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Cracking and desiccation of water treatment sludge for incorporation into soils for alternative liner material production

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ABSTRACT

Cracks may lead to hydraulic failure in soils due to increase of hydraulic conductivity which facilitate water infiltration, impacting negatively for liner materials. Therefore, cracking and desiccation investigation on liner material is advised. Water treatment sludge (WTS) is a by-product resulting from water treatment plants, and it seems to be suitable for geotechnical applications and soil replacement due to hydraulic latent properties, chemical similarities to soils, and mechanical behaviour. In this work WTS samples were incorporated into soil in different ratios – 05%; 10%; 15% and 20% of waste in dried mass of the geocomposites. The four mixtures, a soil sample and a WTS were tested according to the following procedure: two different circular Petri dishes samples were used, 5mm(H5) and 10mm(H10), and two cylindrical compacted samples with 65-70mm of diameter and 20-140mm of height (EDO-TRI, respectively) - dried for 10 days in controlled temperature and humidity. Water release curves (WRC), digital images correlation supported Crack Intensity Factor (CIF) index results were obtained for each material. Cracking behaviour results were compared with the permeability through falling head laboratorial tests, and studies around WTS ratio. Composites with 10% and 15% had the best results, showing no cracks during Petri dishes procedures for H10, in addition, the permeability for these materials reached the maximum for liner production – 10^{-9} m/s according to European and American directives - making possible the development of an alternative and feasible liner material.

Keywords: Cracking, desiccation, soil incorporation, water treatment sludge, liner material.

1 INTRODUCTION

Cracking generate weakness and leaching in earthworks, and it is prone for fine-grained soils (Yesiller, et al., 2000); (Peron, et al., 2012; Wei, et al., 2020). Its presence affects directly mechanical and hydraulic aspects of soils, fracture mechanism theory and numerical modelling methods (finite or discrete elements modelling) results are used to understand the pattern of cracks. Mainly that pathogeny is caused by tensile stress of suction when it is higher than the stress inside the soil, creating geotechnical problems. That instability can cause accidents or even failures in structures like slopes, foundations, embankments, dams, and liners earthworks in general.

According to (Wei, et al., 2020), field crack pattern is not formed simultaneously, and tend to be orthogonal or non-orthogonal, premising a homogeneous soil, it will be developed perpendicularly to the maximum stress direction. The governing mechanics of crack development are based in main subjects: volumetric shrinkage, failure criterion of soils under tension, and the abovementioned fracture mechanism (Peron, et al., 2012).

Compaction characteristics have directed influence in several geotechnical parameters as void index, capillarity, and cracking appearance. Knowing that soils can be composed of two or three phases, for completely dry case, they have solid phase and air in the pores, while a fully saturated soil has solid and liquid phase in the pores. However, the most found in nature are partially saturated soils composed of all three phases, solid, liquid and air (Craig, 2007; Matos Fernandes, 1995). Water occurs into soils in three different ways: pore water – inside the pores, free and oriented which affect the primary behaviour of soils -, adsorbed water – adsorbed by clays and retained between crystalline structure layers -, and hydration water – present in clay mineral crystal, it cannot be removed by oven drier. Water is inside void's soil, and its movement lead to seepage and permeability, water has no shear strength, it is almost incompressible, although transmits water pressure, pore pressure for saturated samples, through soil's mass.

Water treatment plants (WTP) generated residues called water treatment sludge (WTS), a solid industrial by-product with chemical composition like aluminium silicates. WTS's properties have been studied for geotechnical purpose and it seems to be suitable for producing liner materials for landfills, dams, ponds, and lagoons which store and prevent soil's infiltration of residues (Marchiori L., et al., 2021a; 2022). Earthwork liners are usually made of clays and geosynthetics, their main properties required are compaction, compressibility and shear strength, chemical compatibility, and hydraulic conductivity. Their durability depends on several resistance tests, one of them is the cracking and desiccation. Therefore, WTS to be considered as a soil substitute, it must work as a soil, thus, physical, chemical, mechanical, and hydraulic characterization laboratorial parameters are the first step to make viable its reuse, then durability tests, followed by field testing program (Marchiori, et al., 2020; 2022).

Thus, the most important parameter to obtain is the crack intensity factor to correlate with the hydraulic conductivity and heavy metals' leaching potential for liner approach. Hydraulic conductivity test will not be done in this work, but it is important to state the maximum according to Bouazza (2002) and DL102-D (2020), is 10^{-9} m/s for base layers. The main objective of this work is to evaluate the impact of WTS:soil geocomposite in cracking and desiccation of a soil's mass, looking to valorize the waste material for an alternative liner material production.

2 MATERIALS AND METHODS

2.1 Mixtures

The WTS was collected at Caldeirão's WTP, located in Guarda, Portugal, and the soil is from a construction site in Castelo Branco, Portugal. WTS:soil geocomposites were developed with dried masses mixtures following the ratios and nomenclatures below:

- 05:95% - 05% of WTS and 80% of soil
- 10:90% - 10% of WTS and 80% of soil
- 15:85% - 15% of WTS and 80% of soil
- 20:80% - 20% of WTS and 80% of soil

Previous studies (Marchiori, et al., 2021a; b; c; d; 2022) characterized geotechnically, chemical, mineralogical, and mechanically the WTS mixtures and the same soil, results are in Table 1 and 2.

Table 1. *Geotechnical and mechanical parameters*

Sample	%fines	%sand	G_S (-)	W_L (%)	W_P (%)	C_C (-)	c' (kPa)	φ' (º)
Soil	8%	92%	2.77	36%	29%	0.100	10	20
05:95%	9%	91%	2.59	38%	32%	0.065	7	24
10:90%	10%	90%	2.48	39%	34%	0.080	5	25
15:85%	12%	88%	2.42	42%	39%	0.130	0	31
20:80%	14%	84%	2.30	55%	54%	0.090	0	30
WTS	28%	72%	2.04	340%	200%	-	-	-

Table 2. *Chemical and mineralogical composition*

Sample	Main Mineralogy			SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Na_2O (%)	MgO (%)	CaO (%)
Soil	Quartz	Muscovite	Kaolinite	54.0	29.5	9.22	0.42	1.61	-
WTS	Quartz	Muscovite	Kaolinite	29.9	60.4	5.00	-	0.59	2.88

2.2 Cracking and desiccation

For the Petri dishes mixtures, a paste was prepared in a porcelain plate using 2x W_L of each sample to saturate them. The paste was disposed in two different Petri dishes with 5mm (H5) and 10mm (H10) of height, and the diameters of 95 ad 88mm, respectively. Compacted samples were prepared in Normal

Proctor w_{opt} + 2% for liner simulation, using an oedometer ring (EDO) with 20mm of height and 65mm of diameter, and a triaxial mould (TRI) with 140mm (height) and 70mm (diameter). Compacted samples of WTS were not done due to no workability or cohesion of the studied residue.

The crack intensity factor (CIF) is defined, where A_c the area of the cracks and A_T the total area of the sample, following:

$$CIF = \frac{A_c}{A_T} \quad (1)$$

For all samples, the photographic records were taken every day around 9am with the same photo device (iPhone11) to maintain the samples scale, the same timetable was done for the weight register. The surface photos were afterwards scanned and analysed using Autodesk AutoCAD to determine CIF.

Curves of water release were performed measuring the weight of the sample and supposing that the difference is due to water lost. All compacted and Petri dishes samples were treated with this procedure.

3 RESULTS AND DISCUSSION

Cracking results in Petri dishes for the soil are shown in Figure 1.

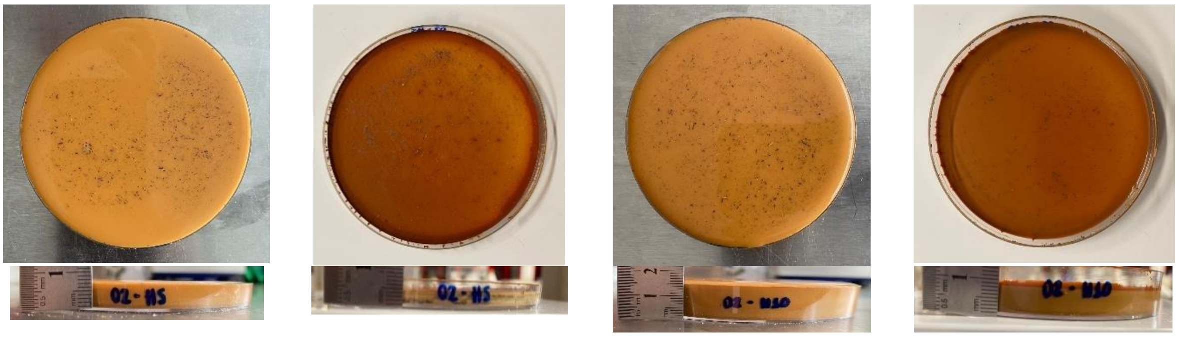


Figure 1. *Soil H5 wet and dry, and H10 wet and dry (from left to right)*

The soil showed no cracks during time independently of the height of the sample. This soil was chosen due to that expected behaviour looking to observe the impact of WTS introduction in crack appearance. Table 3 and Table 4 present photos over each of the geocomposites – 05:95% to 20:80% - and for WTS in Petri dishes H5 and H10, respectively, during the first 7 days of drying procedure, and a photograph on 30 days – called ∞ - to observe the samples totally dried. Compacted samples (EDO and TRI) are exposed in Table 5.

Table 3. *Cracking photos during time for WTS samples in H5 Petri dishes.*

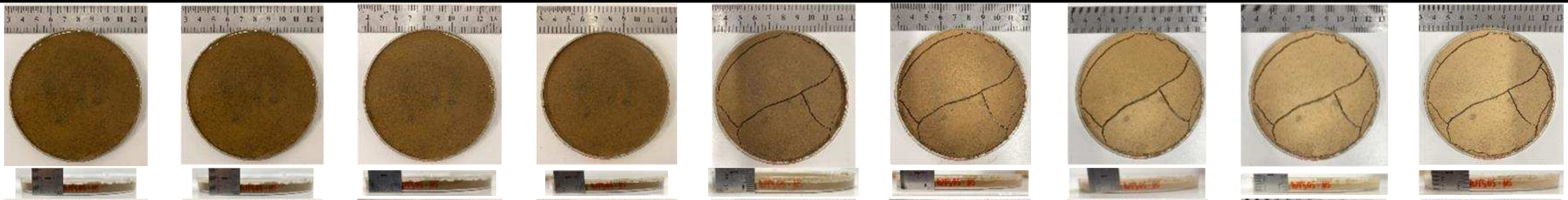
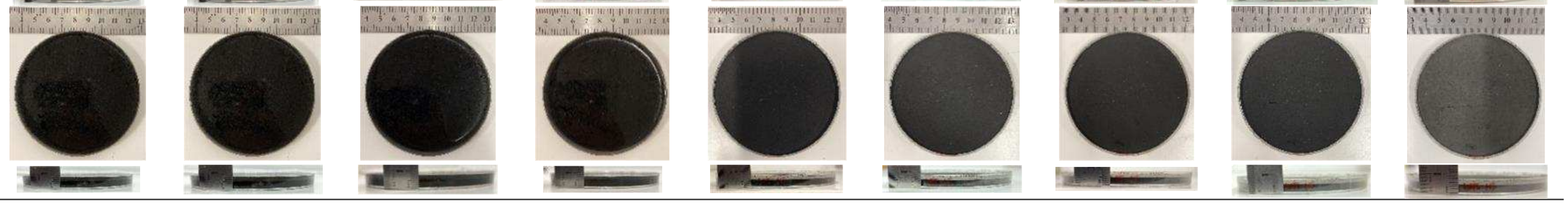
Sample H5	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	∞
05:95%									
10:90%									
15:85%									
20:80%									
WTS									

Table 4. Cracking photos during time for WTS samples in H10 Petri dishes

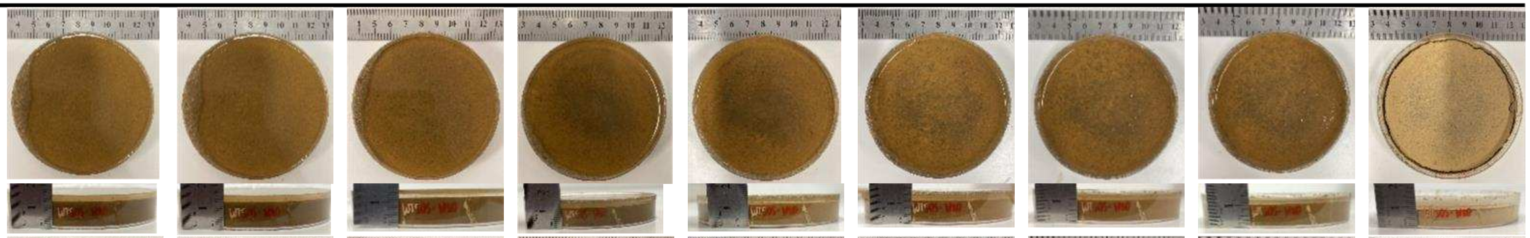
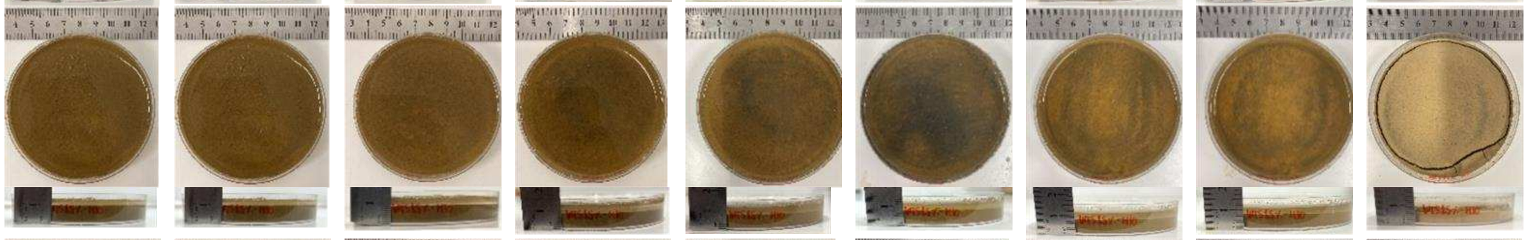
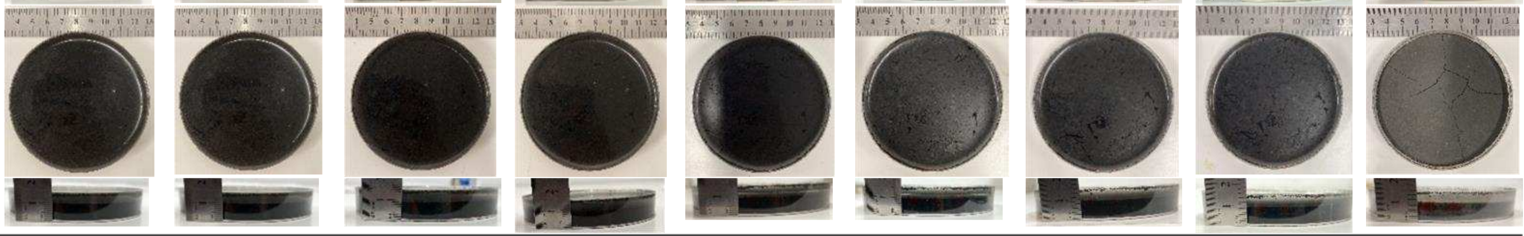
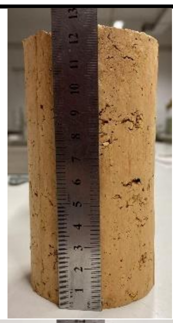
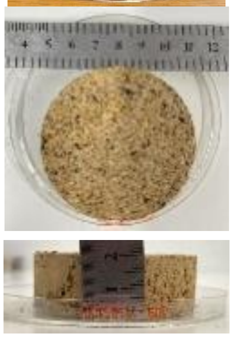
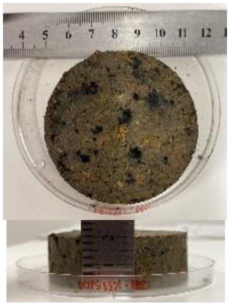
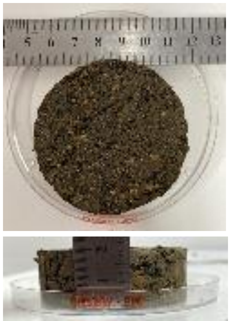
Sample H10	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	∞
05:95%									
10:90%									
15:85%									
20:80%									
WTS									

Table 5. *Desiccation of compacted samples during time*

Samples	Wet (w_{opt})		Dry	
	EDO	TRI	EDO	TRI
SOIL				
WTS05%				
WTS10%				
WTS15%				
WTS20%				

It can be observed that for H5 samples, cracks appear for all test; it start to appear in day 4, 6, 5, 6, and 7 for 05:95%, 10:90%, 15:85%, 20:80% and WTS, respectively, thus all the sample within low thickness is prone to crack, the ratio for height:diameter (H:D) in this case was around 5:92 or 5.5%. Although for

10:90% to 20:80%, the crack was smaller than 05:95%, and curiously the WTS by itself showed less opening. That behaviour can be explained by the homogeneity of the mixtures. When introducing around 15% of waste into soil, seems to void-filling as the WTS is finer than the soil. Within 5%, seems to just rearrange the soil particles, as with 100% of residue, the particles are homogeneous as well but in a different arrangement.

A similar behaviour for WTS occurred in H10 tests, even with H:D of 10:88 or 11% - double of H5 ratio – small cracks appear, but only for infinite time; Besides, for the geocomposites, all of them had no cracks for the first 7 days, and still stabilized for infinite, therefore borders shrinkage happened due to the shape of Petri dishes.

Compacted samples did not crack significantly as they behave like a granular soil, all tested materials were classified as well-graded sand with silt (SM-SW) by (Marchiori L. , et al., 2022) according to the Unified Soil Classification System (USCS). That results corroborated with studies like (Wei, et al., 2020); (Peron, et al., 2012) and (Yesiller, et al., 2000).

The water release curves (WRC) are plotted in Figure 2 for compacted samples results, and Petri dishes' H5 and H10 tests are presented in Figure 3.

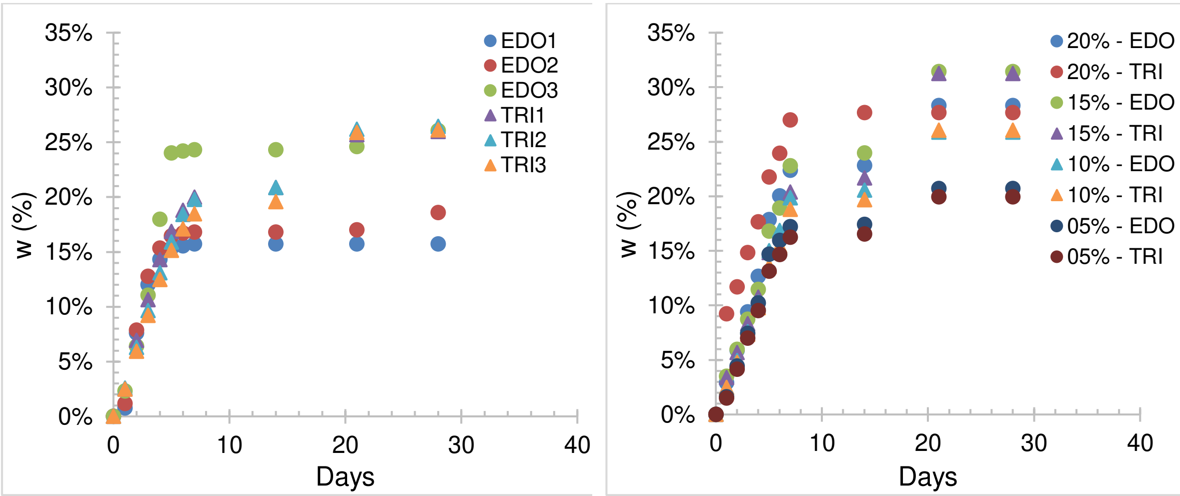


Figure 2. *Compacted samples of soil's WRC (left), and WTS mixtures' WRC (right)*

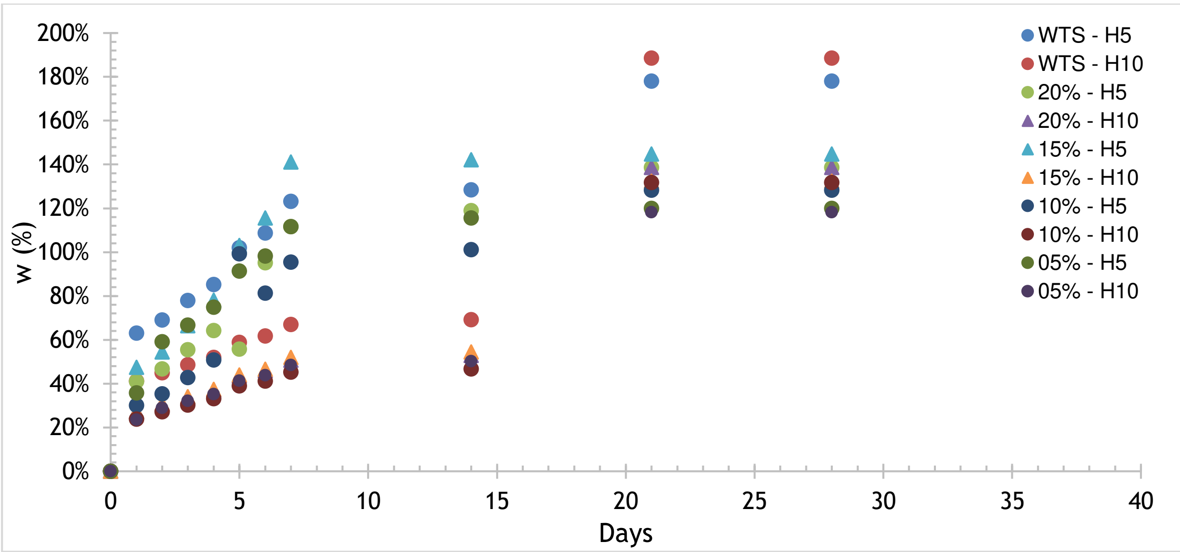


Figure 3. *Petri dishes samples of WTS and mixtures' WRC*

The angular coefficient – inclination – up to 7 days of dot's tendency in Figure 2 and Figure 3 can be analysed as suction of the tested samples, because for actual suction measurement (in kPa), it is needed a setup with a psychrometer measurer within a data acquisition system. In Figure 2, the period up to 7 days is difficult to differ each sample, which was left this way to be observed that this initial suction does not change significantly according to WTS ratio. Due to the samples were small the parameter chosen to be measured was the evaporation in water content. Along with this, the y-axis exposed as water content (w) is the amount of water which evaporates from the samples measured by days.

WRC of the compacted soil were prepared in triplicates, 3 for EDO sample, and 3 for TRI; they all are very similar in the first 7 days, then TRI samples lost around 5% of moisture more than EDO samples. As TRI have more height than EDO, that can be explained due to a higher self-consolidation of the sample creating more pressure to expel water from pores. The same occurred for the mixtures, but distinguish less than 5% between EDO and TRI, possibly stabilizing the release of water within the size of the sample. As the initial angular coefficient of all WRC are similar, the velocity of drying is like all tests.

WRC for Petri dishes were expected to behave differently since sampling process used the water content according to the liquid limit of each sample, so, the final release of water corroborated with the initial moisture amount. It was also observed that the angular coefficient of the curves is increasing as the WTS amount increases, thus, the incorporation of WTS into soils seems to improve the water release potential. This behaviour is justified as the suction is happening faster when the angular coefficient is higher, however not necessarily high suction due to an insufficient number of small pores that allow suction development as the WTS seems to have a filling-property into composites (Yessiler, et al., 2000).

CIFs were obtained following the method described in Section 2 as shown in Figure 4 and Table 6 shows CIF for all samples.

Figure 4. *AutoCAD's CIF method*

Table 6. *CIF and k results.*

	CIF (%)				(Marchiori, et al., 2022a)
Sample	**EDO**	**TRI**	**H5**	**H10**	**k (m/s)**
Soil	0.0%	0.0%	0.0%	0.0%	$6 \times 10^{-11} - 3 \times 10^{-9}$
05:95%	0.0%	0.0%	<u>1.4%</u>	0.0%	$1 \times 10^{-9} - 6 \times 10^{-9}$
10:90%	0.0%	0.0%	<u>1.7%</u>	0.0%	$7 \times 10^{-10} - 2 \times 10^{-9}$
15:85%	0.0%	0.0%	<u>2.9%</u>	0.0%	$2 \times 10^{-10} - 1 \times 10^{-9}$
20:80%	0.0%	0.0%	<u>1.6%</u>	0.0%	$8 \times 10^{-10} - 2 \times 10^{-8}$
WTS	-	-	<u>0.1%</u>	<u>0.9%</u>	-

Since crack appearance is not a design parameter for liner, a CIF value (CIF=0.0%) was adopted to be the maximum required for liner design within this work. Thus, the underlined values in Table 3 declassified H5 mixtures as potential liner material, all other samples seem to be valuable for liner application due to CIF=0.0% (no cracks stared). Although, (Marchiori, et al., 2022) analysed hydraulic conductivity for the same samples and concluded that only 15% of WTS is the ideal for an alternative liner production due to hydraulic conductivity lower than 10^{-9} m/s.

4 CONCLUSIONS

The main conclusions around cracking and desiccation behaviour for WTS incorporation into soils for liner material production are:

- WTS incorporation into soils have no significant impact over cracking;
- Compacted mixtures behave like typical granular soils in terms of crack and desiccation, WTS seems to stabilize fine-grained soils, and filling the voids of sandy soils;

- All samples of composites in Petri dishes with H:D ratio higher than 10% have no cracks (CIF=0.0%), possibly giving an adapted H:D ratio for liner construction;
- Incorporation of WTS into soils improved the water release potential or velocity of suction as it is a finer material, stabilizing clayey soils.

Further research will be conducted for a better evaluation of WTS for liner material production, namely by testing the residues' consistency and durability in a long-term behaviour and field scale to better understand their impact in hydro-mechanical characteristics of soil.

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