PROPERTIES OF NATURAL REINFORCED EARTH-BASED COMPOSITES: ADVANTAGES AND DRAWBACKS WITH SYNTHETIC REINFORCEMENTS

C. Rivera-Gómez[1], C. Galán-Marín[1] and F. García-Galindo[1]

[1]Department of Building Construction, University of Seville
Avda. Reina Mercedes 2, 41012, Seville, Spain
Email: crivera@us.es, cgalan@us.es, fgg.ark@gmail.com

Keywords: Earth-based composites, Natural vs. synthetic reinforcement, Physical and technical properties, Sustainability, Comparative review

ABSTRACT

The increase of awareness of the need to improve the sustainability of the construction industry and the concurrent development of "Green Technologies" has led to the raise of bio-composite materials with natural reinforcements for building applications. This process has involved the revival of the interest in the use of natural reinforced earth materials. Of these, the earthy materials with natural or synthetic reinforcements belong to a field that hasn't been very much developed beyond traditional or emergency applications in architecture.

The most determining aspect to develop products and systems based on reinforced earth based composites is the huge diversity on its physical and mechanical properties. Composites properties depend on diverse variables, among which are those concerning the type of soil and ground grain, type of reinforcement fibers (natural or synthetic), natural conditions in which were obtained, processing methods and characteristics of the possible matrices used as stabilizers.

This paper aims for a comprehensive review of literature of the available natural or synthetic reinforced earth based composites. General characteristics of the mainly used reinforcement agents depending on its origin, type, composition, structure, chemical composition and mechanical properties of the studied material (animal hair, jute, sisal, coir, flax, hemp, pineapple fiber, bamboo, rice husk, oil palm, etc). Moreover, different processing methods to improve physical and chemical characteristics, together with processing systems and factors affecting the production and characteristics of these composites will be considered (moisture content, type of reinforcement, ratios, distribution, coupling agent, etc.).

The present review is intended to update the overview the research of these kind products as well as to outline the main objectives and issues addressed in these current lines of research.

1 INTRODUCTION

Earth is one of the most commonly used building materials. Ancient cultures used earth for building houses, fortresses, palaces and religious buildings and it is estimated that today one third of the world's population lives in houses constructed from Earth. Houses are still built from earthen materials in developed countries and there are well known examples in countries such as the United States of America for instance "The Tucson residence" [1] and in Belgium - "The Residence Korbeek" [2]. Earth construction has also been used within religious buildings such as the Chapel of reconciliation in Berlin [3] and within industrial architecture, for example, "The Bodegas La Raia" in Piemonte, Italy.

There are several pillars for sustainable architecture, developed and detailed by multiple authors such as Garrido [4]. Also there are many different construction techniques throughout the world that have been adopted for working with raw earth. Most of them are ancient techniques that have existed with minor changes through many centuries to the present day, whilst others are modern inputs.

Construction methods are often strongly related to local customs, the local climate and the characteristics of the available soil.

The main earthen construction techniques are rammed earth or pisé (de terre), Adobe, cob, compacted earth blocks (CEB) or earth bags. Rammed earth is the construction of monolithic walls by compacting earth between a few planks of wood. It has been used in a variety of different building typologies throughout the world. Compacted earth blocks (CEBs) are bricks of raw soil with a low water content which are manufactured by a simple pressing device which uses mechanical pressure to obtain regular forms and improved loadbearing ability. A further form of earth construction, currently under development, is "superadobe" and this system comprises earth bags. It was developed by the Iranian architect Nader Khalili [5] and uses polypropylene bags or textiles stuffed with soil to allow solid constructions.

2 FIBRES AND REINFORCEMENTS

The standard fibre-reinforced soil is defined as a soil mass that contains randomly distributed, discrete elements (fibers) that provide an improvement in the mechanical behavior of the soil composite [6]. Fibre reinforced soil behaves as a composite material in which fibers of relatively high tensile strength are embedded in a matrix of soil. Shear stresses in the soil mobilize tensile resistance in the fibers, which in turn imparts greater strength to the soil [7-9].

Different literature reviews show that short fiber soil composites can be divided into two distinct categories. One group comprises a soil with a randomly direct inclusion of fibers into the matrix, i.e. soil mass. The other group consists of oriented fibrous materials, e.g. the Geo-Synthetics family [10, 11]. The former category is not as well-known as the second, not only in terms of optimizing fiber properties, fiber diameter, length, surface texture etc., but also in the reinforcing mechanism [10].

As stated in the introduction early civilizations discovered that it was possible to improve load bearing capacity of soils through the utilization of a stabilizing agent like pulverized limestone or calcium [12]. An alternative natural strengthening system utilizes the presence of plant roots as a natural means of incorporating randomly oriented fiber inclusions in the soils. These plant fibers improve the strength of the soils and therefore consequently the stability of natural slopes [11-17].

The concept of fiber reinforcement was therefore recognized more than 5000 years ago. Ancient civilizations used straw and hay to reinforce mud blocks in order to create reinforced building blocks and there are several examples of reinforced soil such as is contained in the Great Wall of China (which demonstrates the earliest examples of reinforced earth using branches of trees as tensile materials)and the Ziggurats of Babylon which contain oven mats of reed.[18].

Modern concepts and principles of soil reinforcement were first developed by Vidal (1969). He demonstrated that the introduction of reinforcement elements in a soil mass increased the shear resistance of the medium [19, 20]. Consequently, research activity which utilized various fibrous materials, which had been incorporated in the past, started again. Since the modern day development of soil reinforcement, nearly 4000 structures have been built in more than 37 countries. [21, 22].

Interestingly, randomly distributed fiber-reinforced soils, known as short fiber soil composites, have recently attracted increasing attention in many geotechnical engineering applications, not only in scientific research environment, but also at field applications [23]. Synthetic staple fibers have been used in soil since the late 1980s, when the initial studies using polymeric fibers were conducted [6].

Finally, it can be concluded that the concept of reinforcing soil with natural fibers originated in ancient times. However, short natural and synthetic fiber soil composites have recently attracted increasing attention in geotechnical engineering for the second time. Therefore, they are still a relatively new technique in geotechnical projects.

2.1. Natural Fibres

At the present time, there is a great awareness that landfill sites are filling up, resources are being used up, the planet is being polluted and non-renewable resources are depleting. There is therefore a pressing need to discover more environmentally friendly materials and consequently a great deal of recent interest has developed worldwide into the potential applications of natural fibers for soil reinforcement. There have been a number of recent experimental research projects and the term "eco-composite" has emerged in literature demonstrating the important role of natural fibers in the modern construction industry [24]. Interestingly, natural fibers have been used for a long time in many developing countries in cement composites and earth blocks because of their availability and low cost [25-27] so this is not an entirely new construction technology.

There are many factors which affect the performance of natural fibers in a composite natural fiber reinforced soil including the particular part of the plant that the fiber originates from, the age of the plant and the method by which the fiber was isolated. [28]

2.1.1. Vegetal Fibres

COCONUT FIBRE (coir). The outer covering of fibrous material of a matured coconut, termed the coconut husk, is the reject of coconut fruit. Coir fibers are normally 50 to 350 mm long and consist mainly of lignin, tannin, cellulose, pectin and other water soluble substances. However, due to their high lignin content, coir degradation takes place much more slowly than in other natural fibers which giving it good durability characteristics and an infield life service of 4 to 10 years. The water absorption of coir is about 130 to 180 percent and the diameter is about 0.1 to 0.6 mm. [25, 29].

SISAL. Sisal is a lingo-cellulosed fiber [30, 31] whose traditional use is as reinforcement for gypsum plaster sheets in the building industry due to its 60 to 70 percent of water absorption and diameter of about 0.06 to 0.4mm. Sisal fibers are extracted from the leaves of the plants, which vary in size between 6-10 cm in width and 50-250 cm in length. In general, Brazil, Indonesia and East African countries are the world´s main producers of sisal fibers [32].

PALM. The palm fibers in date production have filament textures with interesting properties such as low costs, plenitude in the region, durability, lightweight, tension capacity and relative strength against deterioration [33]. Fibers extracted from decomposed palm trees are found to be brittle, and exhibit low tensile strength and modulus of elasticity as well as a very high water absorption [34].

JUTE. Jute is abundantly grown in Bangladesh, China, India and Thailand. It is extracted from the fibrous bark of jute plants which grow as tall as 2.5 m and contain base stem diameters of approximately 25 mm. There are several different varieties of jute fibers with varying properties [34, 35].

FLAX. Flax is probably the oldest textile fiber known to mankind. It has been used since ancient times for the production of linen cloth [36, 37]. Flax is a slender, blue flowered plant grown for its fibers and seeds in many parts of the world [34].

BARLEY STRAW. Barley straw is widely cultivated and harvested once or twice annually in almost all rural areas all over the world and can be used in producing composite soil blocks with better structural characteristics. Unfortunately, relatively little published data is available on its performance as a reinforcement element in either soil or earth blocks. It is however important to note that during Egyptian times, straw or horsehair was added to mud bricks and furthermore straw mats were used as a form of reinforcement in early Chinese and Japanese housing construction [38-40]. From the late 1800s, straw was also used in the United States as a wall bearing element or infill [41]. Barley straw is claimed to be the most cost-effective practice to retain soil in artificial rainfall tests [42].

BAMBOO. Bamboo fiber is a regenerated cellulose fiber. Bamboo can thrive naturally without using any pesticide and is seldom eaten by pests or infected by pathogens. Scientists have found that bamboo containss a unique anti-bacteria and bacteriostatic bio-agent named "Bamboo Kun" [43]. Furthermore, it is important to note that the root rhizomes of bamboo are excellent soil binders preventing erosion [44, 45].

CANE. Cane or sugarcane belongs to the grass family and grows up to 6 m high with a diameter up to 6 cm. Bagasse is the fibrous residue which is obtained in sugarcane production after extraction of the juice from the cane stalk containing a diameter of up to 0.2 to 0.4 mm. However, waste cane fiber has limited use because of the residual sugars and limited structural properties within the fiber itself. The residual sugars can result in a detrimentally affected finished product due to the fact that a stiffer bonding phase generates in the composite structure. Therefore, “Cement Board” produced from sugar cane waste has been recently introduced to the market [46]. The authors recommend the application of these fibers in soil reinforcement as a potential area of research.

2.1.2 Animal Fibres

α-KERATIN FIBERS. A review on the existing literature shows that most studies of natural fibers are focused on cellulose-based/vegetal fibers from renewable plant resources. This is due to the fact that natural protein fibers have poor resistance to alkalis and cement (an alkaline product) is present nowadays in many building construction materials. There are very few studies describing composites from protein fibers such as animal hairs. Barone and Schmidt [47] reported on the use of keratin feather fiber as a short-fiber reinforcement in LDPE composites and showed that protein fibers have good resiliency and elastic recovery. The keratin feather fiber for these tests was obtained from chicken feather waste generated by the US poultry industry. [48].

2.2. Synthetic Fibres

2.2.1 Plastic Fibres

POLYPROPYLENE (PP). Polypropylene fiber is the most widely used material utilized in laboratory tests of soil reinforcement [49-55]. Currently, PP fibers are used to enhance soil strength properties, reduce shrinkage properties and to overcome chemical and biological degradation [56-58]. Puppala and Musenda indicated that PP fiber reinforcement enhanced the unconfined compressive strength (UCS) of the soil and reduced both volumetric shrinkage strains and swell pressures of the expansive clays [58].

POLYESTER (PET). Consoli et al. indicated that due to the inclusion of PET fibersin sand both peak and ultimate strength were improved and this was also dependent on fiber content [57]. Kumar et al. tested highly compressible clay in unconfined compression (UC) test with 0%, 0.5%, 1.0%, 1.5% and 2.0% flat and crimped polyester fibers. Three lengths of 3 mm, 6 mm and 12 mm were chosen for flat fibers, whilst crimped fibers were cut to 3 mm long. The results indicated that as the fiber length and/or fiber content increases, the UC value will improve. Crimping of fibers leads to a slight increase in UC [58] and these results are comparable to those found by Tang et al. [59].

POLYETHYLENE (PE). The feasibility of reinforcing soil with polyethylene (PE) strips and/or fibers has also been investigated to a limited extent [55, 60-63] and it has been reported that the presence of a small fraction of high density PE fibers can increase the fracture energy of the soil [64]. Consequently, GEOFIBERS® are typically 25-50mm long, discrete fibrillated or taped polypropylene strands that are mixed or blended into sand or clay soils [65]. It is important to note that some researchers have applied the term "geofiber" for PP fibers used in soil reinforcement [e.g. 53, 63 y 65].

NYLON. Kumar and Tabor studied the strength behaviour of silty clay with nylon fiber with varying degrees of compaction. This study indicated that peak and residual strength of the samples for 93 percent compaction were significantly more than the samples compacted at the higher densities [68, 69]. Gosavi et al reported that by mixing nylon fibers and jute fibers, the California Bearing Ratio (CBR) value of the soil was enhanced by about 50% of that of unreinforced soil, whereas coconut fiber increased the value by as much as 96%. The optimum quantity of fiber to be mixed with soil is therefore found to be 0.75%, and any addition of fiber beyond this quantity does not seem to have any significant increase in the CBR value [70, 71].

POLYVINYL ALCOHOL (PVA). Polyvinyl alcohol (PVA) fiber is a synthetic fiber that has recently been used in fiber-reinforced concrete due to its weather resistance, chemical resistance (especially alkaline resistance) and tensile strength being superior to that of PP fiber. PVA fiber has a significantly lower shrinkage from heat than either nylon or polyester. It has a specific gravity of 1.3, a good adhesion property which assists donding with cement and a high antialkali characteristic. For this reason, PVA fibre is suitable for utilization as a soil reinforcing material [72]. The inclusion of PVA fiber therefore seems to produce more effective reinforcement in terms of strength and ductility compared with other fibres under the same cementation. Park et al. found that the addition of 1%

PVA fibre to 4% cemented sand resulted in a two times increase in both the UCS and the axial strain at peak strength when compared with the non-fiber-reinforced specimen [72]. In addition, Park reported that at 1% fibre dosage, the values of ductility were greater than four, regardless of the cement ratios used.[73].

There is much recorded in the literature about soil-fibre reinforcement, but it is not easy to establish an equivalence about the performance of the different fibres due to the amount of variables apart from the fibre type itself: fibre length, fibre percentage, type of soil and characterization, stabilization agent id considered… Table 1 shows the characteristics of different fiber types used for soil reinforcement according to the literature.

	Ref	Optimized fiber content %	Fiber length Mm	Fiber tensile strength (MPa)	Stabilizer	Unreinforced soil Compressive strength (MPa)	Reinforced soil Compressive strength (MPa)	Compressive strength increment %
VEGETAL FIBRES								
Coconut fibre(coir)	[25]	4	50	76-102	No	1,5	1,8	120%
	[29]	1	5-15		Lime (5%)	0,3	0,8	267%
Flax	[35]	0,6	8,5	-	Portland cement (3-10%)	1,79	3,5	196%
Hibiscus cannabinus	[36]	0,2	30	1000	No	2,45	2,9	118%
Sisal	[25]	4	50	-	No	1,5	2	133%
	[31]	0,75	20	-	No	0,018	0,066	367%
ANIMAL FIBRES								
Wool	[48]	0,25	10	120-174	No	2,23	3,05	137%
PLASTIC FIBRES								
Polypropylene (PP)	[49]	0,15	12	350	No	0,20	0,28	140%

Table 1: Characteristics of different fiber types used for soil reinforcement.

2.2.2 Metal and Glass Fibres

STEEL FIBERS. Steel fibre reinforcement are found in concrete structures and are also used as reinforcement in soil–cement composites [74-76]. In addition, steel fibres improve soil strength, but the improvement is not as significant as in the other case) [77]. Ghazavi and Roustaie have recommended that in cold climates, where soil is affected by freeze–thaw cycles, polypropylene fibers are preferable to steel fibers as polypropylene fibers possess a smaller unit weight than steel fibers. In other words, the PP fibers decrease the level of sample volume increase more than steel fibers [77].

GLASS FIBERS. Consoli et al. indicated that the inclusion of glass fibres in silty sand effectively improved peak strength [68]. In other work, Consoli et al. examined the effect of PP, PET and glass fibers on the mechanical behavior of fiber-reinforced cemented soils. Their results showed that the inclusion of PP fibres significantly improved the brittle behavior of cemented soils, whereas stresses at failure slightly decreased. Unlike the case of PP fiber, the inclusion of PE and glass fibers slightly increased the stresses at failure and slightly reduced the brittleness [78]. Maher and Ho studied the behavior of Kaolinite-fiber (PP and glass fibers) composites, and found that the increase in the unconfined compressive strength (UCS) was more pronounced in the glass fiber-reinforced specimens [78].

5 CASE STUDY

The present case study compares the effect of polypropylene and wool fibers on the mechanical properties of natural polymer based stabilized soils. The aim of the study is to investigate the influence of different fiber reinforced natural polymer stabilized soils with regards to mechanical properties and fiber adhesion characteristics. Test results in this study have compared the effects of adding natural and synthetic fibers to clay soils and discussed the importance of an optimum soil specification. A correlation between the micro structural analysis using scanning electron microscope (SEM), fiber typology, fiber–matrix bonds and the mechanical properties of the stabilized soils is also discussed.

5.1 Fibres used

5.1.1. Polypropylene

Polypropylene (PP) is a thermoplastic polymer used in a wide variety of formats and applications such as plastic food containers, carpets and insulation. It has a variety of advantageous engineering properties such as resistance to fatigue, physical damage and freezing, as well as being unusually resistant to many chemical solvents, bases and acids. Polypropylene fibers are generally superior to polyamide fibers, for example, with regards to elasticity and resiliency properties but they have a lower wear resistance. Their resistance to various external conditions is largely determined by the effectiveness of added stabilizers. PP filaments and monofilaments are used in the manufacture of floating cables, nets, filter fabrics and upholstery whereas PP fibers are used in carpeting, blankets, outerwear fabrics, knitwear, and filter fabrics. PP fibers are cylindrical and usually have a uniform and homogeneous section of around 40 µm. They display good heat-insulating properties but are sensitive to heat and ultra-violet radiation.

Synthetic Fibers	E-glass	Polypropylene	Polyester	Polyamide
Moisture absorption (%)	-	0.01	0.4	6
Natural Fibers	Hemp	Jute	Ramie	Coir
Moisture absorption (%)	8	12	12–17	10
Natural Fibers	Sisal	Flax	Cotton	Wool
Moisture absorption (%)	11	7	8–25	10–28

Table 2. Fiber absorption assessment.

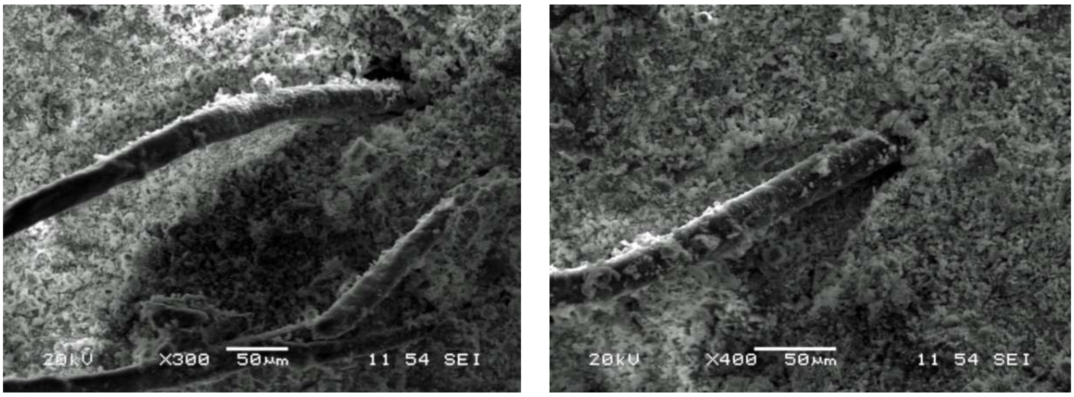
5.1.2. Wool

Natural protein-based fibers are generally obtained from animal hairs and secretions. These protein fibers generally have a greater resistance to moisture and heat than natural cellulosic and vegetal fibers, however proteins fibers have little resistance to alkalis, so they are not appropriate for use within mixes that contain cement. A very common natural protein fiber containing keratin is wool, which grows outwards from the skin of sheep. Different species of sheep produce different types of wool with varied fiber length, diameter and other differing physical characteristics. Generally however, fine wool fibers are 40–127 mm in length, 14–45 µm in width, are roughly oval in cross-section and grow in a wavy type of form which gives rise to a degree of twist.

To date, wool has not been looked at in great detail as fiber reinforcement. It is a hygroscopic fiber, which takes up moisture in vapor form, and tiny pores in the cuticle make the fiber semi-permeable, allowing vapor to pass through to the heart of the fiber. This means that wool can easily absorb up to 30% of its weight in moisture without feeling damp or clammy, which is obviously a significant advantage to animals trying to keep warm in wet weather (table 2).

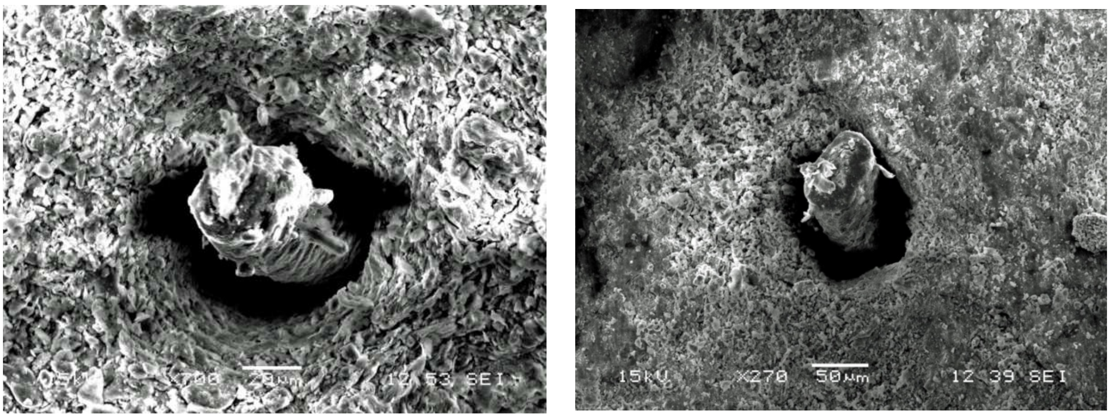
5.2. SEM Analysis

Scanning electron microscopy (SEM) has been shown to be a useful tool for the direct study of polymer-soil matrix interfaces. In particular, SEM studies have helped to illustrate the spatial relationships between the various components of matrices and reinforcement fibers. The samples in this project were examined by scanning electron microscopy (SEM), using a JEOL JSM-6460LV microscope in CITIUS laboratory of the University of Seville (Seville, Spain). As can be seen in Figures 1 and 2 different shrinkage degrees around the PP and wool fibers were measured depending on the type of fiber used. The soil retraction ranges were of a smaller margin in PP fibers (Figure 3a–c) than in wool ones (Figure 4a–c), giving a variation in these samples between 15 and 40 µm.



(**a**) (**b**)

Figure 1. (a) Different samples of SEM of Polypropylene fiber in the red soil mix (×300); (b) SEM of Polypropylene fiber in the yellow soil mix (×400)



(**a**) (**b**)

Figure 2. (a) Different samples of SEM of wool fiber in the red soil mix (×700);
(b) SEM of wool fiber in the yellow soil mix (×270).

5.3. Discussion

Natural fibers compared to most synthetic fibers have much higher absorption coefficients. As a result, when specifying the use of natural fibers for stabilizing soils in order to produce ecologically friendly materials, a prior plasticity analysis of the soil will be particularly important. The resistance loss relating to the type of fiber used was generally much higher in the three point bending tests than in the compression tests. When examining the flexural results, the graphs clearly demonstrate that the margin of difference between the PP reinforced and wool fiber reinforced soil types was generally greater than the margin of variation within the compression tests. This could be explained by the fact that in the compression tests, the nature of the test is to press down on the sample thereby compacting voids and improving adhesion, whereas in the flexural tests a central point load is applied to induce bending. Reduced bonding between the fiber and the soil matrix has a significant effect on bending strength as the fibers are particularly important in flexural situations to provide tensile strength and adhesion. It is therefore critical that the adhesive bond between the polymer matrix and fiber is as strong as possible. In the case of the wool fibers, there are high percentages of water absorption and subsequent desorption generating significant shrinkage across the fiber section, giving rise to the voids observed in the SEM pictures. These SEM tests clearly demonstrate that the fiber/soil bond is significantly reduced in the wool fibers compared with PP fibers.

9 CONCLUSIONS

A review of the existing literature on compacted soil both with stabilizers and without them has been carried out throughout this study. In any case, the main focus of the analysis has been the different formulations and fiber reinforcement procedures with various soils.

As general conclusion it can be stated that several variables can be seen in the literature such as: type, length and pre-treatment of fibres; different compositions and soil plasticity index; use, type and proportion of stabilizers, and different dosages of water-soil. All this hinders greatly to establish an effective correlation between the mechanical results of different mixtures.

In this sense, and given the fact that the availability of soil has a strong local character, both the type and proportion as the treatment of fiber is in relation to this. The type of fiber to be used as reinforcement is a factor closely associated with the local and geographical availability of fibers, especially in the case of natural fibres. This fact determines multiple combinations to achieve acceptable results in relation to the minimum levels of mechanical resistance to be achieved.

The lengths of the reinforcement fibers tend to be short in size < 50mm being generally between 5-25mm. The fundamental difference between natural and artificial fibers does not rely in a different mechanical behaviour but in their much higher water absorption coefficients for. This fact has an impact both in the soil moisture process and in the adherence soil-fibre due to the shrinkage of the fibre section when dried. It has been detected that the interface fibre-matrix is a critical factor that has tried to be countered on numerous occasions with previous treatments of waterproofing of the fibers.

ACKNOWLEDGEMENTS

This research project has been partially funded by the TEP-1988 project PANEL of the 2012 call of the Dirección General de Investigación, Tecnología y Empresa. Consejería de Economía, Innovación, Ciencia y Empleo. Junta de Andalucía.

The authors wish to acknowledge the IUACC “Instituto Universitario de Arquitectura y Ciencias de la Construcción” for the necessary support to develop this research. We would also like to express our gratitude to the Foundation INNOVARCILLA, also known as the Andalusian Ceramics Technology Centre. Also want to thank Francisco José Caballero Muñoz, Álvaro Arrans Gallardo and José Alejandro Gutiérrez Bautista, undergraduate students for their invaluable assistance in conducting the experimental phase of this research.

REFERENCES

[1] http://www.rammedearth.com/re.html. last visited 20/12/2011
[2] Minke, Gernot. 2000. Earth construction handbook. The Building Material Earth in Modern Architecture. Southhampton [UK] ; Boston : WIT Press,
[3] http://inhabitat.com/sacred-soil-the-rammed-earth-reconciliation-chapel-in-berlin/. last visited 20/12/2011
[4] De Garrido. Luís. 2008. Análisis de proyectos de arquitectura sostenible. Ed MacGraw-Hill
[5] http://calearth.org/building-designs/what-is-superadobe.html. last visited 20/12/2011
[6] Li C. Mechanical response of fiber-reinforced soil, PhD thesis, Faculty of the Graduate School of the University of Texas at Austin, 2005.
[7] Jamshidi R, Towhata I, Ghiassian H, Tabarsa R. Experimental evaluation of dynamic deformation characteristics of sheet pile retaining walls with fiber reinforced backfill, Soil Dyn Earth Eng 2010; 30: 438–446.
[8] Ghiassian H, Jamshidi R, Tabarsa A. Dynamic performance of Toyoura sand reinforced with randomly distributed carpet waste strips, 4th dec geol earth eng and soil dyn conf, Sacramento, California, USA, 18–22 May 2008.
[9] Abtahi M, Ebadi F, Hejazi M, Sheikhzadeh M. On The Use Of Textile Fibers to Achieve Mechanical Soil Stabilization, 4th Int Tex Cloth Des Conf, Dubrovnik, Croatia, 5-8 October 2008.
[10] Abtahi M, Sheikhzadeh M, Hejazi M. Fiber-Reinforced Asphalt-Concrete Mixtures- a Review, Cons Buil Mat 2010; 24: 871-877.
[11] Baker W, The reinforcement of turf grass areas using plastics and other synthetic materials: a review, Int Turf grass Soc Res J 1997; 8: 3-13.
[12] http://EzineArticles.com/3917867
[13] Kaniraj R, Gayathri V. Geotechnical behavior of fly ash mixed with randomly oriented fiber inclusions, Geot Geomem 2003; 21: 123–149.
[14] Brown B, Sheu S. Effect of deforestation on slopes. J Geotech Eng ASCE 1975; 101: 147–165.
[15] Waldron J. Shear resistance of root-permeated homogeneous and stratified soil, Soil Sci Soc Ame J 1977; 41: 843–849.
[16] Wu H, Erb T, Study of soil-root interaction, J Geotech Engng ASCE 1988; 114: 1351–1375.
[17] Wu H, Beal E, Lan C. In-situ shear test of soil-root system. J Geotech Eng ASCE 1988; 114: 1376–1394.
[18] Rao J, Jute Geotextile for improving the performance of Highway Embankment on soft Marine Soil", Proc. Nat. Sem Jute based Geotextiles, New Delhi, India, 1996.
[19] Vidal H, The principle of reinforced earth, High Res Rec 1969; 282: 1–16.
[20] Akbulut S, Arasan S, Kalkan E. Modification of clayey soils using scrap tire rubber and synthetic fibers, App Clay Sci 2007; 38: 23–32.
[21] Juyol P, Sastry G and Rao M. Rehabilitation of a mined area in Himalaya by Geojute and other measures, Proce 5th Int Conf On Geotextiles, Singapore, 1994.
[22] Azeem A and Ati A. Erosion and Control techniques for Slopes of Banks and Cuttings, Ind Geotech Conf, Calcutta, 1992.
[23] Leflaive E, Soil reinforced with continuous yarns: Texol, 11th Int Conf on Soil Mech and Found Eng, San Francisco, USA, 1985.
[24] Hanafi I, Few C, Partial Replacement of Silica by white Rice Husk Ash in Natural Rubber Compounds; The Effects of Bond, Iran Polym J 1998; 7: 255-261.
[25] Ghavami K, Filho R, Barbosa P, Behaviour of composite soil reinforced with natural fibers, Cem Concr Comp 1999; 21: 39–48.
[26] Savastano H, Warden G, Coutts P. Brazilian waste fibers as reinforcement for cement-based composites, Cem Concr Comp 2000; 22: 379–384.
[27] Nilsson H, Reinforcement of concrete with sisal and other vegetable fibers, Swed Counc for Build Res, Document DIY, Stockholm, Sweden, 1975.

[28] Rowell M, Han S, Rowell S. Characterization and Factors Effecting Fiber Properties, Nat Pol and Agr Comp 2000; 115-134.
[29] V. Anggraini, A. Asadi, B.B.K. Huat, H. Nahazanan, Effects of coir fibers on tensile and compressive strength of lime treated soft soil, Measurement (2014), doi: http://dx.doi.org/10.1016/j.measurement.2014.09.059
[30] Mishra S, Mohanty K, Drzal T, Misra M, Hinrichsen G. A Review on Pineapple Leaf Fibers, Sisal Fibers and Their Biocomposites, Macromol Mat Eng 2004; 289: 955–974.
[31] J. Prabakar, R.S. Sridhar, Effect of random inclusion of sisal fibre on strength behaviour of soil. Construction and Building Materials 16 (2002) 123–131
[32] Kishore J, Rao K. Moisture Absorption Characteristics of Natural Fiber Composites, J REINF Plast Comp 1986; 5: 141-150.
[33] Yusoff M, Salit M, Ismail N, Wirawan R. Mechanical Properties of Short Random Oil Palm Fiber Reinforced Epoxy Composites, Sains Malay 2010; 39: 87–92.
[34] Swamy N. New reinforced concretes, Surry university press, 1984.
[35] M. Segetin, K. Jayaraman, X. Xu, Harakeke reinforcement of soil–cement building materials: Manufacturability and properties. Building and Environment 42 (2007) 3066–3079
[36] Y. Millogo, J. Morel , J. Aubert , K. Ghavami, Experimental analysis of Pressed Adobe Blocks reinforced with Hibiscus cannabinus fibers. Construction and Building Materials 52 (2014) 71–78
[37] Harriette L, the Potential of Flax Fibers as Reinforcement for Composite Materials, Eindhoven University Press, Eindhoven, the Netherlands, 2004.
[38] Salehan I, Yaacob Z, Properties of Laterite Brick Reinforced with Oil Palm Empty Fruit Bunch Fibers, Pertanika J Sci & Tech 2011; 19: 33 – 43.
[39] Li C. Large volume, high-performance applications of fibers in civil Engineering, J Appl Pol Sci 2009; 83: 660-686.
[40] Mansour A, Srebric J, Burley J. Development of Straw-cement Composite Sustainable Building Material for Low-cost Housing in Egypt, J Appl Sci Res 2007; 3: 1571-1580.
[41] Bainbridge B, Athene S. Plastered Straw Bale Construction, The Canelo Project Report, Canelo, Arizona, USA, available from: www.osbbc.ca
[42] Key L, Straw as an erosion control mulch, a technical report from US Agriculture Department, Portland, Oregon, No. 49, 1988.
[43] http://www.swicofil.com/products/015bamboo.html
[44] Qin Y, Xu J, Zhang Y. Bamboo as a potential material used for Windmill Turbine Blades, a technical report available from www.rudar.ruc.dk, 2009.
[45] Lin D, Huang B, Lin S. 3-D numerical investigations into the shear strength of the soil–root system of Makino bamboo and its effect on slope stability, Ecol Eng 2010; 36: 992-1006.
[46] http://www.ati-composites.com/PDF/Bulletin-SugarCaneBuildingBoard.pdf
[47] Barone JR, Schmidt WF. Polyethylene reinforced with keratin fibres obtained from chicken feathers. Compos Sci Tech 2005;65:173–81.
[48] Galán-Marín, C. ;Rivera-Gómez, C.; Petric, J. 2010. Clay-based composite stabilized with natural polymer and fibre. Construction and Building Materials 24 (2010) 1462–1468.
[49] Tang C, Shi B, Gao W, Chen F, Cai Y. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil, Geotex Geomem 2007; 25: 194–202.
[50] Khattak J, Alrashidi M, Durability and mechanistic characteristics of fiber reinforced soil–cement mixtures, Int J Pav Eng 2006; 7: 53–62.
[51] Santoni L, Tingle S, Webster L. Engineering properties of sand–fiber mixtures for road construction, J Geotechl and Geoenv Eng 2001; 127: 258–268.
[52] Viswanadham S, Phanikumar R, Mukherjee V. Swelling behavior of a geofiber-reinforced expansive soil, Geotex Geomem 2009; 27: 73–76.
[53] Yetimoglu T, Salbas O. A study on shear strength of sands reinforced with randomly distributed discrete fibers, Geotex Geomem 2003; 21: 103–110.
[54] Yetimoglu T, Inanir M, Inanir E. A study on bearing capacity of randomly distributed fiber reinforced sand fills overlying soft clay, Geotex Geomem 2005; 23: 174–183.
[55] Vasudev D. Performance Studies on Rigid Pavement Sections Built on Stabilized Sulfate Soils, Msc thesis, University of Texas at Arlington, 2007.

[56] Musenda C. Effects of Fiber Reinforcement on Strength and Volume Change Behavior of Expansive Soils, M.S. Thesis, The University of Texas at Arlington, Arlington, Texas, 1999.
[57] Puppala J, Musenda C. Effects of Fiber Reinforcement on Strength and Volume Change Behavior of Expansive Soils, Trans Res Boa, 79thAnnual Meeting, Washington, USA, 2000.
[58] Consoli C, Prietto M, Pasa S. Engineering behavior of a sand reinforced with plastic waste, J Geotech and Geoenvir Eng ASCE 2002; 128: 462-472.
[59] Kumar A, Walia B, Mohan J. Compressive strength of fiber reinforced highly compressible clay, Cons Buil Mat 2006; 20: 1063–1068.
[60] Tang C, Shi B, Chen W. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil, Geotex Geomem 2006; 24: 1–9.
[61] Orman E. Interface shear strength properties of roughened HDPE, J Geotech Eng ASCE 1994; 120: 758-761.
[62] Bueno S. The mechanical response of reinforced soils using short randomly distributed plastic strips, in Recent developments in soil and Pavement mechanics, Almeida (ed.) Balkema, Rotterdam, 401-407, 1997.
[63] Dutta K, Sarda K, CBR behavior of waste plastic strip-reinforced stone dust/fly ash overlying saturated clay, Turk J Eng and Envir Sci 2007; 31: 171-182.
[64] Sobhan K, Mashnad M. Tensile strength and toughness of soil – cement – fly ash composite reinforced with recycled high density polyethylene strips, J Mat in Civ Eng ASCE 2002; 14: 177-184.
[65] Miller J, Rifai S. Fiber reinforcement for waste containment soil liners, ASCE J Envir Eng 2004; 130: 891-896.
[66] Tutumluer E, Kim I, Santoni L. Modulus Anisotropy and Shear Stability of Geofiber-Stabilized Sands, Trans Res Rec 2004; 1874: 125-135.
[67] Jadhao D, Nagarnaik B. Performance Evaluation of Fiber Reinforced Soil- Fly Ash Mixtures, 12th Int Conf of Int Assoc for Comp Meth and Adv in Geomech (IACMAG), Goa, India, 2008.
[68] Kumar S, Tabor E. Strength characteristics of silty clay reinforced with randomly oriented nylon fibers, EJGE 2003; 127: 774-782.
[69] Chauhan S, Mittal S, Mohanty B. Performance evaluation of silty sand subgrade reinforced with fly ash and fiber, Geotex Geomem 2008; 26: 429–435.
[70] Gosavi M, Patil A, Mittal S, Saran S. Improvement of properties of black cotton soil subgrade through synthetic reinforcement, J the Inst Eng (India) 2004; 84: 257–262.
[71] Park S, Effect of fiber reinforcement and distribution on unconfined compressive strength of fiber-reinforced cemented sand, Geotex Geomem 2009; 27: 162–166.
[72] Park S. Unconfined compressive strength and ductility of fiber-reinforced cemented sand, Cons Build Mat 2011; 25: 1134-1138.
[73] Segetin M, Jayaraman K, Xu X. Harakeke reinforcement of soil–cement building materials: Manufacturability and properties, Build Env 2007; 42: 3066–3079.
[74] Boominathan S, Senathipathi K, Jayaprakasam V, Field studies on dynamic properties of reinforced earth, Soil Dyn and Earth Eng 1991;10: 402–406.
[75] Murray T, Farrar M, Temperature distributions in reinforced soil retaining walls, Geotex Geomem 1988; 7: 33–50.
[76] Ghazavi M, Roustaie M. The influence of freeze–thaw cycles on the unconfined compressive strength of fiber-reinforced clay, Cold Reg Sci Tech 2010; 61: 125–131.
[77] Consoli C, Montardo P, Donato M, Prietto M. Effect of material properties on the behavior of sand–cement–fiber composites, Ground Improv 2004; 8: 77–90.
[78] Maher H, Ho C. Mechanical properties of Kaolinite/fiber soil composite, J Geotech Eng 1994; 120: 1381–93.