22% CBR value is suitable for the category of poorly graded sandy soil and also well graded sandy soil if the composite is to be used in the subgrade layer.

Based on the results of this study, reinforcing sand with 12.5%, 22.5% and 32.5% PET plastic waste flakes increase the CBR value to 12%, 21% and 22% respectively. This shows that the sand-PET plastic composite may be used as a subgrade layer material in the flexible pavement construction. This can be advantageously used for optimal design of foundations that results in material, labour, and cost savings. However, it is recommended that field trials be done and its performance in the field assessed before applied on a major road as a subgrade material. For the case of footway and cycleway construction, sand-PET plastic waste composite may be suitable though still field trials need be done before its full application.

5.3 Sand-PET Plastic Waste Composite Application in Bio-Stabilisation of Slopes

Biotechnical stabilisation or usually know as Bio-stabilisation, is the technique used to control soil erosion and protect soils on slopes (Gray & Sotir 1996). Bio-stabilisation technique utilises both mechanical elements such as structures and biological elements such as plants. Unlike inert construction technique, which uses mechanical elements only like concrete retaining walls, articulated block walls, rock armour (rip rap), and gabion mattresses; and also live construction technique which utilises biological elements like seeding (grasses and forbs), transplanting (shrubs) and vetiver grass (Abramson 2002). Therefore, it is important to say that plants affect the hydrology and mechanical stability of slopes in several ways. Whereby, plant roots penetrate the soil mass and increase its shear resistance, and also the plants control the surface runoff (Abramson 2002).

Bio-stabilisation applies the statistical and mechanical engineering principles to analyse and design the conventional slope protection systems (Elias 1997; Gray & Sotir 1996). In the same way, it engages the horticulture and plant science principles aiming at selecting, propagating, and establishing suitable plant materials for erosion control purposes (Elias 1997; Gray & Sotir 1996). This technique offers a cost-effective and attractive approach for stabilising slopes against erosion and shallow mass movement (Elias 1997). Bio-stabilisation technique is mostly applied in the stabilisation of slopes, river banks, and railway and highway embankments.

The researched sand-PET plastic waste composite having PET plastic waste of 22.5% by sand weight, can be used as a slope stabilisation material. This can be done in conjunction with planting trees on the slope surface with its roots placed below the composite in organic rich soils.

5.4 Sustainability of Soil-PET Plastic Waste Composite

Sustainability of a system is its ability to serve and retain its functionality over time, and can be achieved when its supplies (capacities) are greater than its demands (loads) (Basu et al. 2014). Sustainability involves social, economic, environmental and engineered systems, and all these systems should be interconnected for a project to be sustainable (Basu et al. 2014). The civil engineering infrastructures use natural and manufactured raw materials in large quantities, and the current trend shows an increased depletion of these natural materials due to increased urbanisation. There is a need to introduce new, environmental-friendly materials and reuse of waste materials. Therefore, the use of PET plastic waste to reinforce poor quality sands promotes sustainable construction in civil engineering infrastructures since it addresses various elements of sustainability including engineering, economic, social and environmental aspects. More so, use of sand-PET plastic waste composite in the construction industry is advantageous over conventional materials as it conserves natural resources, conserves energy, preserves the environment and reduces the life-cycle costs (Saride et al. 2010).

Furthermore, sustainability issues are particularly important for critical civil engineering infrastructures that sustain the life of human existence. Therefore, the geo-structures of all infrastructural systems are essential components, and failure of geo-structures like earth retaining walls, embankments, and foundation strata often spells catastrophes to the natural and human environment surrounding it (Basu et al. 2014). These geo-structures are resource intensive, and hence, their failure translates into significant economic loss for the community. Therefore, engineers should provide critical geo-structures which provide the basic services that allow modern communities and global society to function (Ainger et al. 2014). Sustainability should be incorporated in all the stages of a civil engineering project from the start, to completion, and throughout the lifetime of the infrastructure.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Chapter 1.3 stipulates the general objective of this research as 'analysing the engineering behaviour of soil reinforced with Polyethylene Terephthalate (PET) plastic waste', and further highlights the specific objectives followed to achieve the research objective. Practically these specific objectives were achieved by the guidance of the methodology detailed in Chapter 3, presentation and discussion of results as seen in Chapter 4. Last but not least, the research objective was achieved by identifying the applications of research findings in the civil engineering field and discussing the sustainability of soil-PET plastic waste composite as seen in Chapter 5. This Chapter presents the conclusions and recommendations of the research findings and also suggests further research to be undertaken by future researchers.

6.2 Conclusions of the Study

- Research concerning reinforcing sand with PET plastic waste is still in its infancy stage and limited. This research has successfully conducted the feasibility of using sand-PET plastic waste composite in the civil engineering field, and added on the existing knowledge.
- Findings indicate that sand-PET plastic waste composite can be applied in the civil engineering field in the area of improving the bearing capacity of the soil as foundation strata, and improving the CBR of the soil to be used in road construction. These results are consistent with published research on reinforcing soil using plastic waste products as highlighted in Chapter 1 and Chapter 2.
- The research material used was cohesionless uniformly graded sand of medium density with particle sizes ranging between 1.18mm to 0,075mm, and assorted uniformly graded PET plastic waste flakes which ranged between 10mm to 1.18mm.

- Reinforcing sand with PET plastic waste reduced the composite weight by 6.75%, 12.5%, and 16.8% when reinforced with PET plastic waste flakes of 12.5%, 22.5% and 32.5% by sand mass respectively. The sand-PET plastic waste composite generally resulted into lower densities compared to the unreinforced sand. Therefore, the lightweight nature of sand-PET plastic waste composite is a distinctive advantage for weight sensitive structures. Though it should be noted that with its lower densities it may fail in certain projects which may require materials of high densities.
- The PET plastic waste flakes percentage increase of 22.5% by sand mass gave the minimum foundation width of 3.23m using the GEO with vertical loads favourable and wind loads leading. The design bearing resistance and total vertical loads equal to 236.5kN.
- It was established that the optimum PET plastic waste which can be used to reinforce the studied sandy soil is 22.5%. This shows that PET plastic waste which would have been littered around or taken into a landfill can be used to reinforce the poor quality soil. This mitigates the challenges faced by both the civil engineering and waste management fields making sand-PET plastic waste composite sustainable. It was also concluded that, reinforcing sand with 32.5% PET plastic waste flakes increases its CBR values to 45%, hence making the composite suitable for road application.
- The direct shear box tests were conducted at three (3) normal stresses of 100kPa, 200kPa and 300kPa. Results showed that as the normal pressure increased so did the shear stress development in the soil specimen. The increased interlocking and frictional resistance between particles yielded to a linear relationship. The shear strength of sand-PET plastic waste composite improved up to the maximum by 15.3% when sand was reinforced with the optimum PET plastic waste flakes of 22.5%. Therefore, improved soil shear strength led to improved bearing capacity of the soil.
- Sand-PET plastic waste composite can be used as a bio-stabilisation constituent material in the process of stabilising slopes and roads or highway embankments.

6.3 Recommendations

- Due to a lack of cohesiveness of the study material (sand and PET plastic waste flakes), a perfect bond for the sand-PET plastic waste composite was not released. In order to attain a perfect bond it is therefore recommended that a cohesive soil like clay particles be integrated with the aim of filling the voids in the composite. This will foster the interaction of the composite constituents making it homogenous hence increasing its capability of sustaining heavier loads.
- The four (4) categories of specimens tested of 0%, 12.5%, 22.5% and 32.5% PET plastic waste flakes inclusion where too few to draw conclusive results. Therefore, further studies of analysing engineering behaviour of sand-PET plastic waste composite with different percentage PET plastic waste inclusion should be conducted. This will increase the number of specimens hence conclusions based on a wide number of specimens will be made and results correlated with this research findings.
- With proper bondage of composite constituents, the composite may also be turned into construction block/brick units. Therefore, the thermal and sound properties of the composite should be investigated, as this will reveal the composite's potential application in constructing residential houses.
- Stabilising the current research materials with chemical compounds like cement or lime, would increase its shear strength and CBR values, however it should be noted that this would be a costly option. Therefore, it is recommended that, sand-PET plastic waste composite having well graded constituent particles, and with good mechanical and chemical bondage should be further investigated, in order to evaluate its engineering properties and civil engineering applications.
- Only a laboratory research study was conducted in order to achieve the main objective of this study of analysing the engineering behaviour of sand-PET plastic waste composite. It's therefore recommended that a field trial be done in order to investigate the performance of the sand-PET plastic waste composite in the field.
- Randomly assorted uniformly graded PET plastic waste flakes which ranged between 10mm to 1.18mm were used in this research. There is a need to carry out further investigations on different polymer length and width. Also higher percentage inclusions

(say between 10% - 50%) of polymer should be investigated and the outcome compared with the current research.

- PET plastics and polymers in general may take about 500 years to degenerate, yet the life span of infrastructures where sand-PET plastic waste composite is applied may be between 20 – 80 years. Once the wastes of the composites are not handled well, they may have negative effects to the society, economy and environment, hence making the product unsustainable. Therefore, it’s recommended that once an infrastructure reaches its life span, the composite wastes ought to be recycled and integrated within other construction materials to come up with a new infrastructure. This practice will make the proposed composite sustainable, by preventing risks to the generations to come and lowering the costs of the project.

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Appendix A Particle Size Distribution Test Results

Table A-1: Calculations of particle size distribution of PET plastic waste flakes.

Sieve aperture (mm)	Mass retained (g)	Percentage retained (%)	Cumulative percentage weight retained (%)	Cumulative percentage passing (%)
13.2	0	0.00	0.00	100.00
10	0	0.00	0.00	100.00
4.75	217.96	43.59	43.59	56.41
2.36	220.7	44.14	87.73	12.27
1.18	31.66	6.33	94.06	5.94
0.6	29.68	5.94	100.00	0.00
0.425	0	0.00	100.00	0.00
0.212	0	0.00	100.00	0.00
0.15	0	0.00	100.00	0.00
Total	**500**			

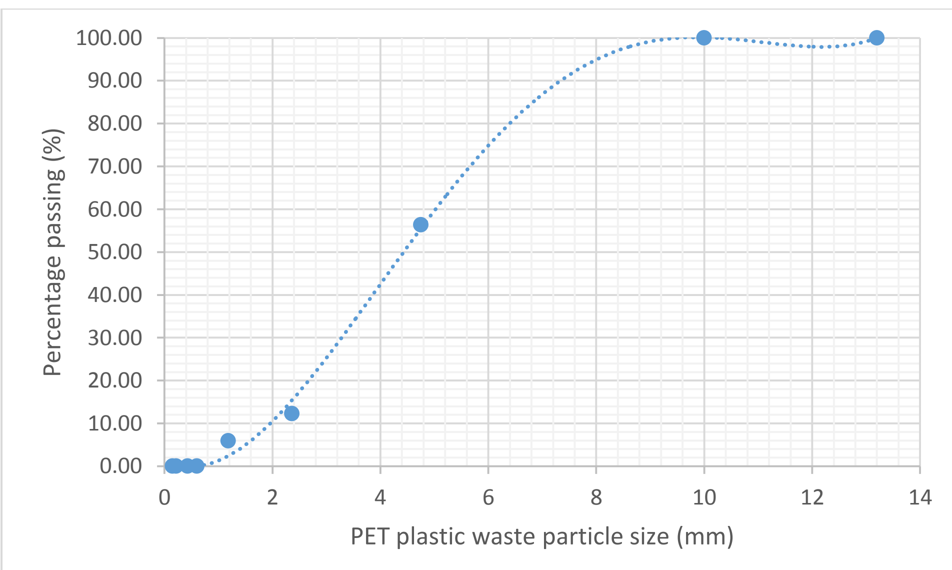


Figure A-1: Particle size distribution curve of PET plastic waste flakes.

Table A-2: Calculations of particle size distribution of sand.

Sieve aperture (mm)	Mass retained (g)	Percentage retained (%)	Cumulative percentage weight retained (%)	Cumulative percentage passing (%)
4.75	0	0.00	0.00	100.00
2	0	0.00	0.00	100.00
1.18	7.04	1.41	1.41	98.59
0.6	85.12	17.02	18.43	81.57
0.425	88.93	17.79	36.22	63.78
0.212	229.21	45.84	82.06	17.94
0.15	62.75	12.55	94.61	5.39
0.075	25.88	5.18	99.79	0.21
<0.075	1.07	0.21	100.00	0.00
Total	**500**			

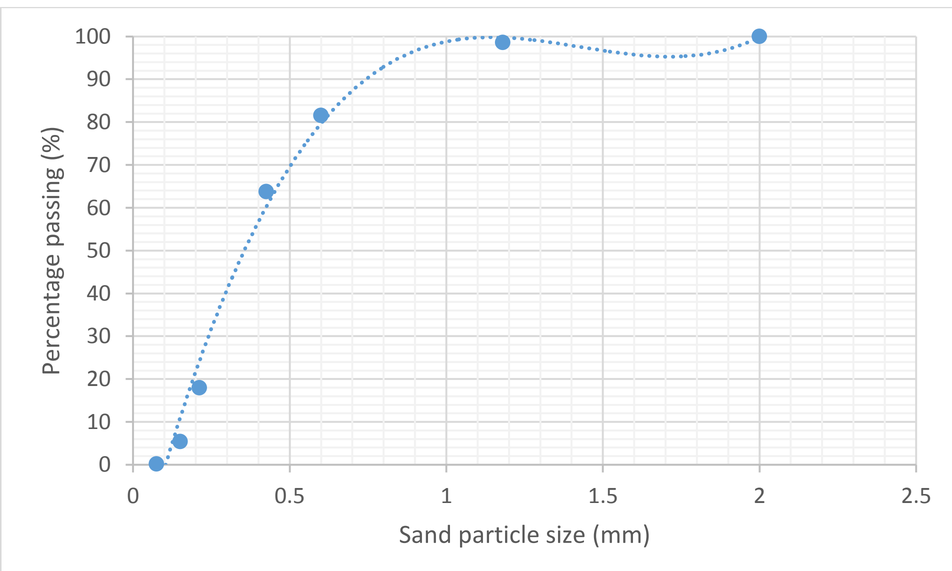


Figure A-2: Particle size distribution curve of sand.

Appendix B California Bearing Ratio (CBR) Test Results

Table B-1: Result of CBR test on sand specimen

Depth of penetration (mm)	Reading	Ring constant	Correction Load (kN)	Reading	Ring constant	Correction -Load (kN)	Reading	Ring constant	Correction -Load (kN)
0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.04	0.00
0.50	11.00	0.04	0.44	5.00	0.04	0.20	14.00	0.04	0.56
1.00	20.00	0.04	0.80	12.00	0.04	0.48	28.00	0.04	1.12
1.50	28.00	0.04	1.12	17.00	0.04	0.68	38.00	0.04	1.52
2.00	35.00	0.04	1.40	23.00	0.04	0.92	45.00	0.04	1.80
2.50	41.00	0.04	1.64	28.00	0.04	1.12	50.00	0.04	2.00
3.00	43.00	0.04	1.72	33.00	0.04	1.32	54.00	0.04	2.16
3.50	42.00	0.04	1.68	36.00	0.04	1.44	55.00	0.04	2.20
4.00		0.04	0.00	39.00	0.04	1.56	56.00	0.04	2.24
4.50		0.04	0.00	40.00	0.04	1.60	57.00	0.04	2.28
5.00		0.04	0.00	40.00	0.04	1.60	58.00	0.04	2.32
5.50		0.04	0.00	39.00	0.04	1.56	63.00	0.04	2.52
6.00		0.04	0.00	39.00	0.04	1.56	60.00	0.04	2.40
6.50		0.04	0.00	38.50	0.04	1.54	58.00	0.04	2.32
7.00		0.04	0.00		0.04	0.00	58.00	0.04	2.32
7.50		0.04	0.00		0.04	0.00	60.00	0.04	2.40
8.00		0.04	0.00		0.04	0.00		0.04	0.00
8.50		0.04	0.00		0.04	0.00		0.04	0.00
9.00		0.04	0.00		0.04	0.00		0.04	0.00

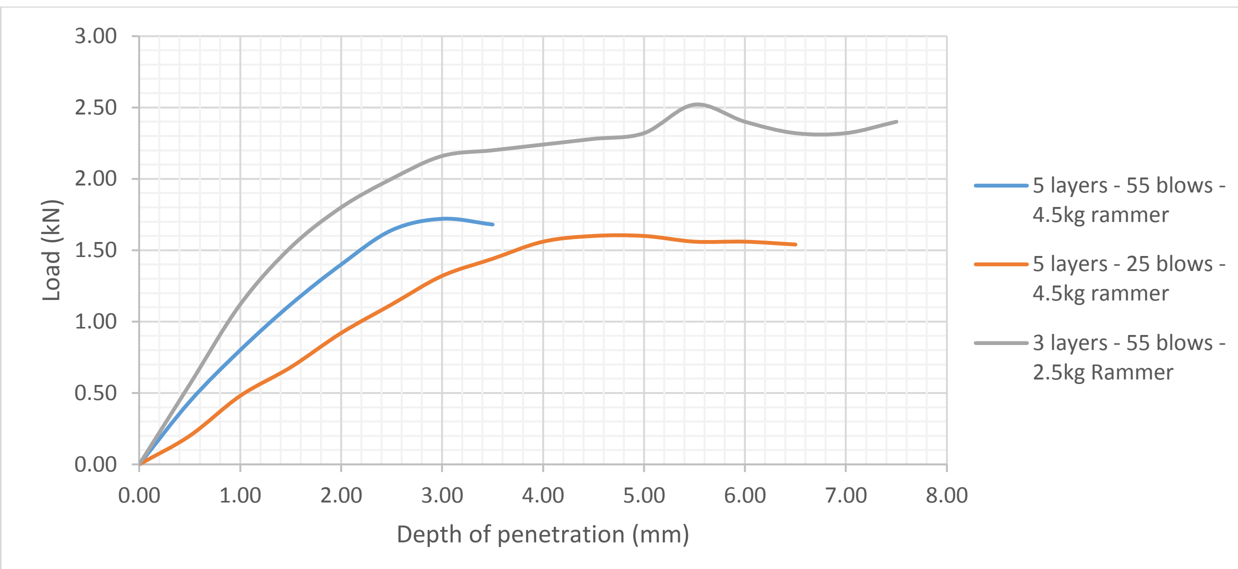


Figure B-1: Sand California Bearing Ratio (CBR) Load (kN) vs Depth of penetration (mm) curves.

Table B-2: Result of CBR test on 12.5% sand-PET plastic waste composite specimen

Depth of penetration (mm)	Reading	Ring constant	Correction - Load (kN)	Reading	Ring constant	Correction - Load (kN)	Reading	Ring constant	Correction - Load (kN)
0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.04	0.00
0.50	5.00	0.04	0.20	2.00	0.04	0.08	18.00	0.04	0.72
1.00	10.00	0.04	0.40	8.00	0.04	0.32	29.00	0.04	1.16
1.50	16.00	0.04	0.64	13.00	0.04	0.52	38.00	0.04	1.52
2.00	22.00	0.04	0.88	19.00	0.04	0.76	45.00	0.04	1.80
2.50	27.00	0.04	1.08	24.00	0.04	0.96	52.00	0.04	2.08
3.00	32.00	0.04	1.28	31.00	0.04	1.24	57.00	0.04	2.28
3.50	38.00	0.04	1.52	36.00	0.04	1.44	61.00	0.04	2.44
4.00	40.00	0.04	1.60	42.00	0.04	1.68	66.00	0.04	2.64
4.50	44.00	0.04	1.76	49.00	0.04	1.96	69.00	0.04	2.76
5.00	48.00	0.04	1.92	55.00	0.04	2.20	0.00	0.04	0.00
5.50	50.00	0.04	2.00	60.00	0.04	2.40	0.00	0.04	0.00
6.00	54.00	0.04	2.16	65.00	0.04	2.60	0.00	0.04	0.00
6.50	56.00	0.04	2.24	69.00	0.04	2.76	0.00	0.04	0.00
7.00	58.00	0.04	2.32	72.00	0.04	2.88	0.00	0.04	0.00
7.50	59.00	0.04	2.36	76.00	0.04	3.04	0.00	0.04	0.00
8.00	61.00	0.04	2.44	77.00	0.04	3.08	0.00	0.04	0.00
8.50	63.00	0.04	2.52	80.00	0.04	3.20	0.00	0.04	0.00
9.00	66.00	0.04	2.64	85.00	0.04	3.40	0.00	0.04	0.00

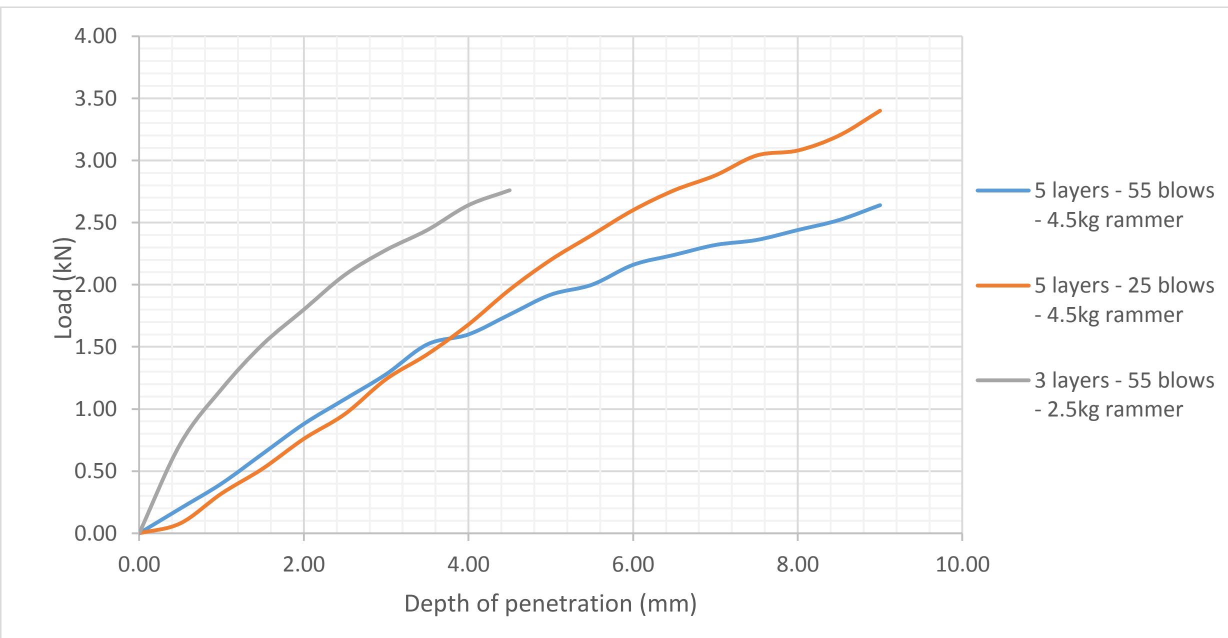


Figure B-2: 12.5% sand-PET plastic waste composite specimen California Bearing Ratio (CBR) Load (kN) vs Depth of penetration (mm) curves.

Table B-3: Result of CBR test on 22.5% sand-PET plastic waste composite specimen

Depth of penetration (mm)	Reading	Ring constant	Correction Load (kN)	Reading	Ring constant	Correction - Load (kN)	Reading	Ring constant	Correction - Load (kN)
0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.04	0.00
0.50	10.00	0.04	0.40	8.00	0.04	0.32	9.00	0.04	0.36
1.00	21.00	0.04	0.84	16.00	0.04	0.64	17.00	0.04	0.68
1.50	32.00	0.04	1.28	25.00	0.04	1.00	25.00	0.04	1.00
2.00	41.00	0.04	1.64	34.00	0.04	1.36	33.00	0.04	1.32
2.50	53.00	0.04	2.12	45.00	0.04	1.80	42.00	0.04	1.68
3.00	72.00	0.04	2.88	57.00	0.04	2.28	50.00	0.04	2.00
3.50	92.00	0.04	3.68	68.00	0.04	2.72	57.00	0.04	2.28
4.00	110.00	0.04	4.40	79.00	0.04	3.16	65.00	0.04	2.60
4.50	128.00	0.04	5.12	89.00	0.04	3.56	70.00	0.04	2.80
5.00	145.00	0.04	5.80	98.00	0.04	3.92	75.00	0.04	3.00
5.50	159.00	0.04	6.36	107.00	0.04	4.28	81.00	0.04	3.24
6.00	172.00	0.04	6.88	117.00	0.04	4.68	86.00	0.04	3.44
6.50	185.00	0.04	7.40	124.00	0.04	4.96	91.00	0.04	3.64
7.00	198.00	0.04	7.92	132.00	0.04	5.28	96.00	0.04	3.84
7.50	210.00	0.04	8.40	140.00	0.04	5.60	101.00	0.04	4.04
8.00	220.00	0.04	8.80	150.00	0.04	6.00	105.00	0.04	4.20
8.50	230.00	0.04	9.20	160.00	0.04	6.40	110.00	0.04	4.40
9.00	241.00	0.04	9.64	168.00	0.04	6.72	115.00	0.04	4.60

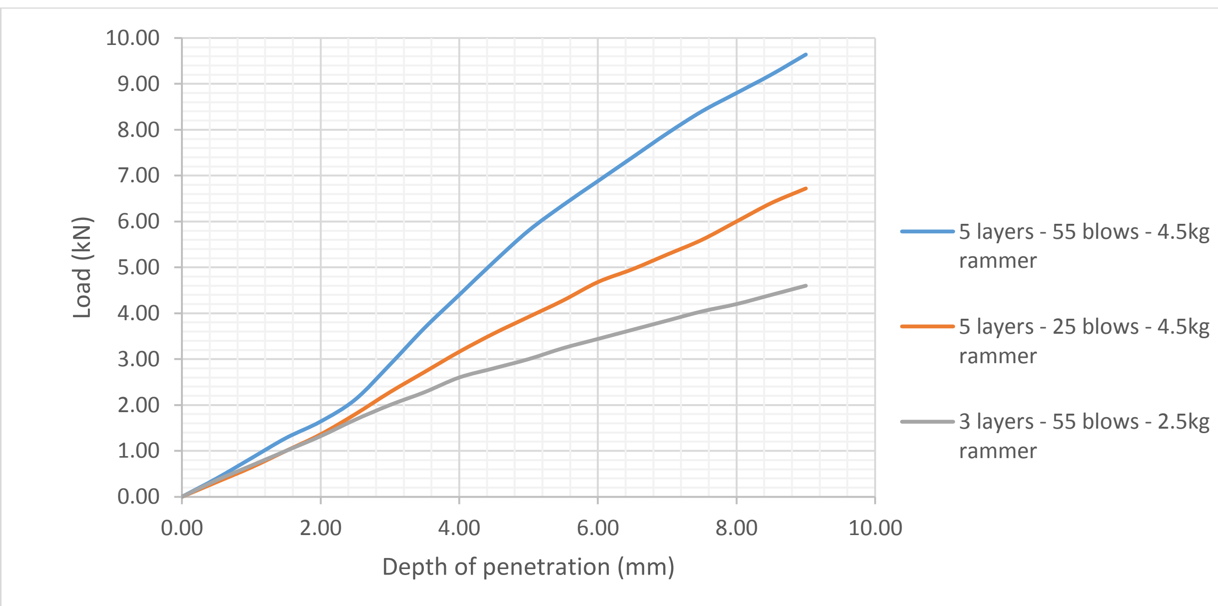


Figure B-3: 22.5% sand-PET plastic waste composite specimen California Bearing Ratio (CBR) Load (kN) vs Depth of penetration (mm) curves.

Table B-4: Result of CBR test on 32.5% sand-PET plastic waste composite specimen

Depth of penetration (mm)	Reading	Ring constant	Correction - Load (kN)	Reading	Ring constant	Correction - Load (kN)	Reading	Ring constant	Correction - Load (kN)
0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.04	0.00
0.50	9.00	0.04	0.36	10.00	0.04	0.40	12.00	0.04	0.48
1.00	17.00	0.04	0.68	18.00	0.04	0.72	20.00	0.04	0.80
1.50	25.00	0.04	1.00	28.00	0.04	1.12	30.00	0.04	1.20
2.00	36.00	0.04	1.44	37.00	0.04	1.48	42.00	0.04	1.68
2.50	47.00	0.04	1.88	48.00	0.04	1.92	52.00	0.04	2.08
3.00	58.00	0.04	2.32	58.00	0.04	2.32	65.00	0.04	2.60
3.50	71.00	0.04	2.84	68.00	0.04	2.72	76.00	0.04	3.04
4.00	85.00	0.04	3.40	81.00	0.04	3.24	87.00	0.04	3.48
4.50	99.00	0.04	3.96	92.00	0.04	3.68	97.00	0.04	3.88
5.00	112.00	0.04	4.48	105.00	0.04	4.20	108.00	0.04	4.32
5.50	124.00	0.04	4.96	117.00	0.04	4.68	118.00	0.04	4.72
6.00	137.00	0.04	5.48	130.00	0.04	5.20	128.00	0.04	5.12
6.50	149.00	0.04	5.96	142.00	0.04	5.68	139.00	0.04	5.56
7.00	161.00	0.04	6.44	153.00	0.04	6.12	150.00	0.04	6.00
7.50	172.00	0.04	6.88	164.00	0.04	6.56	162.00	0.04	6.48
8.00	185.00	0.04	7.40	176.00	0.04	7.04	175.00	0.04	7.00
8.50	197.00	0.04	7.88	185.00	0.04	7.40	186.00	0.04	7.44
9.00	210.00	0.04	8.40	197.00	0.04	7.88	194.00	0.04	7.76

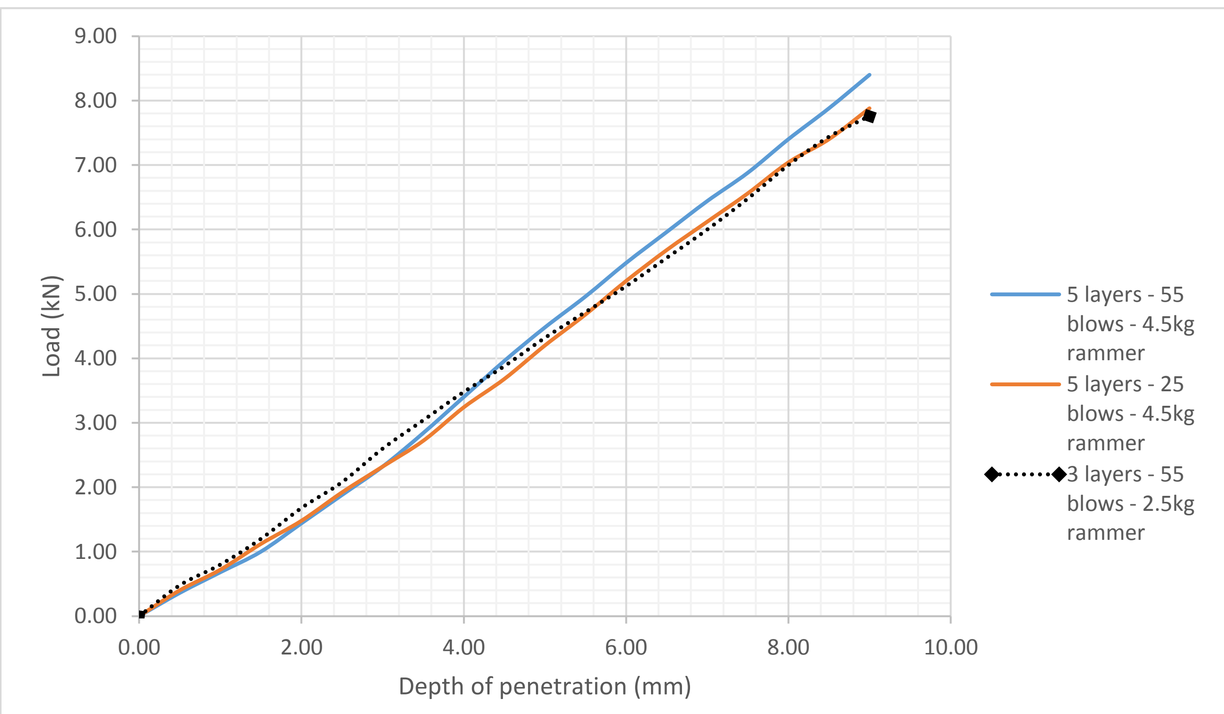


Figure B-4: 32.5% PET California Bearing Ratio (CBR) Load (kN) vs Depth of penetration (mm) curves.

Appendix C Compaction Test Results

Table C-1: Compaction results of sand

1	**Aproximate values**							
a	Water added (millilitre)	ml	280	560	840	980	1120	1330
	Precentage moisture content	%	4	8	12	14	16	19
	Assumed moisture content + hygroscopic moiture content (D1)	%	4	8	12	14	16	19
b	**Dry Density**							
	Point No.		1	2	3	4	5	6
	Mould No.		17	17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42	42
	Mass of mould + wet soil	g	7436	7661	7924	7986	8000	8038
	Mass of mould	g	3337	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	4099	4324	4587	4649	4663	4701
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1655.365	1681.556	1720.125	1712.789	1688.328	1659.176
2	**Actual values**							
a	**Moisture**							
	Container no.		12	17	SA	X3	T3	T
	Mass of container + wet soil	g	619.9	518.3	666.9	610.0	695.0	671.6
	Mass of container + dry soil	g	605.3	491.6	623.9	569.3	637.1	606.4
	Mass of container	g	238.8	152.1	236.8	236.9	235.5	236.9
	Mass of water	g	14.6	26.7	43.0	40.7	57.9	65.2
	Mass of dry soil	g	366.5	339.5	387.1	332.4	401.6	369.5
	Moisture content (D)	**%**	**4.0**	**7.9**	**11.1**	**12.2**	**14.4**	**17.6**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1655.63**	**1683.67**	**1733.931**	**1739.58**	**1711.68**	**1678.28**

F = Factor of modulus = (100/v)*1000. V is the volume of the mould
D = moisture content (%) = (mass of water/mass of dry soil)*100

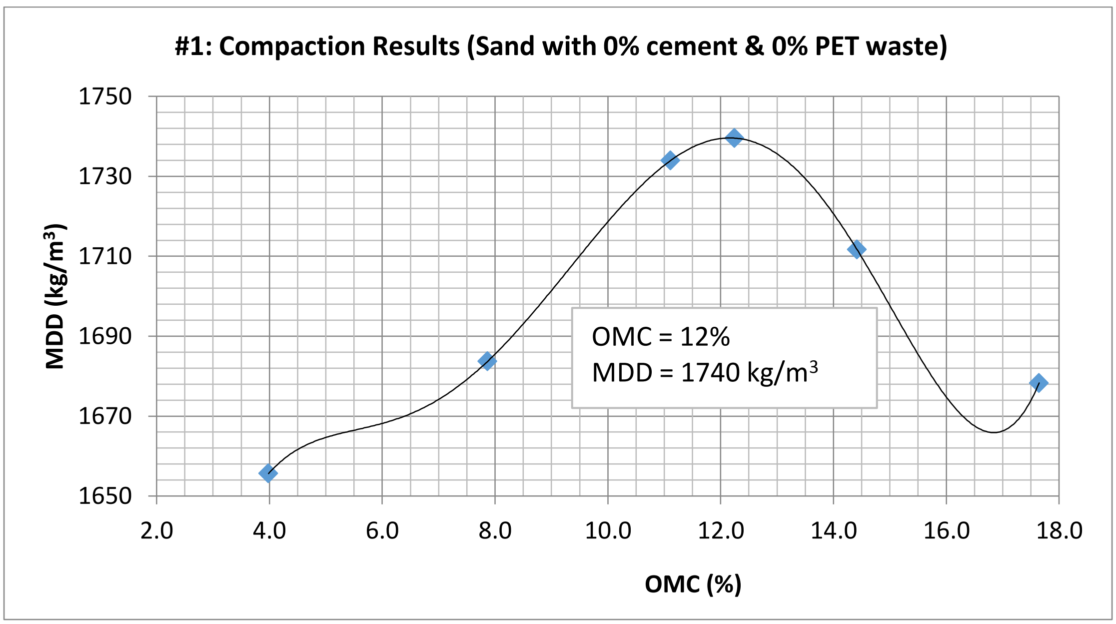


Figure C-1: Compaction results of sand MDD vs OMC curve

Table C-2: Compaction results of 12.5% sand-PET plastic waste composite specimen stabilised with 3% of cement.

1	**Aproximate values**					
a	Water added (millilitre)	ml	560	700	840	1120
	Precentage moisture content	%	8	10	12	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	16
b	**Dry Density**					
	Point No.		1	2	3	4
	Mould No.		17	17	17	17
	Mould Factor (F)		42	42	42	42
	Mass of mould + wet soil	g	7414	7523.5	7628.5	7776
	Mass of mould	g	3337	3337	3337	3337
	Mass of wet soil (W)	g	4077	4186.5	4291.5	4439
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1585.5	1598.482	1609.3125	1607.224
2	**Actual values**					
a	**Moisture**					
	Container no.		T3	WP	6A	A4
	Mass of container + wet soil	g	597.9	600.1	569.1	631.2
	Mass of container + dry soil	g	574.4	571.7	538.3	580.6
	Mass of container	g	235.6	237.4	236.8	236.9
	Mass of water	g	23.5	28.4	30.8	50.6
	Mass of dry soil	g	338.8	334.3	301.5	343.7
	Moisture content (D)	**%**	**6.9**	**8.5**	**10.2**	**14.7**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1601.27**	**1620.65**	**1635.368**	**1625.13**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould						
D = moisture content (%) = (mass of water/mass of dry soil)*100						

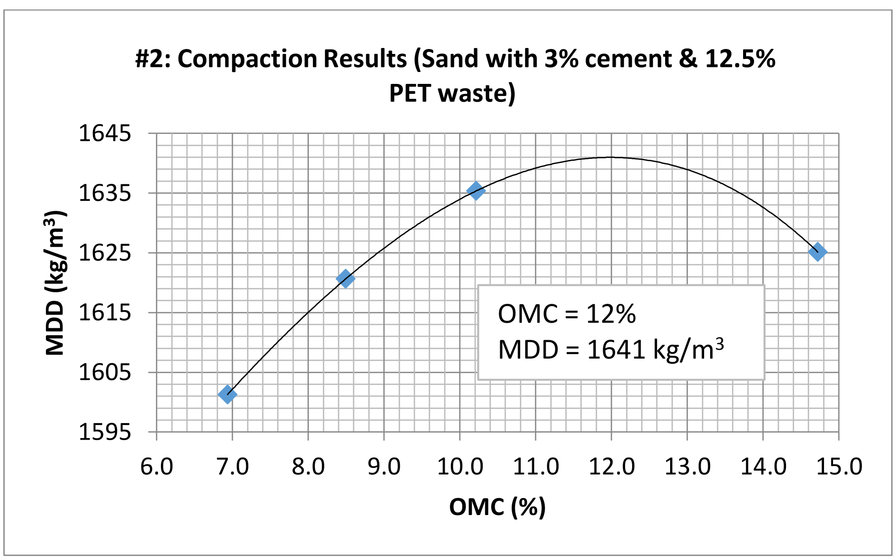


Figure C-2: MDD vs OMC curve for 12.5% sand-PET plastic waste composite specimen stabilised with 3% of cement

Table C-3: Compaction results of 22.5% sand-PET plastic waste composite specimen stabilised with 6% of cement.

1	**Aproximate values**							
a	Water added (millilitre)	ml	560	700	840	980	1120	1260
	Precentage moisture content	%	8	10	12	14	16	18
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16	18
b	**Dry Density**							
	Point No.		1	2	3	4	5	6
	Mould No.		17	17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42	42
	Mass of mould + wet soil	g	7331	7371	7458.5	7560	7639.5	7676
	Mass of mould	g	3337	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3994	4034	4121.5	4223	4302.5	4339
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1553.222	1540.255	1545.5625	1555.842	1557.802	1544.39
2	**Actual values**							
a	**Moisture**							
	Container no.		57	T3	12	14	SA	A4
	Mass of container + wet soil	g	526.5	573.1	555.1	616.2	626.6	622.0
	Mass of container + dry soil	g	506.9	548.7	528.2	579.5	584.2	575.7
	Mass of container	g	197.6	235.5	238.6	237.2	236.8	237.0
	Mass of water	g	19.6	24.4	26.9	36.7	42.4	46.3
	Mass of dry soil	g	309.3	313.2	289.6	342.3	347.4	338.7
	Moisture content (D)	**%**	**6.3**	**7.8**	**9.3**	**10.7**	**12.2**	**13.7**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1577.51**	**1571.83**	**1583.906**	**1601.91**	**1610.49**	**1603.22**

F = Factor of modulus = (100/v)*1000. V is the volume of the mould

D = moisture content (%) = (mass of water/mass of dry soil)*100

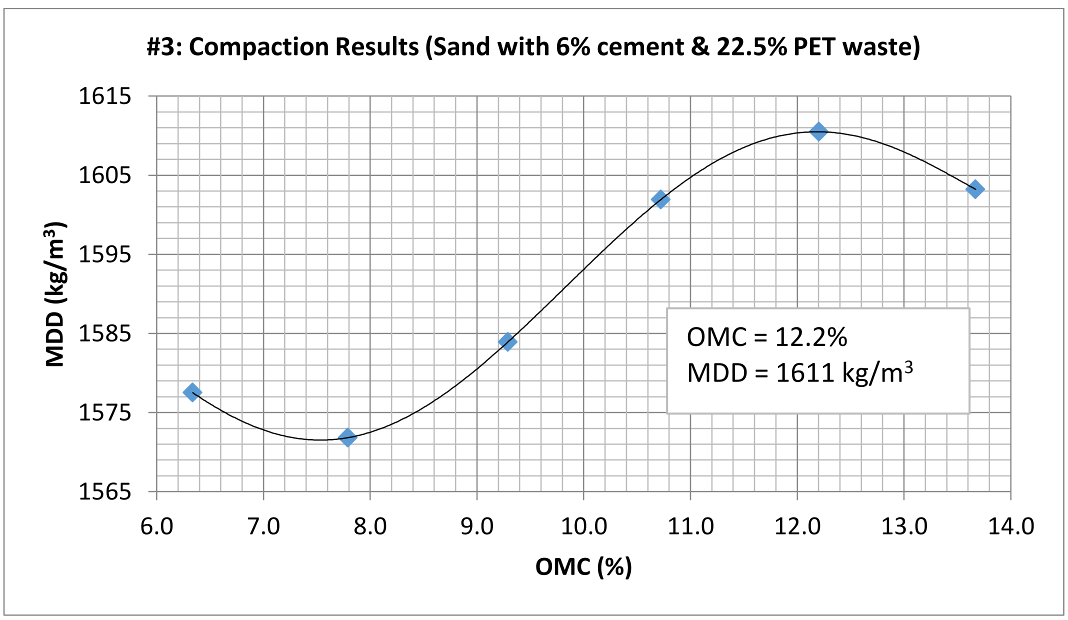


Figure C-3: MDD vs OMC curve for 22.5% sand-PET plastic waste composite specimen stabilised with 6% of cement

Table C-4: Compaction results of 32.5% sand-PET plastic waste composite specimen stabilised with 9% of cement.

1	**Aproximate values**							
a	Water added (millilitre)	ml	400	500	600	700	800	
	Precentage moisture content	%	8	10	12	14	16	18
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16	18
b	**Dry Density**							
	Point No.		1	2	3	4	5	6
	Mould No.		17	17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42	42
	Mass of mould + wet soil	g	7150	7346	7342.5	7441	7530	7392.5
	Mass of mould	g	3337	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3813	4009	4005.5	4104	4193	4055.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1482.833	1530.709	1502.0625	1512	1518.155	1443.483
2	**Actual values**							
a	**Moisture**							
	Container no.		3B	Z4	T3	2B	90	12
	Mass of container + wet soil	g	656.8	585.1	591.9	596.2	655.1	629.6
	Mass of container + dry soil	g	634.1	561.1	563.9	561.7	612.0	585.6
	Mass of container	g	237.4	237.1	235.7	221.3	237.3	238.7
	Mass of water	g	22.7	24.0	28.0	34.5	43.1	44.0
	Mass of dry soil	g	396.7	324.0	328.2	340.4	374.7	346.9
	Moisture content (D)	**%**	**5.7**	**7.4**	**8.5**	**10.1**	**11.5**	**12.7**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1514.78**	**1567.66**	**1550.068**	**1565.06**	**1579.39**	**1511.58**
	F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
	D = moisture content (%) = (mass of water/mass of dry soil)*100							

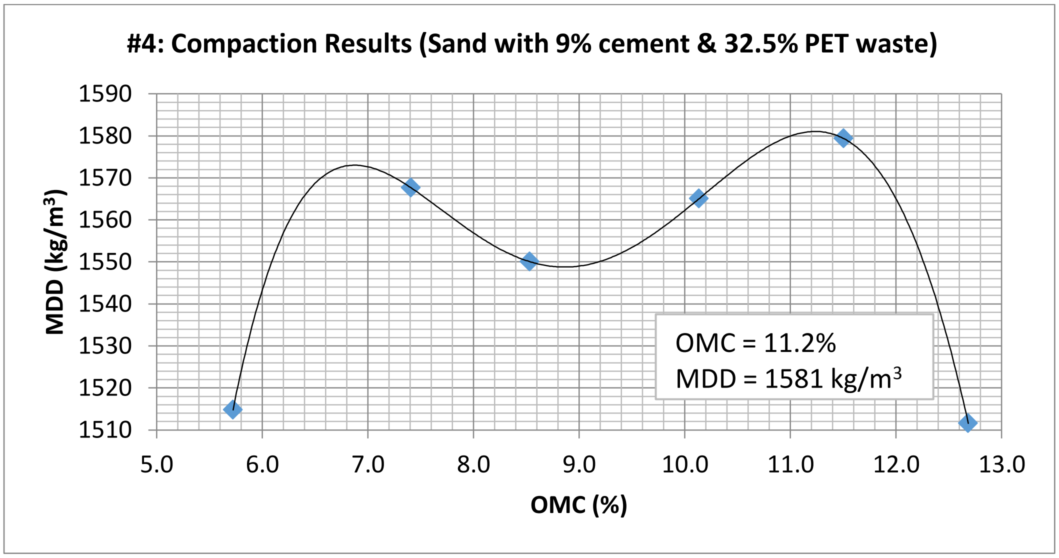


Figure C-4: MDD vs OMC curve for 32.5% sand-PET plastic waste composite specimen stabilised with 9% of cement

Table C-5: Compaction results of 12.5% sand-PET plastic waste composite specimen stabilised with 9% of cement.

1	**Aproximate values**						
a	Water added (millilitre)	ml	480	600	720	840	960
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7573	7737.5	7810.5	7925	7920.5
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	4236	4400.5	4473.5	4588	4583.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1647.333	1680.191	1677.5625	1690.316	1659.543
2	**Actual values**						
a	**Moisture**						
	Container no.		WP	57	2B	SI	SA
	Mass of container + wet soil	g	601.6	561.6	640.1	633.7	679.8
	Mass of container + dry soil	g	579.0	533.1	602.5	593.3	628.6
	Mass of container	g	237.4	197.2	221.3	237.7	237.0
	Mass of water	g	22.6	28.5	37.6	40.4	51.2
	Mass of dry soil	g	341.6	335.9	381.2	355.6	391.6
	Moisture content (D)	**%**	**6.6**	**8.5**	**9.9**	**11.4**	**13.1**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1668.72**	**1703.66**	**1710.184**	**1730.37**	**1702.48**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

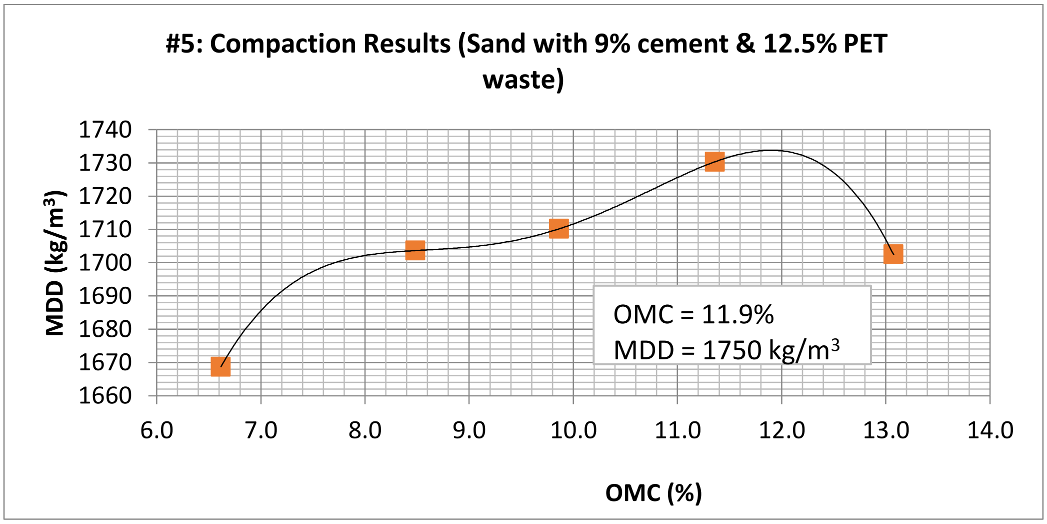


Figure C-5: MDD vs OMC curve for 12.5% sand-PET plastic waste composite specimen stabilised with 9% of cement

Table C-6: Compaction results of 22.5% sand-PET plastic waste composite specimen stabilised with 9% of cement.

1	**Aproximate values**						
a	Water added (millilitre)	ml	400	500	600	700	800
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7368.5	7480	7572	7703	7735.5
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	4031.5	4143	4235	4366	4398.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1567.806	1581.873	1588.125	1608.526	1592.56
2	**Actual values**						
a	**Moisture**						
	Container no.		12	6A	T3	A4	SA
	Mass of container + wet soil	g	553.5	604.3	620.3	615.1	589.3
	Mass of container + dry soil	g	533.2	578.2	588.2	578.1	551.4
	Mass of container	g	202.6	236.7	235.7	237.0	237.1
	Mass of water	g	20.3	26.1	32.1	37.0	37.9
	Mass of dry soil	g	330.6	341.5	352.5	341.1	314.3
	Moisture content (D)	**%**	**6.1**	**7.6**	**9.1**	**10.8**	**12.1**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1595.27**	**1616.51**	**1630.244**	**1654.28**	**1648.58**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

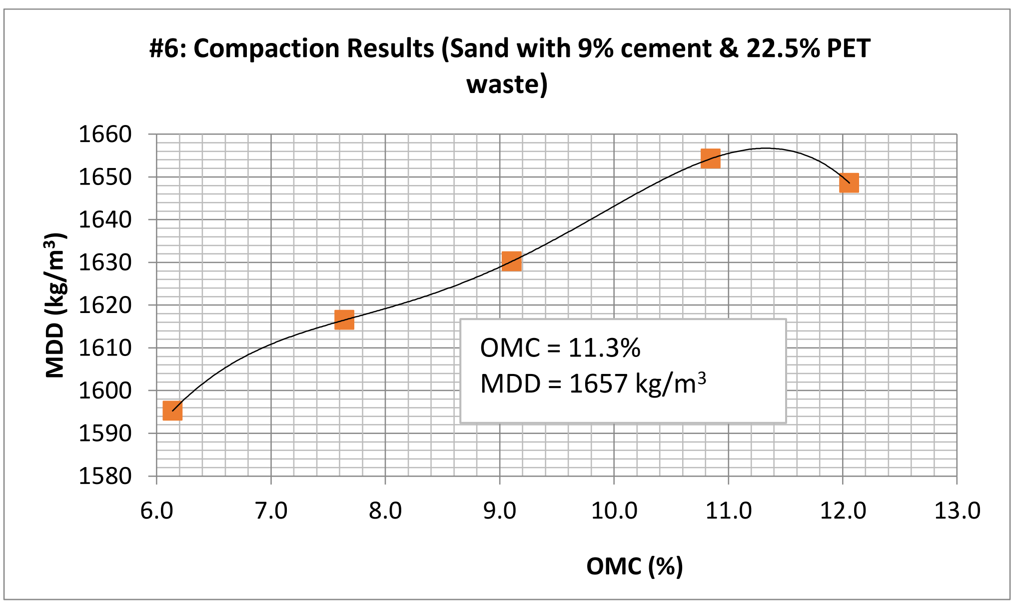


Figure C-6: MDD vs OMC curve for 22.5% sand-PET plastic waste composite specimen stabilised with 9% of cement

Table C-7: Compaction results of 32.5% sand-PET plastic waste composite specimen stabilised with 6% of cement.

1	**Aproximate values**						
a	Water added (millilitre)	ml					
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7137	7152.5	7271	7334.5	7395.5
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3800	3815.5	3934	3997.5	4058.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1477.778	1456.827	1475.25	1472.763	1469.457
2	**Actual values**						
a	**Moisture**						
	Container no.		WP	14	X4	12	SI
	Mass of container + wet soil	g	560.3	612.5	602.7	596.1	594.3
	Mass of container + dry soil	g	541.1	585.9	573.2	562.9	557.0
	Mass of container	g	237.5	237.3	236.5	238.8	237.4
	Mass of water	g	19.2	26.6	29.5	33.2	37.3
	Mass of dry soil	g	303.6	348.6	336.7	324.1	319.6
	Moisture content (D)	**%**	**6.3**	**7.6**	**8.8**	**10.2**	**11.7**
b	**Dry density = (W*F)/(100 + D)**	kg/m^3	**1501.07**	**1488.9**	**1519.177**	**1522.94**	**1526.42**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

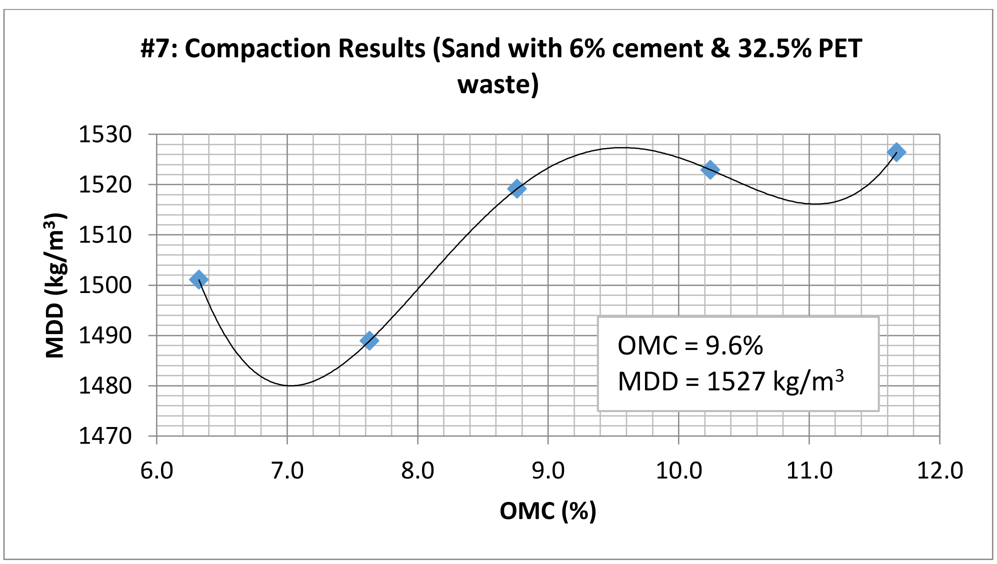


Figure C-7: MDD vs OMC curve for 32.5% sand-PET plastic waste composite specimen stabilised with 6% of cement

Table C-8: Compaction results of 32.5% sand-PET plastic waste composite specimen stabilised with 3% of cement.

1	**Aproximate values**						
a	Water added (millilitre)	ml					
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7024	7114	7186	7289.5	7310.5
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3687	3777	3849	3952.5	3973.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1433.833	1442.127	1443.375	1456.184	1438.681
2	**Actual values**						
a	**Moisture**						
	Container no.		A4	57	12	2B	14
	Mass of container + wet soil	g	542.4	489.0	517.4	545.6	609.6
	Mass of container + dry soil	g	524.9	468.3	491.3	514.6	569.7
	Mass of container	g	237.1	197.1	202.4	221.3	237.2
	Mass of water	g	17.5	20.7	26.1	31.0	39.9
	Mass of dry soil	g	287.8	271.2	288.9	293.3	332.5
	Moisture content (D)	**%**	**6.1**	**7.6**	**9.0**	**10.6**	**12.0**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1459.78**	**1473.85**	**1482.635**	**1501.36**	**1490.06**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

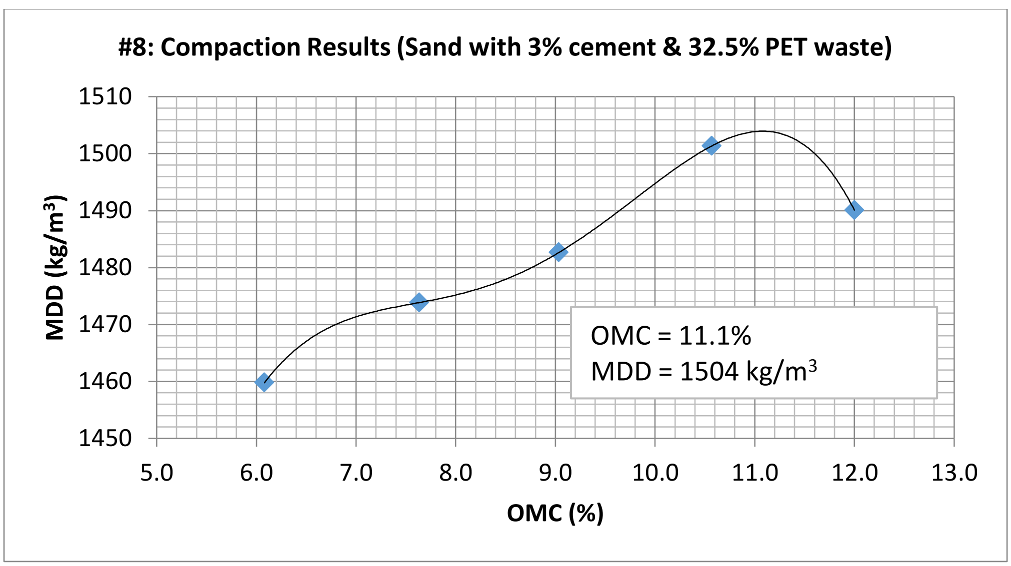


Figure C-8: MDD vs OMC curve for 32.5% sand-PET plastic waste composite specimen stabilised with 3% of cement

Table C-9: Compaction results of 12.5% sand-PET plastic waste composite specimen.

1	**Aproximate values**						
a	Water added (millilitre)	ml	480	600	720	840	960
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7417.5	7481	7643	7708.5	7740
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	4080.5	4144	4306	4371.5	4403
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1586.861	1582.255	1614.75	1610.553	1594.19
2	**Actual values**						
a	**Moisture**						
	Container no.		12	14	2B	A4	57
	Mass of container + wet soil	g	563.3	648.8	622.7	606.9	690.3
	Mass of container + dry soil	g	537.2	613.7	581.9	565.0	627.8
	Mass of container	g	202.4	237.2	221.2	237.1	197.1
	Mass of water	g	26.1	35.1	40.8	41.9	62.5
	Mass of dry soil	g	334.8	376.5	360.7	327.9	430.7
	Moisture content (D)	**%**	**7.8**	**9.3**	**11.3**	**12.8**	**14.5**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1589.87**	**1592.06**	**1624.74**	**1628**	**1614.92**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

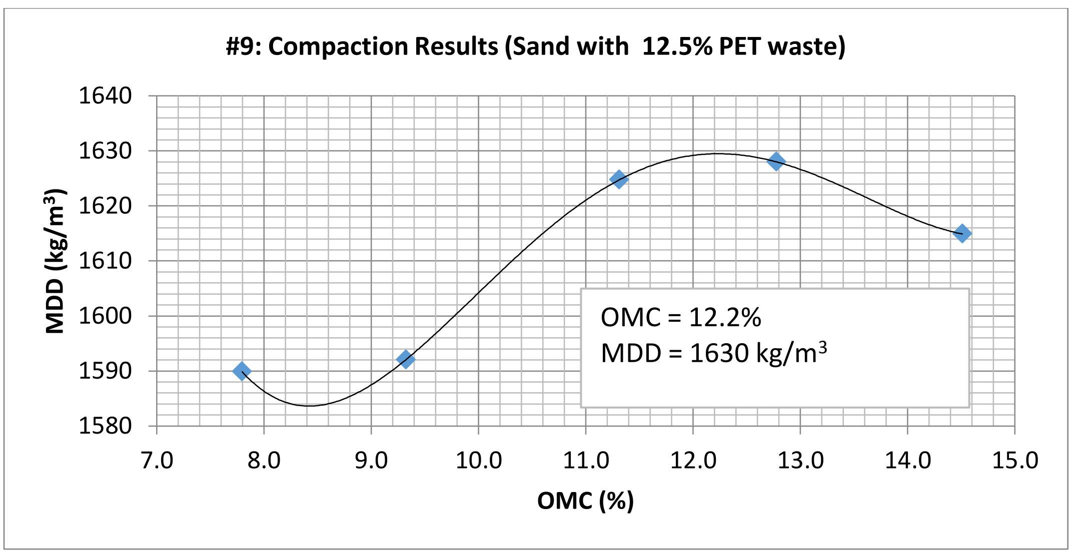


Figure C-9: MDD vs OMC curve for 12.5% sand-PET plastic waste composite specimen.

Table C-10: Compaction results of 22.5% sand-PET plastic waste composite specimen.

1	**Aproximate values**						
a	Water added (millilitre)	ml	400	500	600	700	800
	Precentage moisture content	%	8	10	12	14	16
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7242	7270.5	7392.5	7460	7530
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3905	3933.5	4055.5	4123	4193
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1518.611	1501.882	1520.8125	1519	1518.155
2	**Actual values**						
a	**Moisture**						
	Container no.		SI	SA	X4	12	WP
	Mass of container + wet soil	g	628.1	575.1	564.3	651.8	602.6
	Mass of container + dry soil	g	601.2	548.5	533.5	607.2	558.0
	Mass of container	g	237.6	237.1	236.4	238.8	237.4
	Mass of water	g	26.9	26.6	30.8	44.6	44.6
	Mass of dry soil	g	363.6	311.4	297.1	368.4	320.6
	Moisture content (D)	**%**	**7.4**	**8.5**	**10.4**	**12.1**	**13.9**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1527.12**	**1522.06**	**1543.316**	**1544.66**	**1545.99**
	F = Factor of modulus = (100/v)*1000. V is the volume of the mould						
	D = moisture content (%) = (mass of water/mass of dry soil)*100						

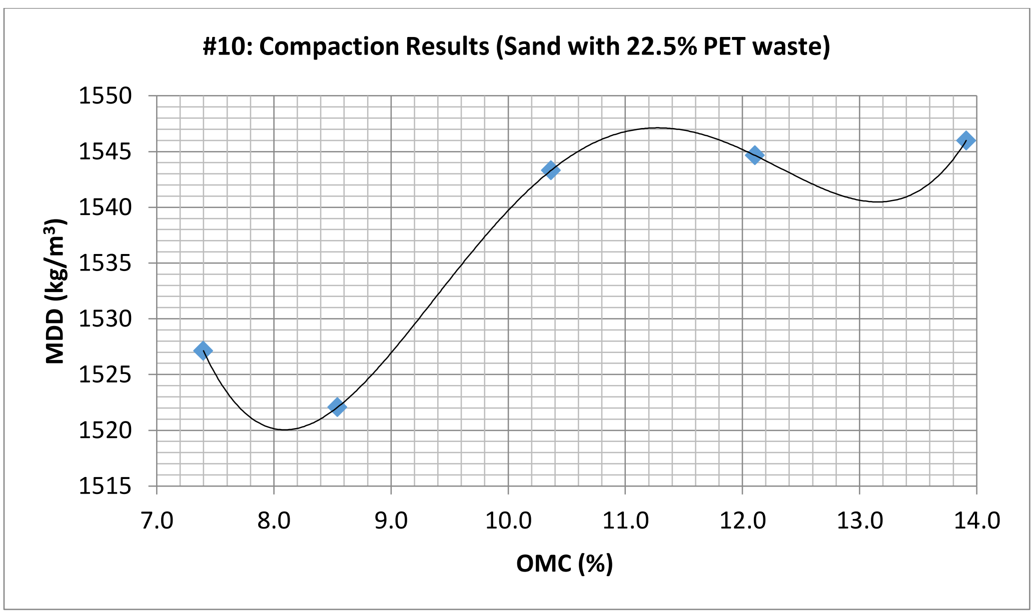


Figure C-10: MDD vs OMC curve for 22.5% sand-PET plastic waste composite specimen.

Table C-11: Compaction results of 32.5% sand-PET plastic waste composite specimen.

1	**Aproximate values**							
a	Water added (millilitre)	ml	400	500	600	700	800	900
	Precentage moisture content	%	8	10	12	14	16	18
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14	16	18
b	**Dry Density**							
	Point No.		1	2	3	4	5	6
	Mould No.		17	17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42	42
	Mass of mould + wet soil	g	7001	7119.9	7147	7193	7304	7374.5
	Mass of mould	g	3337	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	3664	3782.9	3810	3856	3967	4037.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1424.889	1444.38	1428.75	1420.632	1436.328	1437.076
2	**Actual values**							
a	**Moisture**							
	Container no.		12	SA	X1	T3	57	X4
	Mass of container + wet soil	g	589.1	541.0	574.0	649.5	582.9	642.2
	Mass of container + dry soil	g	568.8	518.7	545.0	609.6	541.4	592.7
	Mass of container	g	238.8	237.1	237.6	235.6	197.2	236.4
	Mass of water	g	20.3	22.3	29.0	39.9	41.5	49.5
	Mass of dry soil	g	330.0	281.6	307.4	374.0	344.2	356.3
	Moisture content (D)	**%**	**6.2**	**7.9**	**9.4**	**10.7**	**12.1**	**13.9**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1449.7**	**1472.23**	**1462.252**	**1463.4**	**1486.87**	**1488.9**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould								
D = moisture content (%) = (mass of water/mass of dry soil)*100								

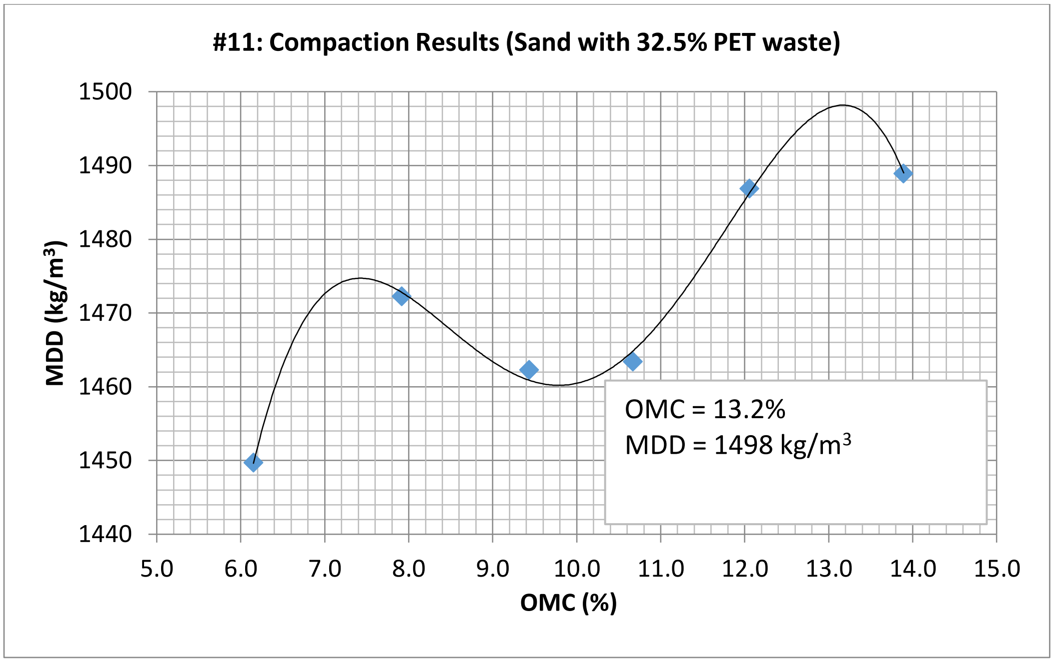


Figure C-11: MDD vs OMC curve for 32.5% sand-PET plastic waste composite specimen.

Table C-12: Compaction results of 0% sand-PET plastic waste composite specimen stabilised with 3% of cement.

1	**Aproximate values**					
a	Water added (millilitre)	ml	560	700	840	980
	Precentage moisture content	%	8	10	12	14
	Assumed moisture content + hygroscopic moiture content (D1)	%	8	10	12	14
b	**Dry Density**					
	Point No.		1	2	3	4
	Mould No.		17	17	17	17
	Mould Factor (F)		42	42	42	42
	Mass of mould + wet soil	g	7766.5	7906	8046.5	8123.5
	Mass of mould	g	3337	3337	3337	3337
	Mass of wet soil (W)	g	4429.5	4569	4709.5	4786.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1722.583	1744.527	1766.0625	1763.447
2	**Actual values**					
a	**Moisture**					
	Container no.		17	51	2B	SA
	Mass of container + wet soil	g	626.2	672.2	655.8	675.5
	Mass of container + dry soil	g	591.6	631.4	611.1	623.9
	Mass of container	g	152.0	207.7	221.3	237.1
	Mass of water	g	34.6	40.8	44.7	51.6
	Mass of dry soil	g	439.6	423.7	389.8	386.8
	Moisture content (D)	**%**	**7.9**	**9.6**	**11.5**	**13.3**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1724.65**	**1750.42**	**1774.501**	**1773.71**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould						
D = moisture content (%) = (mass of water/mass of dry soil)*100						

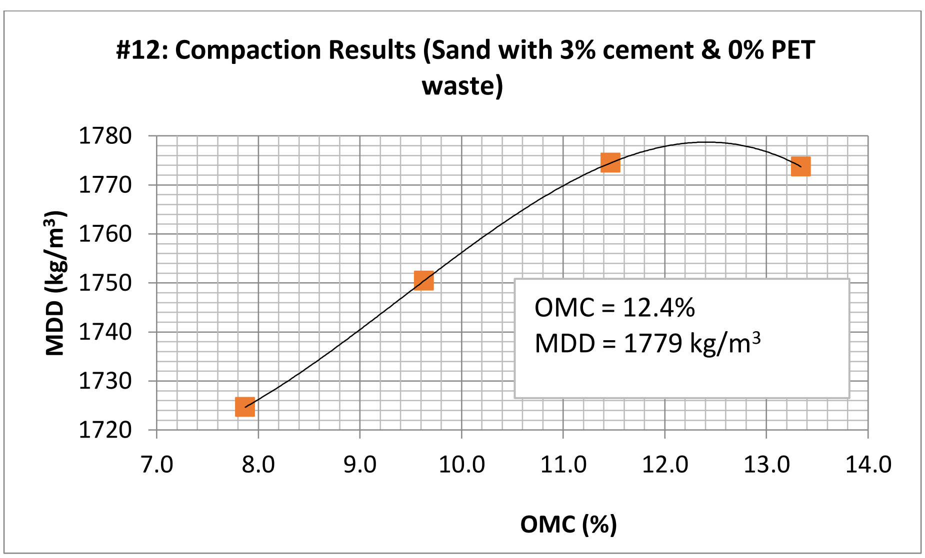


Figure C-12: MDD vs OMC curve for 0% sand-PET plastic waste composite specimen stabilised with 3% of cement

Table C-13: Compaction results of 0% sand-PET plastic waste composite specimen stabilised with 6% of cement.

1	**Aproximate values**						
a	Water added (millilitre)	ml	420	560	700	840	980
	Precentage moisture content	%	6	8	10	12	14
	Assumed moisture content + hygroscopic moiture content (D1)	%	6	8	10	12	14
b	**Dry Density**						
	Point No.		1	2	3	4	5
	Mould No.		17	17	17	17	17
	Mould Factor (F)		42	42	42	42	42
	Mass of mould + wet soil	g	7718.5	7867.5	8001.5	8135	8144.5
	Mass of mould	g	3337	3337	3337	3337	3337
	Mass of wet soil (W)	g	4381.5	4530.5	4664.5	4798	4807.5
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1736.066	1761.861	1780.9909	1799.25	1771.184
2	**Actual values**						
a	**Moisture**						
	Container no.		3B	WP	X4	90	16
	Mass of container + wet soil	g	656.8	563.3	735.1	688.2	636.4
	Mass of container + dry soil	g	634.1	537.0	693.0	642.1	585.5
	Mass of container	g	237.4	187.1	237.4	236.5	195.1
	Mass of water	g	22.7	26.3	42.1	46.1	50.9
	Mass of dry soil	g	396.7	349.9	455.6	405.6	390.4
	Moisture content (D)	**%**	**5.7**	**7.5**	**9.2**	**11.4**	**13.0**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1740.63**	**1769.79**	**1793.372**	**1809.5**	**1786.26**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould							
D = moisture content (%) = (mass of water/mass of dry soil)*100							

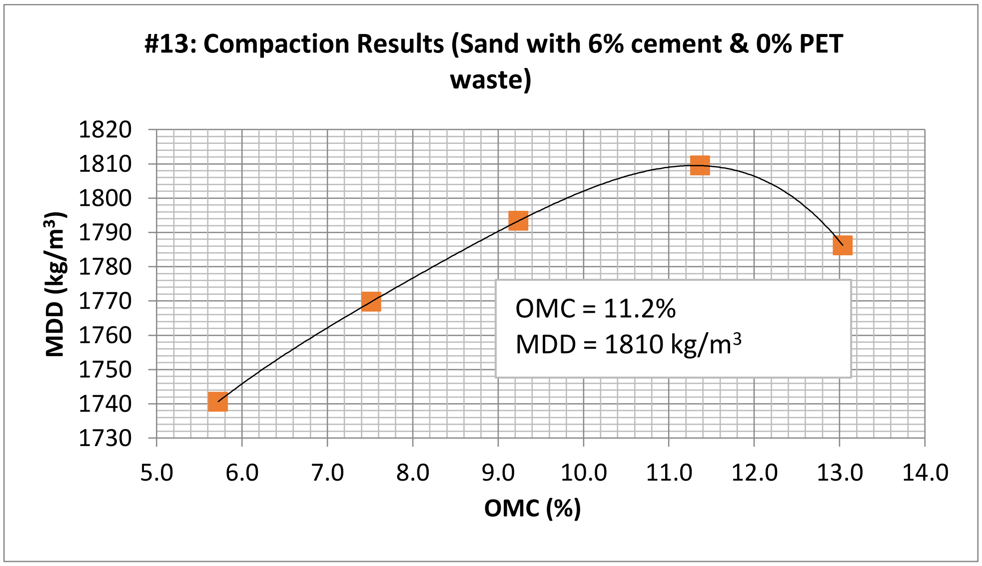


Figure C-13: MDD vs OMC curve for 0% sand-PET plastic waste composite specimen stabilised with 6% of cement

Table C-14: Compaction results of 0% sand-PET plastic waste composite specimen stabilised with 9% of cement.

1	**Aproximate values**					
a	Water added (millilitre)	ml	420	560	700	840
	Precentage moisture content	%	6	8	10	12
	Assumed moisture content + hygroscopic moiture content (D1)	%	6	8	10	12
b	**Dry Density**					
	Point No.		1	2	3	4
	Mould No.		17	17	17	17
	Mould Factor (F)		42	42	42	42
	Mass of mould + wet soil	g	7818	7957	8097	8185
	Mass of mould	g	3337	3337	3337	3337
	Mass of wet soil (W)	g	4481	4620	4760	4848
	Approximate Dry Density = (W*F)/(100+D1)	kg/m^3	1775.491	1796.667	1817.4545	1818
2	**Actual values**					
a	**Moisture**					
	Container no.		Z4	80	XI	24
	Mass of container + wet soil	g	680.5	597.6	706.5	659.0
	Mass of container + dry soil	g	657.6	569.6	668.4	613.1
	Mass of container	g	237.3	192.2	237.9	183.4
	Mass of water	g	22.9	28.0	38.1	45.9
	Mass of dry soil	g	420.3	377.4	430.5	429.7
	Moisture content (D)	**%**	**5.4**	**7.4**	**8.9**	**10.7**
b	**Dry density = (W*F)/(100 + D)**	**kg/m^3**	**1784.78**	**1806.38**	**1836.653**	**1839.65**
F = Factor of modulus = (100/v)*1000. V is the volume of the mould						
D = moisture content (%) = (mass of water/mass of dry soil)*100						

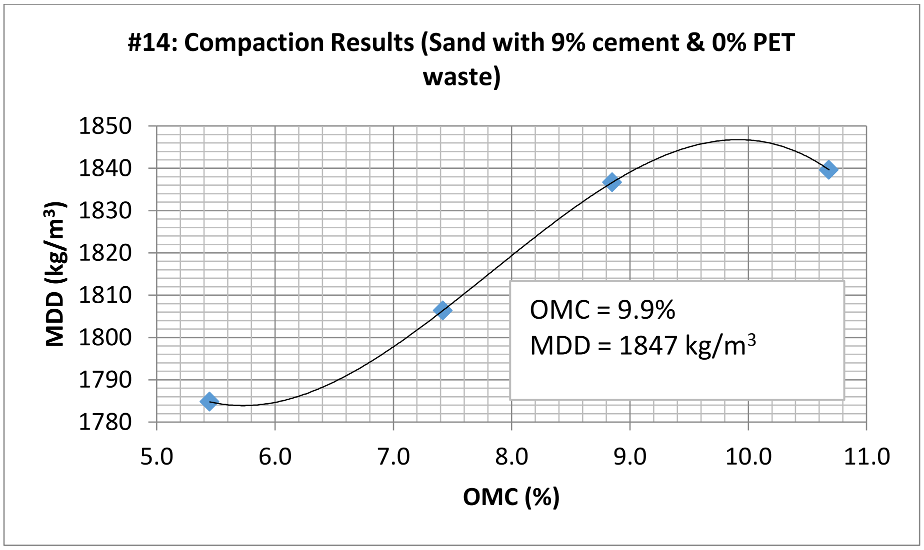


Figure C-14: MDD vs OMC curve for 0% sand-PET plastic waste composite specimen stabilised with 9% of cement

Appendix D Unconfined Compression Strength Test Results

Table D: Unconfined compression strength results.

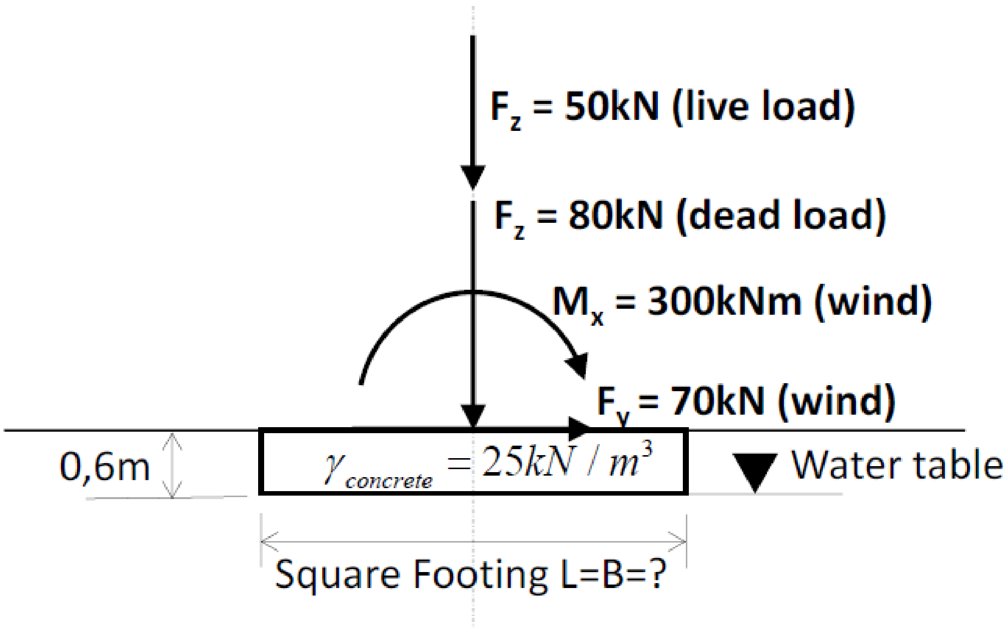
Specimen No.	Date made	Date tested	Modified AASHTO Data		Specimen Data					
			MDD (Kg/m^3)	OMC (%)	PET Plastic waste content (%)	Cement content (%)	Radius of specimen (m)	Crushing Load (kN)	UCS (kPa)	Average UCS (kPa)
2	2nd/June	9th/June/2014	1641	12	12.5	3	0.0762	16	877.12	914
							0.0762	16	877.12	
							0.0762	18	986.76	
3	2nd/June	9th/June/2014	1611	12	22.5	6	0.0762	23.7	1299.24	1283
							0.0762	23.3	1277.31	
							0.0762	23.2	1271.83	
4	2nd/June	9th/June/2014	1581	11.2	32.5	9	0.0762	33.6	1841.96	1884
							0.0762	32.2	1765.21	
							0.0762	37.3	2044.79	
5	2nd/June	9th/June/2014	1734	11.9	12.5	9	0.0762	38.5	2110.58	2134
							0.0762	39.9	2187.33	
							0.0762	38.4	2105.10	
6	2nd/June	9th/June/2014	1657	11.3	22.5	9	0.0762	33.1	1814.55	1820
							0.0762	32	1754.25	
							0.0762	34.5	1891.30	
7	4th/June	11th/June/2014	1527	9.6	32.5	6	0.0762	22.9	1255.38	1261
							0.0762	21.4	1173.15	
							0.0762	24.7	1354.06	
8	4th/June	11th/June/2014	1504	11.1	32.5	3	0.0762	18.8	1030.62	1031
							0.0762	19.6	1074.48	
							0.0762	18	986.76	
12	4th/June	11th/June/2014	1779	12.4	0	3	0.0762	16	877.12	923
							0.0762	17	931.94	
							0.0762	17.5	959.35	
13	4th/June	11th/June/2014	1810	11.2	0	6	0.0762	22	1206.04	1197
							0.0762	21.5	1178.63	
							0.0762	22	1206.04	
14	5th/June	12th/June/2014	1847	9.9	0	9	0.0762	55.5	3042.52	2958
							0.0762	53.9	2954.81	
							0.0762	52.5	2878.06	

Appendix E Indirect Tensile Strength Test Results

Table E: Indirect tensile strength results

Specimen No.	Date made	Date tested	Modified AASHTO Data		Specimen Data					
			MDD (Kg/m^3)	OMC (%)	PET Plastic waste content (%)	Cement content (%)	2/πld (m)	Crushing Load (kN)	ITS (kPa)	Average ITS (kPa)
2	2nd/June	9th/June/2014	1641	12	12.5	3	32.89	0.496	16.31	23
							32.89	0.694	22.83	
							32.89	0.863	28.38	
3	2nd/June	9th/June/2014	1611	12	22.5	6	32.89	3.369	110.81	106
							32.89	2.266	74.53	
							32.89	4.054	133.34	
4	2nd/June	9th/June/2014	1581	11.2	32.5	9	32.89	6.888	226.55	219
							32.89	7.353	241.84	
							32.89	5.69	187.14	
5	2nd/June	9th/June/2014	1734	11.9	12.5	9	32.89	7.808	256.81	280
							32.89	8.515	280.06	
							32.89	9.193	302.36	
6	2nd/June	9th/June/2014	1657	11.3	22.5	9	32.89	7.067	232.43	257
							32.89	7.574	249.11	
							32.89	8.846	290.94	
7	4th/June	11th/June/2014	1527	9.6	32.5	6	32.89	2.426	79.79	96
							32.89	3.152	103.67	
							32.89	3.174	104.39	
8	4th/June	11th/June/2014	1504	11.1	32.5	3	32.89	0.745	24.50	25
							32.89	0.789	25.95	
							32.89	0.749	24.63	
12	4th/June	11th/June/2014	1779	12.4	0	3	32.89	0.7	23.02	23
							32.89	0.742	24.40	
							32.89	0.676	22.23	
13	4th/June	11th/June/2014	1810	11.2	0	6	32.89	4.593	151.06	158
							32.89	5.279	173.63	
							32.89	4.522	148.73	
14	5th/June	12th/June/2014	1847	9.9	0	9	32.89	14.548	478.48	516
							32.89	15.155	498.45	
							32.89	17.405	572.45	

Appendix F Bearing Capacity of Soil-PET Plastic Waste Composite



Design situation

This is a square foundation for a building, $0.6m$ embedment depth, groundwater level is at great depth and the minimum foundation width, B is the unknown.

Soil conditions

The unreinforced sand and Sand-PET plastic waste composite parameters ($c' = 0kPa, \varphi', \ \gamma_{bulk}, and\ \gamma_{sat}$) used in the calculations are as seen the Appendix F tables.

Characteristic values of actions

- Permanent vertical load $G_k = 80kN$ plus weight of the foundation
- Variable vertical load $Q_{vk} = 50kN$ (at top of foundation)

- Permanent horizontal load = 0
- Variable horizontal load $Q_{hk} = 70kN$ at a height of $0.6m$ above the ground surface
- Variable loads are independent of each other.

Ultimate limit state design (ULSD) using an analytical method

This exercise aimed at determining the minimum dimensions $(L = B)$ for a square footing that satisfy the requirements of the STR, STR-P and GEO limit states from SANS 10160 (SABS 2011).

The partial factors for actions for the ultimate limit state are as seen in Appendix F and extracted from Table 3 of SANS 10160-1:2010, Edition 1.

The formulas used to determine the dimensions of the footing are listed below and used in the spread sheet to get actual values, which are summarised in Table F-1 and Appendix F Tables.

Design loads

Total vertical design load (V_d) and total horizontal load (Q_{hd}) are the design loads of values. Total vertical design load $(V_d) = \gamma_G(G_{vk} * B^2 * d * \gamma_c) + \left(\gamma_Q * Q_{vk}\right)$ where

- γ_G = geotechnical (unfavourable) partial factor
- G_{vk} = permanent vertical load
- B = pad width
- d = pad depth
- γ_c = unit weight of concrete
- γ_Q = geotechnical (unfavourable) partial factor
- Q_{vk} = variable vertical load

Total horizontal load $(Q_{hd}) = Q_{hk} * \gamma_Q$ where

- Q_{hk} = variable horizontal load
- γ_Q = geotechnical (unfavourable) partial factor

Bearing resistance

The aim is to verify that the total vertical design loads (V_d) are less than the design drained bearing resistance (R_{vd}). All the calculations were performed by inserting the following formulas into an excel sheet which is attached and also presented in the Appendix F Table F-2 to F-5 and summarised in Table F-1 below.

The value of the design drained bearing resistance (R_{vd}) is calculated using equation, D.2 of Annex D: EN1997-1 (Eurocode7 1995).

$R_{vd} = A'\left((c'N_cS_ci_c) + \gamma_{bulk}Z\left(N_qS_qi_q\right) + 0.5\gamma_{sat}B'\left(N_\gamma S_\gamma i_\gamma\right)\right)$, the following formulas and calculations are aimed at solving the equation. Calculations where achieved by use of excel spread sheet and the summary is as seen in Appendix F.

The design moment on the base of pad is $M_d = Q_{hd}(h + d)$ where

- Q_{hd} = total horizontal load
- h = height of load (Q_h)
- d = pad depth

Eccentricity, $e = {M_d}/{V_d}$ where

- M_d = design moment
- V_d = total vertical design load

Checking that $\frac{B}{3} - e > 0$, where

- B = pad width
- e = eccentricity

The Effective width $B' = B - 2e$, where

- B = pad width
- e = eccentricity

Effective length $L' = B$ (Pad width)

Effective Area, $A' = B'L'$

N_q = Bearing capacity factor for overburden pressure

= $e^{\pi tan\varphi'_d} tan^2\left(45^o + \frac{\varphi'_d}{2}\right)$

N_γ = Bearing capacity factor for self-weight of soil

= $2\left(N_q - 1\right)tan\varphi'_d$

S_q = Shape factor for overburden pressure

= $1 + \left(\frac{B'}{L'}\right) sin\varphi'_d$

S_γ = Shape factor for self-weight of soil = 0.7

i_q = Load inclination factor for overburden pressure

= $(1 - H/(V + A'c'cot\varphi'_d))^m$

Where $H = Q_{hd}$, $V = V_d$, $c' = 0$, $m = 2\,(2 + B'/L')/(1 + B'/L')$

i_γ = Loading inclination factor for self-weight of soil

= $(1 - H/(V + A'c'cot\varphi'_d))^{m+1}$

From $R_{vd} = A'\left((c'N_cS_ci_c) + \gamma_{bulk}Z\left(N_qS_qi_q\right) + 0.5\gamma_{sat}B'\left(N_\gamma S_\gamma i_\gamma\right)\right)$, and since $c' = 0$

$$R_{vd} = A'\left(\gamma_{bulk}Z\left(N_qS_qi_q\right) + 0.5\gamma_{sat}B'\left(N_\gamma S_\gamma i_\gamma\right)\right)$$

Checking $R_{vd} - V_d > 0$,

Sliding Resistance

V_d = Total vertical design load

= $G_{vk} + G_{padk}$

H_d = Q_{hd}

R_{hd} = $V_d\left(tan^{\delta}\right)/\gamma_R$

$R_{hd} - H_d > 0.$

Table F-1: Summary of bearing capacity of sand-PET plastic waste composite. (STR, STR-P, and GEO limit state design conforming to SANS 10160)

Description	Symbol	Units	PET plastic waste (%)			
			0%	**12.5%**	**22.5%**	**32.5%**
Calculated angle of friction	ϕ	degree	38.5	40.3	44.4	41.1
Calculated bulk density	γ_{bulk}	kN/m^3	17.4	16.3	15.47	14.98
Assumed saturated density	$\gamma_{saturated}$	kN/m^3	19.4	18.3	17.47	16.98
Foundation (B-Pad) width (m)						
(STR)	V unfav. Q leading	m	0.423	0.385	0.289	0.380
	V unfav W leading	m	2.866	2.844	2.793	2.841
	V fav. W leading	m	3.348	3.330	3.289	3.328
(STR-P)	V unfav. Q leading	m	0.402	0.366	0.275	0.361
(GEO)	V unfav. Q leading	m	0.577	0.535	0.422	0.533
	V unfav W leading	m	3.225	3.198	3.125	3.197
	V fav. W leading	m	3.323	3.298	3.230	3.297
Bearing Resistance for Geo (V fav. W leading)						
Design drained bearing resistance	R_{vd}	kN	245.67	243.13	236.5	243.08
Total vertical design load	V_d	kN	245.67	243.13	236.5	243.08
Checking $R_d - V_d > 0$		kN	0	0	0	0
Sliding Resistance Geo (V fav. W leading)						
	R_{hd}	kN	156.33	164.95	185.28	169.64
	H_d	kN	91.00	91.00	91.00	91.00
Checking $R_{hd} - H_d > 0$		kN	65.33	73.95	84.28	78.64

Table F-2: Calculation of bearing capacity of unreinforced sand.

Description	unit	STR			STR-P	GEO		
		V unfav. Q leading	V unfav. W leading	V fav. W leading	V unfav. Q leading	V unfav. Q leading	V unfav. W leading	V fav. W leading
B - Pad width	m	0.423	2.866	3.348	0.402	0.577	3.225	3.323
Load factors								
γ_G - Structural		1.20	1.20	0.90	1.35	1.00	1.00	1.00
γ_Q - Imposed		1.60	1.60	0.00	1.00	1.30	1.30	0.00
γ_{wind} - Wind		1.30	1.30	1.30	1.00	1.30	1.30	1.30
ψ_Q - Imposed		1.00	0.30	0.30	1.00	1.00	0.30	0.30
ψ_{wind} - Wind		0.00	1.00	1.00	0.00	0.00	1.00	1.00
Charasteristic loads								
G_{vk} - Permanent vertical load	kN	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Q_{vk} - Variable vertical load	kN	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Q_{hk} - Variable horizontal load	kN	70.00	70.00	70.00	70.00	70.00	70.00	70.00
h - height of Q_h	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
d - pad depth	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
V - Volume of pad	m^3	0.11	4.93	6.73	0.10	0.20	6.24	6.63
γ_c - concrete	kN/m^3	25.00	25.00	25.00	25.00	25.00	25.00	25.00
G_{padk} - pad weight	kN/m^2	2.68	123.17	168.14	2.43	4.99	156.01	165.67
Design loads								
V_d - Total vertical design load	kN	179.22	267.81	223.32	161.28	149.99	255.51	245.67
Q_{hd} - Total horizontal load	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
Bearing Resistance								
Mx - wind	kNm	300.00	300.00	300.00	300.00	300.00	300.00	300.00
M_d - Design moment	kNm	0.00	342.00	342.00	0.00	0.00	342.00	342.00
e - Eccentricity		0.00	1.28	1.53	0.00	0.00	1.34	1.39
Checking **B/3 - e > 0**		0	0	0	0	0	0	0
B' -Effective width = B - 2e	m	0.42	0.31	0.29	0.40	0.58	0.55	0.54
L' Effective length = B	m	0.42	2.87	3.35	0.40	0.58	3.23	3.32
A' Effective area = B' x L'	m^2	0.18	0.89	0.95	0.16	0.33	1.77	1.79
γ_ϕ - Shearing resistance (tanϕ)		1.00	1.00	1.00	1.00	1.25	1.25	1.25

γ_c - effective cohesion		1.00	1.00	1.00	1.00	1.00	1.00	1.00
γ_R - Bearing resistance (Rv)		1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma_{k,bulk}$	kN/m^3	17.40	17.40	17.40	17.40	17.40	17.40	17.40
$\gamma_{d,\ bulk}$	kN/m^3	17.40	17.40	17.40	17.40	17.40	17.40	17.40
$\gamma_{k,\ saturated}$	kN/m^3	19.40	19.40	19.40	19.40	19.40	19.40	19.40
$\gamma_{d,\ saturated}$	kN/m^3	19.40	19.40	19.40	19.40	19.40	19.40	19.40
γ - water density	kN/m^3	9.81	9.81	9.81	9.81	9.81	9.81	9.81
γ'_d - bouyant density	kN/m^3	9.59	9.59	9.59	9.59	9.59	9.59	9.59
ϕ'_k - angle of internal friction	degree	38.50	38.50	38.50	38.50	38.50	38.50	38.50
ϕ'_d - effective angle of internal friction	degree	38.50	38.50	38.50	38.50	32.47	32.47	32.47
q' = ($\gamma_{d,bulk}$*d) overburden pressure at foundation level	kN/m^2	10.44	10.44	10.44	10.44	10.44	10.44	10.44
N_q - Bearing capacity for overburden pressure		52.31	52.31	52.31	52.31	24.50	24.50	24.50
N_γ - Bearing capacity for self-weight of soil		81.62	81.62	81.62	81.62	29.91	29.91	29.91
s_q - Shape factor for overburden pressure		1.62	1.07	1.05	1.62	1.54	1.09	1.09
s_γ - Shape factor for self-weight of soil		0.70	0.97	0.97	0.70	0.70	0.95	0.95
m		1.50	1.90	1.92	1.50	1.50	1.85	1.86
i_q - Load inclination factor for overburden pressure		1.00	0.45	0.37	1.00	1.00	0.44	0.42
i_γ - Load inclination factor for self-weight of soil		1.00	0.30	0.22	1.00	1.00	0.28	0.27
R_{vd} - Design drained bearing resistance	kN	179.22	267.81	223.32	161.28	149.99	255.51	245.67
V_d - Total vertical design load	kN	179.22	267.81	223.32	161.28	149.99	255.51	245.67
Check $R_d - V_d > 0$	kN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sliding Resistance								
$V_d = G_{vk} + G_{padk}$	kN	179.22	267.81	223.32	161.28	149.99	255.51	245.67
$H_d = Q_{hd}$	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
$\delta_d = \phi'_d$	degree	38.50	38.50	38.50	38.50	32.47	32.47	32.47
$R_{hd} = V_d \tan\delta / \gamma_R$	kN	142.56	213.02	177.64	128.29	95.45	162.59	156.33
Check $R_{hd} - H_d > 0$	kN	142.56	122.02	86.64	128.29	95.45	71.59	65.33

Table F-3: Calculation of bearing capacity of 12.5% sand-PET plastic waste composite.

Description	unit	STR			STR-P	GEO		
		V unfav. Q leading	V unfav. W leading	V fav. W leading	V unfav. Q leading	V unfav. Q leading	V unfav. W leading	V fav. W leading
B - Pad width	m	0.385	2.844	3.330	0.366	0.535	3.198	3.298
Load factors								
γ_G - Structural		1.20	1.20	0.90	1.35	1.00	1.00	1.00
γ_Q - Imposed		1.60	1.60	0.00	1.00	1.30	1.30	0.00
γ_{wind} - Wind		1.30	1.30	1.30	1.00	1.30	1.30	1.30
ψ_Q - Imposed		1.00	0.30	0.30	1.00	1.00	0.30	0.30
ψ_{wind} - Wind		0.00	1.00	1.00	0.00	0.00	1.00	1.00
Charasteristic loads								
G_{vk} - Permanent vertical load	kN	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Q_{vk} - Variable vertical load	kN	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Q_{hk} - Variable horizontal load	kN	70.00	70.00	70.00	70.00	70.00	70.00	70.00
h - height of Q_h	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
d - pad depth	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
V - Volume of pad	m^3	0.09	4.85	6.65	0.08	0.17	6.13	6.53
γ_c - concrete	kN/m^3	25.00	25.00	25.00	25.00	25.00	25.00	25.00
G_{padk} - pad weight	kN/m^2	2.22	121.32	166.36	2.01	4.30	153.37	163.13
Design loads								
V_d - Total vertical design load	kN	178.67	265.59	221.72	160.71	149.30	252.87	243.13
Q_{hd} - Total horizontal load	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
Bearing Resistance								
Mx - wind	kNm	300.00	300.00	300.00	300.00	300.00	300.00	300.00
M_d - Design moment	kNm	0.00	342.00	342.00	0.00	0.00	342.00	342.00
e - Eccentricity		0.00	1.29	1.54	0.00	0.00	1.35	1.41
Checking **B/3 - e > 0**		0	0	0	0	0	0	0
B' -Effective width = B - 2e	m	0.38	0.27	0.25	0.37	0.54	0.49	0.48
L' Effective length = B	m	0.38	2.84	3.33	0.37	0.54	3.20	3.30
A' Effective area = B' x L'	m^2	0.15	0.76	0.82	0.13	0.29	1.58	1.60
γ_ϕ - Shearing resistance (tanϕ)		1.00	1.00	1.00	1.00	1.25	1.25	1.25

γ_c - effective cohesion		1.00	1.00	1.00	1.00	1.00	1.00	1.00
γ_R - Bearing resistance (Rv)		1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma_{k,bulk}$	kN/m^3	16.30	16.30	16.30	16.30	16.30	16.30	16.30
$\gamma_{d,\ bulk}$	kN/m^3	16.30	16.30	16.30	16.30	16.30	16.30	16.30
$\gamma_{k,\ saturated}$	kN/m^3	18.30	18.30	18.30	18.30	18.30	18.30	18.30
$\gamma_{d,\ saturated}$	kN/m^3	18.30	18.30	18.30	18.30	18.30	18.30	18.30
γ - water density	kN/m^3	9.81	9.81	9.81	9.81	9.81	9.81	9.81
γ'_d - bouyant density	kN/m^3	8.49	8.49	8.49	8.49	8.49	8.49	8.49
ϕ'_k - angle of internal friction	degree	40.30	40.30	40.30	40.30	40.30	40.30	40.30
ϕ'_d - effective angle of internal friction	degree	40.30	40.30	40.30	40.30	34.15	34.15	34.15
q' = ($\gamma_{d,bulk}$*d) overburden pressure at foundation level	kN/m^2	9.78	9.78	9.78	9.78	9.78	9.78	9.78
N_q - Bearing capacity for overburden pressure		66.94	66.94	66.94	66.94	30.00	30.00	30.00
N_γ - Bearing capacity for self-weight of soil		111.84	111.84	111.84	111.84	39.35	39.35	39.35
s_q - Shape factor for overburden pressure		1.65	1.06	1.05	1.65	1.56	1.09	1.08
s_γ - Shape factor for self-weight of soil		0.70	0.97	0.98	0.70	0.70	0.95	0.96
m		1.50	1.91	1.93	1.50	1.50	1.87	1.87
i_q - Load inclination factor for overburden pressure		1.00	0.45	0.36	1.00	1.00	0.43	0.42
i_γ - Load inclination factor for self-weight of soil		1.00	0.29	0.21	1.00	1.00	0.28	0.26
R_{vd} - Design drained bearing resistance	kN	178.67	265.59	221.72	160.71	149.30	252.87	243.13
V_d - Total vertical design load	kN	178.67	265.59	221.72	160.71	149.30	252.87	243.13
Check $R_d - V_d > 0$	kN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sliding Resistance								
$V_d = G_{vk} + G_{padk}$	kN	178.67	265.59	221.72	160.71	149.30	252.87	243.13
$H_d = Q_{hd}$	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
$\delta_d = \phi'_d$	degree	40.30	40.30	40.30	40.30	34.15	34.15	34.15
$R_{hd} = V_d \tan^{\delta} / \gamma_R$	kN	151.52	225.23	188.03	136.29	101.29	171.56	164.95
Check $R_{hd} - H_d > 0$	kN	151.52	134.23	97.03	136.29	101.29	80.56	73.95

Table F-4: Calculation of bearing capacity of 22.5% sand-PET plastic waste composite

Description	unit	STR			STR-P	GEO		
		V unfav. Q leading	V unfav. W leading	V fav. W leading	V unfav. Q leading	V unfav. Q leading	V unfav. W leading	V fav. W leading
B - Pad width	m	0.289	2.793	3.289	0.275	0.422	3.125	3.230
Load factors								
γ_G - Structural		1.20	1.20	0.90	1.35	1.00	1.00	1.00
γ_Q - Imposed		1.60	1.60	0.00	1.00	1.30	1.30	0.00
γ_{wind} - Wind		1.30	1.30	1.30	1.00	1.30	1.30	1.30
ψ_Q - Imposed		1.00	0.30	0.30	1.00	1.00	0.30	0.30
ψ_{wind} - Wind		0.00	1.00	1.00	0.00	0.00	1.00	1.00
Charasteristic loads								
G_{vk} - Permanent vertical load	kN	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Q_{vk} - Variable vertical load	kN	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Q_{hk} - Variable horizontal load	kN	70.00	70.00	70.00	70.00	70.00	70.00	70.00
h - height of Q_h	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
d - pad depth	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
V - Volume of pad	m^3	0.05	4.68	6.49	0.05	0.11	5.86	6.26
γ_c - concrete	kN/m^3	25.00	25.00	25.00	25.00	25.00	25.00	25.00
G_{padk} - pad weight	kN/m^2	1.26	117.05	162.26	1.13	2.68	146.46	156.50
Design loads								
V_d - Total vertical design load	kN	177.51	260.46	218.04	159.53	147.68	245.96	236.50
Q_{hd} - Total horizontal load	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
Bearing Resistance								
Mx - wind	kNm	300.00	300.00	300.00	300.00	300.00	300.00	300.00
M_d - Design moment	kNm	0.00	342.00	342.00	0.00	0.00	342.00	342.00
e - Eccentricity		0.00	1.31	1.57	0.00	0.00	1.39	1.45
Checking **B/3 - e > 0**		0	0	0	0	0	0	0
B' -Effective width = B - 2e	m	0.29	0.17	0.15	0.27	0.42	0.34	0.34
L' Effective length = B	m	0.29	2.79	3.29	0.27	0.42	3.12	3.23
A' Effective area = B' x L'	m^2	0.08	0.47	0.50	0.08	0.18	1.07	1.09
γ_ϕ - Shearing resistance (tanϕ)		1.00	1.00	1.00	1.00	1.25	1.25	1.25

γ_c - effective cohesion		1.00	1.00	1.00	1.00	1.00	1.00	1.00
γ_R - Bearing resistance (Rv)		1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma_{k,bulk}$	kN/m^3	15.47	15.47	15.47	15.47	15.47	15.47	15.47
$\gamma_{d, bulk}$	kN/m^3	15.47	15.47	15.47	15.47	15.47	15.47	15.47
$\gamma_{k, saturated}$	kN/m^3	17.47	17.47	17.47	17.47	17.47	17.47	17.47
$\gamma_{d, saturated}$	kN/m^3	17.47	17.47	17.47	17.47	17.47	17.47	17.47
γ - water density	kN/m^3	9.81	9.81	9.81	9.81	9.81	9.81	9.81
γ'_d - bouyant density	kN/m^3	7.66	7.66	7.66	7.66	7.66	7.66	7.66
ϕ'_k - angle of internal friction	degree	44.40	44.40	44.40	44.40	44.40	44.40	44.40
ϕ'_d - effective angle of internal friction	degree	44.40	44.40	44.40	44.40	38.08	38.08	38.08
q' = ($\gamma_{d,bulk}$*d) overburden pressure at foundation level	kN/m^2	9.28	9.28	9.28	9.28	9.28	9.28	9.28
N_q - Bearing capacity for overburden pressure		122.70	122.70	122.70	122.70	49.43	49.43	49.43
N_γ - Bearing capacity for self-weight of soil		238.36	238.36	238.36	238.36	75.88	75.88	75.88
s_q - Shape factor for overburden pressure		1.70	1.04	1.03	1.70	1.62	1.07	1.06
s_γ - Shape factor for self-weight of soil		0.70	0.98	0.99	0.70	0.70	0.97	0.97
m		1.50	1.94	1.96	1.50	1.50	1.90	1.91
i_q - Load inclination factor for overburden pressure		1.00	0.43	0.35	1.00	1.00	0.42	0.40
i_γ - Load inclination factor for self-weight of soil		1.00	0.28	0.20	1.00	1.00	0.26	0.24
R_{vd} - Design drained bearing resistance	kN	177.51	260.46	218.04	159.53	147.68	245.96	236.50
V_d - Total vertical design load	kN	177.51	260.46	218.04	159.53	147.68	245.96	236.50
Check $R_d - V_d > 0$	kN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sliding Resistance								
$V_d = G_{vk} + G_{padk}$	kN	177.51	260.46	218.04	159.53	147.68	245.96	236.50
$H_d = Q_{hd}$	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
$\delta_d = \phi'_d$	degree	44.40	44.40	44.40	44.40	38.08	38.08	38.08
$R_{hd} = V_d \tan^{\delta}/\gamma_R$	kN	173.83	255.06	213.52	156.22	115.69	192.69	185.28
Check $R_{hd} - H_d > 0$	kN	173.83	164.06	122.52	156.22	115.69	101.69	94.28

Table F-5: Calculation of bearing capacity of 32.5% sand-PET plastic waste

Description	unit	STR			STR-P	GEO		
		V unfav. Q leading	V unfav. W leading	V fav. W leading	V unfav. Q leading	V unfav. Q leading	V unfav. W leading	V fav. W leading
B - Pad width	m	0.380	2.841	3.328	0.361	0.533	3.197	3.297
Load factors								
γ_G - Structural		1.20	1.20	0.90	1.35	1.00	1.00	1.00
γ_Q - Imposed		1.60	1.60	0.00	1.00	1.30	1.30	0.00
γ_{wind} - Wind		1.30	1.30	1.30	1.00	1.30	1.30	1.30
ψ_Q - Imposed		1.00	0.30	0.30	1.00	1.00	0.30	0.30
ψ_{wind} - Wind		0.00	1.00	1.00	0.00	0.00	1.00	1.00
Charasteristic loads								
G_{vk} - Permanent vertical load	kN	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Q_{vk} - Variable vertical load	kN	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Q_{hk} - Variable horizontal load	kN	70.00	70.00	70.00	70.00	70.00	70.00	70.00
h - height of Q_h	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
d - pad depth	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60
V - Volume of pad	m^3	0.09	4.84	6.65	0.08	0.17	6.13	6.52
γ_c - concrete	kN/m^3	25.00	25.00	25.00	25.00	25.00	25.00	25.00
G_{padk} - pad weight	kN/m^2	2.16	121.10	166.14	1.95	4.26	153.32	163.08
Design loads								
V_d - Total vertical design load	kN	178.59	265.32	221.52	160.64	149.26	252.82	243.08
Q_{hd} - Total horizontal load	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
Bearing Resistance								
Mx - wind	kNm	300.00	300.00	300.00	300.00	300.00	300.00	300.00
M_d - Design moment	kNm	0.00	342.00	342.00	0.00	0.00	342.00	342.00
e - Eccentricity		0.00	1.29	1.54	0.00	0.00	1.35	1.41
Checking **B/3 - e > 0**		0	0	0	0	0	0	0
B' -Effective width = B - 2e	m	0.38	0.26	0.24	0.36	0.53	0.49	0.48
L' Effective length = B	m	0.38	2.84	3.33	0.36	0.53	3.20	3.30
A' Effective area = B' x L'	m^2	0.14	0.75	0.80	0.13	0.28	1.57	1.59
γ_ϕ - Shearing resistance ($\tan\phi$)		1.00	1.00	1.00	1.00	1.25	1.25	1.25
γ_c - effective cohesion		1.00	1.00	1.00	1.00	1.00	1.00	1.00
γ_R - Bearing resistance (Rv)		1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma_{k,bulk}$	kN/m^3	14.98	14.98	14.98	14.98	14.98	14.98	14.98
$\gamma_{d,\ bulk}$	kN/m^3	14.98	14.98	14.98	14.98	14.98	14.98	14.98
$\gamma_{k,\ saturated}$	kN/m^3	16.98	16.98	16.98	16.98	16.98	16.98	16.98
$\gamma_{d,\ saturated}$	kN/m^3	16.98	16.98	16.98	16.98	16.98	16.98	16.98

ɣ - water density	kN/m^3	9.81	9.81	9.81	9.81	9.81	9.81	9.81
ɣ'$_d$ - bouyant density	kN/m^3	7.17	7.17	7.17	7.17	7.17	7.17	7.17
ϕ'$_k$ - angle of internal friction	degree	41.10	41.10	41.10	41.10	41.10	41.10	41.10
ϕ'$_d$ - effective angle of internal friction	degree	41.10	41.10	41.10	41.10	34.91	34.91	34.91
q' = ($ɣ_{d,bulk}$*d) overburden pressure at foundation level	kN/m^2	8.99	8.99	8.99	8.99	8.99	8.99	8.99
N$_q$ - Bearing capacity for overburden pressure		74.96	74.96	74.96	74.96	32.93	32.93	32.93
N$_ɣ$ - Bearing capacity for self-weight of soil		129.04	129.04	129.04	129.04	44.56	44.56	44.56
s$_q$ - Shape factor for overburden pressure		1.66	1.06	1.05	1.66	1.57	1.09	1.08
s$_ɣ$ - Shape factor for self-weight of soil		0.70	0.97	0.98	0.70	0.70	0.95	0.96
m		1.50	1.92	1.93	1.50	1.50	1.87	1.87
i$_q$ - Load inclination factor for overburden pressure		1.00	0.45	0.36	1.00	1.00	0.43	0.42
i$_ɣ$ - Load inclination factor for self-weight of soil		1.00	0.29	0.21	1.00	1.00	0.28	0.26
R$_{vd}$ - Design drained bearing resistance	kN	178.59	265.32	221.52	160.64	149.26	252.82	243.08
V$_d$ - Total vertical design load	kN	178.59	265.32	221.52	160.64	149.26	252.82	243.08
Check **R$_d$ - V$_d$** > **0**	kN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sliding Resistance								
V$_d$ = G_{vk} +G_{padk}	kN	178.59	265.32	221.52	160.64	149.26	252.82	243.08
H$_d$ = Q_{hd}	kN	0.00	91.00	91.00	0.00	0.00	91.00	91.00
^{δ}**$_d$** = ϕ'$_d$	degree	41.10	41.10	41.10	41.10	34.91	34.91	34.91
R$_{hd}$ = $V_d tan^{δ}/ɣ_R$	kN	155.80	231.45	193.25	140.13	104.17	176.44	169.64
Check R_{hd} - **H$_d$** > **0**	kN	155.80	140.45	102.25	140.13	104.17	85.44	78.64