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Preliminary experimental investigation into the use of recycled fibres from textile waste for the improvement of embankments

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Highlights

- Basic properties of mixtures comprising sandy silt and linen fibres are tested in laboratory.
- Laboratory testing on fibre-soil mixture necessitates careful sample preparation.
- Linen fibres reduce the soil maximum density and enhance water absorption.
- The fibre-soil mixture exhibits apparent higher compressibility and permeability.

Abstract: Failures that occurred in the last few decades highlighted the need to raise awareness about the emergent risk related to the impact localised degradation phenomena have on embankments. Common interventions aimed to improve embankments, such as the reconstruction of the damaged area or the injection of low-pressure grouts to fill fractures and burrows, may cause the weakening of the structure due to discontinuities between natural and treated zones. Moreover, since such repair techniques require huge volumes of materials, more sustainable solutions are encouraged. At the same time, the textile and fashion industries are looking for sustainable waste management and disposal strategies to face environmental problems concerned with the voluminous textile waste dispatched to landfills or incinerators. The use of soil mixed with textile waste in embankment improvement has been investigated to identify an effective engineering practice and to provide a strategy for the circular economy of textiles. Preliminary laboratory tests have been conducted on soil specimens collected from the Secchia River embankment, Northern Italy, to define the appropriate mixture proportions and to compare physical properties and hydro-mechanical behaviour of natural and treated soils. The results show that an appropriate fibre content offers manageable and relatively homogeneous mixtures. The indluence on soil consistency is mainly due to the textile fibre hydrophilic nature. The addition of fibres reduces the maximum dry density and increases the optimum water content. At low stress levels, the compressibility and hydraulic conductivity appear higher, however macro voids produced during sample preparation may alter the findings.

Keywords: circular economy, embankment, experimental technique, reinforced soil, textile waste

INTRODUCTION

The embankments designed for water confinement and flood defence undergo alterations due to natural aging and the action of external forces. Material degradation, differential settlements and soil-atmosphere interaction, such as the cyclical wetting and drying, cause irreversible cracking at the surface, while wildlife burrowing contributes to loss of the internal embankment integrity.

Cracks and cavities enhance the surface and internal erosive action by atmospheric agents and groundwater. The climate change is accelerating the deterioration process, as it increases the intensity and frequency of extreme weather events, which now frequently take the form of torrential downpours and prolonged droughts (Andersen and Shepherd, 2013; Stirling *et al.*, 2021).

In January 2014, in Italy, exemplary levee failures occurred along the Secchia River (Modena). The process was triggered by animal burrowing and resulted in the release of more than 36 mln m^3 of water onto an area of about 50 km^2 (Orlandini, Moretti and Albertson, 2015). In May 2023, on the plane between Bologna and Ravenna, levee's breaches occurred due to foundation and overtopping erosion (ARPA-E, 2023).

Embankment improvement entails restoring the structure's integrity through crack filling and burrow closure, protection against surface erosion and groundwater flow control to prevent piping; in other words, a variety of interventions that necessitate a priority order and the selection of the most appropriate methodologies, sometimes beyond standard ground improvement techniques and towards sustainability (Jayanthi and Singh, 2016; Bigham, 2020).

The performance of natural soils enriched with fibres has been studied with reference to civil and geotechnical engineering applications. Moreover, the idea of using fibres from textile waste has been recently explored (Tedesco and Montacchini, 2020; Rahman, Siddiqua and Cherian, 2022). In fact, the textile industry produces significant amounts of industrial and consumer waste which has not been included in a circular economy. This makes it one of the most environmentally problematic industries (Manshoven *et al.*, 2019).

This research has a twofold objective to design effective and sustainable methodologies for embankment improvement and to recycle textile waste otherwise deposited at landfills or incinerated. The use of fibre-treated soils opens interesting opportunities for the strengthening of mechanical characteristics, the controlling of water retention properties with hydrophilic or hydrophobic fibres, and the reducing of soil erodibility while avoiding strong heterogeneities that can result, for example, from the use of grout injections. The article presents a preliminary laboratory investigation into natural soils treated with textile fibres. The investigation focuses on the basic properties and hydromechanical behaviour during oedometric compression tests.

MATERIALS AND METHODS

GENERAL INFORMATION

The study examines samples of soil collected during the relocation of an old embankment along the Secchia River (Modena, Italy – 44°40'32.0"N, 10°53'43.6"E). After a preliminary classification of the natural soil, fibres from textile waste have been added to evaluate their effect on basic and hydro-mechanical properties. The initial phase of the experimental programme focuses on natural linen fibres, derived from pre-consumer industrial processing scraps that are mechanically treated to produce threads. Due to their natural origin, linen fibres are environmentally compatible, degradable, and have hydrophilic properties (Morton and Hearle, 2008).

The laboratory tests on natural and treated soil have been conducted at the Laboratorio Prove Materiali of Politecnico di Milano, Italy. The preliminary treatment of textile waste to produce usable fibres was provided at the Multi-Lab of Centro Tessile Cotoniero e Abbigliamento (Busto Arsizio (VA), Italy).

PHYSICAL AND GEOTECHNICAL PROPERTIES OF THE SOIL

The physical and geotechnical properties of the natural soil were assessed through standard laboratory tests. The soil specific gravity, which is the specific weight of solid particles normalised to the specific weight of water, was evaluated using the water pycnometer method (AASHTO T100-22, 2022). It produced a dimensionless value Gs = 2.715. Sedimentation and sieving methods (respectively ASTM D7928-21, 2021 and ASTM D6913-17, 2017) resulted in the grain size distribution curve shown in Figure 1. The soil consisted of clay (14%), silt (46%), and sand (40%), and it was classified as sandy silt with clay. The Atterberg liquid and plastic limits (w_L and w_P, respectively) were determined according to ASTM D4318-10 (2010), yielding the following results: w_L = 28.5% and w_P = 18.8%, the plasticity index is I_P = 9.7%. The compaction characteristics of the soil were assessed using both standard (ASTM D698-12, 2021) and modified (ASTM D1557-12, 2021) methods in the Proctor device. Compaction curves (Fig. 2) helped to estimate the optimum water content and maximum dry density at w_{opt} = 14%, $\rho_{d,\max}$ = 1840 kg·m^{-3} with the standard effort, and w_{opt} = 12%, $\rho_{d,\max}$ = 1950 kg·m^{-3} with the modified effort. The two curves are critical in determining soil sensitivity to low vs high compaction energies: however, only the standard compaction method was employed in the study on fibre-reinforced soils, since a low compaction energy is in general more realistic for regular on-site applications on river embankments.

The basic properties of the treated soil were assessed on mixtures of soil and linen fibres of about 1.5 cm in length. Two mixtures were examined, with fibre content of 0.5 and 1% of the dry weight of the soil, as suggested in earlier studies on fibre reinforced soils (e.g. Furumoto *et al.* (2002)).

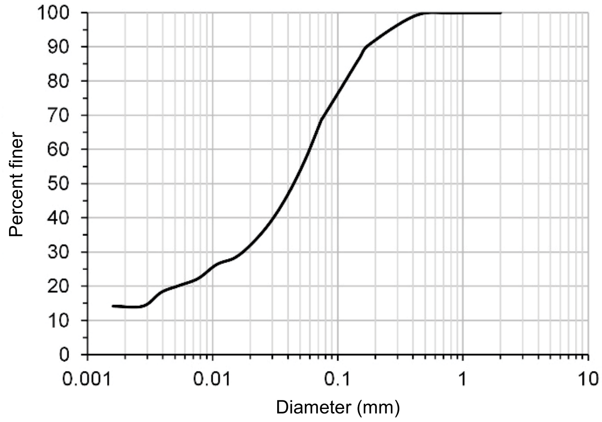

Fig. 1. Grain size distribution curve of the natural soil from the Secchia River old levee; source: own study

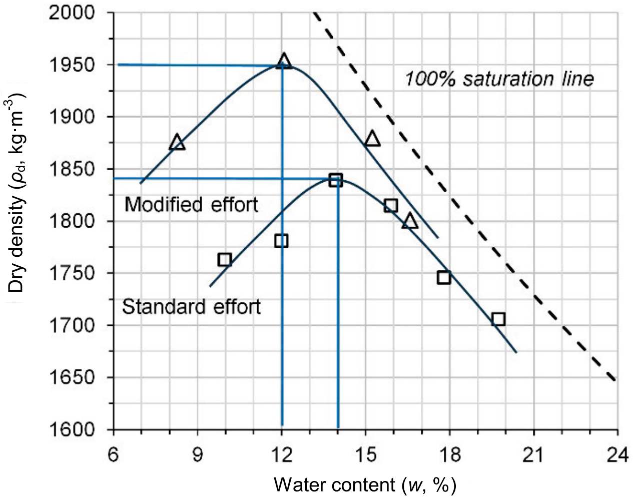

Fig. 2. Proctor tests on natural soil with standard effort (w_{opt} =14%, $\rho_{d,max}$ =1840 kg·m^{-3}) and modified effort (w_{opt} =12%, $\rho_{d,max}$ = 1950 kg·m^{-3}); w_{opt} = optimal water content, $\rho_{d,max}$ = maximum dry density; source: own study

To assess the effect of fibres on the consistency state of the wet soil, the Atterberg liquid and plastic limits were estimated as for the untreated soil. A large number of tests were performed to deal with inhomogeneity due to random orientation of the fibres. The liquid limits were estimated using 17 and 10 samples for the mixtures with 0.5 and 1% of linen fibres, respectively, while 4 samples were used to evaluate the plastic limit of each mixture. To obtain the correct proportion of fibres with respect to the dry weight of the soil, each sample was prepared separately, and the soil (Photo 1a) was mixed with the required amount of fibres (Photo 1b) and water to reach the target consistency (Photo 1c). The results are reported in the following section.

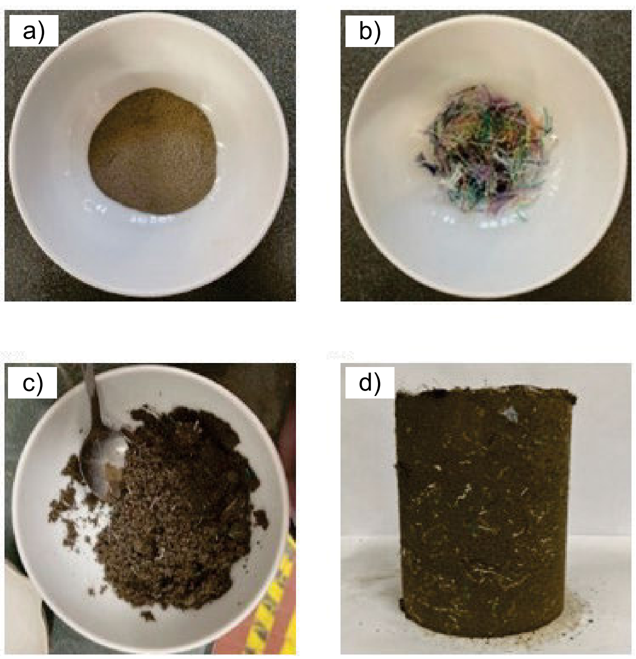

Photo 1. Mixture preparation: a) dry natural soil, b) linen fibres, c) mixture obtained with the addition of water, d) cylindrical sample resulting from Proctor compaction; the pictures refer to the mixtures with fibre content of 1% (phot.: *C. Rossignoli*)

RESULTS

BASIC PROPERTIES OF THE FIBRE TREATED SOIL

The results based on the Casagrande method applied to natural and treated soils are reported in Figure 3. Due to the limited volume involved in the Casagrande test, special attention was given to the sample preparation to reduce heterogeneities. The Atterberg limits and the plasticity index for natural and treated soils are summarised in Table 1.

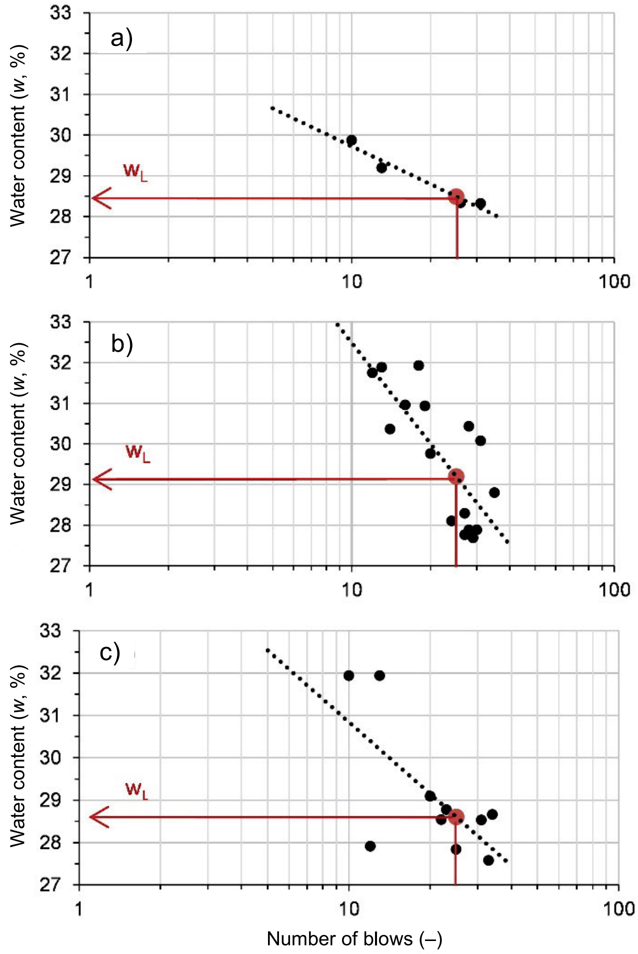

Fig. 3. Estimation of the liquid limit (w_L) of: a) natural soil, b) treated soil with 0.5% linen fibres, c) treated soil with 1% linen fibres; black points are the experimental results, whereas red points identify the liquid limit; source: own study

Table 1. Liquid limit (w_L), plastic limit (w_P), and plasticity index (I_P) for natural and treated soils

Soil	w_L	w_P	I_P
	%		
Natural soil	28.5	18.8	9.7
Treated soil – linen 0.5%	29.2	20.4	8.8
Treated soil – linen 1%	28.6	22.6	6.0

Source: own study.

The compaction characteristics for the fibre treated soils were determined through standard Proctor tests. The mixture was placed in three layers into a mould of given dimensions and compacted using standard effort; the procedure was repeated for different proportions of water content. In this case too, each mixture was prepared separately to guarantee the target percentage of fibres. The sizeable quantity of required material resulted in specimens that appeared rather homogeneous on a large volume (about 1000 cm^3) – Photo 1d. Simple tests were carried out to confirm the uniformity of the fibre distribution over the volume.

Figure 4 presents the standard compaction curves and shows the influence of fibres on maximum dry density and optimum water content. The addition of fibre leads to an overall reduction of the mixture density, resulting in a decrease of the maximum dry density from 1840 to 1750 $kg \cdot m^{-3}$. The water content needed for optimum compaction increases from 14 to 17%, due to the hydrophilic nature of fibres.

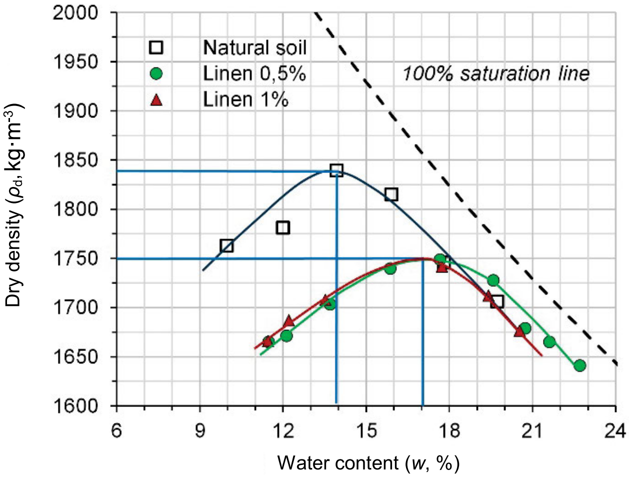

Fig. 4. Standard Proctor tests on natural soil (w_{opt} = 14%, $\rho_{d,max}$ = 1840 $kg \cdot m^{-3}$) and treated soil (w_{opt} = 17%, $\rho_{d,max}$ = 1750 $kg \cdot m^{-3}$); source: own study

PRELIMINARY ASSESSMENT OF HYDRO-MECHANICAL PROPERTIES

Oedometer tests (acc. to ASTM D2435-11 (2011)) were conducted to evaluate the compressibility of natural and fibre treated soils. The samples were obtained by coring the cylindrical specimens reconstituted with the Proctor compaction at a water content of 16%. At that specific water content, the void ratio (e) estimated from the compaction curves was equal to 0.50 for the natural soil and 0.56 for the treated soil. However, despite the due care applied during coring, the presence of fibres caused partial damage and fissuring on the lateral surface that contributed to a larger average porosity of the treated soil samples. The initial average void ratio turned out to be equal to 0.63, instead of the expected 0.56.

Afterwards, the samples were water saturated by capillary rise and subjected to oedometer tests that included a loading phase in four steps (0–10, 10–20, 20–50 and 50–100 kPa), and an unloading phase in one step (100–10 kPa). This enabled to assess compressibility and swelling properties, respectively. The oedometric consolidation curves are shown in Figure 5. The different ranges of void ratio covered in the two tests indicate the different compressibility and swelling of the two materials. The oedometric stiffness modulus assessed for the various loading steps is reported in Figure 6. In the unloading step, the stiffness modulus values are 10,200 kPa and 9,400 kPa for the natural and treated soil, respectively.

For the steps 10–20, 20–50 and 50–100 kPa, the sample hydraulic conductivity was indirectly estimated from the coefficient of consolidation, based on the one-dimensional consolidation theory (Terzaghi and Peck, 1960). The variation of hydraulic conductivity with increasing stress is reported in Figure 7.

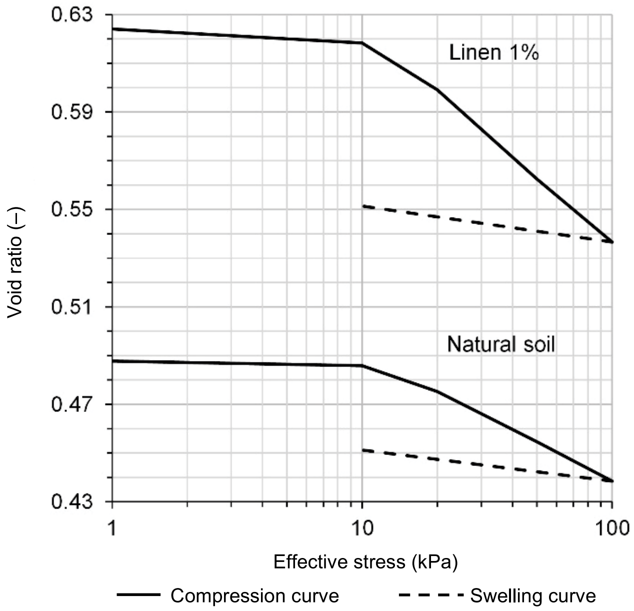

Fig. 5. Compression and swelling curves in oedometric conditions for the natural soil and for the soil treated with 1% linen fibres; source: own study

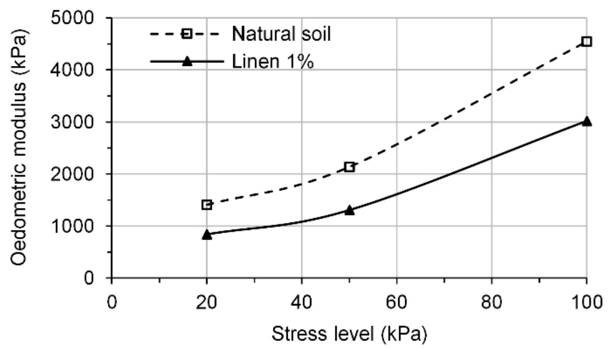

Fig. 6. Oedometric stiffness modulus as a function of the stress level; source: own study

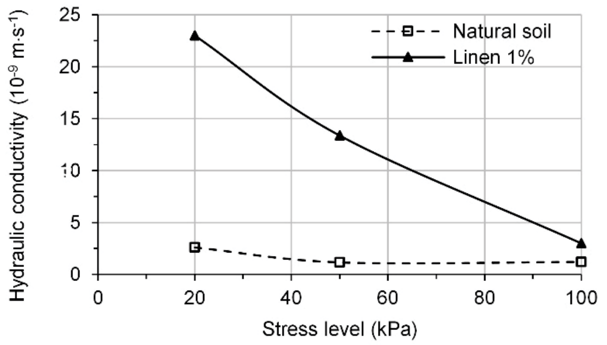

Fig. 7. Hydraulic conductivity as a function of the stress level in oedometric conditions; source: own study

DISCUSSION

Considering that the operational procedures of soil mixing and sample coring require special care and that result dispersion also depends on heterogeneities, the laboratory investigation allows preliminary inferences about the influence of fibres on soil consistency, compaction degree, compressibility, and hydraulic conductivity.

Figure 3 reveals that for treated soils the same number of blows is required for different water content values, i.e. the treated soil exhibits a consistency that is less affected by the water content. This could be due to the hydrophilic nature of linen fibres which can absorb and retain water, as well as the increased cohesion that fibres create among soil grains. The same factors would account for the increase in the plastic limit: the soil maintains a semi-solid consistency up to higher water content levels.

In terms of compaction response (Fig. 4), the addition of fibres reduces the maximum dry density achievable during compaction. Such a decrease is mainly due to the interaction between fibres and the solid matrix. In particular, the presence of fibres may introduce additional void spaces, thus allowing more air to be trapped within the soil. Moreover, the addition of fibres may hinder the movement of soil particles, inhibiting the close packing of grains and reducing their ability to interlock. Concerning the influence of the fibre content, a minor difference between cases with different percentages of fibres is found. This aspect requires further investigation, for instance, the extension of tests to include samples with higher fibre content.

The soil compressibility and hydraulic conductivity, as assessed through oedometric tests at low stress levels, appear to be affected by the fibre inclusion (Figs. 6 and 7): the treated soil exhibits a stiffness against compression equal to 60–66% of that for natural soil, for loading up to 100 kPa and a stiffness during unloading equal to 92% of that for natural soil. However, the initial porosity of the treated soil sample needs to be better controlled in order to properly compare the two cases. The initial macro voids created during coring along the lateral surface of the treated soil sample may have contributed to the higher compressibility and hydraulic conductivity. In fact, with increasing vertical compression, which presumably tends to close macro voids easily, the hydraulic conductivity of the treated soil decreases by an order of magnitude, whereas in the natural soil it decreases by half.

CONCLUSIONS

The use of soil mixed with textile fibres is investigated as an effective and sustainable solution to repair embankments. A preliminary laboratory investigation has been conducted on soil mixed with linen fibres to evaluate their effect on the basic properties of soil.

The first conclusion concerns the compatibility of the natural soil, sandy silt recovered from an old river levee, and linen fibres, which allows to obtain manageable and relatively homogeneous mixtures. The test results show that the influence of fibres on soil consistency is mainly due to their hydrophilic nature and to their ability to create apparent cohesion among soil grains.

The addition of fibres to soil reduces the maximum dry density by hindering particle interlocking and introducing additional void spaces. Moreover, the presence of hydrophilic fibres in soil increases the optimum water content by enhancing water absorption within the fibre structure.

Oedometer tests have been performed on natural and treated soil samples, indicating that the treated soil may have higher compressibility and hydraulic conductivity at low stress levels. However, localised damage in the treated soil samples may have affected the test results, highlighting the need for further improvement in the sample preparation.

Further research will also examine the shear strength and erodibility properties of treated soils, as critical aspects for their application in earth embankments. Moreover, laboratory tests on samples with dimensions higher than standard ones will be performed to investigate the influence of the tested volumes, while also considering different geometries (i.e. shape and length) for the textile fibres.

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CONFLICTS OF INTERESTS

The authors declare no conflict of interest.

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