STABILIZATION MECHANISMS OF OIL PALM EMPTY FRUIT BUNCH (OPEFB) FIBRE REINFORCED SILTY SAND

by

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LIST OF ABREVIATIONS

Abbreviation	Description
ABS	Acrylonitrile Butadiene Styrene
ADVDPC	Advanced Pressure/Volume Controller
ANOVA	Analysis Of Variance
BFTA	Bradshaw Field Training Area
CD	Consolidated Drained
CU	Consolidated Undrained
EFB	Empty Fruit Bunch
ERDC	U.S. Army Engineer Research And Development Center
FTIR	Fourier Transform Infrared
GLM	General Linear Model
JRAC	Joint Rapid Airfield Construction
LCP	Liquid Crystal Polymer
MEK	Methyl Ethyl Ketone
OPEFB	Oil Palm Empty Fruit Bunch
PGBT	President George Bush Turnpike
PVA	Polyvinyl Alcohol
PWC	Polymer–wood composite
SEM	Scanning Electron Microscopy
USCS	Unified Soil Classification System

LIST OF SYMBOLS

Symbol	Definition
A_f	Area of fibres
D_r	Relative density
F^*	Coefficient of interface friction
F_i	Coefficient of internal friction
$M_e(w)$	Mass of water at equilibrium
M_{eq}	Equivalent gradient of critical state line
$M_i(s)$	Initial mass of the sample
$M_r(w)$	Relative molecular mass of water
Q_t	Molar percentage
S_{eq}	Equivalent shear strength of fibre reinforced specimens
$a^{'}$	Adhesive component
$c^{'}$	Cohesion of unreinforced soil
$c_{i,M}$	Coefficient of interaction for critical state line gradient
$c_{i,c'}$	Coefficient of interaction
$c_{i,\Gamma}$	Coefficient of interaction related to the Γ
$c_{i,\lambda}$	Coefficient of interaction the λ_{eq}
$c_{i,\phi'}$	Coefficient of interaction
d_f	Diameter of fibre
e_f	Modulus of elasticity of the fibre
f_v	Volumetric fibre content
l_f	Length of fibre
t_p	Fibre-induced distributed tension
t_t	Distributed tension
$\sigma_1^{'}$	Effective major principal stress
σ_{1f}	Major principal stress at failure
$\sigma_3^{'}$	Effective minor principal stress
σ_N	Nominal confining stress level
$\sigma_{f,ult}$	Ultimate tensile strength of the individual fibres
$\sigma_{n,ave}^{'}$	Average normal stress acting on the random fibres
$\sigma_{n,crit}$	Critical confinement of the shear strength envelope
σ_n	Confining stress acting on the fibres

σ_t	Tensile stress within a single fibre
$\bar{\sigma}_{ij}$	Macroscopic stress
$\overline{\sigma_1}$	Major principal stress within the homogenized material
$\overline{\sigma_3}$	Minor principal stress within the homogenized material
τ_f	Interface frictional resistance along fibre
$\phi^{'}$	Friction angle of unreinforced soil
ΔS	Shear strength increase of fibre reinforced soil
W_d	Weight of the dried specimen
W_w	Weights of the samples
φ	Friction angle of soil
Ψ	Orientation angle of the distorted fibres
A	Total area of soils in shear
D	Energy dissipation rate
R	Radius of the Mohr's circle
S	Shear strength of the unreinforced soil
a	Adhesion intercept of surface friction
c	Cohesion of soil
f	Gravimetric fibre content
i	Initial orientation of fibre
p	Mean of the maximum and minimum principal stresses
q	Deviator stress
s	Length of the portion of fibre over which slippage occurs
t	Mobilized tensile strength
x	Horizontal shear displacement
z	Thickness of shear zone
α	Empirical coefficient
δ	Angle of skin frictional resistance
η	Aspect ratio
θ	Angle of shear distortion
ξ	Empirical coefficient correlated to sand parameters
υ	Specific volume
ω	Angle of shear distortion

MEKANISMA PENSTABILAN PASIR BERKELODAK BERTETULANG OLEH SERAT TANDAN KOSONG BUAH KELAPA SAWIT (OPEFB)

ABSTRAK

Pelbagai jenis kaedah pengukuhan telah digunapakai dalam meningkatkan kekuatan tanah. Ini menyebabkan semakin banyak kajian dilakukan dalam mengenalpasti sumber baru yang lebih sesuai sebagai alat pengukuhan. Gentian pendek yang dihasilkan dari polimer ataupun bahan semula jadi telah digunakan untuk meningkatkan kekuatan ricih tanah, Penggunaan bahan semulajadi adalah disarankan sebagai satu sumber yang dapat menghasilkan bahan yang lebih berpotensi untuk meningkatkan kekuatan struktur tanah berdasarkan sifat-sifatnya yang mesra alam dan kos yang lebih efektif.

Analisis menunjukkan kesan perubahan morfologi dengan ciri serat tandan kosong buah kelapa sawit (OPEFB). Gentian tersalut dengan Acrylonitrile butadiene styren (ABS) memberi perlindungan yang boleh melindungi dari pembiorosotan. Ciri penyerapan bagi gentian dapat dikurangkan melebihi 40% dengan adanya salutan, yang mana mampu menbantu mengekalkan prestasi pada tahap malar.

Kajian ini telah dijalankan dengan menggunakan serat tandan kelapa sawit kosong, OPEFB yang telah dicampur dengan pasir berkelodak untuk mengenalpasti kekuatan, sifat mekanikal dan kesan penggunaan serat tersalut secara rawak. Campuran tanah diuji dengan ujian tiga paksi di bawah keadaan salir dan tidak tersalir.

Ujian tiga paksi dijalankan untuk mengenal pasti tindak balas serat terhadap kekuatan pasir berkelodak yang telah disalut dan tidak disalut serat . Dalam kajian ini, serat OPEFB telah dicampurkan dengan pasir berkelodak untuk mengkaji perubahan kekuatan dalam ujian tiga paksi. Spesimen telah diuji dibawah keadaan salir dan tidak tersalir dengan 0.25% dan 0.5% kandungan serat dan panjang yang berbeza iaitu 15 mm, 30 mm and 45 mm.

Hasil daripada kajian di dapati serat tandan kelapa sawit kosong tersalut dapat meningkatkan kekuatan ricih pasir berkelodak bagi serat OPEFB disalut dan tidak disalut. Serat disalut menunjukkan peningkatan geseran keluasan permukaan serat diantara serat dan butiran tanah dengan meningkatkan ruang permukaan. Berdasarkan kajian yang dilakukan, pasir berkelodak terkukuh yang mengandungi 0.5% serat tersalut dengan panjang serat 30mm dapat meningkatkan sudut geseran sebanyak 25% dan 45% bagi kejelekitan di bawah keadaan tak tersalir dibandingkan dengan spesimen kawalan. Ini menunjukkan bahawa kekuatan ricih campuran tanah dan serat tersalut dapat dipertingkatkan.

Keputusan ujian telah dibandingkan dengan sistem kerangka kerja diskret bagi menilai model. Sistem kerangka kerja diskret telah menunjukkan perhubungan yang bererti (signifikan) dengan keputusan ujikaji. Model keadaan genting telah di bangunkan berdasarkan model kerangka kerja diskret untuk menganalisis laluan tegasan dan kelakuan keadaan genting bagi tanah bertertulang serat. Didapati bahawa model keadaan genting menaunjukkan perhubugan bererti dengan keputusan ujikaji.

STABILIZATION MECHANISMS OF OIL PALM EMPTY FRUIT BUNCH (OPEFB) FIBRE REINFORCED SILTY SAND

ABSTRACT

A wide range of reinforcements have been used to improve soil performance to increase the soil strength. This has caused increased interest in identifying new accessible resources for reinforcement. Short fibres made of polymeric or natural material have been used to improve the shear strength of soil. It has been suggested that natural resources may provide superior materials for improving soil structure, based on their cost-effectiveness and environment-friendly aspects.

The effect of coating on morphology changes and the properties of palm empty fruit bunch (OPEFB) fibres were also studied. The fibres coated with Acrylonitrile Butadiene Styrene (ABS) provided acceptable protection against the biodegradability of the OPEFB fibre. Fibre coating reduced more than 40% of absorption property of the fibres, which can protect the fibres.

This study was conducted using oil OPEFB fibres mixed with silty sand to determine the strength, mechanical behaviour and the effect of fibre coating in randomly distributed fibre-reinforced soil. Soil mixtures were subjected to the triaxial compression test under drained and undrained conditions

Triaxial compression tests were conducted to evaluate the response of randomly distributed fibre on the strength of coated and uncoated fibre reinforced silty sand. In this study, OPEFB fibre was mixed with silty sand soil to investigate the relative strength increase in terms of triaxial compression. The specimens were

tested under drained and undrained conditions with fibre content 0.25% and 0.5% and different lengths of 15 mm, 30 mm and 45 mm.

Inclusion of randomly distributed discrete fibres significantly improved the shear strength of silty sand for coated and uncoated OPEFB fibre. Coated OPEFB fibres increased the shear strength of silty sand compared to uncoated fibres. Coated fibres shown higher interface friction between fibre and soil particles by increasing the surface area. Reinforced silty sand containing 0.5% coated fibres of 30 mm length exhibited approximately 25% increase in friction angle (ϕ') and 45% in cohesion (c') under undrained conditions. The results indicate that the shear strength parameters of the soil-fibre mixture (ϕ' and c') was improved significantly.

The test result was compared with discrete framework system to evaluate the model. The discrete framework system was shown significant correlation with experimental results. The critical state model was developed based on the discrete framework model to analyse the stress path and critical state behaviour of fibre reinforced soil. It was found that the critical state model shown significant correlation with experimental result.

CHAPTER 1
INTRODUCTION

1.1 Improvement of soil performance

Construction of civil engineering structures on weak or soft soil is difficult without any soil improvement due to their poor shear strength and high compressibility. Improvement of soil properties like shear strength and permeability characteristics of soil can be undertaken by a variety of ground improvement techniques such as the use of prefabricated vertical drains (e.g. Abuel-Naga *et al.*, 2006; Chu *et al.*, 2006) or soil stabilization.

A wide range of reinforcements used in the improvement of soil performance cause of attention to new accessible resource. Soil reinforcement is an effective and reliable technique for improving the strength and stability of soil. There are different methods of soil reinforcement, such as the use of textile reinforcements (e.g. strips, geotextile, geogrid, etc) within earth structures that it is a conventional method of fibre reinforcing. In this method, planar inclusions provide tensile resistance to the soil in a particular direction but planar reinforcement requires enough embedment length and need a properly designed anchorage to provide enough pullout resistance.

The use of fibre reinforcement has been suggested in recent years for various geotechnical applications. Short discrete fibres, if mixed uniformly within the soil mass, can provide isotropic increase in the strength of the soil composite without introducing continuous planes of weakness and decreased the stiffness of the soil. Also, fibre-reinforcement solutions do not require design and the discrete fibres are simply added and can mixed randomly with soil, in much the same way as cement, lime, or other additives. Fibre-reinforcement can use for increasingly adopted in geotechnical projects such as the repair of failed slope and the stabilization of thin soil veneers like building base and sub base in roads and airport (Yetimoglu and Salbas, 2003).

Soil reinforcing is one of accepted methods of increasing the tensile strength of the soil. There are approximate methods for the design of structures with planar reinforced soil that exist, although there have been many experimental researches on the reinforcement of soils with randomly disturbed natural and synthetic fibre materials but the behaviour of soils reinforced with randomly distributed fibres needs additional evaluation. Past researches have shown that the addition of fibres within soil increases the peak shear strength and reduces the post-peak strength loss. The increase in shear strength due to fibre-reinforcement has been usually quantified by an increased 'equivalent' friction angle and cohesion, which have been typically determined by testing fibre reinforced soil specimens.

Limited information has been reported on the use of randomly distributed discrete fibres for soil reinforcement. Metal fibres, metal strips and artificial fibres of polymer compound due to their uniform material properties and reproducibility had been useful as reinforcement materials. Some limited information are available on the use of natural fibres like jute and coir fibres. Natural fibres have been used for a long time in many developing countries in cement composites and earth blocks because of their availability, low cost, strength, environment friendly nature and bulk availability. However, In addition to these stated advantages, it has some practical drawbacks, such as reproducibility and biodegradability.

1.2 Objective of the study

This study was conducted to determine the mechanism of oil palm empty fruit bunch (OPEFB) fibre as a new material on stabilized shear strength of the silty sand therefore; four main objectives were carryout as follow.

- To design treatment of OPEFB fibre from biodegradability as a soil reinforcement material

- To compare the shear strength and stress-strain relation of OPEFB fibre reinforced silty sand.

- To analyse the stress-path of OPEFB fibre reinforced silty sand in the critical state.

- To develop mathematical model for reinforced soil with OPEFB fibres.

1.3 Problem statement

The OPEFB fibre as a solid waste materiel can contaminate the environment. The OPEFB fibre was used to study the behaviour of the fibre to improve the soil strength. The experimental data can be used to define the methods of analyses and numerically describe the effect of fibres in stress path and stress-strain relation. Fibre morphology, soil properties and behaviour of fibre reinforced soil evaluated to determine the mechanisms of the fibres content and fibre length.

Statistical analyses and mathematical model are needed to estimate by comparing the experimental results. The mathematical model can be used as base for analysing the effect of fibres on soils in geotechnical projects and numerical modelling software.

1.4 Structure of thesis

This thesis is divided into five (5) chapters. Chapter 1 briefly introduces the research, including objective and scope of works for study. A review of the previous research on fibre-reinforcement is presented in Chapter 2 to provide the background of this research. Chapter 3 describes the research methodology which was used in the research and an overview of the experimental testing. In Chapter 4, the result of experimental tests, modelling and summary are described. The result of fibre reinforcement on silty sand and the effects of coating on morphology and properties of OPEFB fibres are described in this chapter. The conclusion and recommendation for this research are presented in Chapter 5.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In ancient times fibres was used for reinforcement of soils. Early civilizations added straws and plant roots to soil bricks and cob wall to improve their properties, although their mechanism may have not been fully understood. However, modern geotechnical engineering has focused on the use of planar reinforcement. The reinforcing of soil with discrete fibres is still a relatively new technique in geotechnical projects.

The concept of fibre-reinforcement in geotechnical projects originally involved the use of plant roots as reinforcement. Most researchers reported that plant roots increase the shear strength of the soil and, consequently, the stability of natural slopes (Fan and Su, 2008; Prandini *et al.*, 1977; Wu *et al.*, 1979). With development of using polymeric fibre since the late 1980s, triaxial compression tests, unconfined compression tests and direct shear tests have been conducted to study the effect of synthetic fibre-reinforcement on shear strength. Additionally fibre reinforcement previously used to improve the road structure. Fibre reinforced subgrade (coir fibre and synthetic fibre) had effectiveness on unconfined compression strength of silty sand soil (Chauhan *et al.*, 2008).

Previous research has shown that fibre-reinforcement can increase the peak shear strength and limited post peak reductions in shear resistance and decreased the stiffness of the soil. Most of the experimental studies were conducted using granular soils. Gray and Ohashi (1983) studied the mechanisms of fibre-reinforcement on dry sand reinforced with different types of fibre by using direct shear tests. Fibres were placed at different specific orientations with respect to the shear plane. The fibre content, orientation of fibres, and modulus of fibres were found to influence the contribution of fibres to the shear strength.

Alrefeai (1991) studied the behaviour of sand reinforced with discrete randomly oriented inclusions, among other factors, on particle shape and size of the sand. The effect of fibre-reinforcement was found to be more significant in fine sand with sub rounded particles than in medium grained sand with sub angular particles. The extensibility of the fibres was also found to influence the soil-fibre interaction. Fibre-reinforcement was reported to increase the shear strength of cohesive soils.

Andersland and Khattack (1979) performed triaxial tests on kaolinite clay reinforced with cellulose pulp fibres. The shear strength under various testing conditions (undrained, consolidated drained, and consolidated undrained) increased with increasing fibre content and the mode of failure changed from brittle to plastic. The ductility of the specimen was also found to increase with increasing fibre content. The load transfer mechanism on the fibre-soil interface was explained as an attraction between soil particles and fibres. Kumar *et al.* (2006) studied the effect of fibre content to improve load carrying capacity of highly compressible clay. Series of unconfined compression tests conducted on randomly distributed plain and crimped polyester fibres. Unconfined compressive strength of clay increases with the addition of fibres and it further increases when fibres are mixed in clay sand mixture. Akbulut *et al.* (2007) evaluated the use of waste fibre materials such as scrap tire rubber, polyethylene, and polypropylene fibre for the modification of clayey soils under unconfined compression, shear box, and resonant frequency tests. Waste fibres improve the strength properties and dynamic behaviour of clayey soils.

Maher and Ho (1994) carried out series of laboratory unconfined compression, splitting-tension, three-point-bending, and hydraulic conductivity tests on kaolinite clay reinforced with fibre, and reported that randomly distributed fibres increase the peak unconfined compressive strength, ductility, splitting tensile strength and flexural toughness of kaolinite clay. The contribution of fibre-reinforcement was found to be more significant for specimens with lower water contents.

Some researchers have studied the use of fibres to improve the ductility of cement-stabilized soils. Consoli *et al.* (1998) reported that fibre-reinforcement increases the peak and residual shear strength of cement-treated soil, and change their brittle behaviour to ductile behaviour. Kaniraj and Havanagi (2001) and Consoli *et al.* (2002) reported similar behaviour when using fibres with soils stabilized with cement or fly ash. Fibre reinforced and effect of fibre on cement stabilization was studied. The behaviour of fibre-reinforced uncemented soil was different from that in fibre reinforced cemented soil. Increasing fibre content could increase the peak axial stress and decreases the stiffness. Otherwise, the loss of post-peak strength and weakens the brittle behaviour of cemented soil decreased with increase in fibre content (Tang *et al.*, 2007). The behaviour of polyvinyl alcohol (PVA) fibre reinforced cemented sand with different distributed in layers also was shown increase in shear strength of soil. Distribution of the fibres in all part of the soil was more effective than layer distribution. The studies conducted on fibre reinforced soil were shown that when the same amount of fibres was reinforced the specimen, the specimen with five layers of fibre inclusion was 1.5 times stronger than the specimen with one layer at the middle.

2.2 Engineering Properties of Fibre Reinforced Soil

A new soil structure with enhanced engineering properties can be created in using short geofibres mixed in soil as reinforcement. The geofibre reinforced soil exhibits significant improved of performance properties. Traditionally, the fibre reinforced soil assumed as a homogeneous material and the design of fibre-reinforcement has been performed using a 'composite' approach. Generally an equivalent shear strength envelope for every condition of soil and fibre used to quantify the response of the composite under shearing.

2.2.1 Shear Strength of Fibre Reinforced Soil

Gray and Ohashi (1983) reported that the envelopes of fibre sand mixture show a bilinear trend. The shear strength envelope of fibre-reinforced specimens was found to be parallel to the envelope of unreinforced soil, once the confining pressure exceeds a critical or 'threshold' value.

Below the critical confining pressure, the reinforced soil showed a higher friction angle than in the unreinforced soil (Figure 2.1). Critical confining pressure is a function of the surface friction properties of fibre and soils (Gray and Alrefeai, 1986). Nataraj and McManis (1997) used direct shear tests on clay and sand reinforced with polypropylene fibrillated fibres obtained. The addition of fibre reinforcement in the sand and clay specimens was reported to substantial increase in the peak friction angle and cohesion values. The shear strength envelope for the clay specimens are described by a combination of curvilinear and linear sections. The friction angle at low confining pressures was found to be slightly larger than that at higher confining pressure. The phenomenon was explained as an effect of dilatancy, which increases the interface shear strength between fibre and soil. This effect is more pronounced at low confining stresses than at high confining stresses.

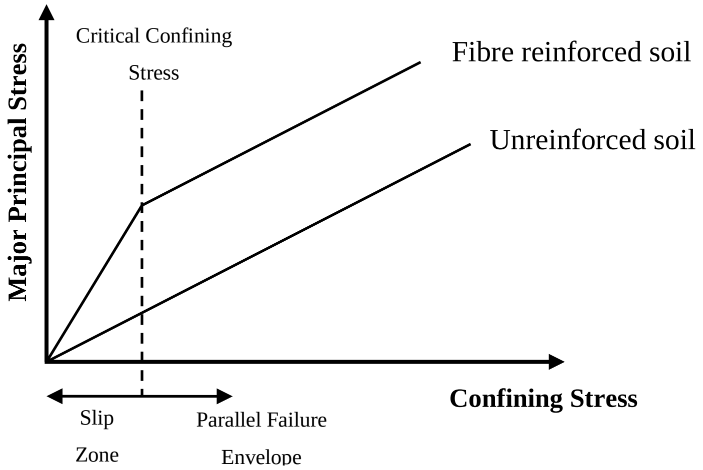

Figure 2.1: Shear strength envelope of fibre reinforced soil
(Gray and Ohashi, 1983)

Previous research on the equivalent shear strength of fibre-reinforced soil has focused on quantifying the effect of fibre content and aspect ratio. Several predictive models have been proposed. These include a load transfer model that requires parameters obtained with non-conventional testing of soil-fibre composites (Maher and Gray, 1990), a strain energy approach that uses energy concepts (Michalowski and Zhao, 1996), and a statistical model based on the regression analyses of previous test results. A recently proposed discrete design methodology (Zornberg, 2002) used concepts derived from limit equilibrium, and requires independent characterization of soils and fibres. Additional experimental results are needed to validate the proposed design models. The accuracy of the prediction of these models also relies on the proper understanding of the mechanism of interface interaction between fibres and soils.

2.2.2 Influence of Fibres on Soil Compaction

Fletcher and Humphries (1991) reported results of compaction tests on silty clay soil specimens reinforced with fibres. It was concluded that the presence of fibres decreases the ability of soil to densify. Unlike the case of sandy gravel reported by Hoare (1979), the test results showed that increasing the fibre content caused a modest increase in the maximum dry unit weight. The optimum water content was found to decrease with increasing fibre content. Other researchers (AlWahab and Al-Qurna, 1995; Nataraj and McManis, 1997; Prabakar and Sridhar, 2002) reported similar results. The results of compaction test on palm fibre reinforced silty sand were shown the maximum dry density decreases and optimum moisture content increases with increasing fibre content (Marandi *et al.*, 2008).

2.2.3 Hydraulic Conductivity of Fibre Reinforced Soil

Maher and Ho (1994) studied the effect of fibres on the hydraulic conductivity of a kaolinite-fibre composite. The fibre inclusion increased the hydraulic conductivity of the composite and the increase was more pronounced at higher fibre contents (up to 4% by weight). Despite the increase, the hydraulic conductivity of the composite was still low enough to be considered for some landfill applications and acceptable to satisfy the requirements for landfill cover design.

2.2.4 Dynamic Responses of Fibre Reinforced Soil

Dynamic responses for sands reinforced with randomly distributed fibres and with fibres orientated vertically to the shear plane were found to be similar (Maher and Woods, 1990). The inclusion of fibres was also reported to improve the reaction of a soil mass under dynamic loading condition. Reported test results have shown that fibres contribute to increase the dynamic shear modulus and decrease the liquefaction potential. Li and Ding, (2002) studied the effect of fibre reinforcement under cyclic test at small strain, the result indicated that elastic shear modulus of reinforced soil significantly affected by factors such as fibre content, confining pressure and loading repetition as well as shear strain. Elastic modulus of fibre-reinforced soil increases with increase of fibre content and confining pressure, and decreases with increase of loading repetition.

2.3 Applications of Fibre Reinforced Soils

The mixing of randomly oriented fibres to a soil mass may be considered similar to other admixtures used for soil stabilization. Fibre reinforcement has been considered in projects relating to slope stabilization, embankment construction, subgrade stabilization, and stabilization of thin surfaces such as landfill covers.

Figure 2.2 to Figure 2.4 show the procedure for spreading of the fibre over the surface, mixing the fibres with soil and compaction, in Joint Rapid Airfield Construction (JRAC) Demonstration Project. Joint exercise between U.S. Army Engineer Research and Development Center (ERDC) and Australian defense forces was constructed to build an unsurfaced airfield in the Bradshaw Field Training Area (BFTA) at the Northern Territory of Australia in June 2007. The exercise was completed in 22 total days of construction, demonstrating a spectrum of technologies designed to speed contingency engineering operations (Newman and White, 2008).

The project was conducted with the culmination of the JRAC Program through advancements in site selection technologies, enhanced construction methodologies, and new materials and techniques for rapid soil stabilization. The soil stabilization technique utilized a combination of polypropylene fibres and high-early strength cement to quickly increase soil load-bearing properties (Joint Rapid Airfield Construction, 2007).

Figure 2.2: Spreading Fibres over the surface (Joint Rapid Airfield Construction, 2007)

Figure 2.3: Fibre and cement mixed using slow speed Terex
(Joint Rapid Airfield Construction, 2007)

Figure 2.4: Compaction of soil and reinforcement mass
(Joint Rapid Airfield Construction, 2007)

Fibre reinforced soil was found to be suitable for repair of failed slopes. The irregular shape of the soil patches limits the use of textile reinforcements, making the fibre reinforcement an attractive alternative. Unlike textile reinforcements, fibre reinforcement does not need large excavation depth and also does not require a large anchorage length. The fibre used as a soil reinforcement called *geofiber* was appropriated for swelling potential mitigation in expansive soils (Viswanadham *et al.*, 2008). Only for the case of fibre reinforced slopes, it was found that increase in soil friction angle due to fibre inclusion leads to an increase normalized reinforcement tension (Zornberg, 2005).

Repairing of the slope with fibre reinforced soil was conducted on Lake Ridge Parkway in 2005. The project was located along Joe Pool Lake in the city of Grand Prairie, Texas (Gregory, 2006). Figure 2.5 shows the initial slope failure along the roadway and damaged on portion of the roadway pavement.

Figure 2.5: Initial slope failure along the roadway (Gregory, 2006)

Fibre reinforced soil was selected as the repair method for the slopes. Figure 2.6 illustrates the construction of soil embankment with polymeric fibres.

Figure 2.6: Fibre reinforced soil Embankment Construction- Lake Ridge Parkway (Gregory, 2006)

The geofibre has also been used mixed with planar geosynthetics for reinforced slopes or walls. Geofibre leading to an increase in the shear strength of the backfill materials, fibre reinforcement was reduced the required amount of planar reinforcement and eliminated the need for secondary reinforcement. Fibre-reinforcement has been reported to be helpful in reduce of the shallow failure on the slope face and reducing the cost of maintenance.

Another application for geofibres is the stabilization of soil surfaces for example landfill covers with fibres. The use of discrete fibres does not require anchoring, whereas, soil stabilization with continuous horizontal reinforcement required fixing the reinforcement into competent material under the soil surface. In contrast, geofibre is economically and technically reasonable. The fibres can be used to increase the stability of soil and control of desiccation cracking (Zornberg, 2005).

In pavement construction, fibre-reinforcement can be used to stabilize a wide variety of subgrade soils ranging from sand to high-plasticity clays (Santoni *et al.*, 2001). Randomly distributed fibre, when used as insertion in highway subgrade, can produce a high performance in the stabilization of weak roads. Many investigators (Raymond, 2002; Tang *et al.*, 2007) have used various types of fibres under different test conditions. The most important findings of the previous research work is that the use of certain fibre, such as synthetic and natural, in road construction can significantly increase pavement resistance to rutting, as compared to the resistance of non-stabilized pavement over a weak subgrade. Permanent deformation in each layer is the indicator of rut formation at the road surface. Consequently this was used as a criterion of pavement performance (Chauhan *et al.*, 2008).

The President George Bush Turnpike (PGBT) is located in the Dallas, Texas area. It is a multi-segment 6-lane toll road that has been constructed by use of fibre reinforcement soil. The fibres were used in the side slopes as a preventive maintenance measure to decrease the potential for the shallow slope failures. In addition, the fibre reinforced soil was used as secondary reinforcement between the geogrid layers in nearby the landfill site (Gregory, 2006). Figure 2.7 shows the mixing process of polymeric fibres with soil.

Figure 2.7: Mixing fibres with soil on the President George Bush Turnpike Project (Gregory, 2006)

Fibre-reinforcement has also been used for stabilization of expansive soil (Puppala and Musenda, 2000; Viswanadham *et al.*, 2008). Fibres were found to reduce shrinkage and swell pressures of expansive clays. The use of fibre was also reported to increase the free swell potential of the soils.

2.4 Fibres Used For Soil Reinforcement

Wide range of reinforcements was used in improvement of soil performance cause of attention to new accessible resource. Fibres such as polymeric fibre usually used as reinforcement as a woven and nonwoven geotextile or geogrid, recently some researches were studied using of discrete fibres, randomly distributed in soil mass. Polymeric fibre and natural fibre are two main fibre source have been used for soil reinforcing. Natural resources due to cost-effective and environment-friendly could be a good material for improvement of soil structure (Prabakar and Sridhar, 2002).

Cellulosic fibres are derived from many renewable resources and have many desirable properties for reinforcement such as low density, high stiffness and low cost (Jacob *et al.*, 2004).

2.4.1 Natural Fibres

Many natural fibres (such as coir, banana, sisal, palmyra, jute, pineapple leaf fibre, etc.) find applications as a resource for industrial materials. Properties of the natural fibres depend mostly on the nature of the plant, locality in which it is grown, age of the plant, and the extraction method used (Sreekala *et al.*, 1997).

Coir is a hard and tough multi cellular fibre with a central portion called ‘‘lacuna.’’, On the other hand, banana fibre is weak and cylindrical in shape. Sisal is an important leaf fibre and is strong. Pineapple leaf fibre is soft and has high cellulose content. Many studies have done on the natural fibre based composite products (Maldas and Kokta, 1990; Pavithran *et al.*, 1987; Shah and Lakkad, 1981; Sreekala *et al.*, 1997). Table 2.1 summarised the chemical and mechanical properties of some natural fibres.

Table 2.1: Chemical and mechanical properties of some important natural fibres

Fibres	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Pectin (%)	Tensile Strength (%)	Elongation (%)	Toughness (MPa)
OPEFB	65	-	19	2	248	14	2,000
Coir	32-43	0.15-0.25	40-45	-	140	25.0	3,200
Banana	63-64	19	5	-	540	3.0	816
Sisal	66-72	12	10-14	0.8	580	4.3	1,250
Pineapple	81.5	-	12.7		640	2.4	970

2.4.2 Properties of Oil Palm Fibres

Oil palm is one of the most economical and very high-potential perennial oil crops. It belongs to the species *Elaeis guineensis* under the family *Palmacea,* and originated in the tropical forests of West Africa. Major industrial cultivation is in Southeast Asian countries such as Malaysia and Indonesia. Large-scale cultivation has come up in Latin America. In India, oil palm cultivation is coming up on a large-scale basis with a view to attaining self sufficiency in oil production.

Oil palm fibre is non-hazardous biodegradable material extracted from oil palm's empty fruit bunch (EFB). Oil palm fibre is an important lignocellulosic raw material. OPEFB fibre and oil palm mesocarp fibre are two types of fibrous materials left in the palm-oil mill.

Mesocarp fibres are left as a waste material after the oil extraction. These fibres must be cleaned of oily and dirty materials. The only current uses of this highly cellulosic material are as boiler fuel and in the preparation of potassium fertilizers. When left on the plantation floor, these waste materials create great environmental problems. Therefore, economic utilization of these fibres will be beneficial (Sreekala *et al.*, 1997).

OPEFB fibre is obtained after the subtraction of oil seeds from fruit bunch for oil extraction. OPEFB fibre is extracted by the retting process of the EFB. Average yield of OPEFB fibre is about 400 g per bunch. Previous studies report the mechanical properties of OPEFB fibres. Table 2.2 shows the summary of oil palm fibre properties (Jacob *et al.*, 2004; Sreekala *et al.*, 2001; Sreekala *et al.*, 1997).

Table 2.2: Physical and mechanical properties of oil palm empty fruit bunch fibre

Chemical constituents (%)	
Cellulose	65
Hemi cellulose	-
Lignin	19
Ash content	2
Physical properties of oil palm fibre	
Diameter (mm)	0.15-0.50
Density (g/mm^3)	0.7-1.55
Linear density (denier)*	2150
Tensile strength (MPa)	100-400
Young's modulus (MPa)	1000-9000
Elongation at break (%)	14
Microfibrillar angle (°)	46

* 1 denier= 1/9000 g/m

2.4.3 Protection of Natural Fibres

Natural fibres, because of their degradability, need protection from any circumferential agents. Natural fibres are amenable to modifications as they bear hydroxyl groups from cellulose and lignin. In addition coating the fibres with any chemical materials reduce their water absorptions and protect them from any bacteria and fungi attack. The hydroxyl groups may be involved in the hydrogen bonding within the cellulose molecules.

Chemical treatments of cellulosic materials usually change the physical and chemical structure of the fibre surface. Effects of alkali, silane coupling agent, and acetylation have been tried on the oil palm fibres. It is reported that the alkali treatment on coir fibre enhances the thermal stability and maximum moisture retention (Mahato *et al.*, 1993).

Prasad *et al.* (1983) reported that the use of alkali treatment on coir fibres improves the mechanical properties of coir-polyester composites. Principal component of the oil palm fibres due to chemical analysis is cellulose. The cellulose content plays a significant role in the fibre's performance. The properties of the particle boards prepared from OPEFB fibre and urea formaldehyde resin have been reported earlier. Many studies were studied on the determination of fibre strength using different techniques (Curtin, 1994; Jarvela, 1984; Nedele and Wisnom, 1994).

Surface characteristics such as wetting, adhesion, surface tension, porosity, etc. can be improved upon modifications. Chemical bleaching of the fibres may cause major changes in fibre surface roughness.

Plasma treatment is another important treatment to reach better interfacial bonding of the fibre to the composite matrix. Improved fibre matrix interactions lead to chemical modifications of natural fibres such as pineapple leaf fibre, sisal, banana, etc. King and co-workers introduced polymeric coatings electrochemically of carbon fibre to improve liquid crystal polymer (LCP) matrix fibres (Sreekala *et al.*, 2000).

2.4.3.1 Acrylonitrile butadiene styrene

Chotirat *et al.* (2007) studied on Polymer–wood composite (PWC) of Acrylonitrile butadiene styrene (ABS) with natural fibre (wood sawdust) that prepared by varying the sawdust contents in order to seek the optimum interfacial strength by considering the mechanical and morphological properties of the composites.

ABS is an important engineering copolymer widely used in industry due to superior mechanical properties, chemical resistance, ease of processing and recyclability (Yang *et al.*, 2004). ABS is a common thermoplastic used to make polymeric wood composites, has good physical properties in comparison with other commodity plastics and is cheap in comparison with other engineering plastics (Huang and Mo, 2002).

ABS is derived from acrylonitrile, butadiene, and styrene. The chemical structure of the ABS showed in Figure 2.8. Acrylonitrile is a synthetic monomer produced from propylene and ammonia. Butadiene is a petroleum hydrocarbon obtained from butane. Styrene monomers, derived from coal, are commercially obtained from benzene and ethylene from coal. The advantage of ABS is that this material combines the strength and rigidity of the acrylonitrile and styrene polymers with the toughness of the polybutadiene rubber. The most amazing mechanical properties of ABS are resistance and toughness.

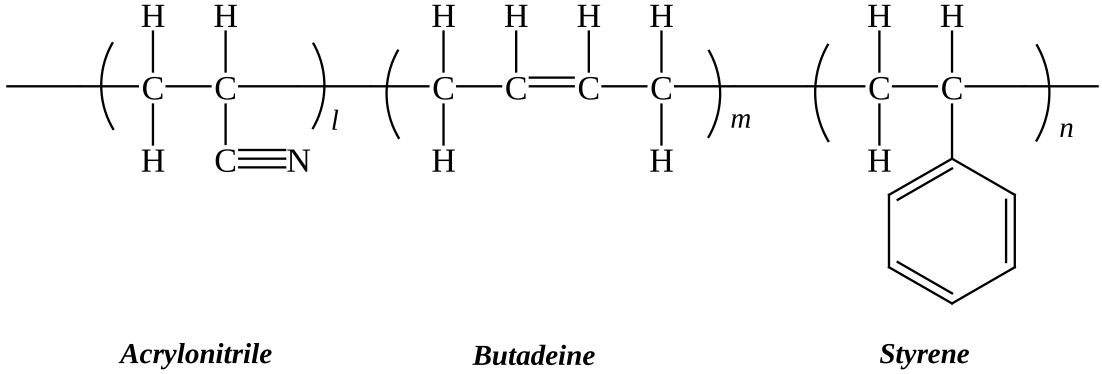

Figure 2.8: Chemical structure of ABS

The chemical resistance for ABS is relatively good and it is not affected by water, non organic salts, acids and basic. The material will dissolve in aldehyde, ketone, ester and some chlorinated hydrocarbons. The properties of molded ABS are shown in Table 2.3 based on MatWeb (2009) material specification data sheet.

Table 2.3: Physical properties of molded ABS

Property	Test Method	Value
Tensile Strength	ASTM D638	44.8 MPa
Flexural Modulus	ASTM D638	2.59 GPa
Tensile Elongation	ASTM D638	15 %
Flexural Yield Strength	ASTM D790	69 MPa
Flexural Modulus	ASTM D790	2.59 GPa

ABS was found to be completely soluble in methyl ethyl ketone (MEK) indicating that no significant gel-forming reactions occur during melt processing. The melt viscosity of the blend is not substantially increased relative to the pure ABS material. The experiments were shown a fundamental difference in rheological response when epoxy functional polymers are blended with emulsion-made versus mass-made ABS materials (Hale *et al.*, 1999).

2.4.3.2 Morphological Analysis of Treated Fibres

Fourier transform infrared (FTIR) spectroscopy is an important tool for investigating the changes in the structure of fibre surface. Previous studies used FTIR to examine the effect of treatment on changes of the chemical bonds in fibre surface (Figure 2.9) (Sreekala *et al.*, 1997). The standard characteristic frequencies for Infrared spectra was shown in Table 2.4.

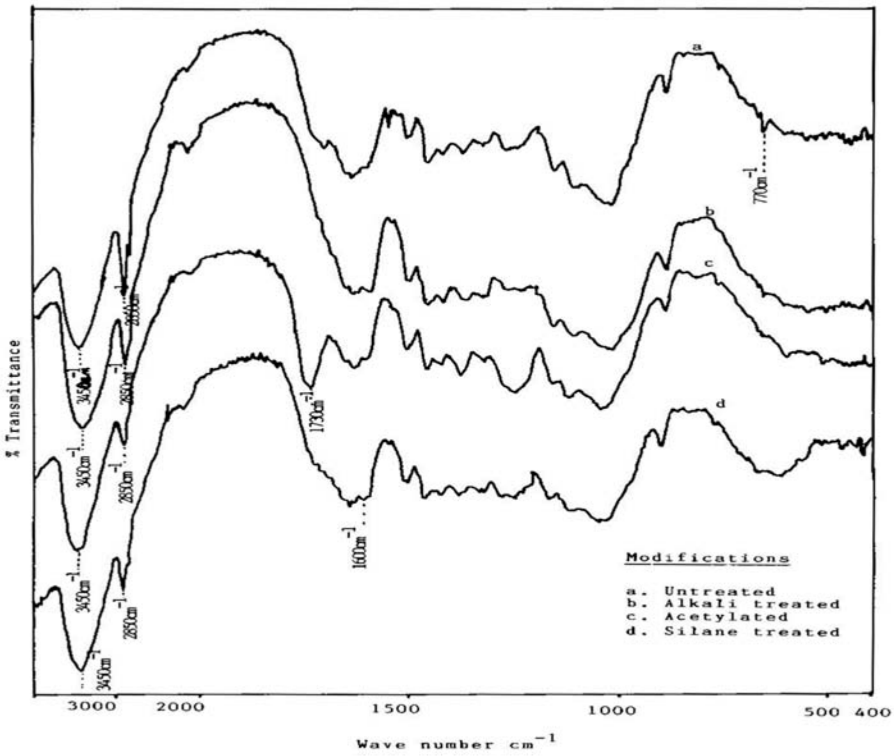

Figure 2.9: Treated and untreated OPEFB Fibre (Sreekala *et al.*, 1997)

Scanning Electron Microscopy (SEM) was used to study the microstructure and the surface morphology of treated and untreated cellulose fibres (Sreekala *et al.*, 1997).