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UCS and CBR behaviour of Perth sandy soil reinforced with waste tyre fibres and cement

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ABSTRACT

Weak and unsuitable soil conditions have always caused problems for civil engineers during the construction of structures. To avoid problems in a cost-effective manner, proper and reliable solutions need to be developed. Fibre reinforcement and cement stabilisation are the most efficient and common methods in geotechnical engineering applications when engineers have problematic soil conditions. These methods can be used in different applications, such as pavement layers, retaining walls and slopes.

Over the past three decades, many studies have been done to investigate the effects of adding synthetic and natural fibres to soil as the reinforcing material alone or with cement. The present work focuses on investigating the characteristics of local Perth sandy soil after inclusion of waste tyre fibres and cement. These wastes can be utilised in ground improvement projects in large quantities and could provide a cost-effective and environmentally friendly strategy that avoids tyre disposal problems.

Fibres for reinforcement applications in soils are available in different types in terms of materials and their geometrical configurations. Using waste materials, which are present nowadays in large quantities and in different forms, such as used tyres and carpets, as reinforcing materials can be environmentally and economically beneficial. In the past, waste tyres have been used in some geotechnical applications, such as highway construction, retaining wall backfill and drainage layers for roads, but the efforts seem to be insufficient. Although much research has been conducted on cement stabilisation, but on fibre reinforcement, and their combination, no comprehensive research has been done to investigate the UCS and CBR behaviour of sandy soils mixed with cement and tyre fibres, especially on the sandy soils available in Perth and its surrounding areas.

A series of laboratory tests including compaction, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted to investigate the effects of adding tyre fibre and cement on the engineering behaviour of Perth sandy soil. The contents were varied from 0 to 5% of dried soil by weight for cement and 1% of dried soil by weight for tyre fibres. The cemented specimens were cured in for 3, 7, 14, and 28 days.

This study aims at investigating the effect of different parameters, including cement content, tyre fibre content, curing time and confining pressure on the CBR behaviour of Perth sandy soils. Feasible, ecologically friendly, and economically reasonable solutions, both theoretically and practically, are studied in this research so that geotechnical/civil engineers can effectively use them in the construction projects.

The compaction test results indicate that the maximum dry unit weight generally increases by adding cement and decreases by tyre fibres inclusion, while adding cement and tyre fibre results in a lower optimum water content.

For the fibre-reinforced and unreinforced materials, the compressive strength increases with an increase in the cement content. Adding 1% of tyre fibres to mixtures increases the UCS of the soil approximately by 10-70%. The results also show that as the curing time increases, the UCS increases, and the effect of curing is more pronounced for higher stabiliser contents.

The results also indicate that adding cement and/or tyre fibres to soil leads to a higher CBR. The addition of 5% cement increases unsoaked CBR value from 11.74 to 19.31%, which is about 64% increase. Moreover, adding 1% tyre fibres to cemented-soil with 5% cement increases unsoaked CBR from 11.74 to 18.58 which shows a 58% increase. It is also noticed that the soaked CBR value for cemented soil with 5% cement increases from 11.74 to 363.63%. The addition of 1% tyre fibres to the cemented-soil mixtures with 5% cement increases the soaked CBR value from 13.78 to 266.89%. Several research studies have presented similar higher values for soaked CBR.

DEDICATION

I would like to dedicate this thesis to my beloved family, especially my compassionate wife for her continuing support and encouragement.

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I would like to gratefully acknowledge the help I received from several sources. My sincere gratitude goes to my principal supervisor, Associate Professor Sanjay Kumar Shukla, for his ongoing encouragement and thoughtful, astute and helpful suggestions and criticisms. I also wish to express my gratitude to my associate supervisors Dr. Hang Vu as well as Professor Daryoush Habibi, Dr. Mehdi Khiadani and Dr. Alireza Mohyeddin for their valuable scientific and technical advices.

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S M Ali BAZAZORDE

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NOTATION

Basic SI units are given in parentheses.

c'	effective cohesion (kPa)
C_c	coefficient of curvature (dimensionless)
C_u	coefficient of uniformity (dimensionless)
D	maximum particle size (mm)
D_{10}	effective diameter (mm)
D_{50}	average grain size (mm)
E	modulus of elasticity (kPa)
e	void ratio (dimensionless)
e_{max}	maximum void ratio (dimensionless)
e_{min}	minimum void ratio (dimensionless)
C_s	specific gravity (dimensionless)
G_{s_c}	specific gravity of cement (dimensionless)
G_{s_f}	specific gravity of tyre fibres (dimensionless)
G_{s_s}	specific gravity of sand (dimensionless)
n	Talbot's grading value (dimensionless)
p'	$(\sigma'_1 + \sigma'_3)/2$ (kPa)
p_c	cement content (%)
P_f	tyre fibre content (%)
q'	$(\sigma'_1 - \sigma'_3)/2$ (kPa)
S	degree of saturation (dimensionless)
UCS	unconfined compressive strength (kPa)
w	water content (dimensionless)
W_c	weight of cement (N)
W_f	weight of tyre fibres (N)
w_{opt}	optimum water content (dimensionless)
W_s	weight of dried soil (N)
ZAV	zero air void (kN/m^3)

ε_a	axial strain (dimensionless)
γ_d	dry unit weight (kN/m^3)
$\gamma_{d_{max}}$	maximum dry unit weight (kN/m^3)
γ_w	unit weight of water (kN/m^3)
σ'_f	effective normal stress at failure (kPa)
σ'_1	effective major principal stress (kPa)
σ'_3	effective minor principal stress (kPa)

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CHAPTER 1

INTRODUCTION

1.1 General

Perth, located on the west coast of Australia, is the capital of Western Australia (WA). It amounts to a third of the area of Australia, with a total area of more than 2,500,000 square kilometres (Geoscience Australia, 2012). WA is divided into five regions; the Kimberley, the North West, South West, the Interior, and the Wheat Belt. The majority of the population live along the beautiful white sandy beaches of the West Australian coast. The Perth region, with a population of more than 2 million, has the majority of WA's population, which is nearly 2.5 million (Australian Bureau of Statistics, 2012). As WA, and especially Perth is improving in several aspects such as economy and tourism, there is a growing need for reliable and suitable infrastructures that call for use of civil and geotechnical engineering principles and practices to be employed.

Over the last few years, developing alternative materials have been able to help to environmental and economic problems. The improved geotechnical materials would be obtained by using the useful techniques of soil stabilization and soil reinforcement through either the addition to soil of cementing agents (lime, Portland cement, asphalt, etc.) or the inclusion of oriented or haphazardly gave out segregated materials such as fibres and tire chips. Use of fibre-shaped waste materials is one of the most incentive techniques in this area. Amount of waste materials such as polyethylene terephthalate (PET) plastic bottles are abundantly and extensively increasing. Engineering applications have been tried to use such materials, but the overwhelming majority of them have been placed in storage or disposal sites (Consoli et al., 2002).

Geotechnical engineering basically deals with the soils and rocks; consequently, the first step of a project is identifying the soil/rock type on which the work will be done. The soil in Perth and its surrounding area is mainly sand, although other types of soil can be found (Stephenson and Hepburn, 1955). Sands are defined as a group of soils having particle sizes between 0.075mm and 2.36 mm (Standards Australia, 1993).

In a construction project, encountering weak or unsuitable soils can be expected; therefore, the most efficient and cost-effective solutions need to be found in such situations. Several remedial solutions are available when a construction project is planned for locations where weak and unsuitable soils are encountered. One of the effective and reliable techniques for improving soil behaviour is soil reinforcement. The technique is used in many structures and projects, such as retaining structure, earthwork, embankment and subgrade stabilization beneath footing and pavement (Gray et al., 1983). In this chapter, a brief introduction of soil stabilisation and reinforcement methods are presented along with objectives and organisation of this thesis.

1.2 Soil stabilisation and reinforcement

Stabilisation and reinforcement are two of the most conventional methods to improve the desired properties of soil. Stabilisation can be defined as improving the important natural characteristics of the soil (increase in fertility) by means of special scientifically substantiated methods.

The properties of a soil can be improved by changing mechanical or chemical it or mixing it either with another soil or with cement, lime and bitumen (Terrel et al., 1979). One of the common stabilisation practices is Cement stabilisation which can be used in different road construction applications such as subgrades, select fill, base and subbase (Wilmot, 2006). However, suitable materials should be used for cement stabilisation. Table 1.1 presents material criteria suitable for cement stabilisation (AustStab, 2012), table 1.2 presents major cement types and composition (AS 3972, 2010).

Soil reinforcement is defined as an application of mixing natural or combinatorial materials such as fibres, cement or geosynthetics to soil to ameliorate shortage caused by the general low tensile and shear strength of soils (Hejazi et al., 2012). The technique of reinforcing soils has been used since ancient times for purposes like reinforcing mud blocks by straw and hay (Hejazi et al., 2012). However, modern soil reinforcement method has been introduced in 1966 by Henry Vidal (Shukla et al., 2009). Nowadays, different reinforcement materials are being pursued as natural materials such as coconut fibre or palm fibre, and geogrids, polypropylene fibres or glass fibres, as synthetic materials (Hejazi et al., 2012).

Table 1.1. Guide to property limits for effective cement stabilization

Property	Limit
Particle size	
Maximum particle size	75 mm *
Passing 4.75mm	>50%
Passing 425 µm	>15%
Passing 75 µm	< 50%
Finer than 2 µm **	< 30%
Plasticity	
Liquid limit	< 40 %
Plastic limit	< 20 %
Plasticity index	< 20 %

* Depends on mixing plan
** At upper limit may need pre-treatment with lime

Table 1.2. Major cement types and composition

Cement type	Portland cement	Type GP (Note 1)	Mineral addition and minor additional constituents (7.5% combined maximum for Type GP and 20% combined maximum for Type GL)			Supplementary cementitious materials (SCM) (Note 4)	
			Mineral additions (Note 2)		Minor additional constituents (Note 3)	Fly ash and/or slag	Amorphous silica
			Fly ash or slag	limestone			
Type GP	92.5 to 100	-	0 to 7.5		0 to 5	-	-
Type GL	80 to 92	-	-		0 to 5	-	-
Type GB	-	<92.5	-	-	-	>7.5	0 to 10

Notes:
1. If Type GB cement consists of Type GP and amorphous silica only, the proportion of Type GP shall be 90% or above.
2. For Type GP the 'mineral additions' may comprise limestone, fly ash or slag, or a combination of these materials, at the discretion of the cement manufacturer.
3. The 'minor additional constituents' addition forms part of the allowable amount of 'mineral addition' in the cement.
4. Type GB cement may contain supplementary cementitious materials (SCMs) comprising either or both fly ash and slag at combined levels above 7.5% and amorphous silica at a level not exceeding 10%.

1.3 Waste tyres and disposal problems

Recently, waste materials such as waste tyres have attracted attention to be used in soil reinforcement. Of the approximately 240 million tires traded in each year, almost 70% or 170 million tires are disposed of directly into the environment. The most common disposal end point is privately and publicly owned stockpiles, which account for around 100 million tires annually. Approximately 28 million tires are disposed of in landfills, and 38 million tires are randomly dumped on roadsides or in rural areas. While these estimates alone are quite large, they do not include the huge backlog of scrap tires from previous years. The stock of tires from past stockpiling has been estimated to be over 2.4 billion (GIA, 2013). In Western Australia. Around 48.5 million equivalent passenger unit (EPU) waste tyres were produced in 2009-2010 (Brindley et al., 2012). Consequently, waste tyres are occupying a considerable amount of valuable space in landfill sites, resulting in severe environmental consequence and an increasing need for new landfill sites (Fig.1.1). Therefore, reuse of waste tyres should be seriously considered.

Fig. 1.1. This 75,000-tones tyre dump near Madrid has presented Spanish authorities with a big problem (BBC NEWS, 2016)

There are six major tire disposal end points which are representative of the total disposal mix: landfills, stockpiles, random dumps, retreads, asphalt mixtures, and energy feeds. The first three end points account for a significant portion of disposed tires. Asphalt mixtures and energy feeds represent the most economical and technically feasible options that could absorb a significant portion of the tires being disposed. There are also some applications of the waste tyres in civil engineering such as in embankment construction or drainage layers in landfills

(Balunaini et al., 2014). However, considering the ongoing increase in the amount of waste tyres, more studies are required to find other applications for theses wastes. Waste tyres can be used in different forms such as whole tyres or tyre fragments. The tyre fragments are categorised in Table 1.3 according to their sizes (ASTM, 2012). Waste tyres also can be used in different shapes such as tyre shreds and tyre chips which are shown in Fig.1.2. Like other additives to be used in soil improvement technics, tyre derived aggregates should be used with a proper host material. Edil and Bosscher (1994) stated that waste tyre additives can be mixed with sandy and clayey soils. Albeit, there may be some difficulties in mixing theses additives with clay, and at the same soil: tyre additive proportion, better performance is observed for sandy soils.

Table 1.3. Types of waste tyre fragments based on size (ASTM, 2012)

Fragment type	Powdered rubber	Ground rubber	Granulated rubber	Tyre chips	Tyre shreds
Size range (mm)	≤ 0.425	0.425 - 2	0.425 - 12	12 - 50	50 - 305

Fig. 1.2. Different processed tyre waste types (Edincliler et al., 2010)

Much research has been conducted previously to investigate the effect of stabilising sand with cement (Abdulla and Kiousis, 1997; Schnaid et al., 2001; Consoli et al., 2007; Consoli et al., 2010; Consoli et al., 2012), reinforcing sand with fibres (McGown et al., 1978; Gray and Ohashi, 1983; Maher and Gray, 1990; Ranjan et al., 1994; Ranjan et al., 1996; Santoni et al., 2001; Shukla et al., 2010; Li and Zornberg, 2013; Nataraj and McManis, 1997; Consoli et al., 2002; Chandra et al., 2008; Tingle et al., 2002; Foose et al., 1996; Edincliler and Cagatay, 2013; Al-Refeai and Al-Suhaibani, 1998; Attom, 2006; Edincliler and Ayhan, 2010;), or the combination of these (Consoli et al., 1998; Consoli et al., 2002; Kalantari et al., 2012; Mousavi and Wong, 2015). However, it seems that more investigation is required since the behaviour of cement-stabilised sand reinforced with tyre fragments has not been investigated comprehensively before. In order to develop an overview, and to find the gap in the literature review and possible limitations of the research area, previous notable studies and efforts have been comprehensively and critically reviewed to define the research problems.

1.4 Objectives and scope of the present work

The Perth region in WA is generally surrounded by sandy soils (Stephenson and Hepburn, 1955), and these vastly available materials can be utilised in civil projects. For example, crushed rock combined with 2% general purpose (GP) cement is used for constructing base course layers for highways in WA (Main Road WA, 2012). This means extra costs for transporting crushed rocks to construction sites where large amounts of sand are present. Therefore, using sand as widely accessible materials for pavement layers, would be cost-effective.

Approximately 1.8 million tyres were sold in 2005 in Western Australia (WA), and this number is increasing every year (Andrich, 2005). Occupying a considerable amount of valuable apace in landfill sites, these waste tyres are causing a growing need for new landfill sites. In addition, waste tyres can lead to severe environmental problems such as sea pollution and fires that result in emission of toxics (Fig.1.3). Consequently, it is both economically and environmentally advantageous to use waste tyres in some applications such as civil engineering, which can be an effective approach to solve the problems associated with waste tyre disposal.

Fig. 1.3. Waste tyres causing environmental problems (Discard Studies, 2011)

This research will contribute at finding a method to use the waste tyre fibres with Perth sand in geotechnical applications such as pavement layers. In order to find economic and ecologically friendly methods, considering the problems stated in the previous sub-section, the objectives of this study are as follows:

- Finding Perth sand characteristics, namely particle-size analysis, specific gravity and compaction parameters
- Investigating the effect of adding tyre chips on *CBR* values of Perth sand
- Assessing the effect of adding cement on *CBR* values of Perth sand
- Evaluating the effect of adding tyre chips together with cement on different *CBR* values of Perth sand
- Checking the feasibility of using the proposed method and its compliance with the standards
- Proposing analytical and numerical solutions
- Comparing test results with proposed analytical and numerical solutions to check their conformity

1.5 Publications Based on the Present Work

1. Bazazorde, S.M.A., Shukla, S.K., and Vu, H., (2018). Compaction and Strength Behaviour of Perth Sandy Soil Reinforced with Waste Tyre Fibres and Cement. *Journal of Materials in Civil Engineering, ASCE* (under preparation).

2. Bazazorde, S.M.A., Shukla, S.K., and Vu, H., (2018). CBR Behaviour of Perth Sandy Soil Reinforced with Waste Tyre Fibres and Cement. *Journal of Materials in Civil Engineering, ASCE* (under preparation).

1.6 Organisation of the Present Work

In this chapter (Chapter 1), the research area is introduced and basic information of the concerned subject is described. A critical review of the previous studies on cement stabilisation and soil reinforcement is presented in Chapter 2. Chapter 3 describes the characteristics of the materials used in this study, along with the methodology of the study. In Chapters 4 and 5, the compaction tests and unconfined compression tests, respectively, conducted on different mixtures of sand, tyre fibres and cement, and the results and comprehensive discussion are presented. Chapter 6 describes the CBR tests conducted on sandy soil and different mixtures of tyre fibre-reinforced soil together with the results and discussion. The summary of the conducted work in the thesis and the conclusions and further research problems are presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The Perth region in Western Australia has different soil types. According to Stephenson and Hepburn (1955), four basic types of soil, namely gravel, sand, silt and clay, occur in the metropolitan region of Perth and Fremantle cities of WA. However, the majority of the soils are sandy. Fig. 2.1 illustrates the distribution of soil types in Perth and its surrounding areas. It is noticed that most parts of the region are marked grey as deep grey sands, dark yellow as excessively drained deep yellowish sand or light yellow as well-drained brownish sands of variable depth overlying coastal limestone. Thus, it can be stated that most areas are covered by sand differing in colours.

According to McPherson and Jones (2005), having already developed a regolith thickness map for the Perth study area based on the initial 604 explained perforations, the categorized regolith data was used to cross-check the thicknesses and assess the spatial distribution of the prevailing regolith material types.

Sands and calcareous deposits (limestone and secondarily cemented calcareous sands) are the regolith materials of the Swan Coastal Plain, with areas in the east closer to the Darling Range characterised by significant deposits of mud (silts and clays) (Tables 2.1, 2.2a and 2.2b). Given the general dominance of these broad regolith material types across the Perth study area, classification of bore records on the basis of material dominance within each profile was undertaken to refine this distribution (McPherson and Jones, 2005).

This chapter demonstrates previous studies relating to improving the engineering characteristics of sandy soils using cement and/or waste tyre fibres.

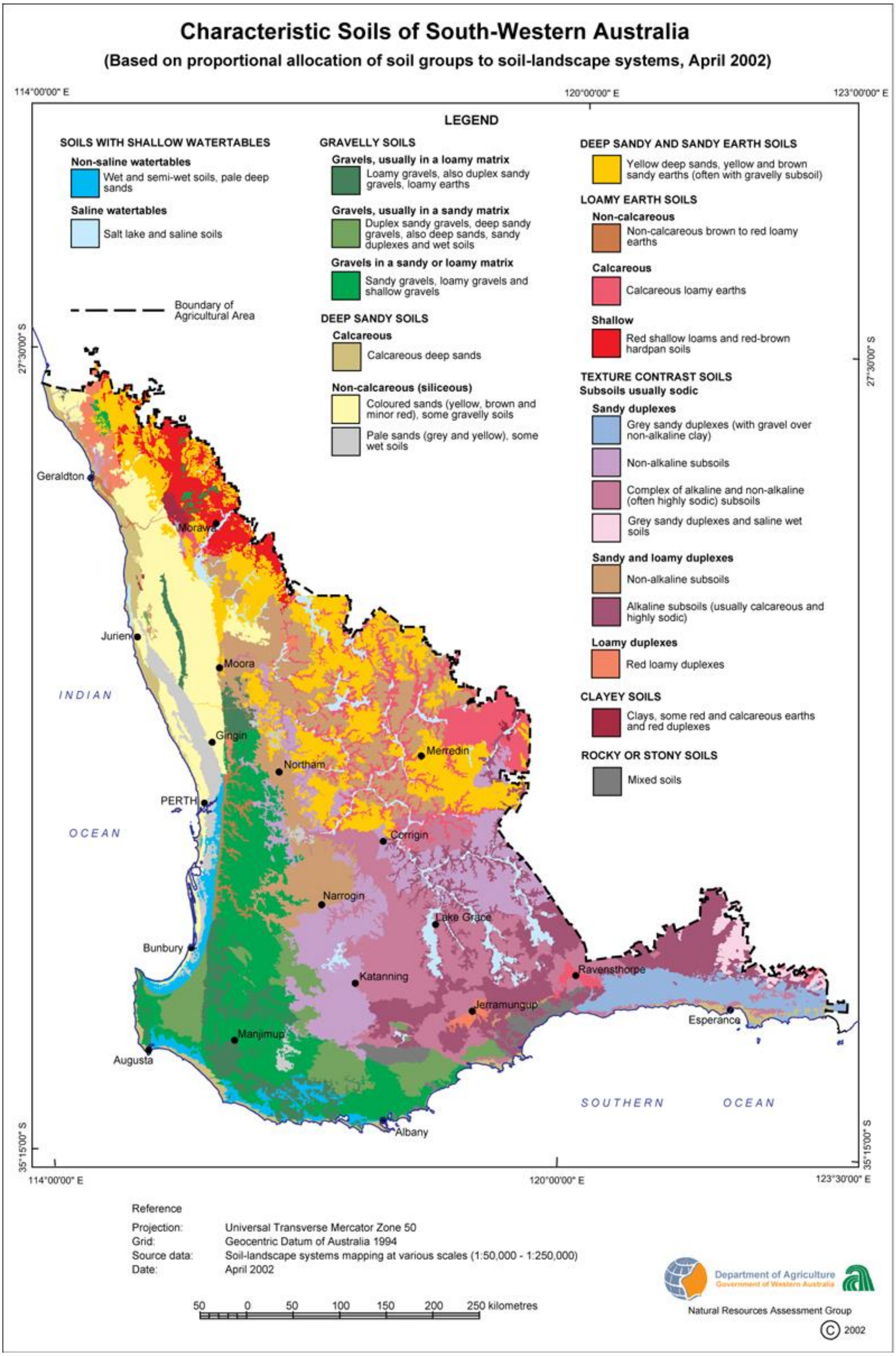


Fig. 2.1. Soil types distribution in Perth and its surrounding areas (after DOA, 2002)

Table 2.1. Summary of simplified regolith classes, dominant materials and number of records attributable to each class from the Perth study (McPherson and Jones, 2005)

Material class	Identifier	Description	No. of records	% of records
Not logged	0	No record for the materials in the specified depth range.	54	0.5
Sand	1	Sand; silty sand; gravel; other coarse unconsolidated materials.	7696	63.1
Mud	2	Silt; sandy silt; clay; sandy clay; mud.	1611	13.2
Limestone	3	Limestone and any materials indurated by calcareous cements, including secondarily cemented calcareous sands.	2030	16.6
Consolidated	4	Materials indurated by non-calcareous cements such as secondarily silicified sands; iron-oxide indurated materials (ferricrete); bedrock.	554	4.5
Coffee rock	5	Generally sands (occasionally muds) partly or completely indurated by organic complexes and iron-oxides.	203	1.6
Other	6	Rubble, fill and construction materials; refuse; organic matter (e.g. peat); other 'items' from the drillers logs not readily attributable to any other material class (e.g. slime, soup, seaweed).	55	0.5

Table 2.2. Regolith materials - (a) > 50% and (b) > 75% of total hole depth for the 2717 logged profiles in the Perth study area (McPherson and Jones, 2005)

(a)

Dominant material	Profiles of 50% of material	% of profiles	Material thickness (m)		
			Minimum	Maximum	Average
Limestone	464	53	5	87	35
Mud	227	30	1	45	18
Sand	1931	73	1	201	24
TOTAL	**2622**	**96.5**			

(b)

Dominant material	Profiles of 50% of material	% of profiles	Material thickness (m)		
			Minimum	Maximum	Average
Limestone	230	26	5	87	36
Mud	81	11	1	45	19
Sand	1580	60	1	78	23
TOTAL	**1891**	**69.5**			

2.2 Cement stabilisation

Since 1950s, the changes in the engineering behaviour of soil by adding cement have been under investigation and the findings have been published in detail in different references and are widely available nowadays. In order to prevent the repetition of known findings and focusing on the new ones, this section will present some of the most significant recent studies.

According to Consoli et al. (2010) different parameters that affected the UCS and the splitting tensile strength (q_t) of a sand treated with cement have been investigated by performing unconfined compression and splitting tensile tests and measuring the matric suction. They collected nonplastic sand from the region of Porto Alegre in southern Brazil, and with the following properties: $G_s = 2.65, C_u = 1.9, C_c = 1.2, D_{50} = 0.16mm, e_{max} = 0.9$ and $e_{min} = 0.6$. Specimens were mixed with cement content of 1, 2, 3, 5, 7, 9 and 12 % (by weight) of a type III Portland cement and 0.64, 0.7 and 0.78 void ratios, then compacted in the cylindrical mould with 50 mm diameter and 100 mm height. Specimens were cured for 7 days. Based on the results, they reported that compressive and tensile strength of the samples were improved by decreasing the porosity. They also reported that UCS and q_t of a cemented sand were related to cement content having a power function. In addition, it was perceived that UCS and q_t were decreased when the ratio of voids/cement increased.

According to Szymkiewicz et al. (2012) different parameters, including particle-size distribution, the content of cement and affecting the strength of cemented sandy soils were investigated by performed unconfined compression tests on six granular soils mixed with cement. The soils, according to the USCS, were SP, with a $D_{50} = 0.21$ mm and uniform gradation; SP, with a $D_{50} = 0.32$ mm and widely spread gradation; SW, with a $D_{50} = 0.39$ mm and widely spread gradation and ML, with a $D_{50} = 0.022$ mm and widely spread gradation. They stated two types of soil were used namely: SF50-SilicaF50 and SF75-SilicaF25 comprising 50 and 75% of the first SP soil and 50 and 25% of the SM soil respectively. A Portland blast-furnace cement was used as the cementing agent with a wide content range of 4.2, 8.4, 12.7, 16, 19.4 and 24.2% (by weight). Specimens were prepared in a cylindrical mould with the diameter of 52 mm and were cured for 7, 14, 21, 28, 56 and 90 days. Based on the results, Szymkiewicz et al. (2012) reported that maximum strength of a sand mixed with cement is always twice the compression strength after 7 days of curing (q_{u7}) or more. In addition, one of the key parameters for strength improvement after the seventh day was cement content. High cement contents (more than 15%) neutralised the effect of particles having a well-graded distribution and resulted in less improvement in strengths achieved after the seventh day.

Singh and Kalita (2013) investigated California bearing ratio on specimens of untreated soil, fly ash, soil-fly ash mixes, and cement treated soil mixes in both unsoaked and soaked conditions. Two type of soils were used in the study: a fine grained residual lateritic soil and granular riverbank sand. The lateritic soil was sample from a nearby hilly area. The sand was collected from the bank deposits of the nearby Brahmaputra River. This sand is classified as SP (poorly graded fine sand). Cement addition was varied up to 3% of the dry weight of the soil. The addition of cement increased the CBR continuously for both the soil mixes for example addition of 2% cement to the sand caused the CBR to increase from 11.0 to 27.4. This is because hydration of cement forms calcium silicate hydrate gel which binds the soil particles and contributes to the development of strength.

2.3 Soil reinforcement

Soil reinforcement, as a technique to improve the strength and stiffness of in situ soil, is widely used to stabilize artificial slopes, retaining walls, and embankments. Through inclusion of fibres, geosynthetics, or soil nails into the soil mass, the stability of geostructures can be significantly enhanced. The interaction between the soil and the reinforcement is a key factor affecting the performance of reinforced soil structures (Zhang et al., 2014). Fig. 2.2 illustrates the mechanism of reinforcement, which works by the mobilisation of tensile forces in the reinforcing agent and accordingly, improving the soil characteristics (Gray and Ohashi, 1983).

Shukla et al. (2009) classified soil reinforcement into two basic groups: systematically reinforced soils, and randomly distributed fibre-reinforced soils. The first group refers to soil reinforcement using geosynthetic sheets or galvanised steel strips oriented deliberately. The second group refers to soil reinforcement by adding and mixing discrete fibres, either natural or synthetic, with soil, a process in which the fibres will be oriented randomly. However, recently, more attention has been paid to randomly distributed fibre-reinforced soils due to its benefits such as simple preparation and offering strength isotropy and limiting potential planes of weakness in comparison to the former group.

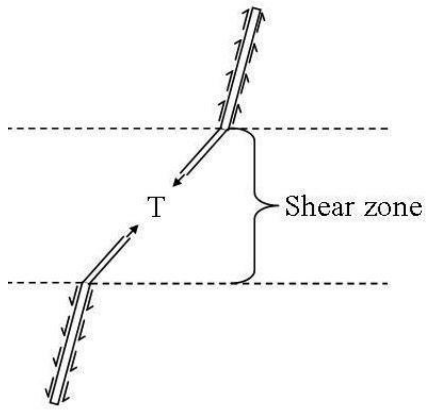


Fig. 2.2. Mechanism of soil reinforcement (after Gray and Ohashi, 1983)

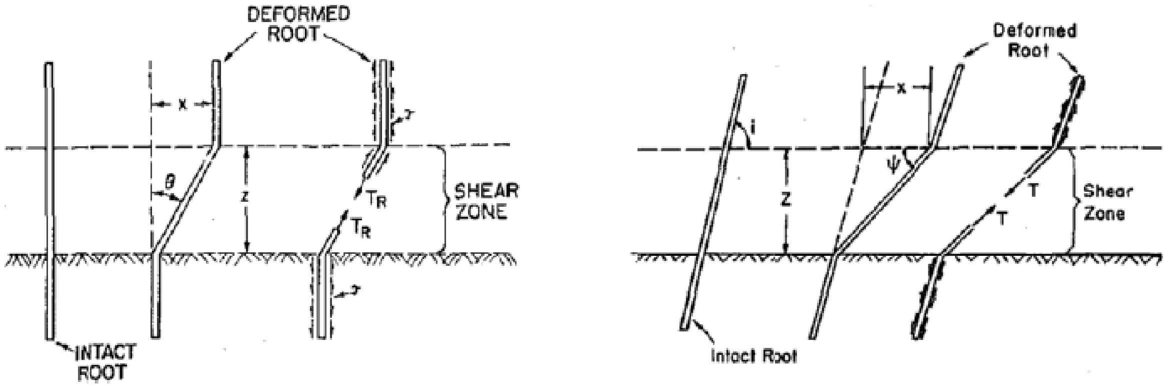
2.4 Fibre reinforcement

Reinforcement of soil with fibres is possibly one of the most effective technique for increasing soil strength. There has been a great deal of research on reinforcing soil with fibres in the past. Here, some of the most notable studies are discussed.

According to Zhange et al., (2014) conventional reinforcement materials in geotechnical engineering come with certain shortcomings. For instance, steel bar reinforcements have a risk of corrosion in aggressive soil environments. Geosynthetics, normally made of polymeric materials, are also found to deteriorate over time (Sawicki and Kazimierowicz-Frankowska, 1998). Fibre-reinforced polymer (FRP) materials, with several advantages over conventional materials, are able to address these problems. Glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) are two commonly used FRP materials for construction. Compared with steel, FRP materials enjoy a number of benefits, such as better corrosion resistance, lighter weight, easier site manoeuvring, and the ability to maintain similar or even better material strengths (Zhang et al., 2014).

Frost and Han (1999) found in their experiments that the FRP-sand interface behaviour is influenced by a number of factors, such as the interface surface roughness, mean grain size of granular materials, and normal stress.

Gray and Ohashi (1983) used a simple model in addition to performing direct shear tests to evaluate the behaviour of sand by adding fibres. The theoretical model was according to the force limiting equilibrium derived from Figure 2.3. A dry sand, collected from a beach in Muskegon, Michigan, was used with 20% and 100% relative densities and the following properties: $D_{50} = 0.23$ mm, C_u = 1.5, $e_{max} = 0.73$ and $e_{min} = 0.5$. Four types of fibres including reed, plastic (PVC), palmyra and copper (wire) fibres with lengths between 2 and 25 cm and diameters of 1-2 mm were used for tests. Fibres were intentionally oriented and were used with area ratios (fibre section area to shear plane area) of 0.25-1.67%. Vertical confining stresses of up to 144 kN/m^2 were applied for the strain controlled test. The test results and the predictions based on the model matched properly. Gray and Ohashi (1983) inferred that fibres improved the maximum shear strength and reduced the strength decrease after failure, and it was almost the same for loose and dense sand; however, with larger shear strains for loose sands. In addition, more length and area ratios of fibres led to more improvement of shear strength. It was observed that the maximum improvement belonged to the fibre inclusion with the initial angle of 60° with respect to the shear plane. A pull-out of fibres was also noticed below a specific vertical confining stress.



(a) (b)

Fig. 2.3. Fibre reinforcement: (a) perpendicular orientation to shear surface; (b) fibre oriented at angle (i) to shear surface (Gray and Ohashi, 1983; Shukla, 2017)

According to Nataraj and McManis (1997), California Bearing Ratio tests were conducted on reinforced and unreinforced clay specimens at maximum dry densities and moisture contents. The preliminary test results for specimens with various fibre contents are shown in Fig. 2.4. The CBR value of 8.44 for the unreinforced clay specimen increases to approximately 12.6 for specimens with a 0.3% fibre content. This is a 48% increase in the CBR value for the unreinforced clay specimen.

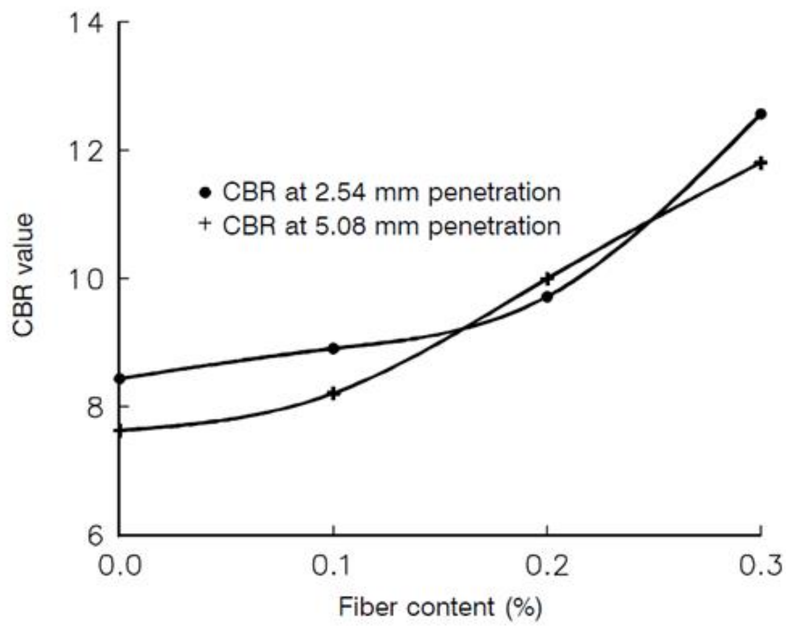


Fig. 2.4. California Bearing Ratio values for reinforced clay specimens with different fibre content (Nataraj and McManis, 1997)

Lawton and Fox (1992) demonstrated that sand reinforced with multioriented geosynthetics results in to the highest ultimate strength in terms of its CBR. Tingle et al. (2002) observed that geo-fibre stabilization of medium sand improves the CBR by about sixfold. This improvement was attributed to the confinement of sand particles by discrete fibres. Paradani et al., (2017) examined the CBR of the subgrade soil reinforced with coconut, jute, and nylon fibres at various percentages and reported an overall increase in CBR by 60%.

2.5 Waste tyres

Waste tyres are occupying a considerable amount of valuable space in landfill sites, resulting in severe environmental consequences and an increasing need for new landfill sites. So, using waste tyres in some applications such as civil engineering would be very advantageous. Therefore, in the recent years, since early 1990s, several researchers have been making attempts to find methods to use these mass-produced wastes that can be an efficient solution to waste tyre disposal problems. Some of the most important studies on utilising waste tyres in geotechnical applications are presented here.

According to Foose et al. (1996), direct shear tests were applied on a sand reinforced with waste tyre shreds to realise whether tyre shreds could be used as a reinforcement material for sand. They also used the model presented by Maher and Gray (1990) to calculate the shear strength of sand reinforced with tyre shreds. The sand, called Portage sand, had particle sizes of 0.2-0.8 mm and the following specifications: $G_s = 2.68$, $C_u = 1$ and $C_c = 1$. Waste tyre shreds they were used with lengths of less than 5 cm (named 5-cm shreds), 5 to 10 cm (named 10-cm shreds) and between 10 to 15 cm (named 15-cm shreds) and with contents of 0, 10, 20 and 30% (by volume of specimens). Samples were prepared in a shear ring of 6.35 mm diameter with sand specific weight of 14.7, 15.7 and 16.8 kN/m^3 and normal pressures of 7-70 kPa were applied during the tests. Foose et al. (1996) reported that inclusion of tyre shreds improved the shear strength of sand, and normal stress, tyre shred content and sand specific weight controlled the shear strength of sand reinforced with shredded tyres. In addition, mixtures with sand specific weight of 16.8 kN/m^3 presented a non-linear strength envelope, while the other two mixtures had almost a linear strength envelope.

The feasibility of reinforcing sand with strips of high-density polyethylene (HDPE) was investigated by Benson and Khire (1994). They suggested that strips cut from reclaimed HDPE might prove useful as soil reinforcement in highway and light-duty geotechnical applications. Al-Refeai and Al-Suhaibani (1998) reported that the inclusion of fibres increased the CBR values of dune sand, and the improvement in the CBR values was maintained over a larger penetration range than with unreinforced sand. The researches of Benson and Khire (1994) and Al-Refeai and Al-Suhaibani (1998) show that adding fibres to the sand will increase the bearing capacity of the soil.

Edincliler and Ayhan (2010) studied the sand shear strength affected by adding tyre fibres. For their research, they conducted two series of direct shear tests including standard and large-scale tests. A uniform and well-graded sand with a $G_s = 2.74$ was used, and two types of waste tyre reinforcement were used namely: tyre crumbs (TC), which were granular, and tyre buffing (TB), which were fibre-shaped. The TCs had particle sizes of 1-3 mm with the aspect ratio of 1, and the TBs were divided into two groups of TB1 and TB2. The length, thickness and aspect ratio range for the TB1 group were 8-10 mm, 2-4 mm and 2-5 respectively. The ranges, in the same order, were 10-50 mm, 4-5 mm and 2-12.5 for the TB2 group. First, sand with different TC contents of 0, 15, 25, 40, 50, 75 and 100% were tested by conducting standard direct shear tests with the normal pressures of 25, 50 and 100 kPa. These tests were done to have an idea of the optimum tyre content for shear strength improvement to use in the second direct shear test series in which a large-scale device was used. In the 300 mm by 300 mm test cell, sand with TC, TB1 and TB2 (separately) were tested with tyre contents of 0, 10, 20, 30 and 100% under 20, 40 and 80 kPa normal pressures. The test results indicated that mixing waste tyre reinforcements with sand increased its shear strength. In addition, shear strength improved with the increase of normal pressures and length and aspect ratio of the inclusions.

According to Edincliler and Cagatay (2013), the addition of buffing rubber increased the CBR value of the mixture, but the addition of granulated rubber decreased it. The addition to sand of 30% buffing rubber by weight having an aspect ratio of 8 increased the CBR value from 8 to 16, which is a 100% increase, and the addition of buffing rubbers having an aspect ratio of 4 resulted in a 44% increase, increasing the CBR value from 8 to almost 12. The use of buffing rubbers with a higher aspect ratio resulted in a higher CBR value in all of the experiments.

2.6 Fibre reinforcement and cement stabilisation

The behaviour of unreinforced, fibre reinforced and cemented sands has been widely investigated and reported in many research works (Shukla, 2017). The most important studies on combinations of reinforcing soil with fibres and stabilising it with cement are presented here.

Park (2011) investigated the unconfined compressive strength (UCS) and ductility of a cemented sand reinforced with polyvinyl alcohol (PVA) fibres. The fibres were 12 mm long and 0.1 mm thick. The cement was standard Portland cement and the soil was a poorly graded sand (SP) according to the USCS, sampled from Nakdong river in South Korea, with the following specification: $D_{50} = 0.28$ mm, $C_u = 1.75$, $G_s = 2.65$. Cement was used in three different contents of 2, 4 and 6% (by weight of soil) and fibres in contents of 0, 0.3, 0.6 and 1% (by weight of soil). After mixing soil, cement and water, the blend was divided into five portions, each of which was mixed manually and randomly with the specified fibre content. The materials then were compacted in five equal layers, and the 70 mm in diameter by 140 mm in height samples were cured for 7 days. From the results, it was noticed that UCS at maximum strength was significantly influenced by adding the fibres. In the specimens with 2% cement ratio, the most enhancement of UCS was observed, to the extent that with 1% inclusion of fibre, *UCS* was increased 3.5 times.

Kutanaei and Choobbasti (2014) conducted compaction and unconfined compression tests on mixtures of sand, fibre and cement to investigate the changes in mechanical behaviours. They used an SP sand (as per the USCS), collected from the coastal area of Caspian Sea in Babolsar, north of Iran, with the following properties: $G_s = 2.78$, $C_u = 2.13$, $C_c = 1.32$, $D_{50} = 0.22$ mm, $e_{max} = 0.8$ and $e_{min} = 0.53$. Polyvinyl alcohol fibres were used having lengths of 12 mm and diameters of 0.1 mm. For the standard compaction tests, cement contents were 0, 2, 4, and 6% (by weight), and fibre contents were 0, 0.3, 0.6 and 1% (by weight). For the unconfined compression tests, specimens had a diameter of 38 mm, a height of 83 mm, cement contents of 0.5 and 6% and fibre contents of 0, 0.3, 0.6 and 1%, and the load was applied with a rate of 1 mm/min. The test results indicated adding cement increases the maximum dry density and decreases the optimum water content, while addition of fibre resulted in a reduction in both parameters. Furthermore, UCS and modulus of elasticity, and consequently, the brittle behaviour, were notably increased by adding cement. Conversely, adding fibres to the cement-treated sand caused an increase in UCS but a decrease in the modulus of elasticity, and accordingly, caused a more ductile behaviour.

According to Kalantari et al. (2012), peat samples stabilized with cement with/without fibres were tested for unconfined compressive strength (UCS) and California bearing ratio (CBR). In order to evaluate the strength of peat stabilized with cement only, both UCS and CBR tests were carried out on undisturbed peat samples and also on peat stabilized with different amounts of cement. The amount of cement used for the UCS test was 5 and 15%, and for the CBR test it was 5, 10, 15, 20, 30 and 50% by weight of peat weighed at its optimum moisture content. The amount of fibre to be used was decided based on the results of CBR test. Fig.2.5 shows the results of the CBR tests carried out on peat stabilized with 5, 15 and 25% cement and 0.1, 0.15, 0.2 and 0.5% fibre and air curing the samples for 90 days. The results show that fibre content of 0.15% gives the highest CBR values.

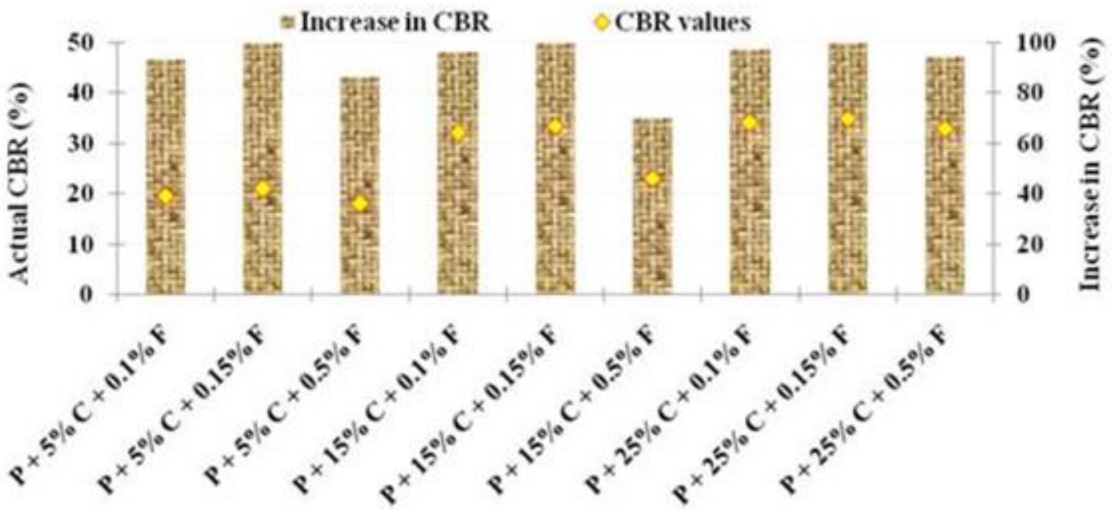


Fig. 2.5. Precent increase and actual CBR vs. amount of cement and fibre (Kalantari *et al*., 2012)

Based on the results, they indicate that as the curing period increases, the CBR values increase as well. With the increase in cement content from 0 to 50%, the CBR values are also increasing. Further, an addition of 0.15% fibres to the cement stabilized peat samples increases the CBR values over samples without fibres. The results show that the CBR increases from 0.8% for undisturbed peat to 145% for peat stabilized with 50% cement and 0.15% fibre. This increase in CBR values can be attributed to the OMC at which the samples were compacted and to the cement and fibres for increasing the strength of the samples. It is observed that the cement (15%) and fibre (0.15%) increased significantly the UCS and CBR values by a factor 13.5 and 79, respectively and hence, it is obvious that fibres can be used to increase the strength of peat. It appears that the randomly distributed fibres limit the potential planes of weaknesses and also prevent the formation and the development of the cracks upon loading and thus increasing the UCS and CBR. Cement and fibres can be used effectively to improve the strength of base course for the pavement construction (Kalantari et al., 2012).

According to Mousavi and Wong (2015), the effect of stabilization of soft clay at optimum moisture content and maximum dry density with cement and kaolin on CBR value is shown in Fig.2.6. The results of laboratory investigation indicate an increase in the shear strength, CBR value and unconfined compressive strength of the treated soil with binder composition of OPC (Ordinary Portland Cement) 8%, K (Kaolin) 2% and SS (Silica Sand) 5%. Besides, it was proven that engineering characteristics of stabilized soil with binder composition of OPC 8%, K 2% and SS 5% are superior to those stabilized with lower percentages (i.e., less than 2%) of kaolin. As for the CBR value, it was found that the CBR value of stabilized clay increased slightly in comparison with the CBR of untreated soil specimen.

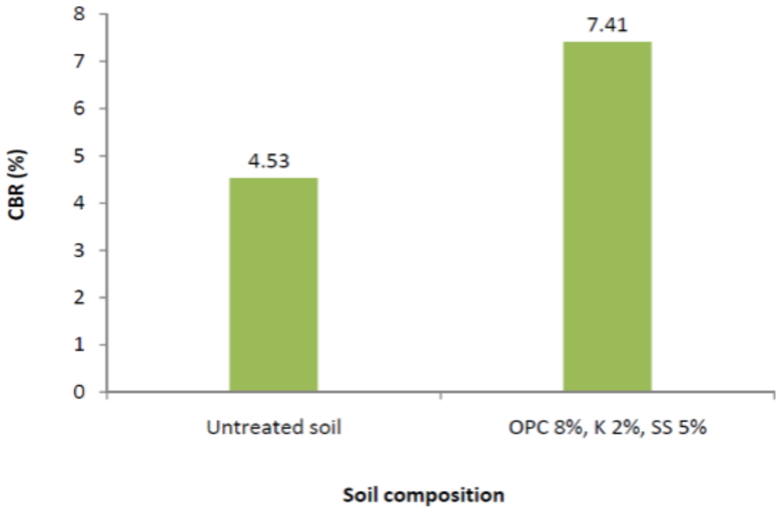


Fig. 2.6. Effect of stabilization on CBR of the soil (Mousavi and Wong, 2015)

2.7 Conclusions

According to the literature review, engineering behaviour of sandy soil mixed with cement, fibres or their combination has been evaluated in previous research works. Moreover, the effect of shredded waste tyre inclusion in sandy soil has been investigated in different aspects. Different characteristics of sandy soil have been improved by adding cement, fibres and both cement and fibres, as research works have presented. Therefore, it is expected that there will be improvement in the engineering behaviour of sandy soils stabilised with cement and reinforced with tyre fibres, and that has to be investigated. So, consideration of engineering behaviour of sandy soil would be very important especially for Perth sandy soil as no comprehensive research works have been done so far.

CHAPTER 3

MATERIALS AND METHODS

3.1 General

This chapter contains the description of materials used in this study and their characteristics. In addition, the methodology of the research is also explained.

3.2 Materials and equipment

3.2.1 Soil

The soil used in this study is sandy soil that was obtained from a quarry in north of Perth in Western Australia. Geotechnical tests including sieve analysis test (Standards Australia, 2009), specific gravity test (Standards Australia, 2006) and relative density test (Standards Australia, 1998a) were conducted to specify the properties of the soil. As per the Unified Soil Classification System (USCS) and based on the test results, the soil was classified as poorly graded sand (SP) (ASTM, 2011). The properties of the soil are presented in Table 3.1, and the particle-size distribution is illustrated in Fig. 3.1 and Fig. 3.2.

Fig. 3.1. Materials used: tyre fibres; sandy soil

Table 3.1. Properties of Perth soil

Properties	Value
Liquid limit (%)	-
Plasticity index (%)	NP
Specific gravity of soil solids (G_s)	2.64
Mean particle diameter (D_{50}) (mm)	0.38
Coefficient of uniformity (C_u)	2.48
Coefficient of curvature (C_c)	1.18
Maximum void ratio (e_{max})	0.76
Minimum void ratio (e_{min})	0.45
Soil group as per the USCS	SP
Maximum dry unit weight (kN/m^3)	17.26
Optimum water content (%)	11.77

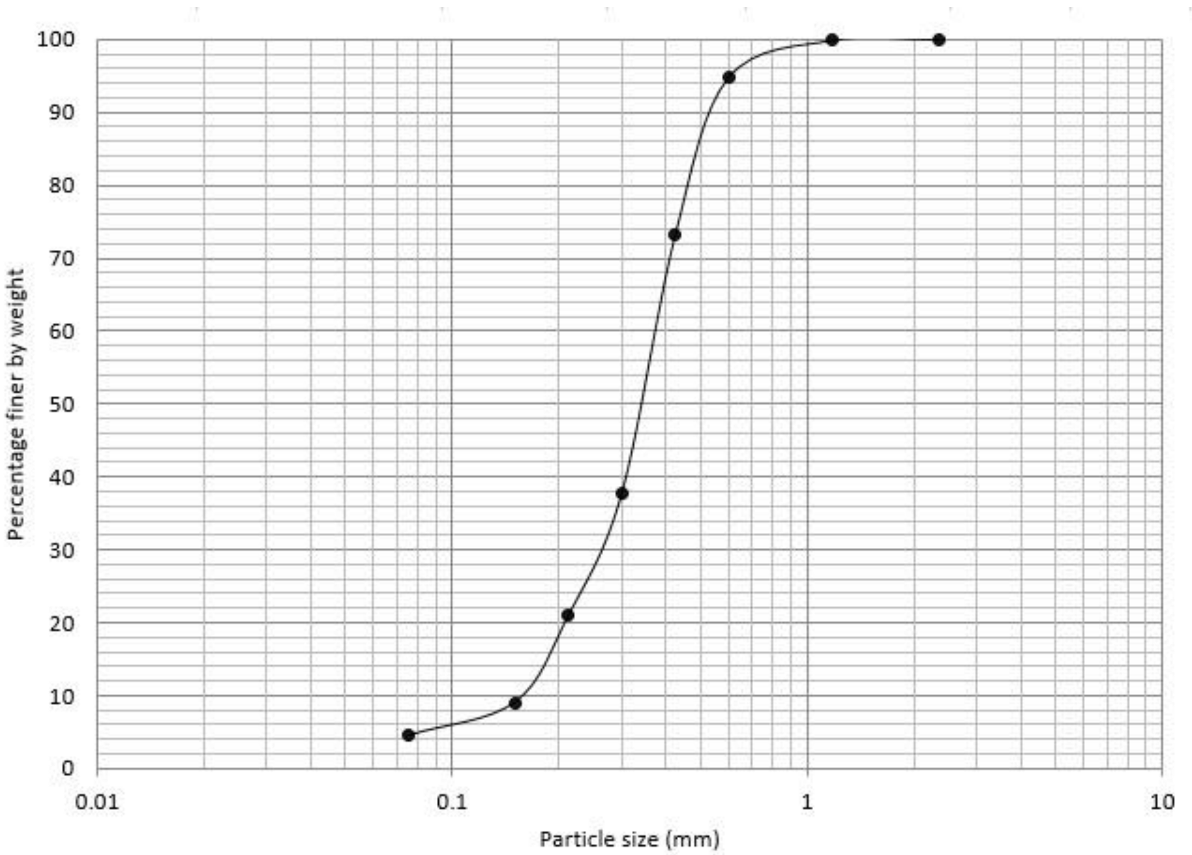


Fig. 3.2. Soil particle-size distribution curve

3.2.2 Cement

The general purpose (GP) cement (Standards Australia, 2010) was used in this study. It had the initial and final setting times of 135 and 195 minutes, respectively (Cockborn Cement, 2008).

3.2.3 Tyre fibres

The tyre fibres without any metal wire and thread have been selected from a local company in Perth. They have length rate 1 to 38 mm, G_s of 1.12 and water absorption of 0.8% as per

Standards Australia (2000). According to ASTM (2012), the fibres fall into the granulated rubber and tyre chips category and they are referred to as tyre fibre in this study. A specific ratio (the ratio of length to diameter) for tyre fibres could not be defined as tyre fibres had various length and diameters. However, Fig. 3.1 shows the tyre fibre used in this study.

3.3 Methodology

In order to analyse the effect of cement content and tyre fibres on the california bearing ratio (CBR), unconfined compressive strength (UCS) and compaction test value of sandy soil, the values were measured by changing cement content and tyre fibres and all the experimental results were illustrated by tables, figures and graphs for an easy understanding and critical discussion.

3.3.1 Mix design

The effect of different parameters such as cement content (p_c) and tyre fibre content (p_f) is one of the objectives of this study. Therefore, forty-two specimens for compaction test, seventy-eight specimens for UCS and thirteen specimens have been prepared containing of different p_c and p_f. The range of cement content (p_c) in soil are 0, 1, 3 and 5% based on dry mass of soil. It is defined as follows:

$$p_c(\%) = \frac{w_c}{w_s} \times 100 \quad (3.1)$$

where w_c = weight of cement, and w_s = weight of dried soil.

The range of cement content was selected in view of the fact that the Main Roads WA currently recommends the cement content of 2 ± 0.1% to produce the hydrated cement treated crushed rock base (HCTCRB) for pavement construction (Main Roads WA, 2012). In addition, although the cement has great benefits in terms of strength improvement, its production has environmental and economic concerns. Therefore, the use of cement should be controlled to be in low contents provided the project requirements permit.

According to Edincliler et al. (2012) having p_f of more than 5% in sand-waste tyre additive mixtures resulted in a reduction in the shear strength. In addition, the use of tyre derived aggregates with a content of less than 5% in soil has received limited attention. Therefore, in the present study, p_f in soil mixtures are 0, and 1% of the dry mass of soil. It is defined as follows:

$$p_f(\%) = \frac{w_f}{w_s} \times 100 \quad (3.2)$$

where w_f = weight of tyre fibres. Table 3.2 presents the several mixtures, with different compositions of soil, cement and tyre fibre, which were prepared for the experiments.

Table 3.2. Details of soil mixtures

Mixture	Cement content (%)	Tyre fibre (%)	Curing period (days)
Sand	0	0	0
Sand+Cement	1, 3, 5	0	0
Sand+Cement+Curing day	1, 3, 5	0	3, 7, 14, 28
Sand+Cement+Tyre fibre	1, 3, 5	1	0
Sand+Cement+Tyre fibre+Curing day	1, 3, 5	1	3, 7, 14, 28

3.3.2 Mixture preparation

To prepare the mixtures of soil with additives prior to compaction in moulds, a specific mass of oven-dried soil was taken, and then the required percentage of tyre fibre and/or cement, based on the dry mass of soil, was weighed and mixed with the soil. Cement was passed through a 1.18-mm sieve to remove probable existing lumps. For samples without cement, water was added to the mixture and mixed until a uniform mixture was obtained and then cured for a minimum of two hours in plastic bags as per AS 1289.5.1.1-2003 for compaction test (Standards Australia, 2003). Generally, any mixture having GP cement should be cured for 2-3 hours before compaction (Standards Australia, 2008); Therefore, for samples containing cement, after adding water, the mixture was mixed for ten minutes, kept cured in plastic bags for 165 minutes, and then mixed for about 5 minutes prior to compaction to eliminate the energy absorption of bonded particles due to initial setting of cement as recommended by West (1959).

3.3.3 Compaction test

Maximum dry unit weight ($\gamma_{d\max}$) and optimum water content (w_{opt}) have been investigated by standard compaction tests and the effect of adding cement and tyre fibres on these parameters also have been considered. The standard compaction tests were conducted as per the Australian standard AS 1289.5.1.1- 2003 (Standards Australia, 2003). The mould of 105 mm diameter and 115.5 mm height was used to compact the mixtures in three layers after preparing, curing and remixing them each layer was compacted by a rammer with 2.7 kg of mass and a drop height of 300 mm (Fig. 3.3).

Fig. 3.3. Compaction mould with compacted sample

3.3.4 Unconfined compression test

Unconfined compression tests were done on mixtures of soil, cement and/or tyre fibres to evaluate the change in strength and deformation characteristics of sandy soil. The tests were conducted following the guidelines of the Australian standard AS 5101.4-2008 (Standards Australia, 2008). The mould with 50 mm diameters and 100 mm height have been used to place the mixtures in for UCS tests (Fig. 3.4). Specimens have been prepared based on the $\gamma_{d\max}$ and w_{opt} of each mixtures result from the standard compaction tests. Although the size of mould has an effect on test results (Ahmed 1993; Edil and Bosscher 1994), and standards set a limitation for maximum particle size for specimen preparation, mould size effect was ignored for simplicity. Each mixture was included three specimens to be tested and average result has been calculated.

Fig. 3.4. The unconfined compression test equipment; the specimen with cement and tyre fibre content; automatic loading machine

3.3.5 California bearing ratio

The CBR test is mostly used in the assessment of granular materials in base, subbase and subgrade layers of road and airfield pavements. Although California bearing ratio (CBR) values have not commonly been used recently in mechanical design, they are good indicators of strength and bearing capacity of a subgrade soil, subbase, and base course material for use in road and airfield pavements. Owing to heavy traffic loads, base and subbase layers of pavement structures are subjected to large tensile stresses The tests were conducted following the guidelines of the Australian standard AS 1289.6.1.1:2014 (Standards Australia, 2014). After the mixtures were cured and remixed prior to specimen preparation, as described earlier, they were placed in a 152 mm by 178 mm split (Fig. 3.5).

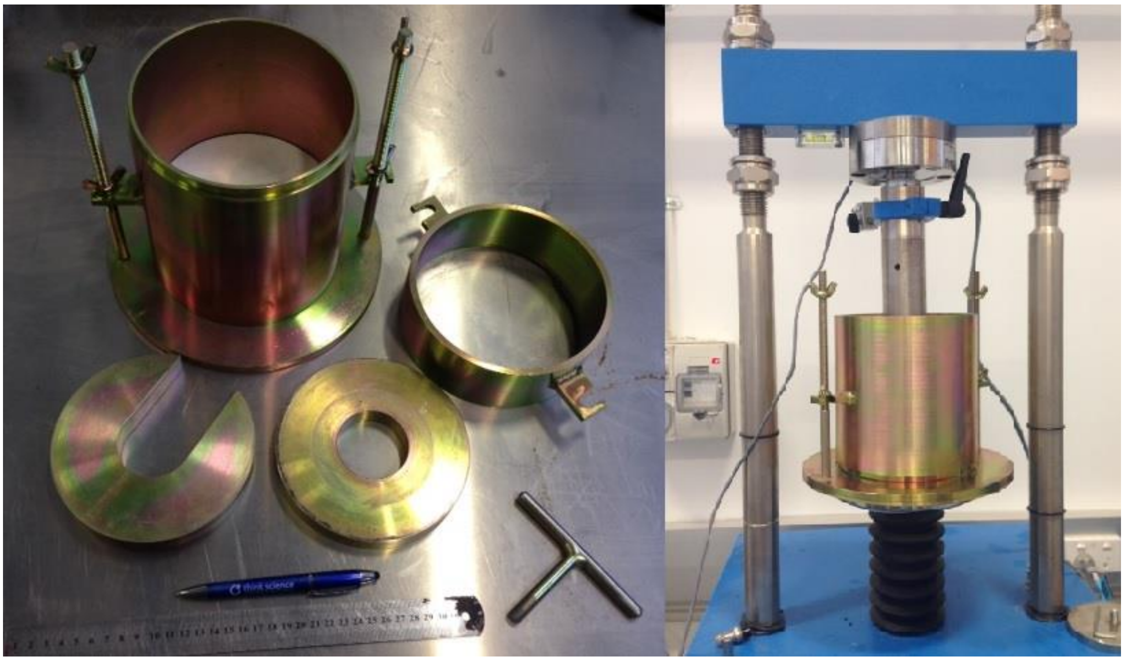


Fig.3.5. CBR equipment and loading machine

In order to improve the reproducibility of the test, the following apparatuses shall be used:

a) Cylindrical metal mould (Fig. 3.6) of known volume, with an internal diameter of 152±1 mm, height of 178±1 mm and wall thickness of at least 5 mm, provided with a metal extension collar and a perforated metal baseplate (Standards Australia, 2014).

b) Metal spacer disc (Fig. 3.7) of 150.0±0.5 mm diameter and 61.00±0.25 mm high, fitted with a removable handle for lifting the disc from the mould (Standards Australia, 2014).

c) Compaction apparatus, including the compaction block, complying with the requirements of AS 1289.5.1.1 or AS 1289.5.2.1, as applicable (Standards Australia, 2014).

d) Metal stem and perforated plate with a mass of 1000±25 g (Fig. 3.8) (Standards Australia, 2014).

e) Metal surcharges, each surcharge having a mass of 2250±25 g, a diameter of 150.0±0.5 mm and a centre hole od 55±1 mm diameter (Fig. 3.9). At least one surcharge shall be annular; the others may be annular or slotted (Standards Australia, 2014).

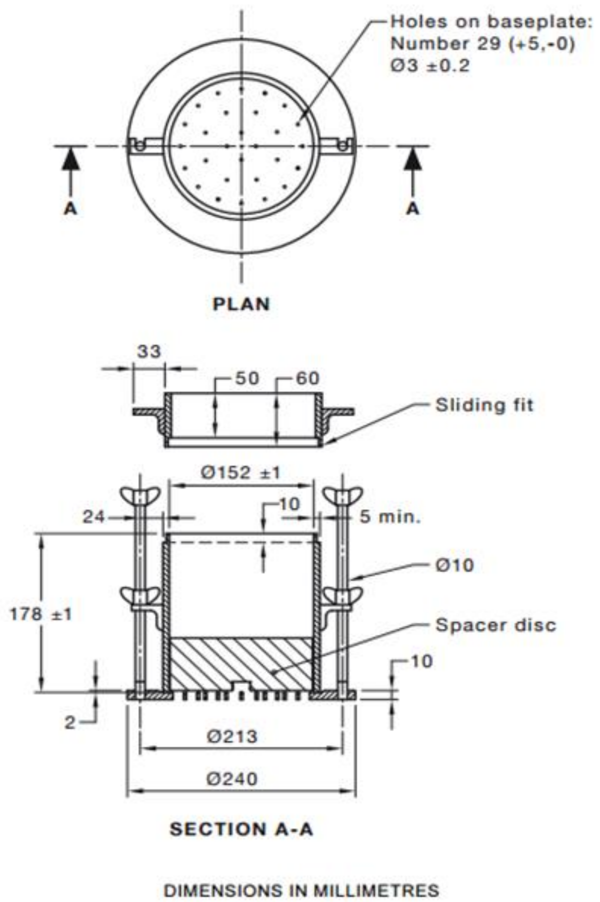


Fig. 3.6. Mould (Standards Australia, 2014)

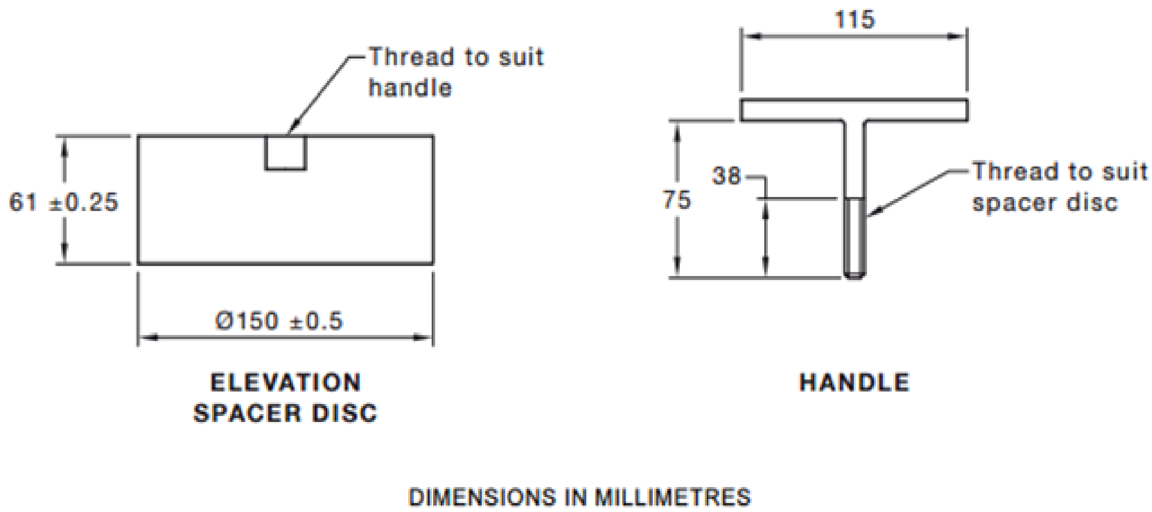


Fig. 3.7. Spacer disc and handle (Standards Australia, 2014)

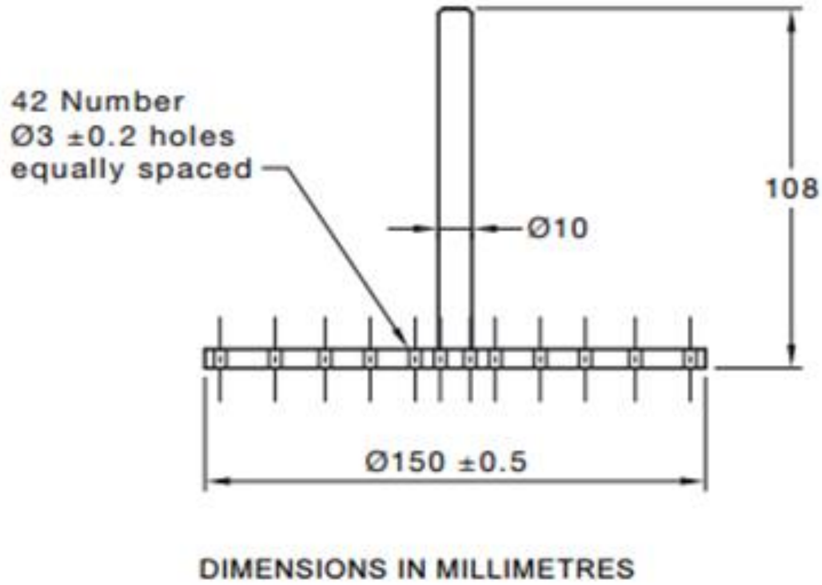


Fig. 3.8. Stem and plate (Standards Australia, 2014)

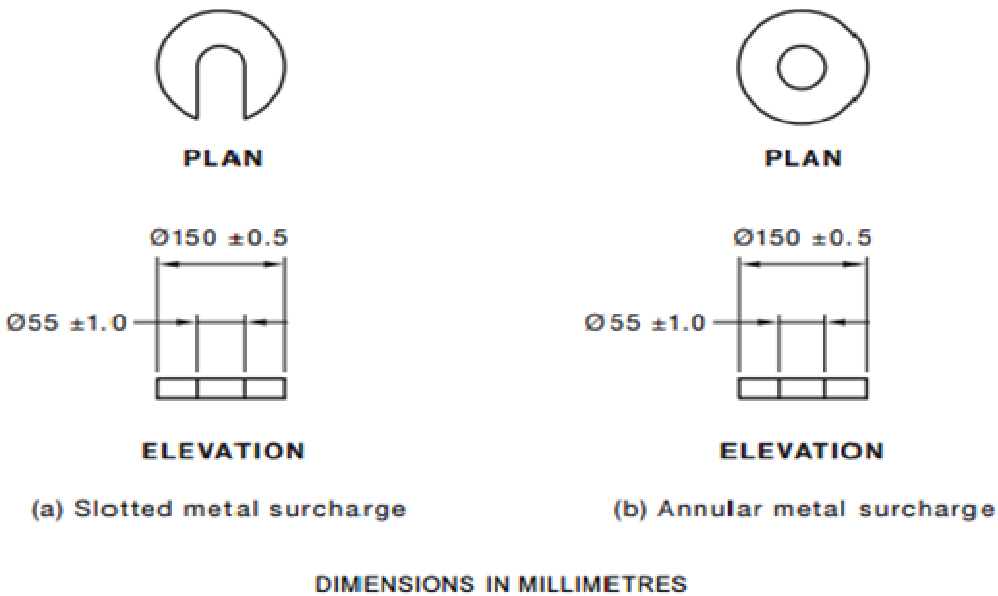


Fig. 3.9. Surcharges (Standards Australia, 2014)

The CBR test involves relatively slow penetration rates (1 mm/min) so that the load on the plunger is unlikely to be related directly to any dynamic properties of the soil, but is likely to be determined by static strength and stiffness. A further correlation-between dynamic and static stiffness-must also be inferred from the use of the CBR in pavement design (Hight and Stevens, 1982).

3.4 Conclusions

An experimental program was undertaken to investigate the changes in the engineering behaviour of a sandy soil being affected by inclusion of different amounts of cement and/or waste tyre fibre. The conducted tests were standard compaction, UCS, and CBR tests. The curing time for cemented samples was 3, 7, 14 and 28 days, and the applied force in CBR test were maximum 50 kN.

CHAPTER 4

COMPACTION BEHAVIOUR

4.1 General

Having the best performance of the material in field in terms of strength will require two essential parameters, the maximum dry unit weight ($\gamma_{d\max}$) and optimum water content (w_{opt}), which are resulted from standard/modified compaction test in geotechnical engineering. According to Consoli et al. (2011), one of the most significant parameters affecting the properties of cemented soil is the level of compaction. Moreover, other research works, such as Foose et al. (1996) and Attom (2006), indicated that unit weight of soil and tyre chip mixture had a significant effect on the shear strength of the mixture. Results of standards compaction tests on different mixtures of 0, 1, 3, and 5% of cement content (p_c) with or without 1% tyre fibre content (p_f) and the change in void ratio (e) and degree of saturation (S) are discussed in this chapter.

4.2 Compaction characteristics of sandy soil

Fig. 4.1 indicates that the compaction curve for Perth sandy soil indicating that $\gamma_{d\max}$ and w_{opt} are 17.26 kN/m3 and 11.77%, respectively. Fig. 4.2 shows the similar curves for several other mixtures to determine the $\gamma_{d\max}$ and w_{opt} of each mixture.

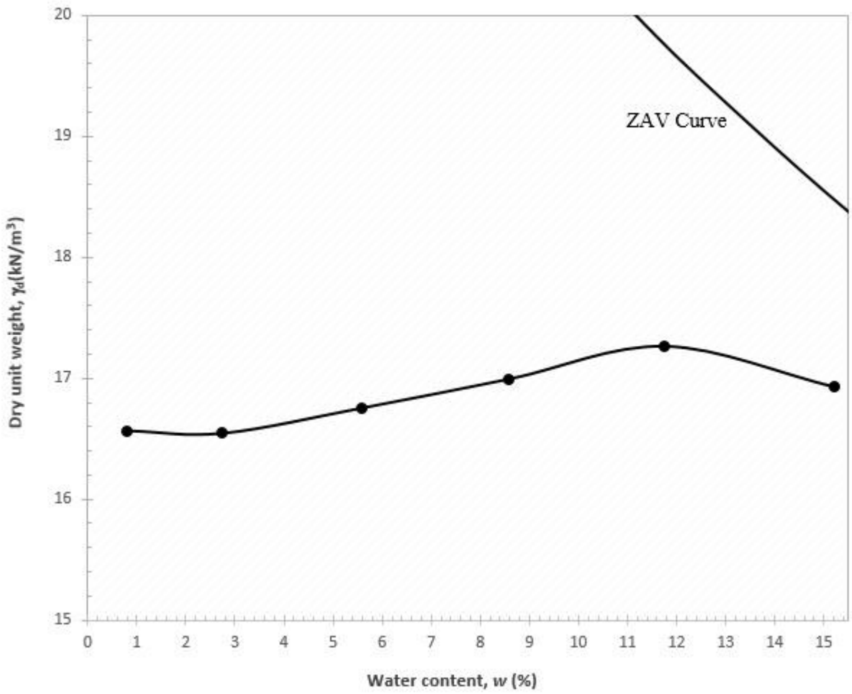


Fig. 4.1. Compaction and zero air void (ZAV) curves for Perth soil

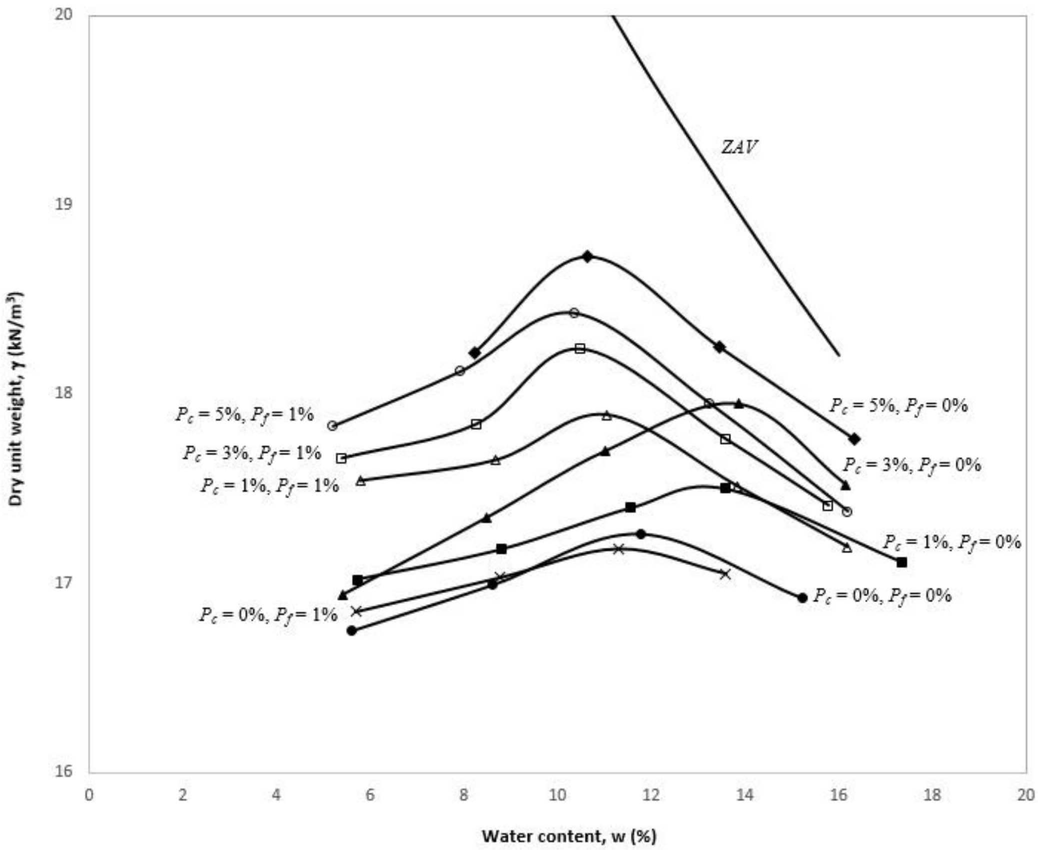


Fig. 4.2. Compaction and zero air void (ZAV) curves for Perth soil for p_c = 1, 3 and 5% and/or p_f = 1%

4.3 Effect of cement and tyre fibre on the compaction characteristics of the mixture

4.3.1 Maximum dry unit weight

The dry unit weight-moisture content relationship for different compaction efforts are presented in Fig. 4.2. These curves indicate that the increase in the compaction effort resulted in an increase in the maximum dry unit weight ($\gamma_{d\max}$) and a decrease in the optimum moisture content (w_{opt}).

Fig. 4.3 shows the gradual increase in dry unit weight values for the cemented soil specimens with cement rate 0, 1, 3, and 5%. The dry unit weight increases by adding 1% tyre fibres and 1, 3, and 5% cement to sandy soil. It is noticed from Fig. 4.3 that for $p_f = 1\%$, $\gamma_{d\max}$ increases with increasing p_c value, but there is much significant increase for $p_c = 1$ and 3%, whereas $\gamma_{d\max}$ slightly decrease with $p_c = 5\%$. This variation occurs because cement consists of much finer particles and has higher G_s than soil and tyre fibres, thus resulting in a dense mixture with cement occupying more voids initially, and then with higher content contributing more unit weight to the mixture due to higher G_s. In the past, a similar trend of variation was reported by some researchers in case of soil stabilised with cement (Al-Aghbari, 2009; Kutanaei and Choobbasti, 2014), and fines, up to specific amount, being added to soil and fine/coarse-grained soils (Deb et al., 2010; Isik and Ozden, 2013).

The decrease of $\gamma_{d\max}$ by adding shredded rubber tyre to sand, sand-cement mixtures, fly ash-lime-gypsum or claylime mixtures was reported earlier (Youwai and Bergado, 2003; Cabalar, 2011; Chan, 2012; Guleria and Dutta, 2012; Edincliler and Cagatay, 2013; Balunaini et al., 2014; Cabalar et al., 2014). This is mainly because G_s of the tyre fibre is less than that of soil and cement. Additionally, tyre fibres have the ability to absorb the compaction energy due to being flexible (Edil and Bosscher, 1994; Özkul and Baykal, 2006).

4.3.2 Optimum water content

Fig. 4.4 indicates the variation of optimum water content with cement content (p_c) varying from 0 to 5% with tyre fibre content (p_f) as 0 and 1%. It is observed that adding tyre fibres to soil generally causes a reduction in w_{opt}. A similar consideration was reported for addition of

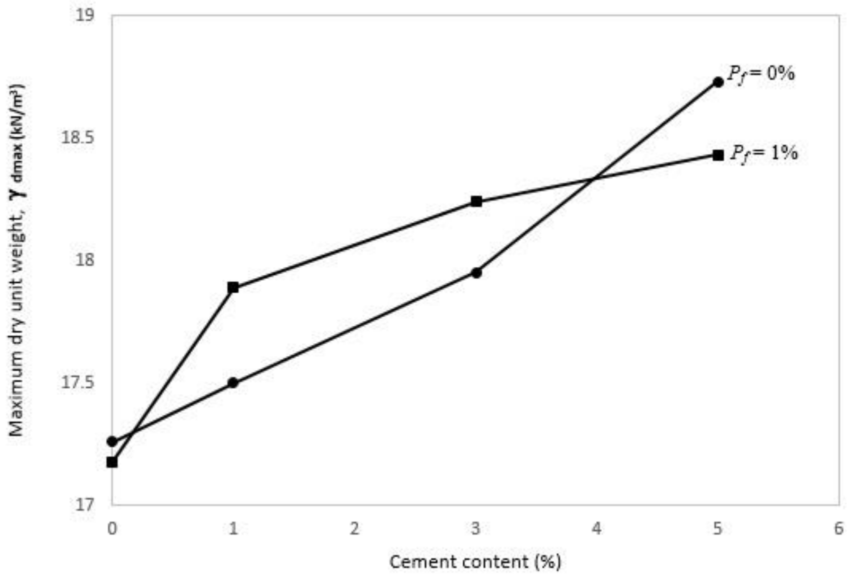


Fig. 4.3. Variation of maximum dry unit weight with different cement contents and fibre

tyre derived aggregates to clay and clay-lime mixtures (Özkul and Baykal, 2006; Kalkan, 2013; Cabalar *et al.*, 2014). However, it may be noted that as p_f increases to 1%, a decrease in w_{opt} takes place whereas the cemented specimens without tyre fibres shows slight increase in w_{opt} with 1 and 3% cement content and decrease in w_{opt} with 5% cement content. Similar results were observed earlier when polyvinyl alcohol fibres were added to sand (Kutanaei and Choobbasti, 2014. Al-Aghbari and Dutta, 2013. Al-Aghbari *et al.*, 2009. Dutta .R .K., 2011). When adding tyre fibres to sand, there are some factors such as water absorption, specific surface area and particle size of materials that tend to affect w_{opt}. Since tyre fibres have negligible water absorption (0.8%) and a large specific surface area, when they are added to sand, lower w_{opt} values are obtained (Kalkan, 2013). On the other hand, tyre fibres particles are generally larger than sand particles; therefore, adding tyre fibres to sand changes the gradation in a way that more voids are created to be occupied by water. These factors counteract each other and affect w_{opt} so that adding more tyre fibres make an insignificant change to w_{opt} for p_f =1%. Similar phenomenon was observed in compaction behaviour of sand-cement kiln dust (Baghdadi and Rahman, 1990), sand-incinerator ash (Mohamedzein et al. 2006), sand-plastic and non-plastic fines (Deb et al., 2010), lateritic soilfly ash (Singh and Goswami, 2012), increasing fines in different soils (Isik and Ozden, 2013) when additives were increased up to a specific amount, and sand-cement mixtures (Kutanaei and Choobbasti, 2014). The sand-cement-fibre mixtures show the same trend as cemented sand mixtures. However, initially,

w_{opt} increases with adding 1% and 3% cement due to the change in gradation caused by tyre fibre, and then with further addition of cement w_{opt} decreases because of the phenomenon explained for the cemented soil mixtures.

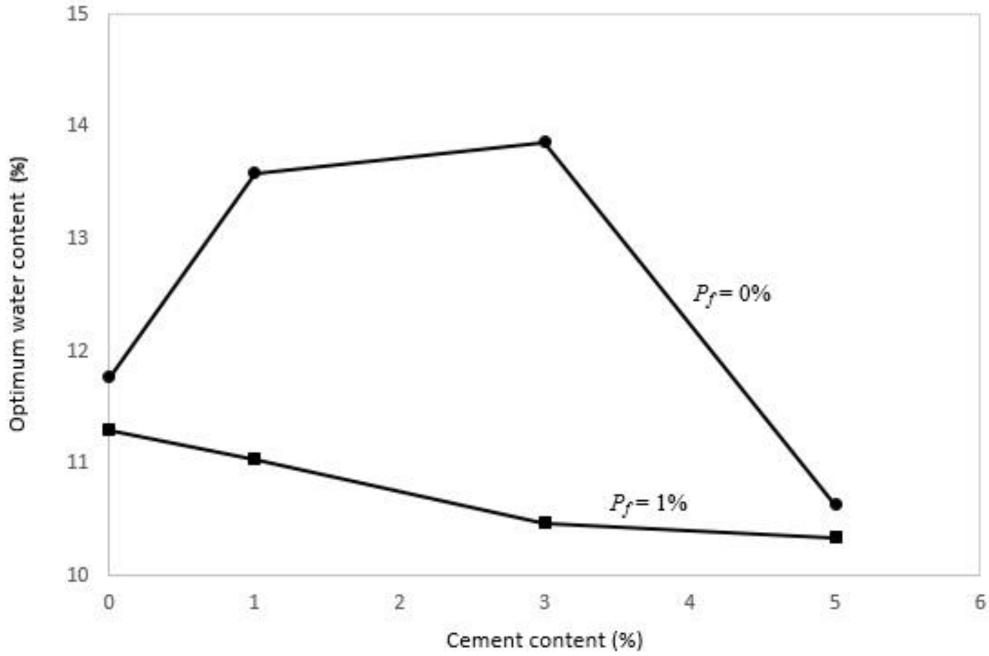


Fig. 4.4. Variation of optimum water content with different cement contents and fibre

4.3.3 Void ratio and degree of saturation at maximum dry unit weight

According to Edil and Bosscher (1994) the mechanical behaviour of tyre chip-soil mixtures may be more dependent on the volume of voids in the mixture rather than $\gamma_{d\,\max}$. An important factor in cement bonding which can be an indication of the level of contact between the particles is the volume of voids (Consoli et al., 2010a). In addition, the amount of water surrounding the particles plays an important role in the engineering behaviour of mixtures, especially when cement is added. Therefore, the void ratio (e) and degree of saturation (S) at the $\gamma_{d\,\max}$ will be investigated in this section.

In order to obtain the e values at the $\gamma_{d\,\max}$ for the mixtures, their specific gravity (G_s) values were calculated by getting the weighted average of the G_s values of the materials in the mixture from the following equation:

$$G_s = \frac{G_{ss}W_s + p_f W_s G_{sf} + p_c W_s G_{sc}}{W_s + p_f W_s + p_c W_s} \quad (4.1)$$

where W_s = weight of dried soil; G_{ss} = specific gravity of soil; G_{sf} = specific gravity of tyre fibres; and G_{sc} = specific gravity of cement.

By having $\gamma_{d\max}$, w_{opt} and G_s values of the mixtures, e values were calculated using the following equation:

$$e = \left(\frac{G_s \gamma_w}{\gamma_d}\right) \quad (4.2)$$

where γ_w = unit weight of water; and γ_d = dry unit weight of the materials.

Fig. 4.5 shows the variation of e at the $\gamma_{d\max}$ with tyre fibre content (p_f), respectively, for cement content (p_c) varying from 0 to 5%. It is noticed from the graphs that generally, adding cement to the mixtures results in slightly lower e values; however, a decrease in $\gamma_{d\max}$ caused a significant variation of e which have been observed by adding 1% of tyre fibre to soil. This may be because of adding tyre fibre changes the gradation of mixtures in a way that more voids will be created. According to Youwai and Bergado (2003) the rearrangement of particles in addition to the compressibility of the tyre fibre can change in e values. In general, soil plus 5% of p_c has the lowest e value of 0.38.

The values of degree of saturation (S) at the $\gamma_{d\max}$ were calculated using the following equation:

$$e \times S = w \times G_s \quad (4.3)$$

where w = water content of the materials.

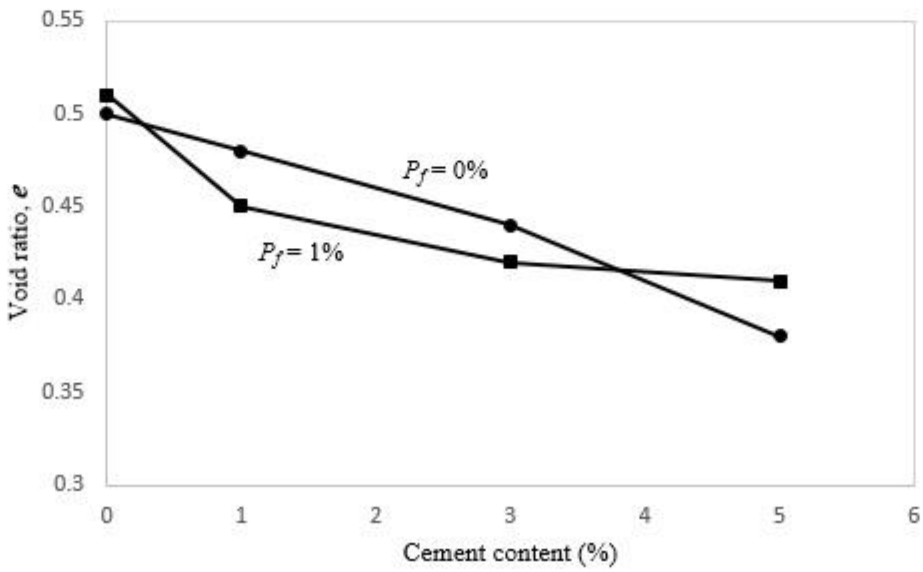


Fig. 4.5. Variation of void ratio at the maximum dry unit weight with tyre fibre content for different cement contents: mixtures of sand, tyre fibres and cement

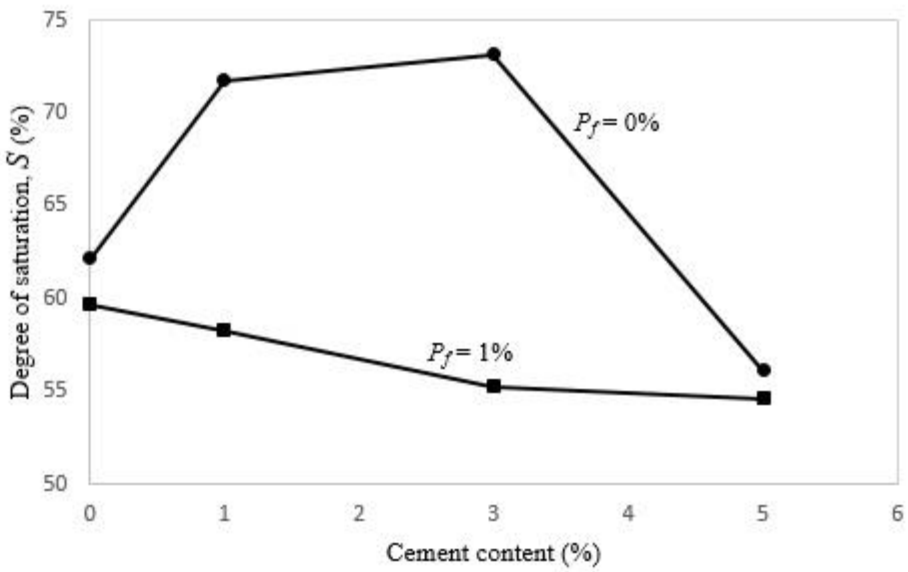


Fig. 4.6. Variation of degree of saturation at the maximum dry unit weight with tyre fibre content for different cement contents: mixtures of sand, tyre fibres and cement

Figs. 4.6 presents the variation of degree of S at the $\gamma_{d\max}$ with p_f for tyre fibres 0 and 1%, respectively for p_c varying from 0 to 5%. The results show that adding 1% tyre fibres generally decreases S. The reason for this reduction is that, by adding tyre fibres, as discussed earlier, the void ratio e increases, while water content (w) decreases, resulting in a lower S because S is the ratio of volume of water to void volume. It is also noticed from Figs. 4.6 that adding cement to soil results in higher S at first that is attributed to the considerable reduction of e.

However, adding more cement does not change S significantly, at least for the p_c values in this study. Generally, soil plus 3% of p_c has the highest S value of 73.18%.

4.4 Conclusions

The following general conclusions have been made from this chapter:

- Adding cement and/or tyre fibre to sandy soil generally reduces the optimum water content (w_{opt}).
- The addition of cement to soil results in an increase of maximum dry unit weight ($\gamma_{d\max}$); while adding tyre fibre to cemented sand mixtures decrease $\gamma_{d\max}$.
- Void ratio (e) at the maximum dry unit weight slightly decreases in mixture of cemented soil with or without tyre fibres.
- Adding tyre fibre leads to lower degree of saturation (S) values. Conversely, adding 1 and 3% of cement increases S at maximum dry unit weight.

CHAPTER 5

UNCONFINED COMPRESSIVE STRENGTH BEHAVIOUR

5.1 General

Unconfined compression test is a simple laboratory testing method to assess the mechanical properties of soils. It provides a measures of the undrained strength and the stress-strain characteristics of the soil. The unconfined compression test is often included in the laboratory testing program of geotechnical investigations. According to several researchers, such as Consoli et al. (2010), Park (2011) and Szymkiewicz *at al.* (2012), the unconfined compression test is by far the most popular method of soil shear testing because it is one of the fastest and cheapest methods of measuring shear strength. The specimens were prepared based on the maximum dry unit weight ($\gamma_{d\max}$) and optimum water content (w_{opt}) as per the Australia standard AS 5101.4-2008.

This chapter presents the procedure and test results of unconfined compression tests conducted on different soil mixtures containing 0, 1, 3 and 5% of cement content (p_c) and 0, and 1% tyre fibre content (p_f).

5.2 Unconfined compressive strength of sand

The unconfined compressive test is mainly conducted on cohesive and reinforced sandy soil mixtures to find out any effect on the unconfined compressive strength (UCS) of the sandy soil. The mixtures were compacted in three layers into the mould with 50-mm diameter and 100-mm height. Three specimens were prepared to be tested for each mixture. The moulds were removed after compaction and cemented specimens were kept in plastic bags for curing. To study the results of soil-cemented-fibre on UCS, both cemented soil specimens and cemented soil with fibres specimens were tested after being cured 0, 3, 7, 14, and 28 days. For testing specimens, using an automatic loading machine controlled by a computer, a load cell and a displacement cell. According to Standards Australia International 2008, a 1-mm/min rate of displacement was selected. The machine was connected to a desktop computer with the relevant software to read the test data and calculate the outputs results. The average of the stress-strain curves of the three specimens tested for the soil was obtained and is shown in Fig 5.1 that indicates the UCS of the soil is 9.45kPa which used only for comparison purposes. For the several other mixtures detailed in Table 3.2, the average stress-strain curves were produced similarly. The corresponding UCS values were read from the average stress-strain curve of each mixture and for the simplicity of comparison, the results are presented in figures.

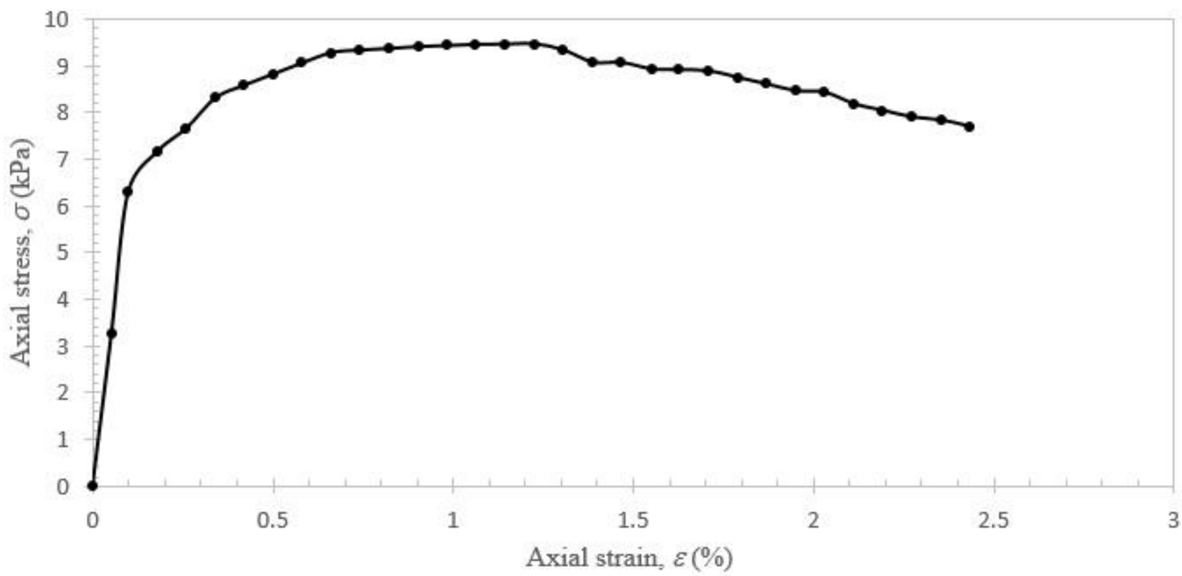


Fig. 5.1. Unconfined compression strength curve for Perth sand

5.3 Effect of cement and tyre fibre on the unconfined compressive characteristics of the mixture

5.3.1 Unconfined compressive strength

It has been noticed that as expected the cement content and tyre fibres have a great effect on the strength of these sand-tyre-cement mixtures. A small difference in cement content has a significant impact on the performance of the specimens. Specimens from the mould were extracted carefully and were placed in sealed plastic bags for 3, 7, 14, and 28 days. Figure 5.2 shows variation of unconfined compression strength curves for Perth soil with/without cement content (p_f) and tyre fibre content (p_c). The variation of UCS values with cement content 1-5% and tyre fibre content 1% is shown in Table 5.1.

Table 5.1 also indicates that the compressive strength increase with an increase in the cement content for the fibre-reinforced and non-reinforced materials. The table also illustrates that adding tyre fibres to cemented soil increase UCS. Adding 1% of tyre fibres to soil increases the UCS of the soil approximately 10-70% for fresh specimens. According to Zorenberg *et al.* (2004) and Santoni et al. (2001) adding different types of fibres to six various sandy soils causes an increase in UCS results, this increase is due to the effect of reinforcement caused by the tyre fibre in soil. This also may be because tyre fibres have larger aspect ratios, leading to higher pull-out resistance, and thus have more reinforcing effect (Zornberg et al. 2004). Increasing tyre fibre content leads to slightly increase in UCS, similar observations were reported earlier by adding tyre fibre to soil (Akbulut et al., 2007; Kalkan, 2013; Maher and Ho, 1993; Consoli et al., 1998, 2002, 2010a; Park, 2011; Hamidi and Hooresfandi, 2013; Kutanaei and Choobbasti, 2014). However, the rate of increase was not the same for different types of fibres indicating the importance of fibre characteristics such as stiffness or surface smoothness. Furthermore, fibre length has been reported as being both effective and ineffective with regards to UCS variations in different fibre reinforced mixtures (Consoli et al., 2002; Akbulut et al., 2007).

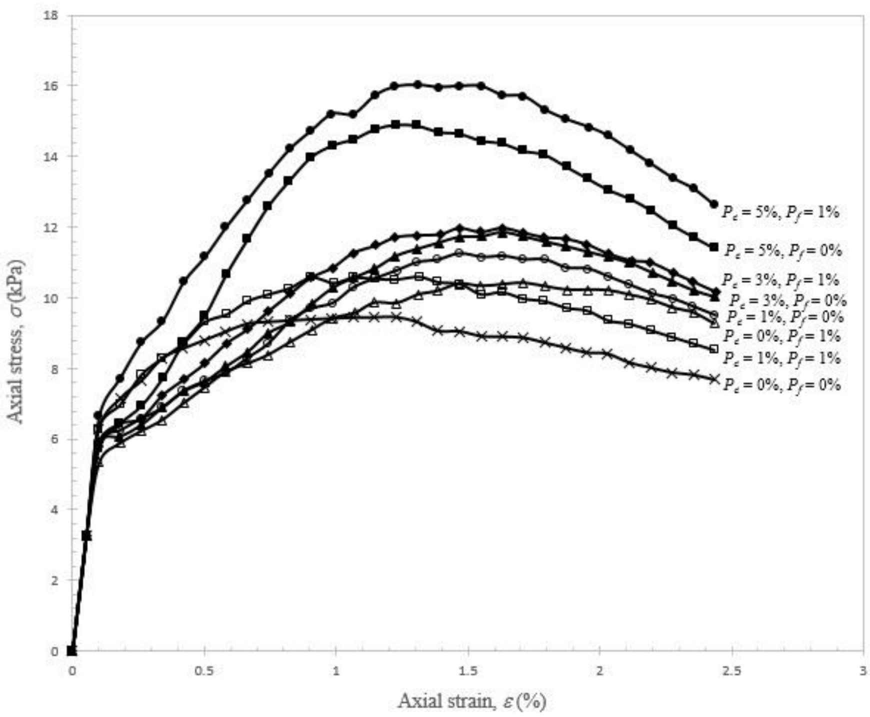


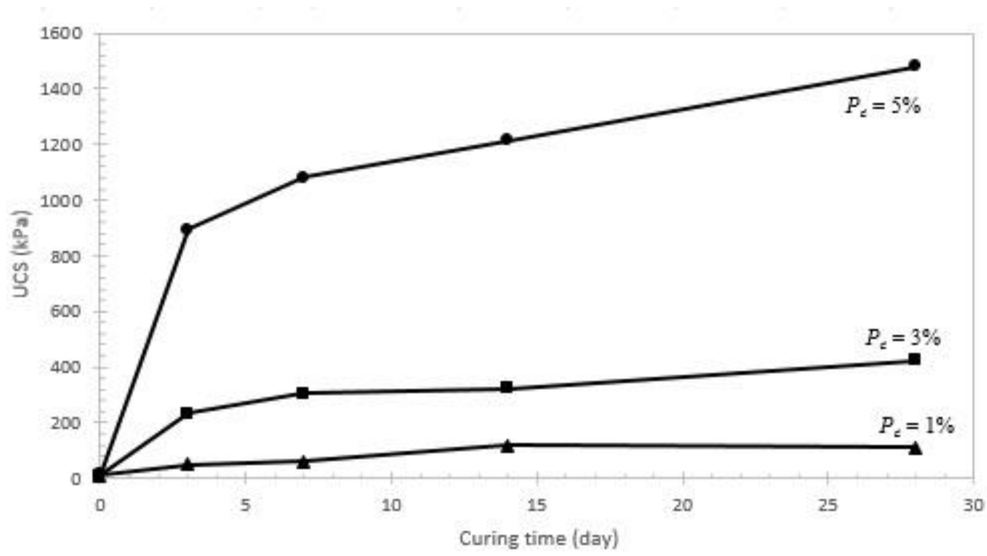
Fig. 5.2. Variation of unconfined compression strength curves for Perth sand with fibres content (p_f) and cement content (p_c) without curing days.

5.3.2 Effect of curing period on UCS

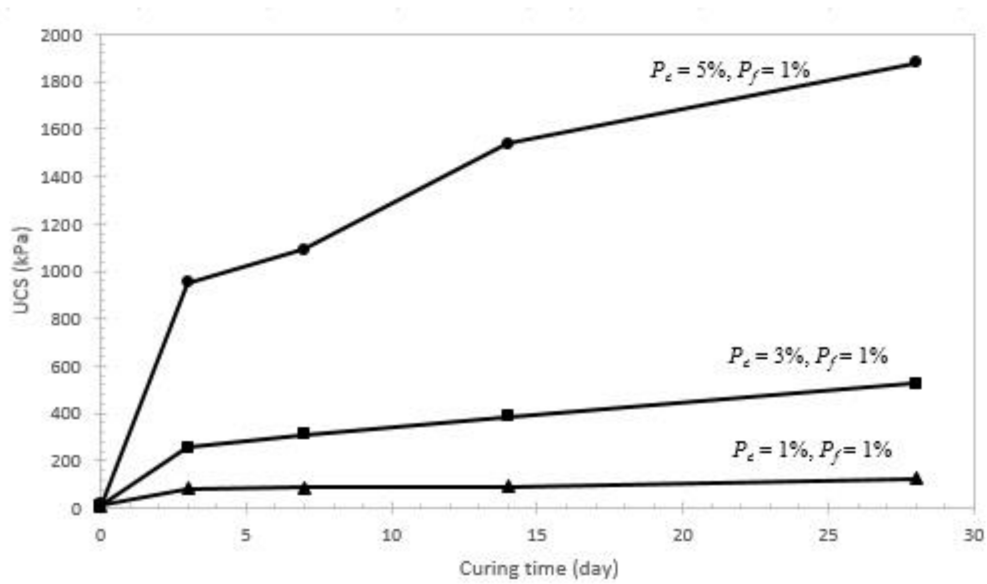
To study the effects of curing time on UCS, both cement-improved soil specimens and cement-fibre-improved specimens were tested after being cured 3, 7, 14, and 28 days. The UCS of treated soil increased significantly over curing time with increasing percentage of cement content and tyre fibres. Specimens were cured in plastic bags for 3, 7, 14 and 28 days. The USC of each specimens was measured on the day of curing and the results are compared as shown in Fig. 5.3(a), Fig. 5.3(b), Fig. 5.4(a) and Fig. 5.4(b).

Table 5.1. Summary of Test Condition and Results

Test ID	Cement ratio (%)	Tyre fibres ratio (%)	Curing Period (days)	Dry unit weight (kN/m3)	Water content (%)	UCS (kPa)	Axial strain (%)
SS0CC0FC0	0	0	0	17.26	11.77	9.45	1.22
SS0CC0FC1	0	1	0	17.18	11.31	10.41	1.71
SS0CC1FC0	1	0	0	17.5	13.59	11.24	1.46
SS3CC1FC0			3			50.78	1.55
SS7CC1FC0			7			62.04	1.87
SS14CC1FC0			14			116.95	1.62
SS28CC1FC0			28			112.96	1.79
SS0CC1FC1	1	1	0	17.89	11.04	10.59	1.31
SS3CC1FC1			3			83.36	1.38
SS7CC1FC1			7			85.97	1.46
SS14CC1FC1			14			90.24	1.71
SS28CC1FC1			28			127.36	1.46
SS0CC3FC0	3	0	0	17.95	13.86	11.86	1.63
SS3CC3FC0			3			232.71	1.22
SS7CC3FC0			7			306.06	1.22
SS14CC3FC0			14			324.49	1.38
SS28CC3FC0			28			424.22	0.90
SS0CC3FC1	3	1	0	18.24	10.47	11.97	1.62
SS3CC3FC1			3			254.9	1.3
SS7CC3FC1			7			310.58	1.38
SS14CC3FC1			14			385.73	1.79
SS28CC3FC1			28			527.76	1.22
SS0CC5FC0	5	0	0	18.73	10.63	14.901	1.22
SS3CC5FC0			3			895.45	1.54
SS7CC5FC0			7			1082.51	0.98
SS14CC5FC0			14			1213.86	1.14
SS28CC5FC0			28			1478.82	1.63
SS0CC5FC1	5	1	0	18.43	10.34	16.01	1.31
SS3CC5FC1			3			952.03	0.9
SS7CC5FC1			7			1090.66	1.47
SS14CC5FC1			14			1539.37	1.62
SS28CC5FC1			28			1877.93	1.54



(a) UCS of cemented soil without tyre fibres

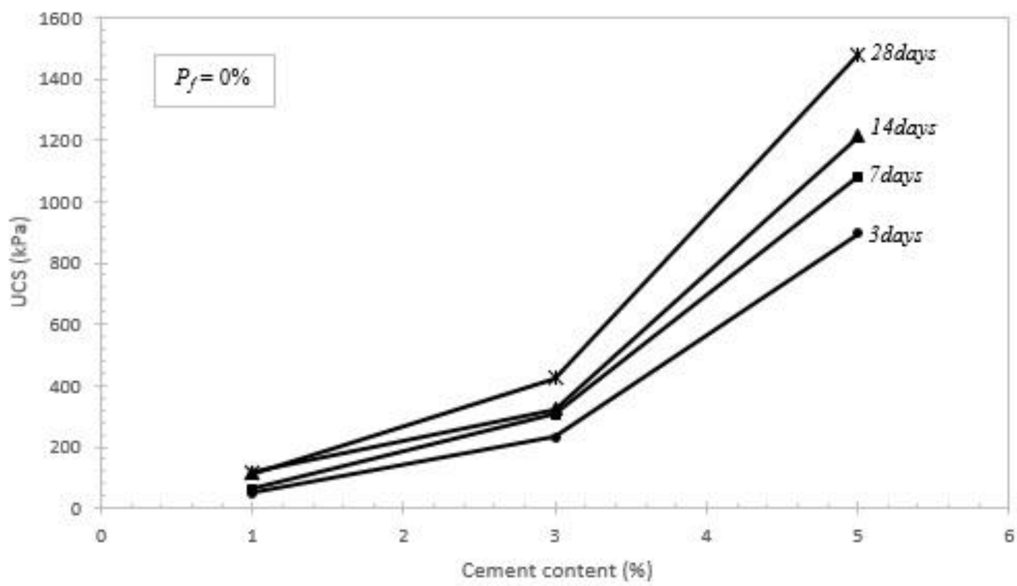


(b) UCS of cemented soil with 1% tyre fibres

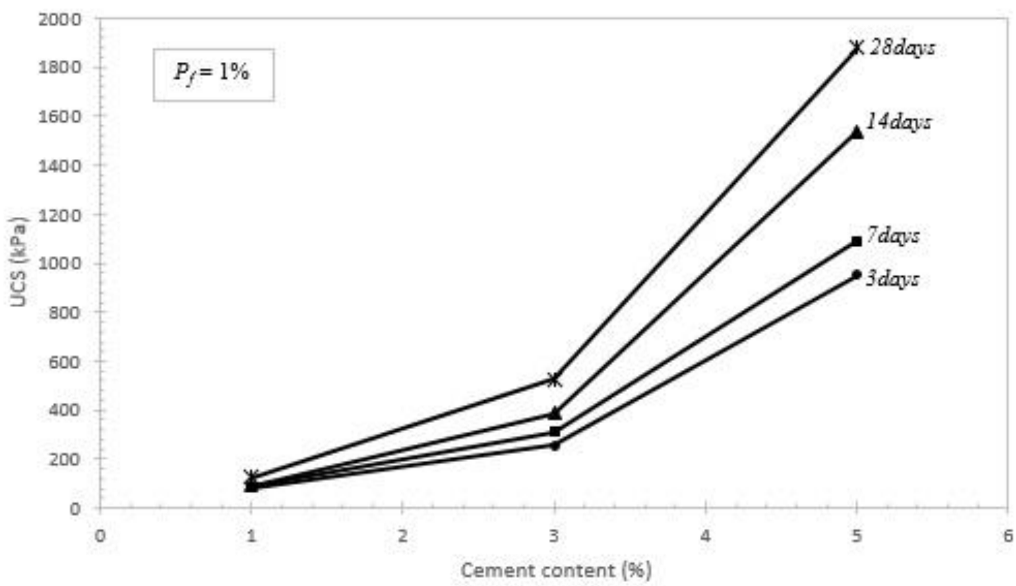
Fig. 5.3. UCS variation due to curing time: (a) without tyre fibres; (b) with 1% tyre fibres

In Fig. 5.3 and Fig. 5.4, the relationships between UCS and curing time for cement-improved and cement-fibre-improved specimens are presented. Also, the effects of cement content, tyre fibres and curing periods are clearly exhibited in Fig. 5.3(a), Fig. 5.3(b), Fig. 5.4(a) and Fig. 5.4(b) as amounts of cement contents were increased and the curing periods were extended from 3 to 28 days. However, the UCS values for treated soil cured at three days was lower than that of the samples cured at 28 days. The values of USC for cemented specimens (p_c = 1, 3 and 5%) without tyre fibres cured at three days ranged between 50.78 and 895.45 kPa. It also was noticed as tyre fibre content increased from 0 to 1%, the treated specimens (p_c =1, 3 and 5%) cured at 3 days indicated by higher UCS values of 83.36 and 952.03 kPa, respectively.

From the test results, the UCS of both cemented and cement-fibre-improved specimens increased with curing time. By using the UCS at a 3-day curing time as a reference, the UCS at a 28-day curing time could increase about 15-122% for both cemented and cement-fibre-improved specimens. As the curing progresses, reaction occur between the soil particles and the cement particles. These reaction generally result in an increase in the stiffness of the cement-treated soil. Chang and Woods (1992) performed a series of electron microscopy tests on different treated soils with various kinds of cement agent. They indicated that the mechanism by which the decrease in porosity of mixture influences the unconfined compressive cement strength of cement-treated soil is related to the existence of a larger number of interparticle contacts. Therefore, the specimens with a high percentage of cement has higher unconfined compressive strength. It was also noticed that the unconfined compressive strength increase with increase of the curing time. According to Kutanaei and Choobbasti (2017), the reason can be inferred to be the elimination of micro-cracks in the cement part of the specimens and hydration development when the sample gets older.



(a) Without tyre fibres



(b) With 1% tyre fibres

Fig. 5.4. Effect of cement, tyre fibre and curing periods on UCS: (a) without tyre fibres; (b) with 1% tyre fibres

Table 5.2. Variation of secant tangent modulus of elasticity

Test ID	$(UCS)_s$, (kPa)	Strain, ε_s	Secant modulus of elasticity, E_s (kPa)
SS0CC1FC0	30	0.005	6000
SS3CC1FC0	32	0.005	6400
SS7CC1FC0	32	0.005	6400
SS14CC1FC0	32	0.005	6400
SS28CC1FC0	32	0.005	6400
SS0CC1FC1	34	0.005	6800
SS3CC1FC1	48	0.005	9600
SS7CC1FC1	44	0.005	8800
SS14CC1FC1	47	0.005	9400
SS28CC1FC1	46	0.005	9200
SS0CC3FC0	32	0.005	6400
SS3CC3FC0	45	0.005	9000
SS7CC3FC0	50	0.005	10000
SS14CC3FC0	48	0.005	9600
SS28CC3FC0	45	0.005	9000
SS0CC3FC1	34	0.005	6800
SS3CC3FC1	44	0.005	8800
SS7CC3FC1	45	0.005	9000
SS14CC3FC1	44	0.005	8800
SS28CC3FC1	45	0.005	9000
SS0CC5FC0	34	0.005	6800
SS3CC5FC0	35	0.005	7000
SS7CC5FC0	50	0.005	10000
SS14CC5FC0	45	0.005	9000
SS28CC5FC0	50	0.005	10000
SS0CC5FC1	32	0.005	6400
SS3CC5FC1	46	0.005	9200
SS7CC5FC1	45	0.005	9000
SS14CC5FC1	44	0.005	8800
SS28CC5FC1	42	0.005	8400

5.3.3 Modulus of elasticity (Initial tangent modulus)

Stiffness and ductility capacity of the materials used in geotechnical applications are of high importance. Various structures have different strength and deformation requirements based on the application. Therefore, understanding the stiffness behaviour of the mixtures used in the current work is beneficial. From the average stress-strain curves of different mixtures, the axial strain 0.5% values were obtained, and their variation with tyre fibre content (p_f) is presented in Table 5.1 and 5.2 for cement content (p_c) of 0 and 1 to 5%, respectively. In order to investigate the stiffness of the sandy soil affected by adding cement and/or tyre fibre, the secant tangent modulus of elasticity (E_s) for each mixture was calculated from the average stress-strain curves using the following equation and presented in Table 5.2.

$$E_s = \left(\frac{UCS}{\varepsilon}\right)_s \tag{5.1}$$

where UCS = the unconfined compressive strength and ε = axial strain.

Figs. 5.5 shows the variation of E_s with p_c = 1, 3 and 5% for samples with or without tyre fibres, respectively. The results indicate that adding 1% tyre fibre to the soil does not have any significant influence on the E_s of the mixtures with 1 to 5% cement content, thus the stiffness of the soil does not change significantly by adding the tyre fibre as observed earlier (Chan, 2012). It can be concluded that adding tyre fibre to cemented soil increases the flexibility of the mixture and prevents an abrupt and brittle failure. An increase in the flexibility of cemented soil by fibre reinforcement was reported earlier (Consoli et al., 1998; Chan, 2012; Hamidi and Hooresfandi, 2013; Kutanaei and Choobbasti, 2014). The lower density of the mixtures induced by the inclusion of tyre fibre in addition to the initial deformation required to mobilise the tensile strength in the extensible tyre fibre may be the reasons of this ductility that delays the failure (Nicholson, 2014; Kutanaei and Choobbasti, 2014).

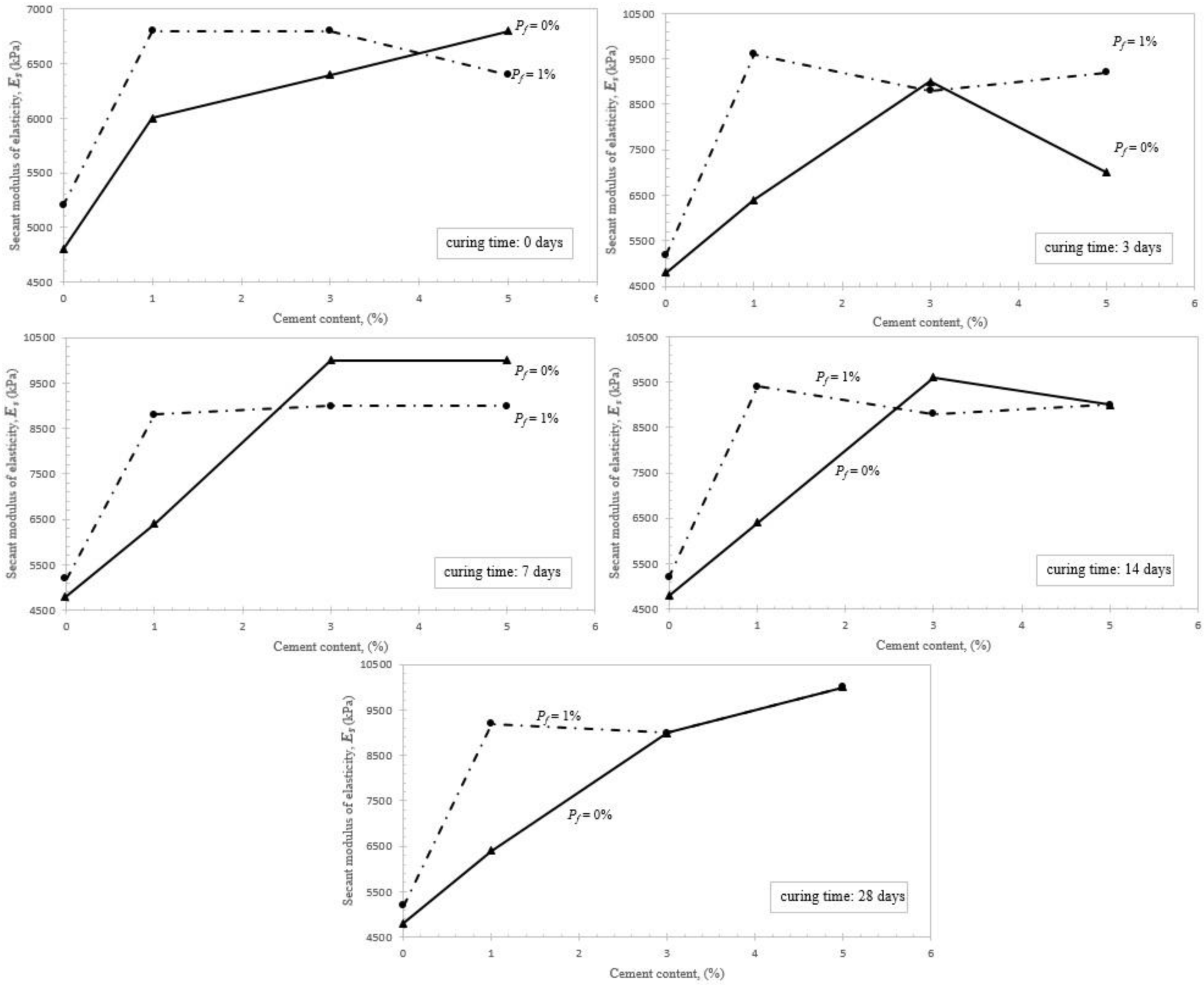


Fig. 5.5. Variation of secant modulus of elasticity with tyre fibre content 1% and/or cement contents of 0 to 5%

In addition, it is observed from Fig. 5.5 that inserting tyre fibre in the soil-cement mixtures has more influence on the E value when p_c is higher, which is due to the counteraction of cement and the tyre fibre effects as explained before. Furthermore, Figs. 5.5 shows that E_s increases with adding cement to the soil and soil-fibre mixtures, and the trend is similar to that of UCS as there is insignificant variation in the axial strain at failure (ε_a) by changing the p_c. This increase indicates that the addition of cement increases the stiffness of the mixture, with cement dominating the improvement at large p_c, as reported earlier (Abdulla and Kiousis, 1997; Consoli et al., 1998, 2009; Park, 2011; Chan, 2012; Kutanaei and Choobbasti, 2014). In addition to the effect of cement hydration on the stiffness improvement, inserting cement in the mixtures increases the $\gamma_{d\max}$, and the density enhancement results in the increase of stiffness (Nicholson, 2014).

5.4 Conclusions

A series of UCS tests on cement-improved soils and cement-fibre-improved soils were conducted. Special attention was paid to the effects of curing time on UCS tests. Some conclusions can be drown as follows:

- The UCS and axial strain at failure (ε_a) increase with the addition of cement and tyre fibre while specimens get older, moreover, no significant change is observed in secant modulus of elasticity (E_s).
- The test results consistently show that UCS of the cement-soil mixture keeps increasing with curing time which can be increased by approximately 15-122%.
- The general stiffness loss due to the addition of tyre fibre to the soil-cement mixtures is compensated by the change in the brittle behaviour of mixtures to a ductile one.

CHAPTER 6

CALIFORNIA BEARING RATIO

6.1 General

The California bearing ratio (CBR) test is a simple strength test that compares the bearing capacity of a material. It is primarily intended for, but not limited to, evaluating the strength of cohesive materials having maximum particle sizes less than 19 mm. It was developed by the California Division of Highways around 1930 and was subsequently adopted by numerous states, counties, U.S. federal agencies and internationally.

This chapter presents the procedure and results of CBR tests conducted on different soil mixtures containing 0, 1, 3 and 5% of cement content (p_c) and 0, and 1% tyre fibre content (p_f) for both soaked and non-soaked condition.

6.2 California bearing ratio

The test most frequently used to characterize the subgrade soil in pavement design is the CBR test. The importance of the CBR test emerged from the following two facts: (1) for almost all pavement design charts, unbound materials are basically characterized in terms of their CBR values when they are compacted in pavement layers; and (2) the CBR value has been affiliated with some constitutive properties of soils, such as plasticity indices, grain-size distribution, bearing capacity, modulus of subgrade reaction, modulus of resilience, shear strength, density, and molding moisture content(Al-Amoudi et al., 2002).

Although the CBR test is only valid for uniform materials, it can show the qualitative benefit of geogrid reinforcement to the material resistance under the same conditions of test and hence can be used for comparing the results. Therefore, CBR tests were conducted on selected soils unreinforced and reinforced with a single layer of the two types of geogrid (Kamel et al., 2004). The strength and stiffness of soils are specified by factors such as drainage conditions, initial effective stress state, water content, structure, loading direction and loading rate. When the

CBR test is performed on fine-grained soils, neither drainage conditions nor the effective stress state of the soil sample can be controlled. This represents a serious shortcoming of the test and means that the relationship between CBR and static strength and stiffness cannot be investigated directly (Hight and Stevens, 1982).

According to Kamel et al., (2004), it is clear that there is a considerable amount of increase in the CBR value of a soil with the geogrid reinforcement. The amount of increase depends upon both the type of soil and geogrid stiffness. For example, in the case of soil A, the CBR value increases from 4.15 percent for unreinforced soil to 5.83 percent when geogrid-1 (of higher stiffness) was placed at 50mm from the top and to 4.99 percent when geogrid-2 (of lower stiffness) was placed at similar level (Table 6.1). The percent increase in CBR value was however, more with geogrid-1, which was of higher stiffness indicating that the stiffness of the grid also has considerable effect on the bearing capacity of the reinforced soil. Table 6.1 shows results of the CBR tests on three types of soil reinforced with geogrid.

Table 6.1. Results of CBR tests for different position of geogrids (Kamel *et al.*, 2004)

Type of grid	Position from top(%) of height	Soaked CBR percent			Percent change with respect to unreinforced sample		
		Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
No Grid	-	4.15	1.1	1.05	-	-	-
Grid – 1	20 (2.5 cm)	5.25	1.52	1.26	27	38	20
	40 (5.0 cm)	5.83	1.84	1.52	40	67	45
	60 (7.5 cm)	6.46	2.24	1.84	56	104	75
	80 (10 cm)	6.83	2.52	2.15	65	129	105
Grid - 2	20 (2.5 cm)	4.62	5.25	1.41	11	28	5
	40 (5.0 cm)	4.99	5.83	1.7	20	66	25
	60 (7.5 cm)	5.83	6.46	1.97	40	79	50
	80 (10 cm)	6.3	6.83	2.23	52	103	75

6.3 Effect of cement and tyre fibre on the California bearing ratio of the mixture

For each selected moisture content and compactive effort, three CBR specimens were prepared by compacting the wetted soil in three layers to achieve a dry unit weight equivalent to that of the compaction test at the selected compactive effort. At each moisture content, three specimens were immediately loaded under a surcharge of 4.5 kg and subjected directly to the

CBR penetration test. In the case of soaked condition, additional CBR specimens were deferred until they had been soaked in water for 4 days under the same surcharge of 4.5 kg. The CBR test was conducted at a loading rate of 1.2 mm/min. To determine the CBR value from the load penetration curves, the loads at penetrations of 2.50 mm and 5.00 mm were determined. Because the CBR is defined as the ratio of the force required to penetrate a circular piston, respectively this ratio was determined as follows:

$$CBR = \left(\frac{\text{Measured force}}{\text{Standrad force}} \times 100 \right)\% \qquad (6.1)$$

The higher of these two values is reported as the CBR value for that specimen (Al-Amoudi et al., 2002).

Standard unsoaked CBR tests were performed on soil specimens containing 0, 1, 3 and 5% cement content with or without 1% tyre fibres. These tests were conducted to study the improvement in the CBR value because it is the most frequently used test method for characterizing the subgrade soil in pavement design. The unsoaked CBR test results for soil reinforced with various amounts of cement and tyre fibres are shown in figure 6.1. It was noticed from the test results that the CBR value for Perth sandy soil was 11.74. The unsoaked CBR value of 11.74 for the unreinforced soil specimen increase to approximately 13.53 for specimens with a 1% tyre fibres content which is a 15.2% increase in the CBR value. For cemented-soil specimens with 1% cement, the CBR value increases to 17.12 which shows a 45.82% increase. In addition, the unsoaked CBR value of 19.31 for specimen with 5% cement has been noticed which is a 64.4% increase in the CBR value. The results show that the unsoaked CBR value of 18.58 for fibre-cement-soil specimens with cement content as 5% and tyre fibre content 1% which increase approximately 58.4%.

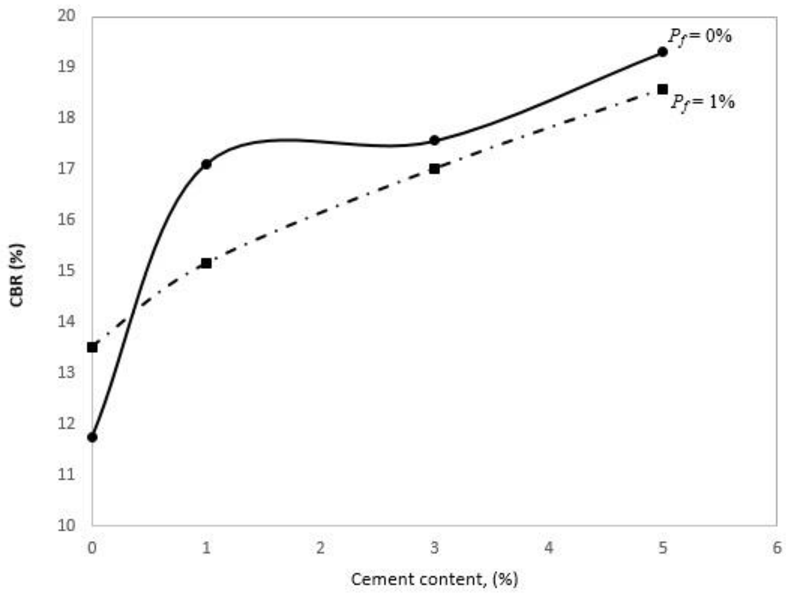


Fig. 6.1. The unsoaked CBR test results for sand reinforced with various amounts of cement and tyre fibres

Standard soaked CBR tests were performed on soil specimens containing 0, 1, 3 and 5% cement with or without 1% tyre fibres. The compacted soil specimens at the optimum moisture content are soaked for 96 hours in a water bath to get the soaked CBR value of the soil as shown in Figure 6.2. The results of soaked CBR has been presented in Figure 6.3 and the percent of increasing in the soaked and unsoaked CBR is shown in Table 6.2. Much researches have been conducted previously to investigate the effect of cement and/or tyre fibres on soaked CBR and higher values of soaked CBR have been presented by previous research studies (Black, 1961; Joel and Agbede, 2011; Baghdadi et al., 1995).

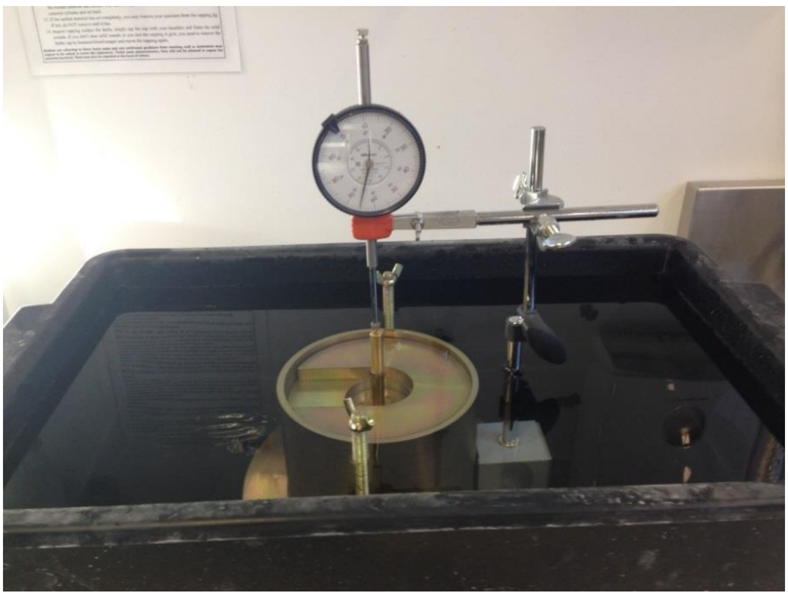


Fig. 6.2. The compacted soil specimen is soaked for 96 hours in a water bath

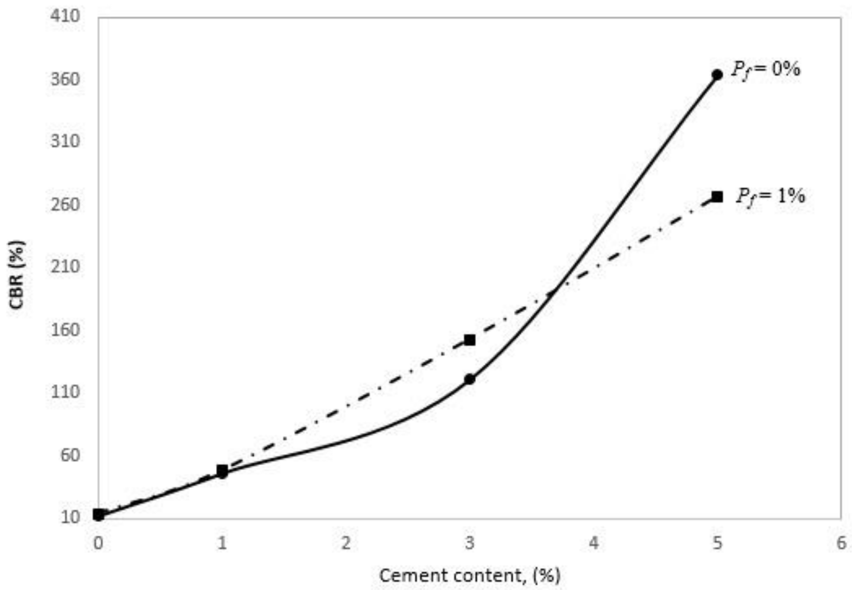


Fig. 6.3. The soaked CBR test results for sand reinforced with various amounts of cement and tyre fibres

Table 6.2. Summery of the CBR values for both soaked and unsoaked specimens

	Test ID	Cement ratio (%)	Tyre fibres ratio (%)	Dry unit weight (kN/m3)	Water content (%)	CBR (%)	Percent of increasing in CBR, (%)
Unsoaked	SS0CC0FC0	0	0	17.26	11.77	11.74	-
	SS0CC0FC1	0	1	17.18	11.31	13.53	15.24
	SS0CC1FC0	1	0	17.5	13.59	17.12	45.82
	SS0CC1FC1	1	1	17.89	11.04	15.16	29.13
	SS0CC3FC0	3	0	17.95	13.86	17.57	49.65
	SS0CC3FC1	3	1	18.24	10.47	17.02	44.97
	SS0CC5FC0	5	0	18.73	10.63	19.31	64.48
	SS0CC5FC1	5	1	18.43	10.34	18.58	58.26
Soaked	SS0CC0FC0	0	0	17.26	11.77	11.74	-
	SS0CC0FC1	0	1	17.18	11.31	13.78	17.78
	SS0CC1FC0	1	0	17.5	13.59	45.9	290.9
	SS0CC1FC1	1	1	17.89	11.04	48.38	312.1
	SS0CC3FC0	3	0	17.95	13.86	120.83	929.2
	SS0CC3FC1	3	1	18.24	10.47	152.95	1202.8
	SS0CC5FC0	5	0	18.73	10.63	363.63	2997.3
	SS0CC5FC1	5	1	18.43	10.34	266.89	2173.3

6.4 Conclusions

The main conclusions that can be drawn from the current chapter are as follows:

- The addition of cement increased the unsoaked CBR value of the mixture. The addition of 1 to 5% cement to soil increased the unsoaked CBR value from 17.12 to 19.31, which is a 12.8% increase. Whereas, the addition of 1 to 5% cement increased the soaked CBR value of the mixture from 45.9 to 363.63, which is a 692% increase.

- Adding 1% tyre fibre increase the CBR value for both soaked and unsoaked mixtures.
- The results indicate that the use of cement and tyre fibres additive will improve the performance of soil.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

Soil stabilization and reinforcement are the processes of altering some soil properties by different methods, mechanical or chemical in order to produce an improved soil material which has all the desired engineering properties. Soils are generally stabilized to increase their strength and durability or to prevent erosion and dust formation in soils. The main aim is the creation of a soil material or system that will hold under the design use conditions and for the designed life of the engineering project. Various materials have been studied and/or used as stabilising agent, such as cement, lime and bitumen, and as reinforcing agent, such as geosynthetics and natural or synthetic fibres. Recently, as the amount of waste materials such as tyres and carpets is dramatically increasing, attentions have been drawn to the reuse of these materials to reduce the environmental consequences associated with these wastes. Currently, waste tyres are being used in some applications such as energy production or safety mat or flooring manufacturing. They are also being utilised in some civil engineering applications such as in embankment construction or drainage layers in landfills (Balunaini et al., 2014).

In the past, some research works have been made to investigate the engineering behaviour of mixtures reinforced with waste tyre (Ahmed, 1993; Edil and Bosscher, 1994; Foose et al., 1996; Youwai and Bergado, 2003; Zornberg et al., 2004; Attom, 2006; Edincliler and Ayhan, 2010; Edincliler et al., 2012; Balunaini et al., 2014). Nevertheless, the attempts seem to be inadequate. In addition, limited attention has been paid to the study of using waste tyre with cement to improve the engineering properties of sandy soils. Therefore, this research aims at investigating the changes in engineering behaviour of the sandy soil available in Perth by adding cement and fibres produced from waste tyres.

The majority of the natural available soil is sandy in Western Australia so the tyre fibre-reinforced cement-stabilised soil may probably be used as a material in road construction projects. Hence, a critical review of the standards around the world was conducted to investigate the current practices in the construction of the base course layers of highways worldwide. As the result of the review, and following a series of analyses, a universal gradation curve is developed for the materials used in the base course of highways.

The poorly graded sand (SP), as per the Unified Soil Classification System (USCS) (ASTM, 2011), has been collected for the experimental study. The cement which has been used in this study was general purpose (GP) cement. It is a commonly cement to use in construction projects in Western Australia. This cement was used as the stabilising agent with contents of 0, 1, 3 and 5%. The tyre fibres were collected from a local company in Perth and contents were 0 and 1%. First, basic geotechnical tests, such as sieve analysis and specific gravity test, were conducted to determine the properties of the materials used. Then, in order to investigate the effect of adding cement and tyre fibres to soil on its engineering behaviour, standard compaction, unconfined compression and California bearing ratio tests were conducted on different mixtures, and the results were analysed and scientifically discussed.

7.2 Conclusions

Based on the results of the study presented in the previous chapters, waste tyre fibres are suitable materials to improve the engineering characteristics of sandy soils and cemented sandy soils, and so they can be utilised in civil engineering applications. The following conclusions are made:

1. The maximum dry unit weight ($\gamma_{d\max}$) of the pure soil and soil-cement mixtures is slightly reduced by adding the tyre fibres ($p_f = 1\%$). Conversely, the addition of cement to soil only and soil-tyre fibre mixtures increases the $\gamma_{d\max}$; the highest and lowest $\gamma_{d\max}$ values are observed for soil with 5% cement (18.73 kN/m^3) and soil with 1% tyre fibre and 5% cement (18.43 kN/m^3), respectively.
2. The addition of tyre fibres and/or cement to soil generally decreases the optimum water content (w_{opt}). However, an insignificant decrease in w_{opt} is observed for the mixtures of soil plus 1% of tyre fibre content (p_f). Soil plus 3% cement with a value of about 13.86% shows the highest w_{opt}, and sand with 1% tyre fibre and 5% cement had the lowest w_{opt} of 10.34.
3. Void ratio (e) at the maximum dry unit weight is decreased by adding cement and/or tyre fibre to pure soil.

4. Adding cement and/or tyre fibre to the mixtures decreases the degree of saturation (*S*) at maximum dry unit weight. The *S* values in soil cemented mixture increase when cement is added at 1 and 3% of dry weight of soil, but increasing cement content (p_c) beyond 3% decreased the value of *S*.
5. The unconfined compressive strength (UCS) increased in soil with the addition of cement and/or tyre fibre, while no significant change is observed in the secant modulus of elasticity (E_s). The addition of cement to soil and TF-reinforced soil increases the *UCS* and *E* significantly in a non-linear way.
6. The highest improvement occurs when 1% tyre fibre is added to soil with 5% cement with 28 days curing time. Furthermore, adding tyre fibre to the cemented soil improves the ductility by increasing the ε and decreasing the E_s.
7. Generally, including TF in cemented soil reduces stiffness. However, the improvement in the ductile behaviour and prevention of sudden brittle failure compensates for the loss in stiffness.

Considering the overall outcomes of the experimental study, the use of waste tyre fibres in soil, with or without cement, is beneficial in civil applications such as slope stabilisation, backfills and embankments by providing a lighter mixture, improving the strength and causing a ductile behaviour that prevents abrupt failure of the structures. In addition, it is an efficient, cost-effective and ecologically friendly strategy to reduce and possibly eliminate the waste tyre disposal problems, while saving natural soil materials.

7.3 Recommendations for future work

The findings of this research suggest an effective solution to the disposal problems associated with waste tyres and show that waste tyre fibres can be used as reinforcing materials in soil and cemented soil in civil engineering projects. Based on the promising results of this study, as well as its limitations, further investigation is recommended on the following aspects:

- Using tyre fibres in lower content increments, such as 0.25 or 0.5%, especially at contents of below 1%.
- Effect of gradation, by using coarser or finer graded soils, on the engineering behaviour of cement-stabilised and tyre fibre-reinforced soil mixtures.
- Effect of water content on the UCS and CBR fibre-reinforced-cemented soil.

- Effect of compaction effort on the UCS and CBR of the soil reinforced with tyre fibre and stabilised with cement.

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