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Article

Analysis of the Influence of the Fiber Type in Polymer Matrix/Fiber Bond Using Natural Organic Polymer Stabilizer

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Abstract: This research study compares the effect of polypropylene and wool fibers on the mechanical properties of natural polymer based stabilized soils. Biocomposites are becoming increasingly prevalent and this growth is expected to continue within a number of sectors including building materials. The aim of this study was to investigate the influence of different fiber reinforced natural polymer stabilized soils with regards to mechanical properties and fiber adhesion characteristics. The polymer includes alginate, which is used in a wide range of applications but has not been commonly used within engineering and construction applications. In recent years, natural fibers have started to be used as an ecological friendly alternative for soil reinforcement within a variety of construction applications. 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.

Keywords: natural polymers; polymer matrix/fiber bond; polypropylene fibers; stabilized soil; mechanical properties; SEM

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1. Introduction

Sustainable and ecologically responsible specification of materials in architectural design has increased in recent years due to concerns about reducing the embodied energy of materials and increasing the opportunities for recycling and/or encouraging opportunities for biodegradability at the end of life of a building. With increasing scrutiny of material compositions, commonly used fibers within composites such as glass and carbon fibers, combined with thermosets such as polyester, polypropylene and polyamide have started to appear less attractive compared with potential natural fiber substitutes such as jute, coir flax and bamboo. Within the scientific community there has therefore recently been a number of research studies which have tested and analyzed natural fiber performance within various polymer matrices, to determine flexural, tension and compression strength characteristics as well as durability performance.

With regards to soil reinforcement in particular, sisal, bamboo, hemp, coir and a few other plant fibers have recently been studied but to date, animal fibers, such as wool, have been relatively neglected in the search for improving soil reinforcement properties. Animal fibers exhibit a large surface area in relation to their bulk and have an ability to form linkages with polymers improving shrinkage resistance and their surface properties play a critical role in many wool applications. An understanding of the chemical structure and behavior of wool fiber surfaces is therefore crucial in order to advance wool processing techniques and finishing technologies as well as examine potential applications for wool across a range of industrial sectors.

Several authors [1–6] provide a broad review of different research studies on biocomposites, natural fibers and biopolymers. Biocomposites are becoming increasingly prevalent and this growth is expected to continue over the coming decades. Biocomposite research has mostly focused on mechanical testing of short-fiber composites, micromechanical studies such as fiber treatments for improved fiber-matrix interface properties and modeling of biocomposite properties [1].

It is important to find mechanisms that will improve the stability of soils and natural fibers [7–12] (which are usually by-products of mainly plants or animals) are a potentially significant resource. Natural fibers can be used as reinforcement in eco-friendly composites suitable for the building industry and these fibers have been tested as reinforcement in cement [13], polymer matrix composites [14–16] and also, to varying degrees, as reinforcing materials in order to improve the engineering properties of different types of soil [17].

There are a variety of interactions which control the load transfer between fibers and their matrices including chemical bonds, secondary interaction forces (van der Waals, acid/base *etc.*) and mechanical interlocking. The quality of the fiber/matrix bond significantly affects not only the overall composite properties, but also the water uptake of the composites and authors such as Joseph *et al.* [18] have showed that improved adherence between sisal fibers and a polypropylene matrix, via chemical treatments, can reduce weight gain due to water sorption, by reducing capillary action.

In this research project, a new approach based on analyzing microscopic structural changes in stabilized specimens has been introduced to try to understand the behavior of the swelling and shrinkage phenomena that occur in natural polymer stabilized soils when dried at room temperature. Four different types of soils from the Andalusia region of Spain, with varying clay mineral contents, and different plasticity index values, were combined with two different types of fibers: one was a synthetic fiber polypropylene (PP) and the other was a natural fiber, wool. These samples were also combined with a form of alginate and then compressed into brick moulds under laboratory conditions at the Universidad de Sevilla. After drying and curing, these samples were then subjected to a series of characterization and mechanical tests and then results compared and analyzed.

All the specimens were carefully dried to their initial water content, in an oven for 24 h and then at room temperature; to evaluate partial shrinkage and the relationship of this change was compared for different amounts of natural fiber within different soil samples. Microscopic structural changes in stabilized specimens were then studied with a scanning electron microscope (SEM) and the results from this analysis were compared with the results of mechanical tests. In addition, physical changes were compared with information relating to the plasticity index, Atterberg limits and the chemical composition of each soil.

2. Materials

2.1. Alginate

Alginates are naturally occurring polymers that occur as sodium alginate, calcium alginate and magnesium alginate salts within the cell walls and intercellular mucilage of seaweed [19]. They contribute to the flexibility and mechanical strength of algal plants [20] and are therefore comparable to the cellulose and pectin components of land based plants [21]. Moreover, they have interesting properties including a high capacity for holding water, improving viscosity and stabilizing emulsions. They are sold in filamentous, granular or powdered forms and in this study a dry alginate in the form of a powder was used which when mixed with water formed a colloidal sol. The chemical reaction, which occurs in this process, produces fibrils that form a gel, because the alginate has within its composition, the salt of calcium sulfate dehydrate, which releases a calcium ion, facilitating the reaction. Interestingly alginate gels have the ability to replicate the characteristics of a semi-solid when the gelation process concludes but to date, only a few previous research studies by Friedemann *et al.* [22] and Galán *et al.* [23,24] have been carried out which incorporate types of alginate into building materials.

2.2. Fibers

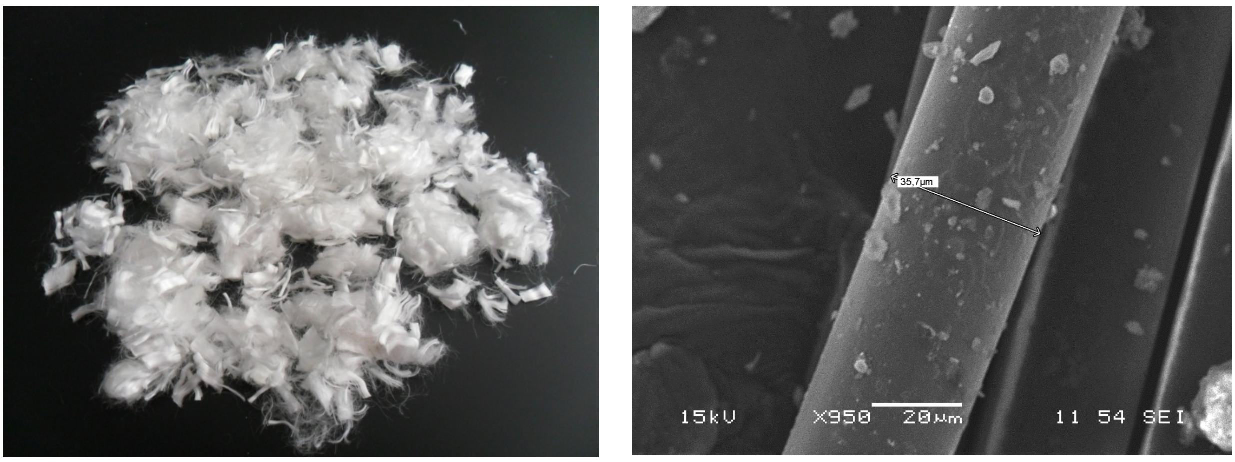
Natural fibers comprise plant fibers such as jute, coir, sisal, bamboo, wood, palm leaf, coconut leaf, coir dust, cotton, hemp, grass, *etc.* but current research is focusing on sisal [25,26], bamboo, jute, hemp, coir and a few other natural, plant-derived fibers. To date, animal fibers such as wool have been relatively neglected in the search for improving soil reinforcement properties despite the fact that these fibers exhibit a large surface area in relation to their bulk. Natural fibers, acting as reinforcement within composites, offer many advantages including good strength properties, low cost, low density, high toughness, good thermal properties, biodegradability, non-abrasive behavior and widespread availability. However, organic products containing cellulose fibers have several negative characteristics, such as an incompatibility with hydrophobic polymer matrices [27] and a tendency to show little resistance to prolonged moisture. Finite natural lengths and large diameters also limit their potential applications.

Despite these disadvantages, many previous studies have demonstrated the positive effects of adding natural fibers as composite, mortar and soil reinforcement improving the particular compound's ability to decrease shrinkage and enhance compressive, flexural and shear strength, if an optimum reinforcement ratio can be found. In many cases today, reinforcing fibers tend to be of a synthetic nature, such as carbon fibers, glass fibre-reinforced plastics and polypropylene, but in recent years, natural fibers have started to be used as an ecological friendly alternative for soil reinforcement within a variety of material applications. Their shrinkage properties are due to the drying effect, but there are innovative chemical treatments now being developed to counteract their absorption characteristics [28]. An understanding of the chemical structure of the fiber surface is therefore crucial in order to advance wool processing and finishing technology as well as examine alternative applications.

2.2.1. 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 (see Figures 1 and 2). They display good heat-insulating properties but are sensitive to heat and ultra-violet radiation.

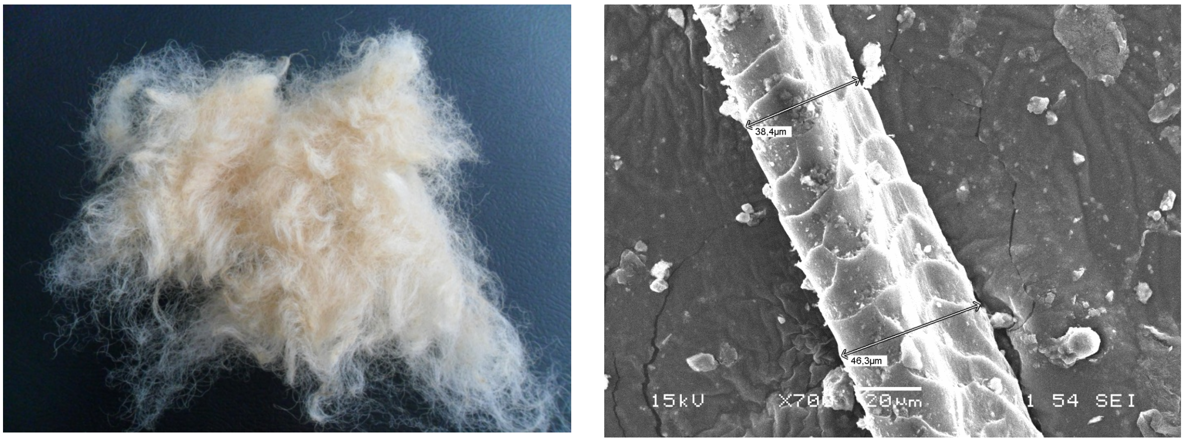
Figure 1. (**a**) Polypropylene fiber (full size image) and (**b**) SEM of polypropylene fiber (×950).



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

PP fibers have a low Young's modulus value, which means that they cannot prevent the formation and propagation of cracks at high stress levels, however they can bridge large cracks in certain circumstances [29,30]. They have also been used to considerably reduce the amount of cracks in various materials and to enhance residual strength [31,32]. There are a few relevant results in natural polymer-soil reinforcement studies incorporating polypropylene fibers. Most of the existing research is oriented towards soil stabilization with cement or lime, the enhancement of soil properties for roads and pavements or the improvement of the characteristics of expansive soils. In cementitious products, additional porosity caused by the melting of polypropylene fibers when exposed to high temperatures, can lead to a decrease of the residual mechanical performances of concretes [33]. Experimental results from various different studies in academic literature on this subject are contradictory. Several studies carried out by authors such as [34,35] show a decrease in residual strength in agreement with the hypothesis relating to increased porosity caused by chemical reactions, whilst other authors such as [36,37] show improvement in residual strength. Nevertheless, PP's low moisture absorption rate compared to most natural fibers, makes Polypropylene, more stable volumetrically (see Table 1).

Figure 2. (**a**) Wool fiber (full size image) and (**b**) SEM of wool fiber (×700).



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

Table 1. Fiber absorption assessment.

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

2.2.2. Wool

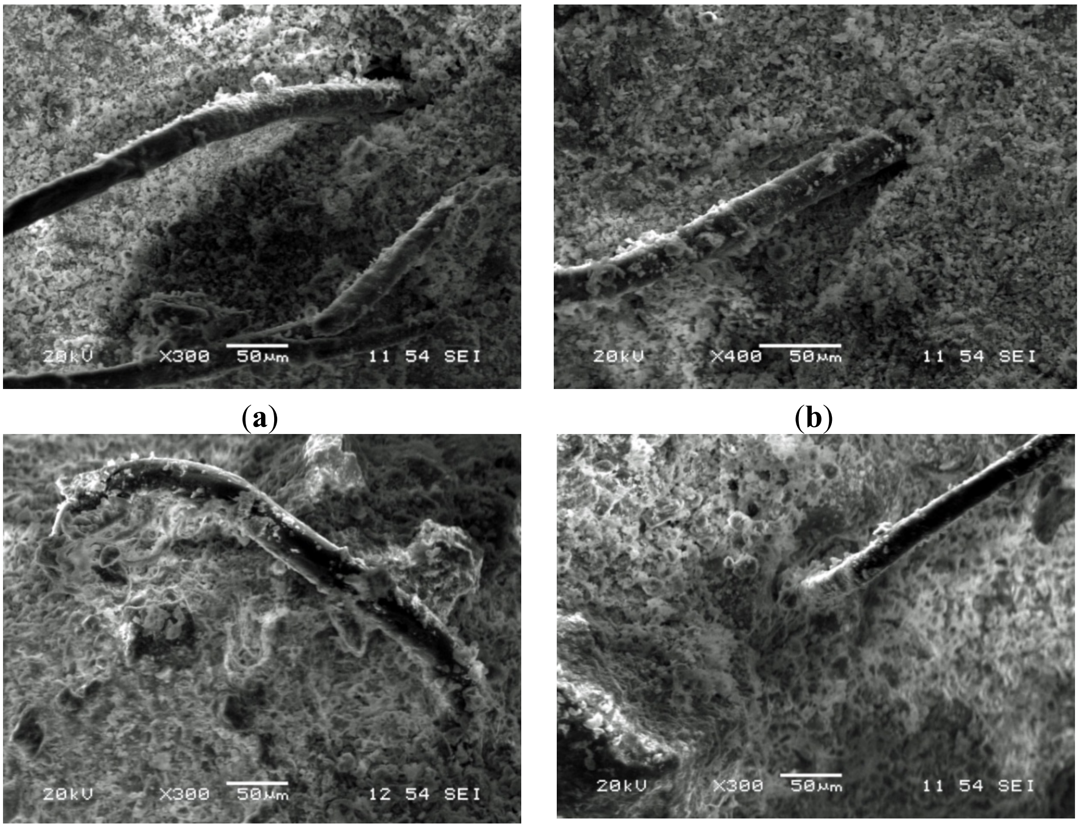
Natural protein-based fibers are generally obtained from animal hairs and secretions. These protein fibers generally have a greater resistance to moisture and heat than natural cellulosic and vegetal fibers, however proteins fibers have little resistance to alkalis, so they are not appropriate for use within mixes that contain cement. A small amount of research has been carried out into the use of animal fibers within composites and Barone and Schmidt [38], for instance, reported on the use of keratin feather fibers as short-fiber reinforcement within LDPE composites; this keratin feather fiber they used had been obtained from chicken waste. 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.

There is generally a two-phase structure for wool fibers, which consists of a water-absorbing matrix, embedded within non-water-absorbing cylinders. The macroscopic appearance and physical structure of the wool fibers is shown in Figures 2 and 3.

Figure 3. (**a**) Different samples of SEM of Polypropylene fiber in the white soil mix (×300); (**b**) SEM of Polypropylene fiber in the yellow soil mix (×400); (**c**) SEM of Polypropylene fiber in the black soil mix (×300); and (**d**) SEM of polypropylene fiber in the red soil mix (×300).



(**a**) (**b**) (**c**) (**d**)

2.3. Soil

Four soils were used in this research project and they were all supplied by the Innovarcilla Foundation (Bailén, Spain), which promotes the activities of the Andalusian Ceramics Technology Centre (Bailén, Spain). The Foundation brings together the most important manufacturers of ceramic construction materials in the Andalusia region and it generously supplied the soils utilized in this research study.

The term "clay" refers to a material that occurs in nature composed primarily of fine grained minerals, which are generally plastic at appropriate water contents but will harden during drying or curing. Different mechanical properties such as plasticity and hardening characteristics vary depending upon the mineralogical composition of the clays, which in the main comprise phyllosilicates with variable contents of quartz, feldspar, carbonates, gypsum, *etc.*

The four different types of clay soils utilized in this research study were identified in accordance with their predominant color; namely White, Yellow, Black and Red and in all cases, the soils were sourced from the Southern region of Spain, Andalusia.

Some of the parameters considered essential in the understanding of the behavior of clays as components within composite materials are described below. In particular, phyllosilicates, which are fine particles (<2 μm) that contribute to the plasticity of clays in their reactions with water, are identified. Indeed, full characterization spectrums for each one of the clays—including the percentage of phyllosilicates—is shown in Table 2.

Table 2. Mineralogical composition of the four types of soil used.

Soil	Clay minerals (%)					Phyllosilicates (<2 μm) (%)				
	Q	**Fd**	**C**	**D**	**Fl**	**Sm**	**Ill**	**Ka**	**Ch**	**P**
White	28	6	25	8	33	68	32	Ud.	Ud.	Ud.
Yellow	40	tr.	15	tr.	45	40	60	Ud.	tr.	Ud.
Black	43	3	18	4	32	32	58	10	Ud.	Ud.
Red	32	5	tr.	10	53	Ud.	66	33	tr.	Ud.

Notes: Q: Quartz; Fd: Feldspar; C: Calcite; D: Dolomite; Fl: Phyllosilicates; Sm: Smectites; Ill: Illite; Ka: Kaolinite; Ch: Chlorite; P: Pyrophyllite; Ud: undetected; tr: traces; Ill: Illite; Ka: Kaolinite; Ch: Chlorite; P: Pyrophyllite; tr.: Traces (1%–3%); Ud.: Undetected.

As can be seen from the table, there are significant variations in the mineral content of the clays and this gives rise to quite different behavior within the polymer matrices. Phyllosilicates consist of sometimes two layers (one tetrahedral "T" and one octahedral "O") that repeat and in other cases three layers that repeat. The former type (known as "T–O" structures), comprise one tetrahedral sheet of silicon linked through oxygen atoms to one octahedral sheet of aluminum and in the three layer T–O–T type two silicate layers surround an octahedral layer filled with Aluminum or Magnesium.

Within the T–O–T type there is a sub-group which exhibits weak bonding between layers thereby facilitating delamination and swelling—this behavior occurs typically in the montmorillonite group of clays. The other group demonstrates that delamination is much more difficult and indeed swelling is not observed in common applications. This group is termed the illite group of clays. The four clay types used for this research study belong to this second group and depending on the type of clay, the surface charges vary, inducing significantly different interactions forces between the clay particles and as a consequence, different rheological properties.

Clay's plasticity is directly related to the size distribution of the clay particles with smaller particles producing greater plasticity. The following Table 3 shows the different percentages of particles smaller than 63 μm in the different clays used in this series of experiments.

Table 3. Percentages of rejections at 63 μm obtained by wet sieving.

Clays	White	Yellow	Black	Red
Rejection at 63 μm	28.1%	23.8%	43.8%	51.1%

In addition, chemical compositions of the four soil samples were obtained after naturally drying the samples and sieving them and then measuring their composition by chemical precipitation as illustrated in Table 4.

Table 4. Chemical analysis of the four types of soil used.

Soil	(%) in weight										
	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	L.O.I.
White	47.5	8.8	3.3	0.0	1.7	16.6	0.4	1.9	0.5	0.1	17.7
Yellow	56.6	12.1	4.2	0.0	2.2	9.1	1.7	3.1	0.0	0.0	10.8
Black	54.2	12.3	4.3	0.1	2.1	10.4	1.4	2.9	0.7	0.1	12.2
Red	58.5	16.7	7.0	0.1	2.8	2.2	0.2	5.0	0.8	0.2	0.08

Note: L.O.I., Loss on ignition.

The water content of each soil type was also determined by using Atterberg Limits [39] which are empirical divisions between the solid, plastic and liquid limits of clay. Different plasticity indexes and different consistencies in mixtures are due to their relative water absorption characteristics and as can be seen below, the four soils showed significant variations in their index of plasticity (Table 5), with the drier White soil having a significantly higher plasticity index.

Table 5. Atterberg limits of the four soils used.

Physical Characteristics	White	Yellow	Black	Red
Liquid Limit	45.4%	32.8%	38.8%	25.6%
Plastic Limit	15.5%	11.1%	18.6%	14.1%
Plasticity Index	29.9%	21.7%	20.2%	11.5%

2.4. Mixes

The samples were prepared by mixing four different ingredients (soil, alginate, fiber and water) in a variety of different proportions. The alginate used was dried alginate as soluble salts from alginic acid, with a content of approximately 15% sodium alginate and calcium fillers that improve the resistance and the irreversibility of the polymerization process. Two types of fibers were used: one a man-made fiber, polypropylene, and the other a natural wool fiber. Both were short fibers 10 mm long randomly distributed at a rate of 0.25% by weight. The water used was the optimum proportion related to the alginate content and the samples were manually compacted and cast in steel prismatic molds 160 mm × 40 mm × 40 mm and specimens from the four soils were prepared in the two following dosages (Table 6).

In the manufacturing process, different consistencies and workability were observed between the different clay samples and typically the White soil appeared to be drier. The consequences of the drier consistency can be observed within the mechanical properties section.

Table 6. Proportions for the different mixes used (by weight).

Proportion	Soil	Alginate Product *	Polypropylene	Wool	Water
Soil_PP	79.5%	1%	0.25%	0.00%	19.25%
Soil_W	79.5%	1%	0.00%	0.25%	19.25%

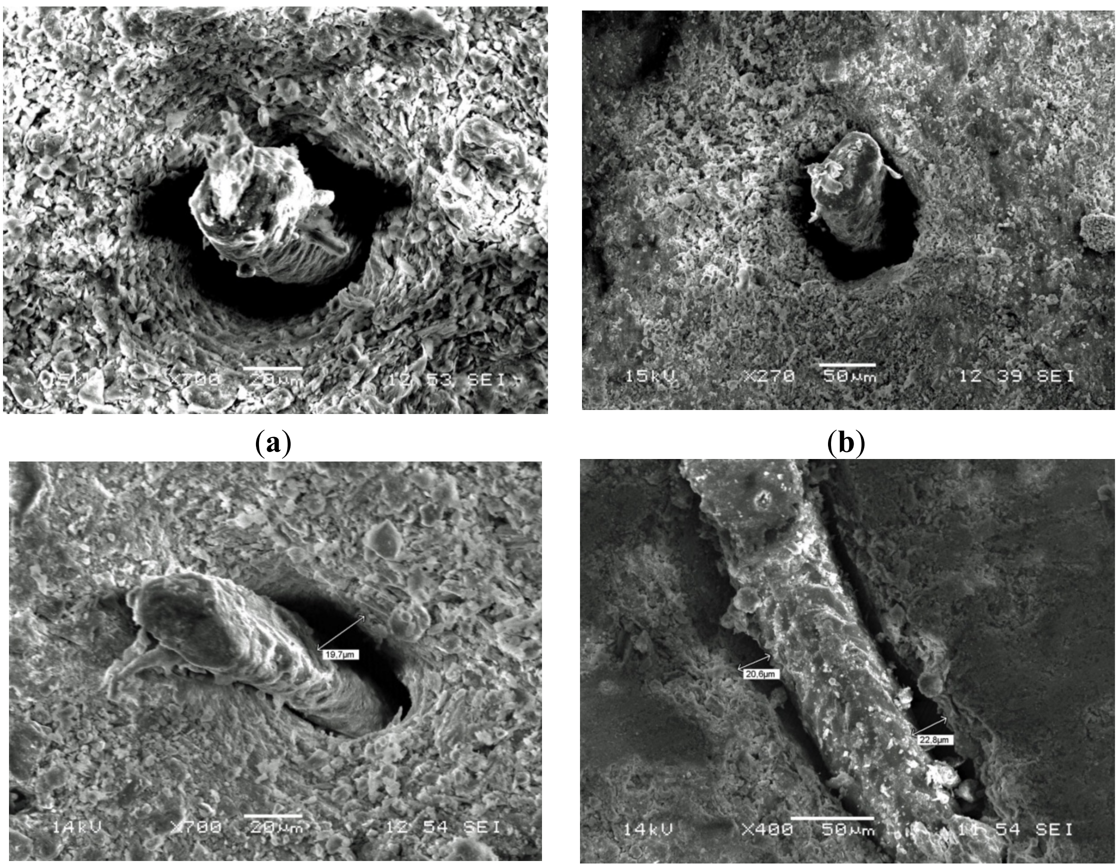
Notes: * Dry alginate (natural polymer); PP, (polypropylene fiber) and W, (wool fiber).

3. Experimental Section

3.1. 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 3 and 4 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.

Figure 4. (**a**) Different samples of SEM of wool fiber in the white soil mix (×700); (**b**) SEM of wool fiber in the yellow soil mix (×270); (**c**) SEM of wool fiber in the black soil mix (×700); and (**d**) SEM of wool fiber in the red soil mix (×400).



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

(**c**) (**d**)

3.2. Mechanical Tests

In order to compare the effectiveness of both types of fiber reinforcement, mechanical tests were carried out to determine compressive and flexural strength properties. The mechanical test results are shown in Table 7 and include average values for three-point bending tests and compressive tests for all four soil types used in the production of the test samples.

Table 7. Compression and flexural tests results. Proportions for the different mixes used (by weight).

Soil	Compression (MPa)					Flexural (MPa)				
	Soil + PP	s.d.	Soil + wool	s.d.	Resistance loss	Soil + PP	s.d.	Soil + wool	s.d.	Resistance loss
Yellow	4.70	0.30	4.42	0.37	6%	1.28	0.13	0.94	0.11	27%
White	2.10	0.18	1.35	0.15	36%	0.41	0.11	0.17	0.04	59%
Black	3.75	0.18	2.52	0.37	33%	1.09	0.07	0.66	0.16	39%
Red	2.90	0.46	2.49	0.52	14%	1.06	0.26	0.99	0.04	7%

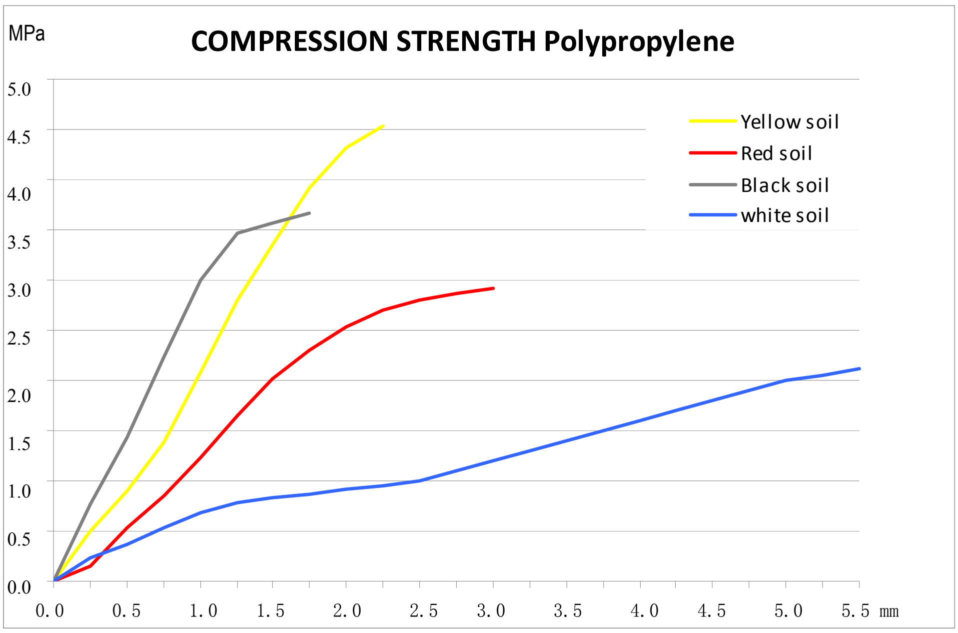
Note: s.d., Standard deviation.

Each value represents the average of a total of seven flexural tests and fourteen compression test specimens. According to the European Standard [40,41] the number of different mixes (proportions) tested should be a minimum of seven specimens of 160mm × 40mm × 40mm per batch.

3.2.1. Compression Strength Results

As shown in Figure 5a,b the compression test results reached significantly higher values for specimens with PP fibers than wool samples for all the soils tested, especially white and black soil.

Figure 5. Comparison of compression strength results (MPa) for all four types of soil (**a**) PP fibers and (**b**) wool fiber.



(**a**)

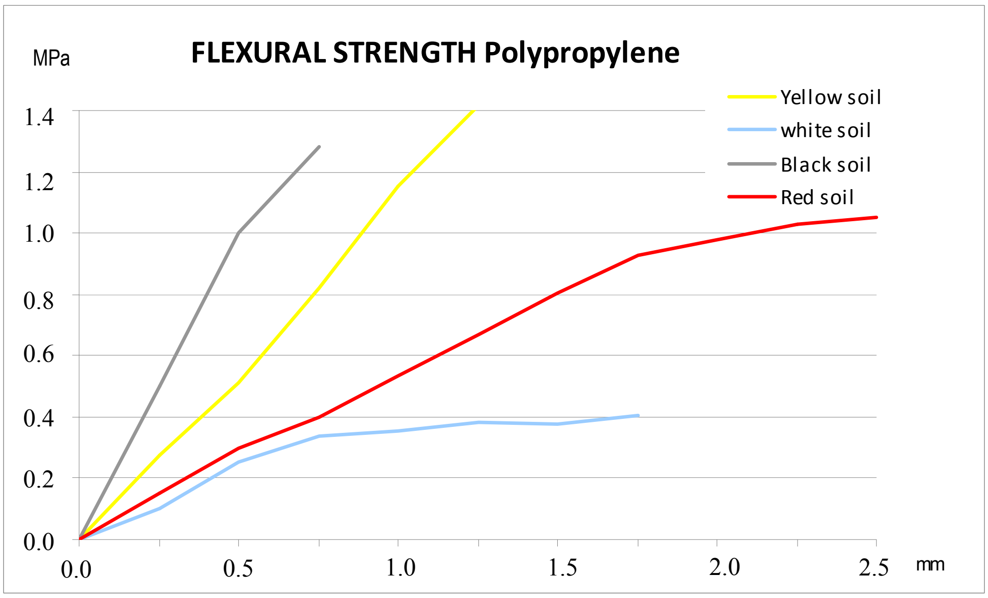
Figure 5. *Cont.*

(**b**)

3.2.2. Flexural Strength Results

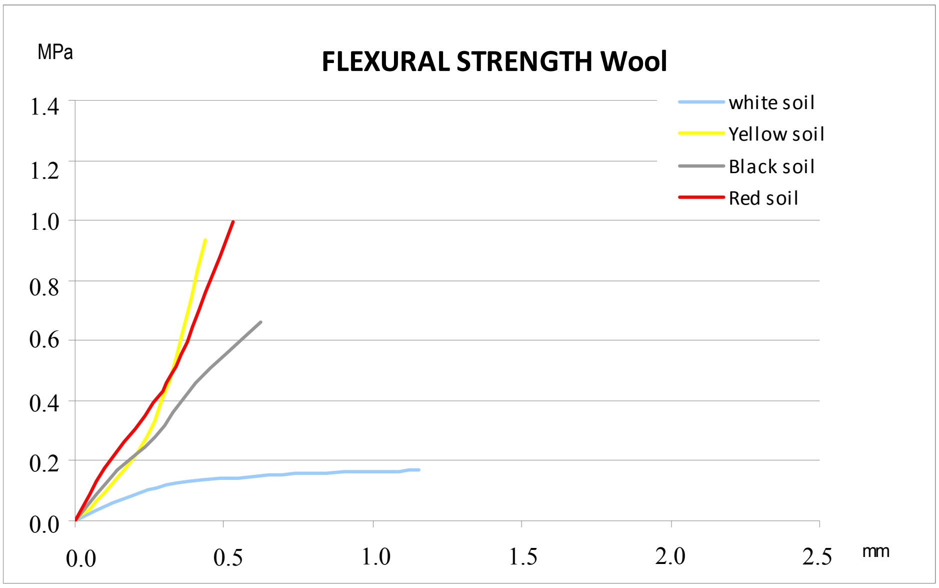
As shown in Figure 6a,b the three point bending test results show quite a different flexural behavior for specimens with PP fibers compared with wool samples for all the soils tested. Three of the four soils tested show higher values using PP fibers: yellow, white and black with only the red soil specimens having similar values regardless of the fiber used.

Figure 6. Comparison of flexural strength results for all four types of soil (**a**) PP fibers and (**b**) wool fiber.



(**a**)

Figure 6. *Cont.*



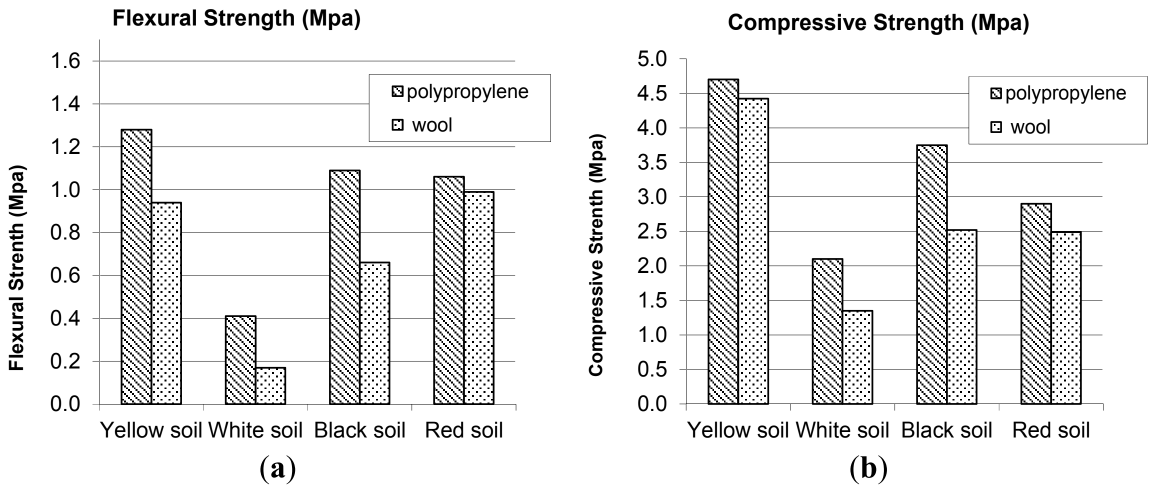
(**b**)

3.2.3. Comparison between Fibers

Mechanical tests showed improved strength values for the three-point bending tests and compressive tests for all four soil types used in the production of test samples, when reinforced with polypropylene fibers. The relationship between the compression values and flexural strength results of all four soils always correlated (as would be anticipated) with the highest values for the Yellow soil, followed by the Black and then Red soil. White soil always produced the worst results.

When comparing PP to wool fiber, the loss of resistance percentages was much higher for flexural compared with compressive strength. Indeed, it was significant in the case of the White soil specimens where the loss of flexural resistance was 59% when using wool instead of PP fiber. However, this difference in flexural resistance was only 7% when using the Red soil. The comparison of results is shown in Figure 7 and the resistance loss percentage is shown in Table 7.

Figure 7. Comparison of polypropylene *versus* wool fiber for all four types of soil (**a**) compression strength results; and (**b**) flexural strength results.



4. Results and Discussion

The analysis of the different clay characteristics *i.e.*, mineralogical and chemical compositions can be interpreted as follows: White clay displays the highest plasticity index and the highest smectite content; indeed, high plasticity values are associated with increased smectite contents [42]. Delamination, and lower plasticity indexes occur in illite clay types and higher contents of illite were found in the Red soil, with smaller differences in the Yellow and Black soils. The White clay had half the illite proportion of the other three soils.

Particle size is directly related to the plasticity index and the Red soil within these samples had the highest percentage of rejection using the 63 μm sieve therefore contains the largest particle sizes. However, it is not simply about particle size, the type of clay minerals in the Red soil is also important for determining its plasticity index result and according to the chemical analysis; the White soil contained the lowest content of hard compounds such as SiO_2, Al_2O_3, Fe_2O_3, MgO, and TiO_2 and the highest percentage of softer compounds such as CaO.

When the samples were examined by scanning electron microscopy (SEM), different shrinkage degrees around the wool and PP fibers were detected depending on the type of fiber used. For PP fiber samples, it was observed that the clay polymer matrix produced less voids around the fiber independent of the type of soil. For the wool fiber mixes, similar shrinkage of the matrix around the fiber surface was observed in all soil types, although slightly increased within the White soil specimens.

The main factors, which affect the adhesion between the fibers and soils are: (a) the cohesive properties of the polymer-soil matrix; (b) the compression friction forces appearing on the surface of the reinforcing fiber due to shrinkage of the soil; and (c) the shear resistance of the polymer-soil matrix, due to the surface form and roughness of the fiber. The dimensional changes of natural fibers due to moisture and temperature variation also have an influence on all three of these adhesion characteristics, because during the mixing and drying of the soil, the natural fibers absorb water and expand. This swelling of the fibers initially pushes away the soil (at the microscopic level) and then at the end of the drying process, the fibers lose the moisture and shrink back almost to their original dimensions leaving very fine voids around themselves. This leads to an increased level of porosity within the polymer matrix and a degree of friction loss between fiber and soil. These results show that the observed loss of strength is not only due to the variation in fiber type but also more importantly the effect of the differing properties of different soil types.

5. Conclusions

This research project focused on the influence of the fiber type in different types of clays, analyzing the polymer-soil matrix relationship at the fiber interface. On the basis of mechanical testing, microscopic analysis and soil chemical analysis and measurements presented in this paper, it is clear that fiber water adsorption, depends not only on the type of fiber (natural or man-made), but also on the type of soil. In addition, the availability of water that can be absorbed by the fiber depends on the plasticity characteristics of the different types of clay. This leads to the conclusion that an appropriate selection of the soil to be reinforced is more important than the selection of the reinforcement itself.

On one hand, SEM images were useful in detecting the different shrinkage degrees around the different types of fiber. On the other hand, SEM images were not able to measure the different degrees of shrinkage relating to different types of soil. The proportion of fiber used for soil reinforcement is usually very low and this implies that the significant difference in mechanical behavior of specimens prepared with different types of clay is due to the internal shrinkage behavior within the polymer-soil matrix and not only the soil-fiber interface.

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. The results also show that the White soil in particular performs poorly in both tests, providing evidence that the type of soil also has a significant effect on the final values. Indeed, this variation shows that in addition to the adhesion properties between the different fibers and the soil, the water absorption and further desorption (in the case of wool fibers) makes it more important to use an appropriate (low shrinkage) soil as this will have a more significant influence than the reinforcement itself.

There appears to be an optimum soil Plasticity Index. If the soil has a very high Plasticity Index (as is the case in the White soil) and therefore is very absorbent, the soil is drier to work with and more difficult to mould. This clearly affects workability and in turn decreases the mechanical resistance. If, however, the Plasticity Index is low (as is the case with the Red soil), workability is improved due to the increased proportion of "available" water but that higher moisture content increases the potential for sample shrinkage and causes greater soil-fiber adhesion problems.

Different Plasticity Index percentages affect the shrinkage effect of the fibers as well as the different crystalline structures for the various clay phyllosilicates. These are both important parameters affecting the mechanical behavior within the natural and synthetic fiber-reinforced soils. Natural fibers have much higher absorption coefficients compared with most synthetic fibers and therefore if natural fibers are to be used to provide more eco-friendly soil stabilization matrices, then a detailed plasticity analysis of the soil as well as a detailed soil characterization analysis describing the clay fractions and phyllosilicate activity will be especially important.

In addition to these physical issues, the soil chemical composition also determines differences in behavior; the red soil contains more metal compounds, such as iron, and the black soil contains softer elements such as carbon. Again, these variations underline the importance of soil charaterisation and the need to understand all the complex parameters and soil characteristics that combine to determine clay/fiber bond and interaction.

The technical benefits of using fibers in soil reinforcement include: preventing the formation of tensile cracks, reducing the thermal conductivity and weight of building materials and decreasing the soil brittleness. Using either natural or synthetic fibers can achieve these benefits. The main advantage however of wool fibers instead of polypropylene in building material manufacturing, is their lower cost, lower environmental impact, improved thermal behavior and lower density. It is hoped that all these advantages, in combination with the selection of a compatible and appropriate soil, would offset the potential decrease in mechanical strength values observed in this research study.

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Author Contributions

Rivera-Gómez is responsible for the performance of the SEM, soil analysis and mechanical test and detailed this part of the paper. C. Galán-Marín is responsible for the research project and has been in charge of writing the results and discussion and conclusions sections to analyze the results. F. Bradley is working on a related research project at the University of Strathclyde and has contributed to the writing of all the sections within the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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