



## Potential of Coir Fibres as Soil Reinforcement

Vivi ANGGRAINI<sup>a\*</sup>

<sup>a</sup>Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia

<sup>a\*</sup>vianggraini@gmail.com

**Abstract** – This paper presents an evaluation of the alternative use of natural cellulose coir fibres for soil reinforcement. Soil reinforcement is defined as a technique to improve the engineering properties of soil. Inserting natural fibres into the soil has been proposed as a reinforcement method. Randomly distributed coir fibre reinforced soils have recently attracted increasing attention in geotechnical engineering due to their strength. Furthermore, there is a need to develop an innovative and sustainable pre-treatment method to improve the effectiveness and performance of coir fibre as soil reinforcement. The primary purpose of this paper is, therefore, to review the characteristics, benefits, applications and weaknesses of coir fibre as soil reinforcement.

**Keywords:** Coir fibre, fibre treatment, soil reinforcement, sustainable material.

### Introduction

Soils generally have low tensile and shear strength, and their characteristics may strongly be influenced by environmental conditions (e.g. dry versus wet). Soil reinforcement involves the incorporation of certain materials with some desired properties into soils which lack those properties (Hejazi, Sheikhzadeh, Abtahi, & Zadhoush, 2012). Therefore, soil reinforcement is defined as a technique to improve the engineering characteristics of soil. The primary purpose of reinforcing soil mass is to improve its stability, to increase its bearing capacity, and to reduce settlements and lateral deformations (Freitag, 1986). There are various soil reinforcement methods, including stone columns, root piles, soil nailing and reinforced earth. Reinforced earth is a composite material consisting of compacted backfill and man-made reinforcing materials such as fibrous materials (geosynthetic family and randomly distributed fibres). The idea of reinforcing soils using fibres is one that has been in use for a long time (Freitag, 1986; Mandal & Murthi, 1989; Prabakar & Sridhar, 2002; Cai, Shi, Ng, & Tang, 2006; Bateni, Ahmad, Yahya, & Azmi, 2011). Initial developments in soil reinforcement led to the use of plant roots and straws in walls made from soil bricks to improve their mechanical properties. Fibre reinforcement in soils acts as homogeneous materials in composites which are fibres, and have high tensile strength included in a soil matrix. Tensile resistance in the fibres affects the shear stress in the soil and contributes greater strength to the soil composites.

The mechanical properties of fibre (synthetic and natural) reinforced soil have been investigated by various researchers. A number of triaxial tests, unconfined compression tests, California bearing ratio

(CBR) tests, direct shear tests, tensile strength tests and flexural strength tests have been conducted on the subject by several researchers in the last few decades (Mandal & Murthi, 1989; Ghavami, Toledo Filho, & Barbosa, 1999; Prabakar & Sridhar, 2002; Cai et al., 2006; Tang, Shi, Gao, Chen, & Cai, 2007; Harish, Michael, Bensely, Lal, & Rajadurai, 2009; Viswanadham, Jha, & Pawar, 2009; Dutta, Khatri, & Venkataraman, 2012; Hejazi et al., 2012; Divya, Viswanadham, & Gourc, 2013; Hamidi & Hoopesfand, 2013; Onyejekwe & Ghataora, 2013; Anggraini, Huat, Asadi, & Nahazanan, 2014). All previous studies have shown that the addition of fibre-reinforcement causes significant improvement in the strength of the soil, and increases its stiffness.

There is a greater consciousness today that landfills are filling up, resources are being used up, the planet is being polluted and that non-renewable resources will not last forever. Also, global trends indicate that the marketplace is leaning towards natural fibre use because of various societal and economical concerns. Coir fibre is an agro-waste by-product obtained from coconut plantations. The use of coir (fruit fibres) as soil reinforcement is a cost-effective method of soil reinforcement in countries like India, Malaysia, Indonesia, Brazil, and many others. Malaysia is one of the largest coconut suppliers with a production of more than 120 million tonnes annually (Ministry of Agriculture Malaysia, 2005). The coir fibres are also thick, strong and have high abrasion resistance. The development of composite materials for buildings using natural fibres such coir fibre with low thermal conductivity is an interesting alternative which can possibly solve environmental and energy problems. Therefore, there is a growing interest in exploiting natural fibres, especially coir fibre, for soil reinforcement in recent years. This paper reviews the characteristics, benefits, and applications of coir fibres in soils to illustrate the reinforcement potential of coir fibre. The paper will also review the use of pre-treatment methods to improve the performance of coir fibre as soil reinforcement.

### **Coconut (Coir) Fibre**

Coir is a natural fibre extracted from the husk of coconuts and used in products such as floor mats, doormats, brushes, and mattresses. Coir is the fibrous material found between the hard, internal shell and the outer coat of a coconut. The fibres are normally 50-350 mm long and consist mainly of lignin, tannin, cellulose, pectin and other water soluble substances (Rowell, Han, & Rowell, 2000).

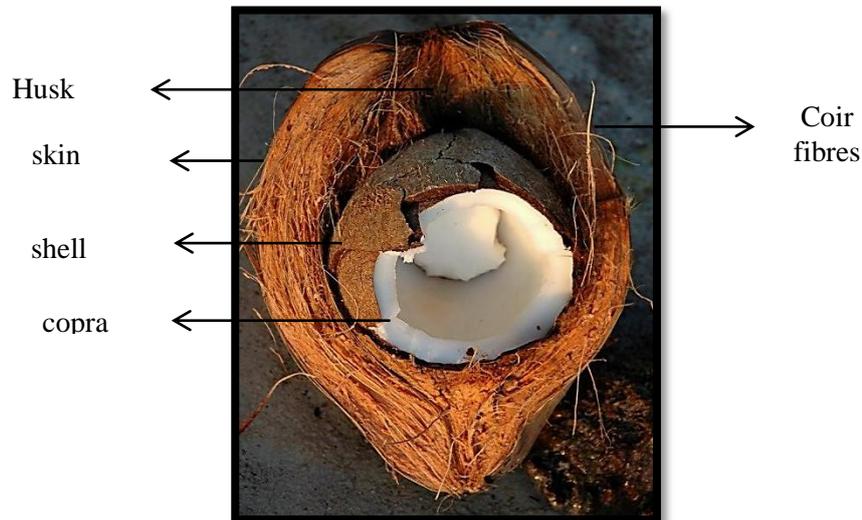


Figure 1: Cross section of a coconut

#### *Types of coir fibre*

Coir fibres are categorized in two ways (Khan, 2007; Gu, 2009). One distinction is based on whether they are recovered from ripe or immature coconut husks. The husks of fully ripened coconuts yield brown coir. Dark brown in colour, it is used primarily in brushes, floor mats, and upholstery padding. On the other hand, white coir comes from the husks of coconuts harvested shortly before they ripen. Generally light brown or white in colour, this fibre is softer and less strong than brown coir fibre.

#### *Coir Fibre Structure*

Coir is the material between the hard internal shell and the outer coat of a coconut. It consists of multi cellular fibres of which the central portion is lumen. Coir fibre is a composite which is deposited on the cell wall as a layer of lignin and hemicellulose. Each cell wall in a coir fibre is about 1mm long and 10 mm in diameter, therefore, the wall of cell is an inhomogeneous membrane (Figure 2). Each coir fibre has complex properties, with each layer structure consisting of a further two layers. The first layer is the thin primary wall, and the next layer is the secondary wall. This secondary wall consists of three layers and the mechanical properties of the fibre can be determined at its thick middle layer.

The middle layers of coir fibres are made of a series of helically wound cellular microfibril which comes from a long chain of cellulose molecules. The microfibrillar angles of fibres are located in between the fibre axis and the microfibrills. The size and characteristics of the angles are varied. The microfibrills vary in diameter of about 10-30nm, and consist of 30-100 cellulose molecules. This contributes to the mechanical strength of the coir fibres (Subaida, Chandrakaran, & Sankar, 2008). The amorphous region of the fibres mainly consists of lignin and hemicellulose, and sometimes pectin. These complex hemicellulose molecules are bonded with hydrogen which acts as a cementing agent. The cementing matrix between the network of cellulose, the hemicellulose and cellulose micro fibrils is defined as the main structural component in the cell of coir fibre. The stiffness of the cellulose and hemicellulose composite depends on a coupling agent from the hydrophobic lignin network. The

lignin networks increases the stiffness of the composite of the network and acts as a coupling agent (John and Anandjiwala, 2008).

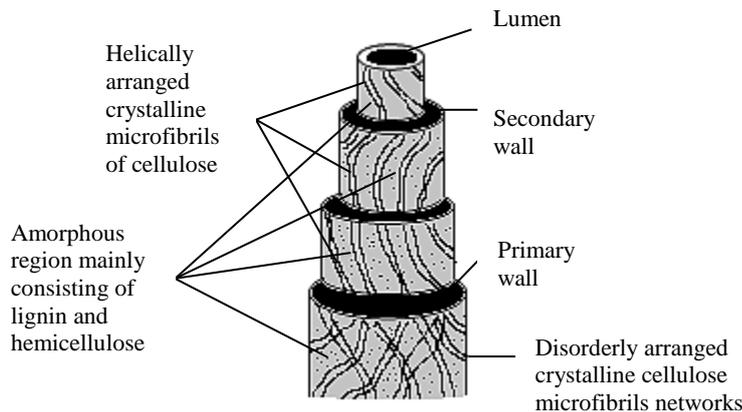


Figure 2: Structure of natural fibre

Critical micro-structural parameters that affect the mechanical properties of natural fibres include cellulose content, cellulose crystallinity, microfibril angle and fibre aspect ratio. Previous studies found that these four parameters are strongly correlated to the tensile properties of natural fibres (McLaughlin & Tait, 1980; Satyanarayana et al., 1982; Mukherjee & Satyanarayana, 1986). Several studies on the prediction of natural fibre tensile properties also found correlation with these four parameters (Gassan, Chate, & Bledzki, 2001; Baley, 2002; Placet, Trivaudey, Cisse, Gucheret-Retel, & Boubakar, 2012).

#### *Structural Properties*

Coir fibre contains more lignin than all other natural fibres, such as jute, flax, linen and cotton. It has a lignin content of 45.84%, which makes it the strongest of all known natural fibres (Eze-Uzomaka, 1991; Ayyar Ramanatha, Nair, & Nair, 2002; Sen & Reddy, 2011a). The strong coir fibre is waterproof and is resistant to saltwater damage. Coir fibre retains its tensile strength in wet conditions (Sivakumar Babu, Vasudevan, & Sayida, 2008). Mostly, coir fibre has higher coefficient friction against synthetic fibres. For example, findings show that coir fibres show significant enhancements at 47.50%, compared to resilient modulus of synthetic fibre at 40% (Chauhan, Mittal, & Mohanty, 2008).

#### **Fibre as soil reinforcement**

##### *Sample preparation*

The mixing of fibres through soil composites is not well discussed in the literature (Hejazi et al., 2012). Mainly, two methods can be taken into account when investigating the mixing of fibre with soil composites. Fibres can either be mixed through soil matrix material manually or a mechanical mixing machine can be used. There are three types of mechanical procedure, namely the tumbler mixer, the concrete mixer and cultivator mixing (Segetin, Jayaraman, & Xu, 2007). Allen (1997) reported that folding fibres through a soil matrix is the most effective method of mixing in the field. This can be done with the use of a front-end loader, a bobcat or similar devices with a bucket

attachment. A major concern for all the above techniques is to ensure a homogenous mixture in the laboratory and in the field.

*Coir fibre as soil reinforcement*

Short coir fibres as soil reinforcement have recently attracted increasing attention in geotechnical engineering. Coir fibres and their features in soil projects are summarized in *Table 1*.

*Table 1: Summary of research performed on widely-used coir fibres to reinforce soil*

D (mm)	SG (g/cm <sup>3</sup> )	E (GPa)	UTS (MPa)	Length (mm)	Optimize fibre percentage	Fibre special property	Soil types used in the literature	Conclusions	Ref
0.20-0.25	0.71	-	-	20-30	0.5%	High tensile capacity	Clay	Reduces the settlement and improves the bearing capacity	(Banerjee, Chattopadhyay, & Guha, 2002)
0.1-0.2	1.15-1.33	4-5	250	10-50	1%	Retains much of its tensile strength when wet  -low tenacity but high elongation Keeps 80% of its tensile strength after 6 months of embedment in clay	Expansive soil	Fibres decrease the MDD of the soil while increasing the OMC	(Sivakumar Babu et al., 2008)
0.1-0.39	-	-	-	15-25	1-5%	Reduces immediate settlement	Clay	Increases strength and stiffness of the soil	(Babu & Vasudevan, 2007)
-	-	-	-	-	~1%	Has proper interaction between coir fibres and soil.	Black cotton soil	Increases OMC, reduces MDD and increases ductility of soil	(Ramesh, Krishna, & Meena, 2011)

0.13- 0.27	-	7.7- 9.5	-	-	-	Has ability to absorb water	Clay	Prevents shrinkage, crack in soil by adhesion or bonding the soil	(Ghava mi et al., 1999)
0.18	-	-	-	15	1.6%	Good strength characterist ic	Clay	Increases the unconfine d strength	(Dutta et al., 2012)

*Table 1* shows that the provision of coir reinforced soils reduces the settlement and improves the bearing capacity. The compaction fibre and soil characteristics below their optimum moisture content, behaved satisfactorily in tensile strength, unconfined compressive strength and flexural strength (Sivakumar Babu et al., 2008). Furthermore, Young's modulus of the reinforced soil evolves in time. The optimum percentage was gained at 1 to 2 % of coir fibre content and the effective length ranged is about 10-50mm. With the fibre content higher than 2%, the relative volume occupied by fibres increases, indicating that the fibre-to-fibre interaction dominated, compared to soil to fibre interactions or soil alone. The degree of interlocking and friction mobilized in the sample is then reduced. Subsequently, the coir fibre inclusion increases the efficiency to transfer the load matrix to coir fibres, especially at 6 months age of curing (Sivakumar Babu et al., 2008).

The maximum dry density of the soil decreases and the optimum moisture content increases with the inclusion of the coir fibre reinforced lateritic soils of up to 1% coir fibre content. The presence of fibre greatly improved water absorption (Ghavami et al., 1999). Ramesh et al. (2010) in their study found that coir fibres and lime-reinforced soils are noticeably better than untreated soils or soils alone with coir fibre in terms of their strength properties. Previous studies have also shown that the efficiency discrete coir fibres reduce swelling potential of expansive soils (Ayyar, Krishnaswamy, & Viswanadham, 1989; Sivakumar Babu et al., 2008).

Coir fibre composites are of particular interest as these composites have high impact strength (Sen & Reddy, 2011b). As a random reinforcing material, coir (1-2%) increases strength, permeability and stiffness of clay soil (Andersland & Khattak, 1979). Andersland & Khattak worked with a coir-concrete composite and concluded that even though the addition of fibre reduced the workability of fresh concrete, marginal improvements in the mechanical strength properties were observed which ranged from 10% to 20%. Recently, coir fibre has been proven to increase significantly the flexural strength, indirect tensile and unconfined compression test of soft marine clay soil (Anggraini, Huat, Asadi, & Nahazanan, 2015a). The performance of coir fibre inclusion in additive soil is remarkable compared to coir fibres and soil only (Anggraini, Asadi, Huat, & Nahazanan, 2015; Anggraini, Huat, Asadi, & Nahazanan, 2015b). Application of randomly distributed chemically treated coir fibre as tensile reinforcement elements with lime in soft soil is feasible in geotechnical engineering, such as in earth platform and soil-foundation engineering. Studies found that bond strength and friction at the interface seem to be the dominant mechanisms controlling the reinforcement benefit. The interactions

occur at the interface between the fibres' surface, and soil grains play key roles in their mechanical behaviour. The micromechanical behaviour of the fibres and matrix interface depends on bonding material properties in the soils, effective contact area and fibre surface roughness. Therefore, there is a need to improve the performance of coir fibres especially in increasing its interaction, its material strength and its durability as soil reinforcement.

### **Natural fibre treatment**

Despite coir fibre's many advantages compared to other plant fibres, its properties still need to be improved to be used in any application. Its low mechanical strength and poor interactions due to its surface are among its weaknesses as soil reinforcements. Structural stability of coir fibres as soil reinforcements depend on the modifications that are made to the coir fibres. Consequently, improving the mechanical performance and the interaction of coir fibre surface with soil using facile approach has attracted many researchers (Eze-Uzomaka, 1991; Ghavami et al., 1999; Sen & Reddy, 2011b). Several methods such as physical methods, chemical methods and biological methods have been used to treat natural fibres (Ghavami et al., 1999; John & Anandjiwala, 2008; Chattopadhyay & Patel, 2009; Bateni et al., 2011; Castellanos, Blanco-Tirado, Hinestroza, & Combariza, 2012; Li, Xi Chai, Yuan Zhang, Pu Du, & Wei, 2012; Chowdhury, Beg, Khan, & Mina, 2013b; Khandanlou, Ahmad, Shameli, & Kalantari, 2013; Ridzuan et al., 2013; Sarbaz, Ghiassian, & Heshmati, 2014).

For a number of these applications, the characteristics of the fibre surface are very important to obtain high interaction in composite. Chemical treatments of the surface of coir fibres have been reported to improve their wettability and to modify their microstructure, surface topography, surface chemical groups and tensile strength (Chattopadhyay & Patel, 2009; Kalia et al., 2011; Chowdhury, Beg, Khan, & Mina, 2013a). In these pre-treatment methods, alkali such as sodium hydroxide (NaOH), is the most common chemical used to improve interfacial compatibility. Calado and Boreto (2008) reported that the untreated fibres have an outer surface layer and this layer is completely removed by chemical treatment with sodium sulphite and acetic anhydride. Upon removal of this outer layer, a rougher but more ordered structure is revealed. These methods may useful to increase adhesion between fibres and soils.

On the other hand, Gu (2008) studied how the alkali treatment of the coir fibres would significantly increase the tensile strength of the produced composites. However, deterioration of the fibres' strength after treatment was unavoidable. Marques et al. (2014) and Silva et al. (2000) found that lime treatment was efficient in preserving the cellulose structure of coconut fibre initially. As cellulose is the main structural constituent of plant fibres and tensile strengths, Young's modulus increases with cellulose content in plant fibres. Without modification, the coir fibre structures will disintegrate over time, but still provides short time protection. Once it receives some modification, the durability of the coir fibres is extended, and they will be able to last longer. As previously mentioned, the durability of the coir fibre can be maintained by using coir composites and abstaining from treating fibres with chemical bleaches or salt (Eze-Uzomaka, 1991; Sen & Reddy, 2011a; Mathura, 2012). The combination method has also been developed, producing palm empty fruit bunch fibres by chemical and physical treatment (Chowdhury et al., 2013a). These findings strongly suggest that copper

nanoparticles under strong alkaline conditions at an elevated temperature (60-120°C) can be used as an effective reinforcing agent in natural fibres to improve their mechanical property and durability. Also, Dutta et al. (2012) further reported that treated coir fibre prior to using NaOH and CCL<sub>4</sub> contributes significantly to the coir fibre's strength compared to untreated fibres. However, all the above pre-treatment methods use harmful materials. Further, it is challenging to apply the pre-treatment methods in the field with large quantities of coir fibres; since the process is conducted at high temperatures.

The new technique approach is the quick precipitation method where nanoparticles could be formed without any additional agent and surfactants at room temperature. This method may be more attractive due to its simple operation, ease of mass production and cost-effectiveness (Khandanlou et al., 2013). The authors revealed that Fe<sub>3</sub>O<sub>4</sub> nanoparticles impregnation was successfully conducted in rice straw by the quick precipitation method. The reaction was performed in aqueous suspension phase under ambient conditions. This method outweighs the cationization process since it is conducted at room ambient conditions and uses environmentally friendly and low cost raw materials.

### **Potential Areas for Future Research**

The use of coir fibres in combination with the soil matrix has had various degrees of success in improving the mechanical properties of soils. All previous studies have shown that the addition of coir fibre reinforcement causes significant improvement in the strengths of the fibre and soil composite. Therefore, coir fibre can be considered as good earth reinforcement materials, which cause significant improvement in the engineering properties of soils. The 10-50mm long fibres, introduced randomly, were used in the reinforcement of the soil composite. It will be necessary to investigate other dimensions in order to establish the optimum length of maximum strength. If short coir fibre is mixed uniformly within the soil mass, it can provide an isotropic increase in shear strength to the soil composites without introducing planes and weaknesses. Therefore, the effect of orientation coir fibres in soil matrix should also be studied.

The inclusion of fibres in soil can significantly increase soil tensile strength and soil tensile failure ductility. The main variable, which generally controls the strength and performance of the improved composite are tensile strength, water absorption of the coir fibres and their bonding with soil. However, more work is necessary to comprehend the influence of coir fibres on the mechanical behaviour of cemented and uncemented soils, especially the interfacial interactions between fibre surface and soil matrix by carrying out fibre pull-out tests. Long term performance of the coir fibre reinforced soil can also be observed.

Based on the success of coir fibre reinforced soil in the laboratory, efforts need to be made to extend this method as an in-situ ground improvement technique. The expected outcome is to reduce settlement, improve bending performance and to reduce tensile cracking at any geotechnical structures. Such research is needed to have better understanding of the potential benefits and limitations of coir fibres with or without other additive applications in more complex geotechnical structures (such as the retaining wall).

Various pre-treatment methods, such as biological and chemical methods, have been introduced to improve the mechanical performance of natural fibres. However, there is a need to develop an innovative and sustainable pre-treatment method that can change the morphology of the coir fibres surface roughness that may cause better mechanical interlocking between fibres and soil matrix and increase fibre tensile strength. Tests on the water absorption to investigate the durability of the soil composite through the intended modification on natural coir fibre should be carried out. Furthermore, in order to understand better the bond between soil matrix and coir fibres, a study of the microstructure is also needed.

### **Concluding remarks**

This paper reviewed the potential of using discrete randomly distributed coir fibre as soil reinforcement. Several things were considered in choosing natural fibres as soil reinforcement, such as their availability, structural properties and low cost. The utilization of randomly distributed coir fibre in soil reinforcement is a new source of materials due to their superior mechanical properties, availability, simple production process and non-hazardous nature. Coir fibre has high lignin content, more than nearly 60%. Young's modulus and tensile strength is high due its initial high lignin content. In tropical and subtropical regions, coir fibres are abundantly available and are relatively cheap. Furthermore, the use of coir fibres will also provide environmental motivation for providing a means for recycling large quantities of coir fibres.

The randomly distributed coir fibre in soil is a simple and feasible technique to be carried out in the laboratory and in the field. The procedures are typically similar to adding additives in soils. Typically, a dosage rate is 0.5 to 2 % by dry weight of coir fibres used as soil reinforcement. Several researchers have recently attempted to study the effect of coir fibre reinforced various soils. All of the published papers have generally shown that the addition of coir fibre reinforced soil significantly increases the strength and stiffness as well as ductility of soils, contributing to fibre characteristics such as tensile strength and modulus of elasticity. Direct shear test, unconfined compression tests, flexural strength, tensile strength and triaxial compression tests have demonstrated that the mechanical properties and shear strength are increased with the addition of coir fibres in soils. The bond strength and friction at the interface between fibre and soil grains are to be the dominant mechanism controlling the reinforcement benefit. The main factors which affect the addition between the reinforcing fibres and soil are the cohesive properties of soils and the shear resistance of the soil due to the surface form and roughness of the coir fibres. Thus, using coir fibre in soil is an effective reinforced soil technique in the geotechnical engineering field.

Despite the many advantages, some modifications would be useful to improve the effectiveness of coir fibres as soil reinforcement. Modifications on its durability, mechanical strength and surface roughness can help improve the strength of the coir fibre and soil interactions. Some pre-treatment methods are also introduced in this paper as well as the advantages and disadvantages of each method. However, research on sustainable modification of natural fibres should be developed and continued.

Furthermore, in order to understand better the bond between soil matrix and coir fibre, a study of the microstructure is needed.

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