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REVIEW ARTICLE

Turning textile waste into sustainable solutions: Enhancing earth embankment repair with fibre treated soils

Chiara ROSSIGNOLI [1*], **Marco CARUSO** [2], **Donatella STERPI** [1]

[1] *Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133, Milano, Italy*
[2] *Politecnico di Milano, Testing Lab for Materials, Buildings and Civil Structures, Piazza Leonardo da Vinci 32, 20133, Milano, Italy*

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ABSTRACT

The textile industry produces a substantial amount of waste, contributing significantly to environmental issues. Most of this waste ends up in landfills or is incinerated, highlighting the need for more efficient waste management solutions to enhance circularity. At the same time, the construction and geotechnical industries play a significant role in the circular economy paradigm, as they are potential recipients of waste materials. In fact, in In recent decades, textile fibres in the form of threads or filaments of diverse size and properties have been used as reinforcing inclusions in treated soils, earth embankments and slopes. Starting from this twofold background, this study investigates the use of natural linen and viscose textile fibres derived from industrial waste in sandy silt soils commonly used in levees. To conduct the research, an experimental laboratory-scale approach was adopted with the aim of defining the appropriate soil-fibres mixture proportions and comparing physical properties and mechanical behaviour of natural and treated soil. The findings indicate that incorporating textile fibres alters soil compaction properties by lowering the maximum dry density and increasing the optimum water content. Furthermore, the presence of fibres can significantly increase soil ductility and shear resistance; however, the effect is highly dependent on the filaments' nature, quantity and geometry, i.e. diameter and length. As the results demonstrate that the geotechnical properties of the treated soil can be engineered to meet specific site requirements, the proposed approach seems a promising solution for earth embankment repair.

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INTRODUCTION

The textile industry generates massive amounts of waste during the manufacturing process and after consumption for both domestic and industrial use, making it one of the most problematic sectors in terms of waste management and environmental impact [1-3]. On the other hand, the construction and geotechnical industries play a significant role in the circular economy paradigm, being possible recipients of waste materials [4]. These two aspects are investigated in Section 2, forming the motivation for this research, which is driven by the urgent need for textile waste management while also promoting environmentally friendly solutions in earth embankment repair and renovation works. Introducing soil treated with fibres derived from textile waste has the dual benefit of using a material of low environmental impact while also valorising industrial waste that would otherwise be discarded.

Specific objectives are: (i) Identification of the textile waste management needs and textile waste availability at a local regional level, as well as methods of inclusion in a recycling process in the geotechnical field; (ii) Selection of environmentally compatible textile materials suitable for use in earth embankments and definition of appropriate mixing and sample preparation techniques; (iii) Assessment of the optimal fibre-soil mixture, based on the enhanced properties, both mechanical (compaction, strength and stiffness) and hydraulic (permeability, water retention, and resistance against erosion).

It is worth noting that these points represent the necessary steps to take when the recycling process starts [5]. In particular, it is critical to verify the textile waste availability within a short distance to the end user location, in order to reduce the environmental impact of transportation, as well as the textile waste nature, to reduce the impact of waste treatments. The preliminary assessment of the treated soil behaviour is also required, with the purpose to identify optimal mixtures for each specific fibre and for each specific on-site application.

* Corresponding Author: chiara.rossignoli@polimi.it (Chiara Rossignoli)

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Other objectives, not addressed in this paper, include the modelling of the mixture's response and its interaction with the on-site compacted soil, for the prediction of the full-scale behaviour and subsequent field applications.

Based on this background and motivation, the aim of the study is to evaluate the benefits of combining natural linen and viscose textile fibres, obtained by treatment of industrial remnants, with a sandy silt soil commonly employed in levees. The novelty of the proposed solution primarily lies in the selection of these specific materials, which differ from those commonly investigated in the literature. Natural textile fibres have been considered, while most studies focus on synthetic fibres. A sandy silt typically employed in embankment construction has been selected, while research on fibre treated soils predominantly examines coarser soils. The physical, mechanical and hydraulic properties of a variety of mixtures are investigated using standard geotechnical testing at the laboratory scale. The results show how the presence of fibres influences the compaction characteristics and shear strength of the treated soil.

LITERATURE REVIEW

This section presents an overview of textile waste in Europe and Italy, along with a review of the current use of textile fibres in the construction and geotechnical sectors, in order to support the motivation and objective of the study presented in this paper.

Textile Wastes in Europe and Italy

In these decades in Europe, despite a slight decrease in the household's expenditure attributed to textile, the fast fashion trend, characterised by low price and low quality products, the faster production and distribution process and a more consumeristic mindset have caused an increase in the number of items consumed per capita [1]. Limiting the analysis to clothes, which accounts for 70% of the total textile products, statistics on consumers habits show that over the last few decades the clothing purchases have increased by 40% and the number of times a cloth is used has decreased by 36%, even considering reuse and resale [2-3]. Although the figures may be uncertain and differences exist among countries, the global trend is worldwide similar [6].

The over consumption causes an over production of discarded textiles, which amounts to nearly 6 million tons per year in Europe, corresponding to about 11.3 kg per capita. The discarded textiles are only partially reused due to poorly organized and not widespread collection systems and to the often too low quality of the collected items. The recycling option involves mechanical or chemical treatments that convert the textile waste into either fibres for new apparel production or downgraded products for industrial uses (filler materials, insulation panels, etc). Finally, part of the collected textile fraction is eventually disposed of in landfills or incinerators, with possible energy recovery, resulting in considerable environmental impacts. Accurate life cycle assessments reveal that when landfill or incineration are considered as end-of-life options for textiles the impacts on climate change are second only to the impacts produced by plastic waste [5].

The global material flow for clothing indicates that 12% of the raw material is lost during clothes production (including factory offcuts and overstocks), 2% is lost during collection and treatment, 1% is reused or fibre-to-fibre recycled, 12% is downgrade recycled, and 73% is landfilled or incinerated [6].

Significant differences exist among countries, even in Europe, in terms of collection and recycling capabilities. In 2016, textile waste in Italy amounted to 466 kton, with 29% coming from municipal solid waste and 71% from commercial activities. Only 18% of the total mass was recovered for reuse (8%) or recycling (10%), the remainder was sent to landfill (57%, equal to 266 kton) or incinerated (25%, equal to 116 kton). With one of the lowest ratios of collected textile to new textiles put in the market, Italy has an estimated 6.3 kg of non-recoverable textile waste per capita [3,7]. The fibre-to-fibre recycling appears to be particularly limited for two main reasons: the first relates to the limited quantity of textile products composed of single fibres which are of interest in terms of recycling (wool or cotton), whereas the majority is made of mixed and synthetic fibers; the second derives from regulations that limit the presence of certain chemical products in secondary raw materials. Moreover, the recycling process is slowed because of difficulties in separating the textile part from accessories and finishes, such as buttons, metal or plastic parts, zippers, etc. [8].

To improve circularity in the textile waste sector, efficient waste management technical solutions are nowadays required, as well as the support of government policies that address each stage of the circular process, starting with a more responsible textile production and consumption [9].

Textile Fibres in the Construction and Geotechnical Sector

The addition of natural or artificial elements, often in the form of filaments, to soil, concrete or composites has long been a widely used technique for improving specific material properties. In recent decades, also textile wastes have been used in products, suited for the building industry, that have required hygrothermal, acoustic or mechanical properties [10-11].

Furthermore, fibres have long been used as reinforcing inclusions in treated soils for geotechnical applications in civil and environmental engineering, primarily for earth embankments reinforcement and slope stabilization [12]. In addition to the mechanical interaction between the fibre and the surrounding soil matrix, which improves the stiffness and strength of the engineered soil, the presence of fibre inclusions has a positive effect on other properties. The fibres, for example, can improve the resistance against internal erosion, influence the ability of the soil matrix to retain or drain water, due to their hydrophilic or hydrophobic properties, and limit the shrinkage/swelling potential of certain clays (Figure 1 (a)). The use of fibres from textile waste in geotechnical engineering is a more recent development. The waste is transformed into threads or filaments of various sizes and properties, which are then uniformly mixed with soil. Comprehensive reviews about fibre treated soils are provided in [13-16].

The aforementioned aspects of the soil behaviour are especially relevant in earth embankments, critical assets as both water defence structures in flood risk mitigation and infrastructures in transportation networks. In recent years, water defence structures have been subjected to an intensification of burrowing fauna activity and to increasingly frequent and extreme climatic events, such as the alternation of prolonged droughts and heavy rainstorm periods, all of which contribute to faster aging, degradation and erosion mechanisms that are difficult to predict and control [17-19].

As a schematic example, Figure 1 (b) shows how the presence of burrows, with their access tunnels, and longitudinal or transverse surface fractures in a water defence embankment can raise the saturation line and promote failures. The embankment damages can be accelerated over time by the gradual erosion induced by rainwaters and flood events. Preserving and restoring the embankment entails re-establishing its integrity, through reconstruction of the damaged parts and closure of burrows and tunnels, protecting against erosion at the base and slopes, controlling seepage and the possible onset of piping. These are a multiplicity of interventions that require prioritization and the selection of suitable solutions, to be explored beyond the traditional ground improvement techniques [14]. Given the dimensions of the bodies to be treated, the required material volumes are considerable, with important economic and environmental consequences in terms of supply, treatment, transport and application.

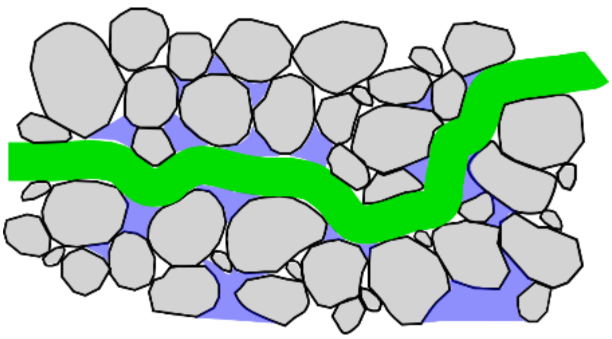

Figure 1(a). Schematic representations of the single textile fibre that influences the mechanical and hydraulic behaviour of the soil matrix.

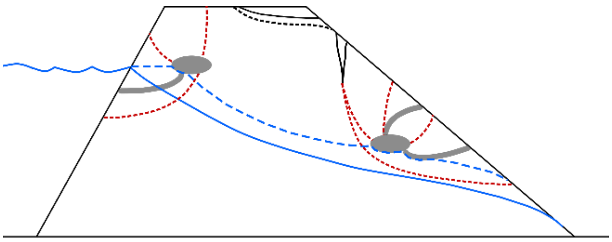

Figure 1(b). Schematic representations of the damaged condition of the earth embankment and its possible evolution: grey areas are animal burrows and tunnels, the dashed blue line is the rise of the saturation line, the black lines are transverse and longitudinal surface fractures, and the red dashed lines are possible failure surfaces.

Nowadays, the embankment repair is typically accomplished by excavation of the damaged areas and backfilling, or by low pressure injection of a filling grout. However, beyond having economic and environmental drawbacks, these techniques have the potential to weaken the earth structure by creating material discontinuities and possible fractures due to grout shrinkage [20]. There is therefore an urgent need to restore the functionality and safety of earth embankments using novel solutions that ensure environmental sustainability and adhere to modern principles of circular economy. Although the use of textile waste represents a down-grading recycle, when compared to cloth reuse or fibre-to-fibre recycle, the Life Cycle Assessment demonstrates that it has a lower environmental impact than landfill disposal or incineration with possible energy recovery [6].

MATERIALS AND METHODS

This section presents the materials and methods used in the study. First, the textile fibres and natural soil are described. Then, the methodology defined and used for the preparation of the soil-fibre mixtures is outlined. Lastly, the compaction characteristics of the treated soil and the properties of the laboratory samples prepared for the experimental tests are reported.

Textile Fibre Selection and Soil Properties

The Centro Tessile Cotoniero e Abbigliamento (Varese, Italy) carried out the preliminary selection and production of textile fibres by treatment of industrial remnants supplied by members of the Industrial Federation of Varese Province. Among these supplied fibres, the following selection was primarily addressed to cellulose-based fibres, due to their environmental compatibility [21]. In particular, linen and viscose remnants from industrial process were readily available in adequate quantities and did not necessitate preliminary impactful chemical treatments. Moreover, linen and viscose are highly hydrophilic materials, therefore able to influence the overall water retention capability of the fibre-soil mixture.

The remnants were mechanically processed to extract single threads. In terms of geometry, the fibres are considered one-dimensional elements characterised by their length and diameter. The diameter was assessed by digital image process of laser microscope images, resulting in diameters of 0.6 ± 0.1 mm for linen and 0.2 ± 0.05 mm for viscose, while the length was adjusted to either 15 or 30 mm by hand cutting. The fibre density was measured by helium pycnometer testing, while the fibre tensile strength was deduced from the literature [22]. It is worth noting that the microscope images enabled the identification of the fibre's structure, the degree of intertwining among the multiple filaments and the surface roughness.

The soil used was collected from an old floodplain embankment of the Secchia River, in province of Modena (Northern Italy) and characterised by standard geotechnical procedures. The soil classification and laboratory tests were conducted at the Geotechnical division of the Testing Lab for Materials, Buildings and Civil Structures of Politecnico di Milano, Italy. From the grain size distribution analysis, the soil was classified as sandy silt with a 14% fraction of inorganic clay of low plasticity [23]. The soil characteristic diameter d_{50} is 0.042 mm, thus leading to fibre to soil diameter ratios of about 14.3 for the linen and 4.8 for the viscose.

Sample Preparation and Testing

The fibre-soil mixture was prepared by manually adding the prescribed amount of fibres to the wet soil and mixing until a homogeneous blend was obtained, as verified by visual inspection. The fiber content f_c, expressed as a percentage, is defined as the ratio of the fibres' weight W_f to the soil's weight W_s, both in dry conditions. The amount of fibres required to reach the target fibre content was evaluated using 0.01 g resolution scales. At the end of the preparation, the mixtures were placed in a hermetic container for 24 hours to guarantee uniform moisture.

The influence of the fibres on the compaction characteristics of the soil was evaluated by Proctor tests [24]. In particular, 5 different configurations were considered, to study the behavior of natural soil and soil treated with linen fibres (f_c = 1%, 2%) and viscose fibres (f_c = 0.5%, 1%). For each configuration, different mixtures were prepared, varying the water content. The soil was compacted in three layers in the Proctor mould, by applying the Standard compaction energy. At the end of each test, the dry density and water content were estimated. By interpolating the experimental points, the compaction curve was obtained for each of the configurations considered.

The influence of fibres on the shear strength of the soil was investigated with drained direct shear tests [25]. The specimens were prepared by Standard Proctor compaction at a water content w of 16%. The cored specimens (side size 60mm and height 40mm) were placed in the shear box and left to saturate for 48 hours with simple water immersion. The shear tests were conducted with three different values of vertical stress (25, 50 and 100 kPa). The shear phase was carried out with a low controlled displacement rate of 0.01 mm/min, to avoid pore water pressure build up.

RESULTS AND DISCUSSION

The study included an experimental programme on natural and fibre treated soil at the laboratory scale. In particular, this section presents the results of laboratory tests aimed to investigate the influence of fibres on soil compaction and shear strength, while constitutive modelling will be addressed in future research. The comparison of results on natural and treated soils allows for the investigation of the effect of the fibre's diameter and length on compaction and shear strength properties of the mixture, and the potential identification of an optimal fibre content for a given fibre type.

Fibres Effect on Soil Compaction

Figure 2 shows the results of the Standard Proctor compaction tests carried out on the natural soil and on soil treated with different contents of linen (a) and viscose (b) fibres. When the interpolation curves are compared, it emerges that the addition of fibres leads to an overall reduction in density, i.e. a lower compaction, resulting in a decrease of the maximum dry density value from 1840 to a minimum value of 1750 kg/m3. This decrease depends on the type and content of fibres and is mainly due to the mechanisms of their interaction with the solid grain matrix: the presence of fibres creates additional voids within the sample during compaction and hinders the movement of the grains, reducing their ability to interlock and form a highly compacted granular structure. Furthermore, it is observed that the addition of fibres increases the optimal water content, required to obtain the maximum compaction, from 14 to 16-17%, also owing to the hydrophilic nature of the fibres.

Fibres Effect on Soil Shear Behaviour

The inclusion of fibres influences the treated soil shear behaviour by various mechanisms. Firstly, regardless of their nature, the fibres reduce the compaction capability (refer to Section 3.1), resulting in a lower degree of grain interlocking and, therefore, a more ductile mechanical response, as shown in Figure 3 by the rather monotonic increase of shear stress with increasing horizontal displacement in direct shear tests on samples with a constant 1% fibre content and 15 mm fibre length.

Secondly, the number of fibre to soil grain contacts influences the ultimate strength condition. Figure 3 shows that the viscose fibres significantly increase the shear strength, while the linen fibres appear to have no influence, due to their different diameters. In fact, for an equal weight, the viscose fibres, which have a smaller diameter and a comparable specific weight, are present in greater quantities within the sample and, consequently, create more contact points with the soil grains, giving the treated soil the appearance of a richer blend. On the contrary, the number of linen fibres is insufficient to guarantee adequate fibre to soil grain contacts, thus limiting the reinforcing effects.

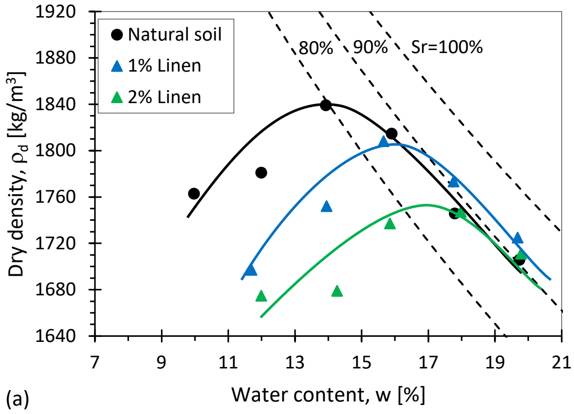

Figure 2(a). Compaction test results on natural soil (black line) and fibre treated soils with linen at 1 and 2% fibre content. The constant saturation degree conditions are shown with dashed lines.

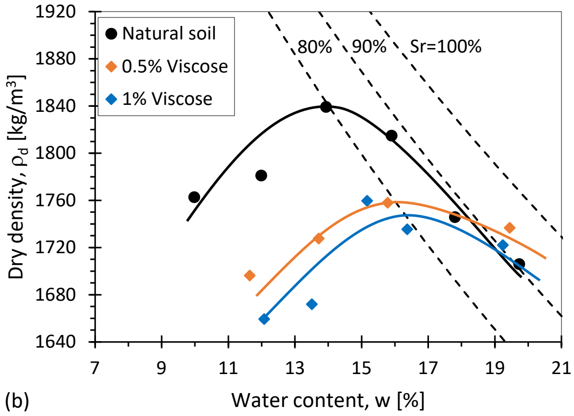

Figure 2(b). Compaction test results on natural soil (black line) and fibre treated soils with viscose at 0.5 and 1% fibre content. The constant saturation degree conditions are shown with dashed lines.

Limiting the investigation to samples treated with viscose fibres at 1% content, the effect of the fibre length is shown by comparing the results of Figure 4. The increased ductility of the treated soil has been confirmed, regardless of fibre length. However, the treatment with 30 mm long fibres appears to have no visible effect on the ultimate shear strength. In this case, in fact, the long fibre tends to become entangled during the soil mixing, compromising an effective fibre-soil interaction, that relies on the fibre stretching, and consequently reducing the ultimate strength enhancement. The shorter fibre length of 15 mm improves the soil strength, as this length guarantees effective fibre to grain soil contacts all along the stretched fibres' surface.

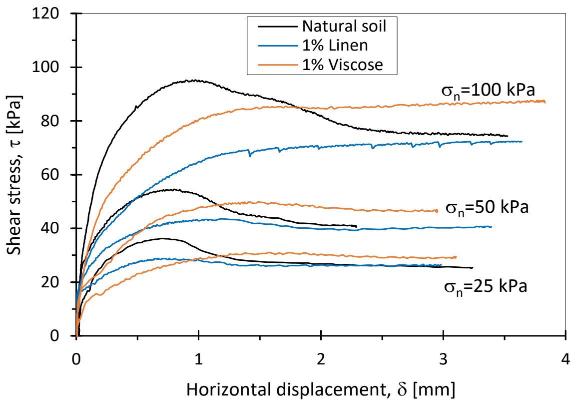

Figure 3. Results from direct shear tests on natural soil and soil treated with linen and viscose fibres at 1% content.

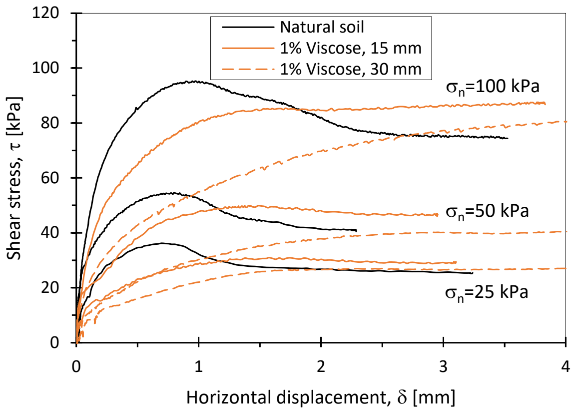

Figure 4. Results from direct shear tests on natural soil and soil treated with 1% viscose fibres of different lengths.

Finally, when focusing on treatments with 15 mm long viscose fibres, the effect of fibre contents ranging from 0.25% to 1.25% is highlighted by comparing the results shown in Figure 5. The greatest improvement of soil shear strength is obtained with a fibre content of 1%; lower contents lead to values close to the one observed for the natural soil, while the higher content of 1.25% results in a general loss of shear strength. In fact, a high fibre content produces fibre clusters that do not appear to be sufficiently interwoven with the soil grain matrix and, consequently, are ineffective in enhancing the soil strength. In this case, the treated soil samples, internally highly discontinuous due to the presence of fibre clusters, exhibit a very ductile behaviour and generally a low shear strength.

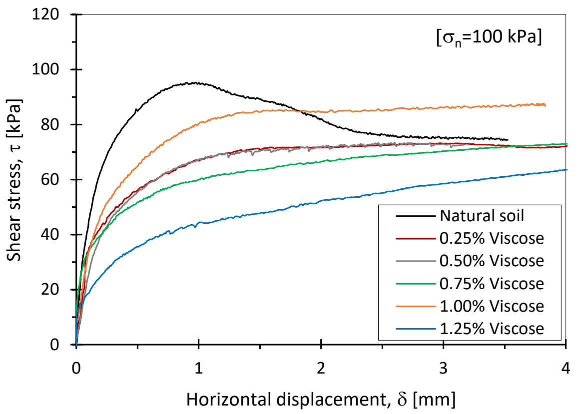

Figure 5. Results from direct shear tests on natural soil and soil treated with 15 mm long viscose fibres and different fibre contents.

Discussion

The laboratory activities indicate that homogeneous fibre-soil mixtures and manageable soil samples can be obtained by selecting suitable fibre contents.
The compaction tests reveal that the inclusion of fibres restricts soil grain movements and creates additional voids in the soil, reducing the maximum dry density that can be achieved with standard compaction. The presence of hydrophilic fibres, with their ability to retain water, contributes to increase the optimal water content. More research is needed on the water retention characteristics of the treated soil, since this property is crucial in the behaviour of earth embankments and particularly water defence earth structures during flood events [26].
Furthermore, the treated soil samples exhibit a ductile behavior when subjected to direct shear and, depending on the fibre geometry and content, may exhibit enhanced shear strength. To obtain such an improvement an adequate interaction between fibres and soil grains must be ensured, which can be achieved selecting appropriate fibre length and content, so to avoid the fibre entanglement and the formation of fibre clusters. In general, tests conducted with different fibre contents have shown that there is an optimal content that results in the maximum increase in soil shear strength.
Other specific characteristics are currently under investigation, such as the fibre roughness, the fibre to soil diameter ratio, and the fibre length to diameter ratio, as well as the influence of the treated soil sample dimensions and sample testing conditions. Moreover, the fibre degradability is a crucial aspect that may limit the long term effectiveness of the technical solution.
Considering the significant dependence of the experimental findings on the specific fibre properties, for a given soil, it is always recommended to conduct geotechnical testing on treated soil samples. Moreover, since scaling rules for extending the results obtained on laboratory scale samples to full scale on-site conditions have yet to be established, on-site tests on full scale prototype applications of fibre treated soil are also recommended.
Finally, it is noteworthy that the fibre treated soil can be tailored to the specific applications. Since the fibre inclusions can affect various mechanical and hydraulic aspects of the soil behaviour in a variety of ways and to varying degrees, the ideal fibre-soil mixture can be designed to achieve the intended characteristics.

CONCLUSION

Following an opportunity driven selection of cellulose-based fibres from industrial textile remnants, a laboratory characterization of natural sandy silt soil treated with various contents of fibres of different nature and geometry was carried out.

The findings indicate that, with a suitable fibre content, manageable and homogeneous mixtures can be obtained and that the hydrophilic characteristics of the selected textile fibres have a significant impact on the soil density and water retention capability. The presence of fibres alters the compaction properties, reducing the maximum dry density and increasing the optimum water content. A more ductile shear behaviour of the treated soil is always observed, while a shear strength increase is observed only when the fibre content reaches an optimal value. However, the shear behaviour is found to be highly dependent on a variety of characteristics that govern the interaction of fibres and soil grains. Therefore, dedicated experimental tests are recommended to help identify, for a given soil, the enhanced properties of specific textile fibre inclusions, and design the optimal fibre-soil mixture. The results obtained demonstrate that the investigated solution is suitable for embankment repair. Practical applications involve the use of fibre-treated soil for mechanical enhancement in the reconstruction of embankment slopes, as the correct soil-fibre mixture can increase soil strength.

As a conclusion, the addition of natural textile fibres derived from industrial waste is an promising treatment for soil used in earth embankment repair and restoration, enabling the possibility of tailoring engineered mixtures with optimal properties for specific applications. However, the implementation at the site scale requires the use of appropriately sized instruments to obtain fibres of the selected length through a mechanical cutting procedure and to mechanically mix the fibres and soil, ensuring a homogeneous mixture within a time compatible with construction site constraints.

Future studies will investigate the potential hydraulic function of fibre-treated soil, given its capacity to influence water content and seepage through the water retention properties of the hydrophilic fibres. In this context, fibre-treated soil could be employed as a construction material in the core of embankments or applied to surficial slopes for erosion control and mitigation of the effects of severe drying-wetting cycles. Moreover, further tests will be carried out on slurry-prepared samples to explore applications requiring a slurry state rather than a compacted one, such as in the filling of animal burrows.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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