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The impact of large microplastics on the physical behavior of soils: implications to marine sediments

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Abstract :

Marine plastic pollution has become a major concern as it threatens marine life and human health. Most of the plastic that enters the ocean is either consumed by animals and/or trapped in sediments. However, there is little information on how sediment properties might be affected. In this article, we explore the impact of microplastic inclusions in marine settings by using PVC plastic chips and two soil samples as analogues. We conducted a comprehensive experimental study to investigate changes in compressibility, strength, stiffness, thermal and hydraulic conductivity, and particle migration by varying plastic content. Results show that as low as 1% of plastic content by volume can lead to irreversible consequences in sediment behavior while coarse particles display a heightened sensitivity than pure fines. As plastic content in sediment increases year-by-year, we anticipate significant repercussions in marine life, the future landscape of the seafloor and subsurface phenomena.

Keywords : Geotech, Marine sediments, Microplastics, Pollution, Soil behavior

Introduction

Since the commercial development of plastics in the 1930s and 1940s, its production has grown exponentially [41], and it became an integral part of our daily life [1] [47] [76]. Microplastics (MP) have a negative social-economic impact on coastal areas, they are also a threat to living marine organisms and human health. Today, plastics are considered a major pollutant and can be found in the most unexpected places: abyssal plains [44] [43] [66], ice [12] [13] [62], mountain lakes [33], the atmosphere [44] [73] and even the human body [55] [23]. They are ingested by marine organisms and thus contaminate the food chain, they can desorb additives like endocrine disruptors and accumulate micropollutants [34] [48]. The invasion of plastics in nature has been so extensive that it has been suggested that they may be used as a geological marker [12] [45] [36].

Worldwide plastic production has grown continuously for more than 50 years, up to 368 Mt in 2019 (Mt = million tons, [64] [65]). By 2015, about 60% of plastic ever produced were discarded (around 4,900 Mt) and accumulated either in landfills or in the environment [35]. The environment is increasingly experiencing a notable influx of microplastics from landfill leachate, with concentrations reaching over hundreds of particles per liter. This phenomenon is mainly linked to the local generation of plastic waste and the methods employed in solid waste management [42] [77] [37]. Earth's ocean acts as a sink for natural and man-made by-products: marine plastic pollution has been reported since the 1970s [60]. About 75-90% of the plastic found in the oceans were originally disposed on land [56] while between 2.8% and 18.6% were river-transported [53]. Once they reach the ocean, plastics are redistributed via oceanic currents and drift [30] or are caught in a burying/resurfacing cycle along coastlines [36]. Studies estimate that floating particles in worldwide oceans account for less than 1% of all plastic that has entered the ocean since the 1950s. It is therefore expected that most of the plastic debris will settle along marine sediments [50].

Hydrocarbon-based plastics such as PE (polyethylene), PP (polypropylene), PVC (polyvinylchloride), PET (polyethylene terephthalate) and PS (polystyrene) are the most non-fiber plastics produced worldwide [35]. Additionally, plastic materials have been improved by plasticizer additives, which are frequently toxic [32] [59]. About 84% of worldwide production are thermoplastics [67]: they are mostly produced for general usage applications. Plastics have unique physical and chemical properties, and durability: they have low-to-moderate strengths and stiffness [76] [18], and their density ranges widely from 0.9-1.0 g/cm^3 for PP and PE up to 1.2-1.6 g/cm^3 for PVC [34] [38] [63] [22]. In general, their thermal conductivity of around 0.1-0.2 W/mK [43] is lower than soils and other geo-materials. Hydrocarbon chains are hydrophobic, water absorption is below 1% on average [19] and water contact angle with most plastics is high (71° to 122°; [31]).

Plastic degradation is probably our only passive and inexpensive way to fight the introduction of human by-products into the environment. Degradation may be physical, chemical or biological: sunlight (ultraviolet UV), oxygen, temperature, micro-organisms and mechanical weathering. Biodegradation along with UV exposure are the most abrasive and efficient source of degradation [4] [71] [20] [3] [2] [57]. Likewise, environmental conditions can either accelerate or decelerate the ageing process. Their fate in marine sediments is still unknown. Due to significant uncertainties in degradation rates, plastics are likely to pose a time-dependent concern and could influence the future marine landscape.

Plastic accumulation in marine sediments

MP are typically defined as plastic fragments of < 5mm (Figure 1). Most of published work on microplastics in marine environments report a range from 0.33-1 to 4.75-5 mm [30] [22]. Regarding its shape, they can be categorized as fibers (1D), fragments (2D and 3D), and pellets (3D). The shape of the particles is relevant to their motion in water, their settlement rate and distribution: because of high specific surface, 1D particles tend to be buoyant and accumulate on beaches. There is no general agreement regarding prevailing shape, although several authors report fibers [44] [36] [16] [26] [79] [81] [86], while others suggest fragments [63] [58] [78].

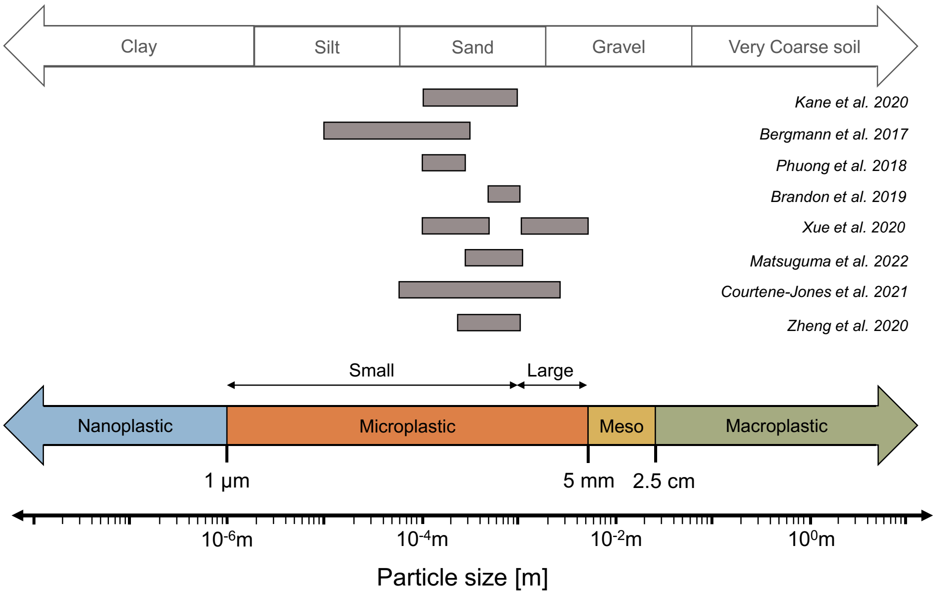

Figure 1. Microplastic particle size recovered in marine sediments of selected sites published in the literature. In most cases, microplastics are found in the mm and sub-mm range, similar to sandy sediments. Note: sizes are typically published in ranges without its distribution.

Plastic deposition in marine environments is energy-dependent with respect to its initial size and shape [36]: low-energy environments, such as lagoons, fjords, and estuaries, are presumed to trap high amounts of MP. Most of the studies were performed in sandy beaches and high-energy locations [36] [53] [22]. It has also been shown that sediment mass movements (turbidites) along with thermohaline circulation produce litter hotspots in abyssal plains [44] [43] [66].

MP are often found in the first tens of centimeters of coastal sediments [63] [79] [81]

[86] [58] and deep-sea [44] [16] [26]. It has been hypothesized that turbidites can bury MP up to a few meters deep [43]. MP size distribution has been proven to be normal, log-normal, bimodal or power law [51]; however, it highly depends on the depositional environment. Sizes range typically from 0.1 up to 1 mm, and they can span up to three orders of magnitude. Nevertheless, we can anticipate smaller sizes to be present but overlooked in older literature. Regarding its concentration per site, the distribution is not so evident: it typically extends from a few particles up to 10,000 particles per kilogram of dry sediment [36] [38]. We collected published data from different locations around the world (Figure 1; USA, Europe, Asia, Oceania) to represent contrasting depositional environments (summarized in Supporting Information Table T1; worldwide extensive databases can be found elsewhere). Because of the uncertainty of distribution and range, we compute the average made from all sites: 1,210 particles per kilogram of dry sediment and a diameter in the order of one millimeter. Our non-exhaustive collection compares well with published databases.

Plastics-soil behavior

Plenty of studies have covered the behavior of the introduction of man-made products to soils. Most published literature is construction-oriented and has used high ratios of plastic/rubber content to soil volume. Nevertheless, conclusions of these studies have highlighted that: synthetic polymer particles can impact the overall soil structure above a concentration threshold [49], interaction between plastic fragments and sediment grain size impacts the overall shear strength and permeability [49] [61] [69], plastic mass affects natural temperature fluctuations of a sediment over time [52]. Regarding microplastics, the published literature is mostly agricultural-based. Conclusions highlights that MP impact bulk density and porosity [82] [21], microbial communities [11], water holding capacity [27] [74], increase rate of evaporation and desiccation, and decrease of hydraulic conductivity [21] [74]; while those

MP with sizes and shapes similar to sediments have less impact into biophysical properties [28]. However, in agricultural soils, the impact of MP should be significant above 0.5% w/w [83]. Review articles pinpointed to the fact that MPs can persist on sediments for decades, however the information available on MP impact on sediment properties is very limited [21] [80].

Scope.

To the best of the authors' knowledge, there has not been an in-depth study reflecting the impact of microplastics with an emphasis on marine sediment behavior and its physical properties. Thus, the objective of this study is to better understand of how microplastics affect the physical characteristics of marine sediments. The goal is to provide a first-order assessment of soil behavior with the inclusion of plastic chips and determine the plastic content threshold to irreversibly modify it. Finally, we extrapolate our results to consider potential implications for marine life and coastal processes.

Materials and Methods

We selected two distinct soil samples, Fontainebleau sand and kaolinite, to serve as extreme depositional cases. As an analogue for microplastic inclusions, we utilized PVC plastic fragments (chips) obtained from pipe cuttings. The choice of this material was driven by several factors: it is one of the most common plastic found; given its high specific gravity, we can expect it to be sedimented alongside with other natural particles (while other lighter plastics might need to be ingested by fauna or driven by other means to reach the seafloor); as well as its ready availability and workability in the lab. While it's acknowledged that the chosen geomaterials and plastic might not capture every situation found in natural environments, they do allow us to minimize uncertainties, ensuring high-quality results within controlled laboratory conditions. Table 1 provides a summary of the physical properties of all materials employed in this study.

<u>Characterization</u>

Particle size and shape. Soils and plastic chips were analysed by laser granulometry (Malvern Mastersizer 3000; Figure 2). Sand and kaolinite particles show a mean diameter D_{50} of 212 μm and 7 μm respectively, while plastic chips are in the order of 804 μm (Table 1; Standards: ASTM D421-85, ASTM D422-63; [5] [6]). Sand-plastic and kaolinite-plastic sample size ratios are ~4 and ~115 respectively ($D_{50,pvc}/D_{50,sediment}$). In addition, we randomly selected 100 sand particles and PVC fragments to compute sphericity and roundness (Figure 3).

Specific Gravity. Due to significant differences between the soil and plastic used in this study, we measured specific gravity Gs for all materials (Standards: ASTM D854; [7]). Results show a similar value for kaolinite and sand $Gs = 2.65 \pm 0.02$; while PVC chips render $Gs = 1.23 \pm 0.01$.

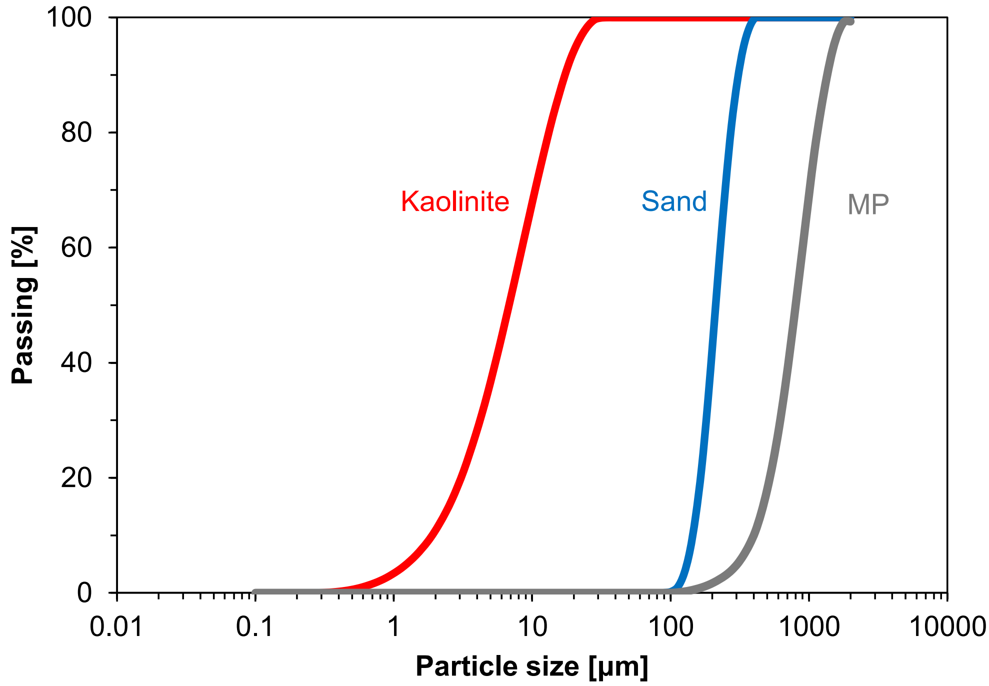

Figure 2. Grain size distribution. Kaolinite, Fontainbleau sand and microplastics particles MP used in this study are shown in red, blue and gray respectively.

Physical properties

To study the impact of plastic inclusions, we prepared soil and PVC-chip mixtures (sand-PVC and kaolinite-PVC) of varying plastic content *PC [%]*: 0, 0.1, 0.2, 0.4, 0.75, 1, 2, 3, 6, 10, 20, 30, 40 and 50% by volume. Due to the important contrast between geomaterials and plastics, origin and density, plastic concentration, *PC,* cannot be compared gravimetrically. Instead, we used the ratio of volumes between plastic *VP* and dry soil *VS* (i.e. $PC = VP/VS$).

Our data compilation showed an average of 1210 plastic particles per kilogram of dry soil, and a mean particle size of ~1 mm in diameter. We computed the plastic content for this average and named it the reference plastic content $PCr = 0.2\%$. Even though this value seems high, even higher *PC* can be found in the literature (from <0.01% up to 0.75% by volume, [36]).

Table 1. Physical properties of the three materials used.

	Fontainebleau sand	Kaolinite	PVC chips	Reference
Producer	SIBELCO FRANCE	SOKA (Societe Kaolinière Armoricaine)	-	
Soil classification	Fine to medium sand	Medium silt	-	ISO 2017 [40]
Size range	92.8 to 453 µm	0.297 to 34.5 µm	102 to 2000 µm	
Particle size D60	226 µm	8.62 µm	996 µm	
D50	212 µm	7 µm	804 µm	
D30	186 µm	4.31 µm	686 µm	
D10	145 µm	1.92 µm	440 µm	
Uniformity coefficient Cu	1.56	4.49	2.26	
Coefficient of curvature Cc	1.06	1.12	1.07	
Specific gravity Gs	2.65	2.65	1.23	ASTM D854 [7]
Thermal conductivity	Quartz: 1.2 to 3.0 W/mK [a]	Kaolin: 0.6 to 1.5 W/mK [b]	PVC block: 0.16 to 0.2 W/mK [c]	a) [25] b) [84] c) [14]

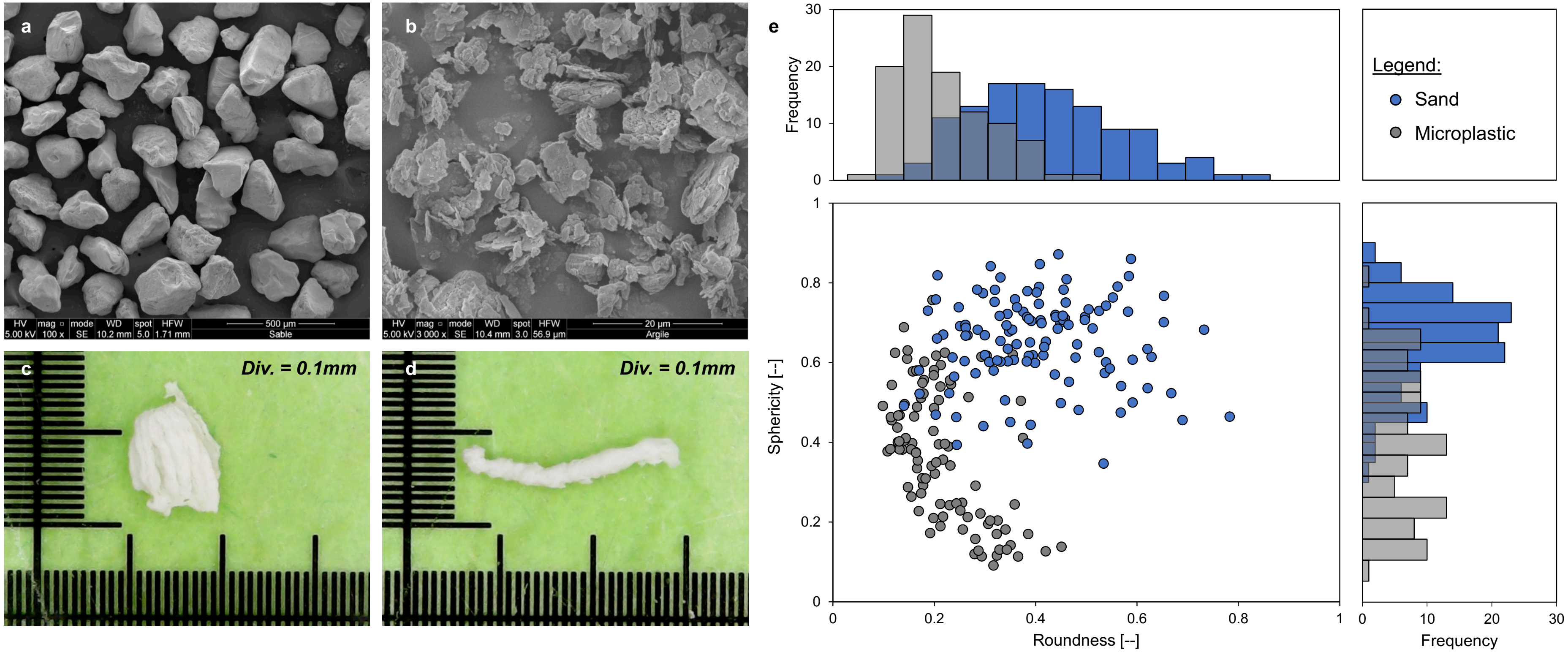

Figure 3. Particles shape factor. SEM images of: (a) Fontainbleau sand and (b) kaolinite. Photographs of microplastics particles: (c) 3D fragments, and (d) 1D strings. (e) shape parameters of sand and MP: roundness and sphericity computed as suggested by [85].

We selected four classical geotechnical tests to study the effects of plastic inclusions in soil properties and behavior: compressibility, hydraulic conductivity, undrained shear strength and shear wave velocity (small-strain stiffness). Additionally, we included thermal conductivity and a 'fragment migration' tests. These allowed us to investigate the geo-hydro-mechanical behavior and simplify field conditions. The following sections describe the experimental methodology and procedure. To facilitate mixing, sand samples were prepared dry while kaolinite samples were at a known high-water content (i.e. liquid limit).

Compressibility and hydraulic conductivity. We conducted standard compressibility tests in a classical oedometer cell under zero-lateral-strain conditions (ASTM D2435, [8]). The sample is contained within the main body of the stainless steel oedometer cell, which is 2 cm tall and 5 cm in diameter. Two porous stones are placed at the base and the top of the sample, allowing water to flow through while preventing soil escape. A flat, rigid loading plate is positioned on top of the soil specimen, making contact with the porous stone. Additionally, the cell is equipped with a graduated tube for water inlet to control flow influx into the sediment, facilitating the measurement of hydraulic conductivity.

To simulate shallow sediments, we applied low vertical stress ranging up to a maximum of 220.64 kPa. We used the coefficient of volume compressibility m_v, as a measure of compressibility in a semi-log plot:

$$m_v = \frac{\Delta H / H_0}{\Delta \log(\sigma')} \qquad (1)$$

where ΔH is the change in sample height, H_0 is the initial size and σ' is the applied effective stress. As $G_s^{PVC} < G_s^{soil}$, void ratio e was computed with the weighted average of Gs_{sample} and named "apparent void ratio" e_{app} (e_{0app} for pre-test).

After each loading step, and once consolidation was fully developed, we conducted a hydraulic conductivity k_{hyd} test via the falling-head method (ASTM D5856, [9]). k_{hyd} can be expressed in terms of apparent void ratio (Equation 2; [70]):

$$k_{hyd} = k_0 \left(\frac{e_{app}}{e_{0,app}}\right)^{\beta} \qquad (2)$$

where k_0 represents the hydraulic conductivity when e_{app}/e_{0app} = 1, and β-exponent is the sensitivity to change of the apparent void ratio.

Undrained shear strength test. We used the vane shear test to conduct undrained shear strength *Su* measurement of the kaolinite-PVC mixtures (ASTM D4648, [10]). The equipment consists of a four-palette vane, 2 cm high and 2 cm in diameter. Once the vane is inserted into the sediment sample, torque stress is applied until the sample fails, thus recording this value *Tu*. The final undrained shear strength is computed according to the ASTM D4648 standard. Given the low peak *Su* values recorded, we repeated each sample five times to obtain a mean value.

Shear wave velocity. Shear wave velocity *Vs* provides insightful information at the particle contact level of the sediment skeleton. We used a zero-lateral-strain cell with bender elements to record wave propagation in the mixtures at low effective stress $\sigma'_z \approx 0$ kPa. The specimen resides in a cell of 5cm tall and 7cm in diameter and a base and a top cap hosts the piezo crystals. The top cap is approached towards the sample until the bender element is fully immersed without applying a vertical load. A sine wave is applied to the bottom bender element and recorded at the top cap. Shear wave velocity is computed from the sample size and first arrival time as suggested in [54].

Thermal conductivity. Soil thermal conductivity represents its capacity for heat conduction. We used a double-needle probe (East30sensors.com) to determine the thermal properties of the mixtures. We mix plastic chips and water-saturated soils in a 5 cm diameter and 5 cm tall container. We then insert the needles and wait for 10 minutes to ensure temperature equilibration with the environment. The first needle is heated up to ~2 degrees Celsius, and the second measures temperature at a given distance. We performed all tests in water-saturated conditions. The rise and drop in temperature at a given distance was compared with the closed-form solution to retrieve its thermal conductivity [17].

Microplastic migration. To observe plastic fragment transfer and accumulation in moving sediments, we simulated a fully sheared specimen. For simplicity, we placed each homogeneous sand-PVC mixture submerged in water in a 500 mL glass cylinder. To avoid differential sedimentation, we first mix plastic chips and dry sand; then the mix is poured into the container in 5 mm layers at the time. At each layer the sample is saturated with deionized water. Once the sample is fully poured, we start the test by tilting the cylinder over 60° and back to a vertical position to ensure full shearing conditions, and then we photographed and reported each last position. While this test does not encompass all aspects of sediment flow, it enabled us to explore potential scenarios in a simple, straightforward, and repeatable manner.

Results and Discussion

Mechanical properties

Large deformation. Figure 4 compiles all compressibility curves. To be able to compare them, we plotted vertical deformation instead of the classical void ratio. An increase in plastic content *PC,* augments the deformation of sand-based samples from -0.24 mm up to -1.37mm for *PC* = 0% and *PC* = 50% respectively. Conversely, in kaolinite-based samples the effect is the opposite: from -3.8 mm up to -2.1 mm for *PC* = 0% and *PC* = 50% respectively. *PC* = 100% has larger deformability than any mixture.

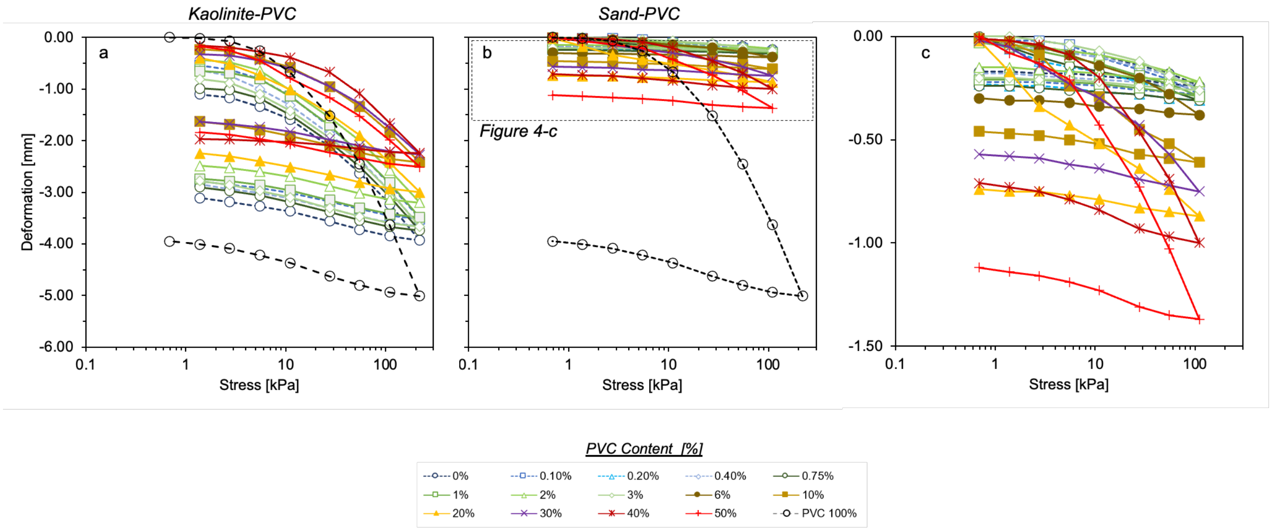

Figure 4. Compressibility tests: (a) kaolinite-PVC mixtures, (b) sand-PVC mixtures, (c) sand-PVC mixtures for content ≤ 50%. The increase of plastic content has contrary effects in deformation: the mixtures become stiffer in fines and more compressible in coarse. Loads 0.1 and 0.5 kPa are not shown due to seating effects.

Small deformation. Shear wave signatures are summarized in Figure 5. Shear wave velocities are in the order of 220 m/s for clean sand, 18 m/s in pure kaolinite and 94 m/s for a PVC pile of chips. In kaolinitic mixtures, as *PC* increases *Vs* varies around 18 m/s, but then increases from *PC* = 20-30%. However, sandy mixtures show a decrease of *Vs* even at lower *PC*, implying that PVC chips are already part of the soil skeleton.

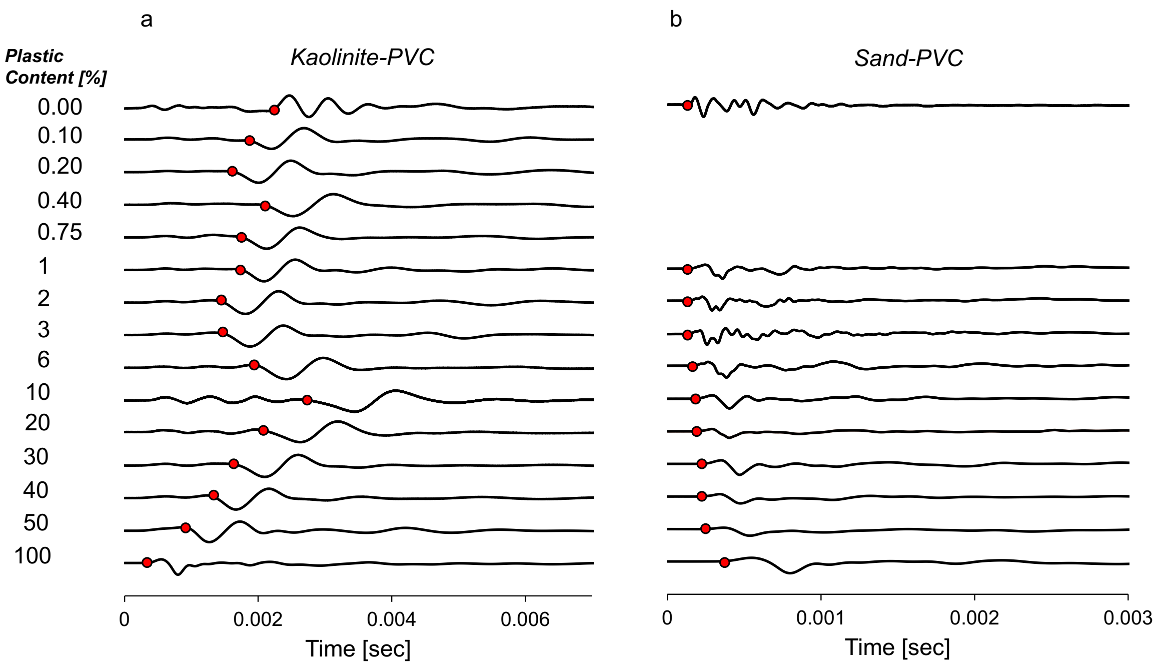

Figure 5. Shear wave signature cascade for: (a) Kaolinite-PVC and (b) Sand-PVC mixtures. The red-colored markers indicate the picked first arrivals. Note x-axis range for both sets is not the same.

Strength. Results from the shear vane test are shown in Figure 6. In general, strength increases as *PC* augments: from 1-2 kPa (at *PC* = 0-20%) up to 5 kPa (at *PC* = 40%). The major impact is noticed at *PC* > 20%. Cases above *PC* = 40% were not studied since its undrained condition cannot be guaranteed.

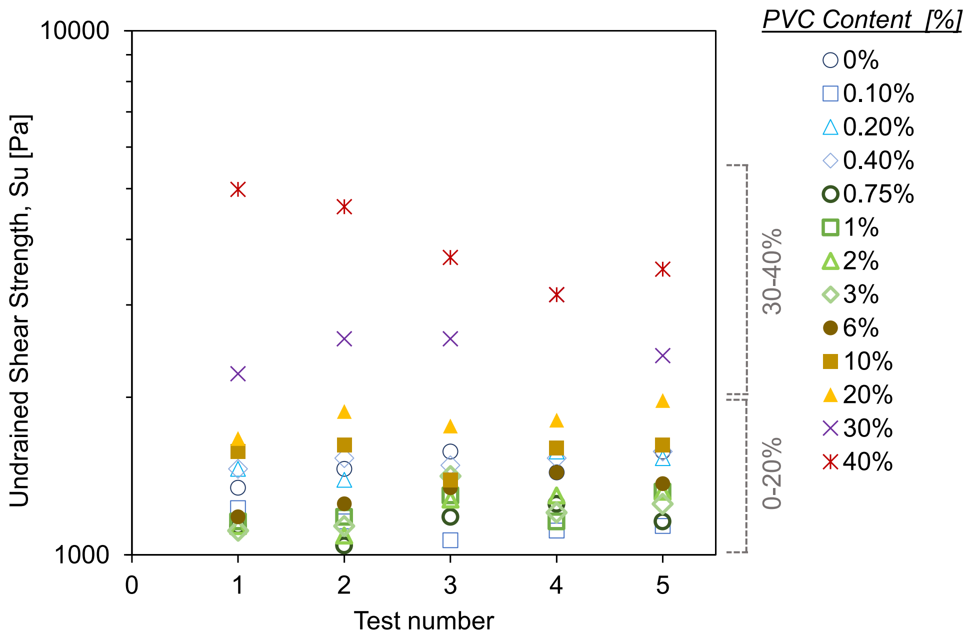

Figure 6. Undrained shear strength. Only kaolinite-based mixtures were tested. Above 40% in PVC content does not guarantee undrained conditions.

<u>Conductivities</u>

Hydraulic. We superimposed all results in a k_{hyd} vs. $e_{app}/e_{o,app}$ plot (Figure 7; see database for soils in [70]). Kaolinitic samples show lower absolute hydraulic conductivity, ranging from 5.16 x10^{-9} to 1.15 x10^{-8} m/s (27.58 kPa) and from 3.16 x10^{-9} to 6.07 x10^{-9} m/s (220 kPa). The hydraulic conductivity of sandy mixtures ranges from 7.1 x10^{-7} to 6.1 x10^{-6} m/s (0.68 kPa) and from 3 x10^{-8} to 3.1 x10^{-6} m/s (110 kPa). An increase in *PC* has different consequences depending on the matrix: in fine sediments, k_{hyd} decreases, while in coarse sediment, it increases.

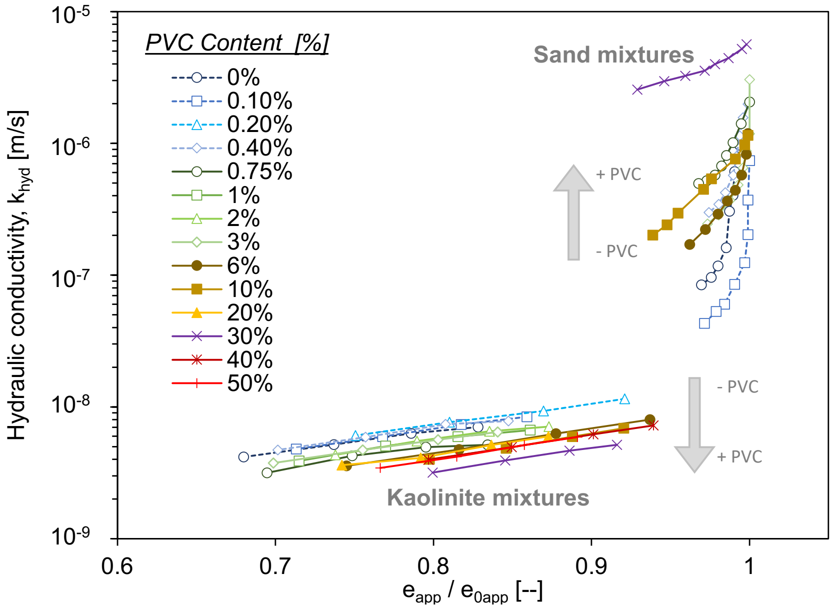

Figure 7. Hydraulic conductivity for sand and kaolinite mixes behavior with apparent void ratio e. An increase of PVC content augments the permeability in sandy based mixtures, while it decreases in fines. Apparent void ratio e_{app} is defined in the text.

Thermal. The thermal signatures of water-saturated sand and kaolinite mixtures are presented in Figure 8. Red dots demark the maximum temperature for the mixtures and *PC* = 100%. Clearly, an increase in *PC* modifies the overall thermal conduction, developing an even more insulated material.

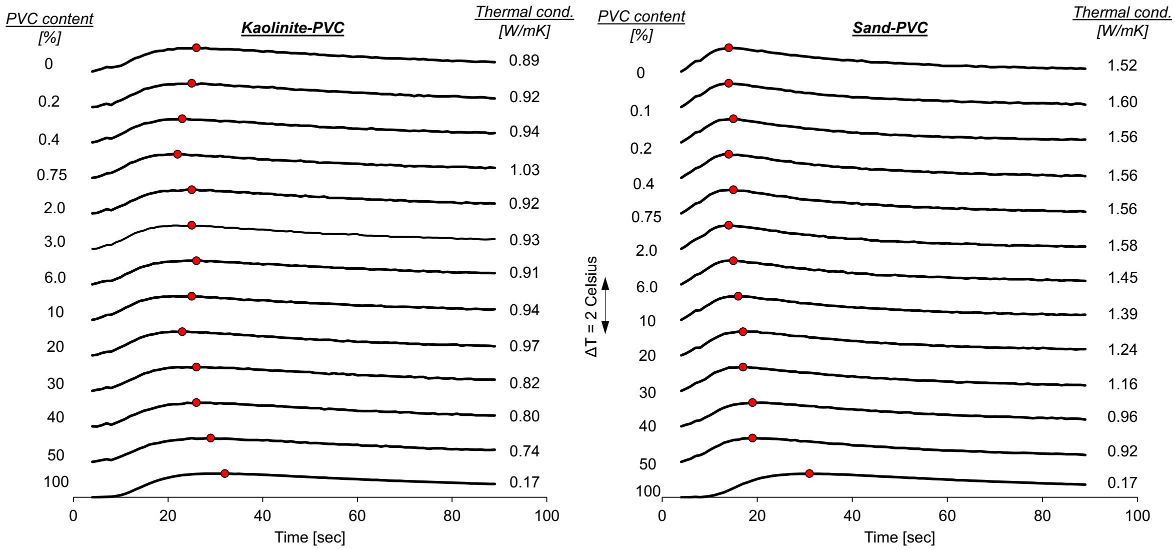

Figure 8. Thermal signatures cascade for Kaolinite-PVC and Sand-PVC mixtures. Red dots show the top of the signatures for 0 and 100% PVC content.

<u>The migration and accumulation of plastic chips</u>

The lab test revealed six patterns (Figure 9): *Surface deposit* (1), *Gathering* (2), *Sliding* (3), *Accumulation* (4), *Holding* (5) and *Entanglement* (6). Plastic particles close to the surface are more likely to remain in its initial position or rise to the surface when sediments are in movement due to its low density (Figure 9a). Repeating the tilting tests gathers the plastic particles over the surface even with low *PC* (Figure 9b). Plastic particles slide above the sand surface toward the bottom of the slope (Figure 9c). Higher *PC* leads to an accumulation of plastic chips buried in the sand at the bottom of the slope (Figure 9d). This accumulation was less evident at low *PC*. With $PC \geq 10\%$, some plastics chips hold the sand on the slope (Figure 9e). At $PC = 20\%$, we observed an entanglement between plastic chips and sand grains at the surface (Figure 9f).

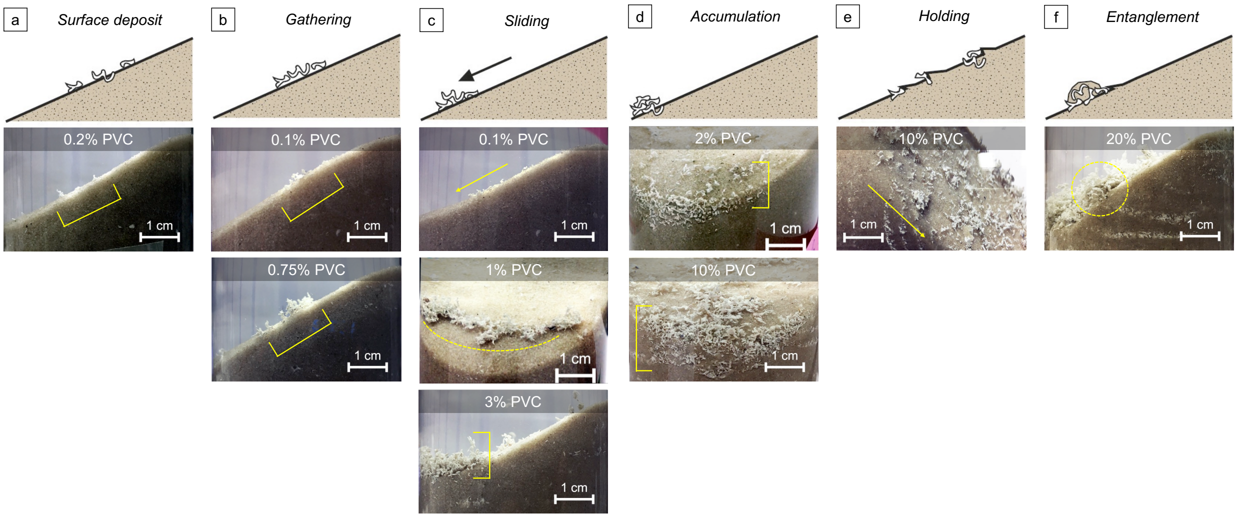

Figure 9. Microplastics migration simulation: (a) surface deposit of plastics, (b) plastics cluster, (c) particles sliding, (d) accumulations at the bottom of the slope, (e) plastics holding sand grains, and (f) entanglement of plastics and sand particles.

<u>Plastic content threshold *t*.</u>

In all cases, the inclusion of plastic fragments modifies the physical properties of the resultant matrix. In general, we observe three different behaviors at low, intermediate and high *PC* (Figure 10). For the purpose of this study, we defined threshold *t* as the *PC* at which the mixture deviates from pure soil behavior (i.e. *PC* = 0%). Each property has its unique threshold value which depends on the skeleton response to the inclusion of plastics chips, the uncertainty of the test measurement, and measurement errors.

The e_{0app} and m_v trend lines of both sandy and kaolinitic mixtures show opposite patterns (Figure 10a and -b). In kaolinitic mixtures, we found the threshold at *t* = 1-2%. Major highlights include: the intrinsic high void ratio of kaolinite results in a drop in e_{0app} and m_v when *PC* increases; when *PC* > 30-50%, the PVC chips form the skeleton of the mixture, they might aggregate, and fine particles remain in the pores of the plastic chip skeleton. Thus, the load-carrying fraction changes abruptly as shown in Figure 10b in a sharp upward turn at *PC* = 50%. This behavior was not explored since it falls beyond the scope of the current study. In sandy mixtures, the inclusion of plastic chips increases e_{0app} and m_v accentuating its impact to the overall behavior. Note that at PC = 100%, the compressibility m_v = 0.092, is higher than any mixture.

Undrained shear strength Su increases above t = 1-3% (Figure 10c). As expected, the large plastic fragments act as discreet stronger inclusion increasing the overall strength. However, the measurement errors increase with PC, highlighting the complex nature of these mixtures.

Shear wave velocity provides unique insights into grain-plastic contact. In sandy mixtures, the threshold is t = 2% while in kaolinite is t = 20% (Figure 10d). The fragments modify the matrix from a grain-grain contact to a less stiff grain-plastic contact. Clearly, Vs measurements highlight in a fast and easy way the impact of fragments in soil-PVC mixtures.

Because of plastic's low thermal conductivity with respect to quartz and water, the increase in PVC chips will inevitably modify the overall thermal conduction. We observe that for sandy-based samples t = 1-2%, but for kaolinite mixtures t = 10% (Figure 10e). Only higher plastic content would lower the thermal conductivity in kaolinitic samples with respect to sandy specimens. Indeed, the higher water content in kaolinitic samples may play a buffer role in the overall behavior of the mixture.

As PC increases in coarse samples, k_{hyd} increases but the β-exponent decreases (Figure 10f) highlighting its low sensitivity to overall volume change. We can propose a t = 10% in this case but the transition is not as clear as other parameters. The increase in permeability can be related to: (1) large and flat PVC chips may develop into preferential paths for water flow, (2) the hydrophobic nature and low roughness of the PVC chips decrease the friction along the streamline, and (3) PVC particles change shape under stress but do not necessarily modify the number of possible flow channels in the sediment. Conversely, k_{hyd} decreases in kaolinitic mixtures along with PC and there is no evident threshold value t for the β-exponent. The large size of PVC chips relative to the kaolinite particles act as an obstacle to the water flow, increasing the tortuosity and thus reducing permeability.

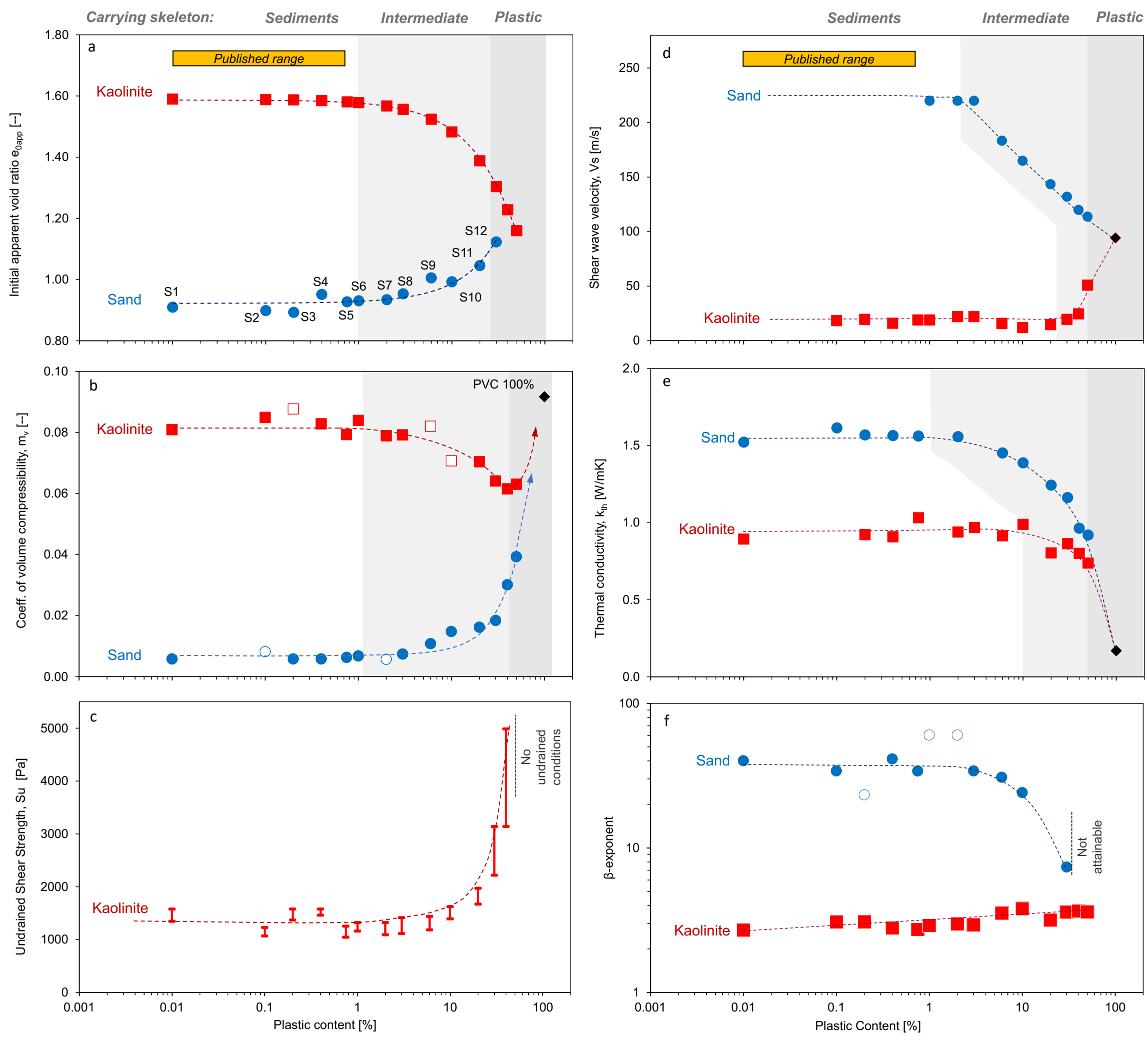

Figure 10. PVC-soil mixtures geotech behavior: (a) Initial apparent void ratio e_{oapp}, (b) coefficient of volumetric compressibility m_v, (c) undrained shear strength Su, (d) shear wave velocity Vs, (e) thermal conductivity k_{th}, and (f) hydraulic conductivity β-exponent. Blue and red markers denote sandy and kaolinitic mixtures respectively. Black markers show the result for 100% PVC content. Orange bars show the typical range found in nature [36] [38].

Our results show that for large plastic fragments, $t > PCr$. However, the minimum value of t (1-2%) is close to the maximum reported PCr (0.75% [36]).

A new sediment skeleton

Results obtained in this work demonstrate that plastics will impact sediment behavior: the inclusion of plastic fragments forms a new skeleton, the load-carrying fraction changes abruptly once the plastic content threshold is surpassed. Our results show that as low as 1-2% of plastic content by volume is sufficient to irreversibly modify a sediment matrix skeleton, and its effects differ from coarse- to fine-based matrix. Shear wave and compressibility results showed that sand mixtures change to a more deformable skeleton as *PC* increases while silty mixtures become stiffer (Figure 11a). From a grain-grain contact, the sediment adopts a grain-plastic contact, plastic fragments might change shape and size when loaded, thus the reduction of voids is biased, the classical definition of void ratio must therefore be revised. However, fines sediments are more deformable than plastic chips, thus the load-carrying fraction remains soil-based and fragments 'float' in fines for higher *PC* in comparison to sandy mixtures (Figure 11b; see also [83] for fine agricultural soils). Above 50% *PC*, the loading carrying fraction might change abruptly from fines-with-plastic-inclusions to plastic-dominated as soon as the plastic chips are in contact with each other. Although this effect is beyond the scope of this study, it may be of significant consequence in highly polluted environments.

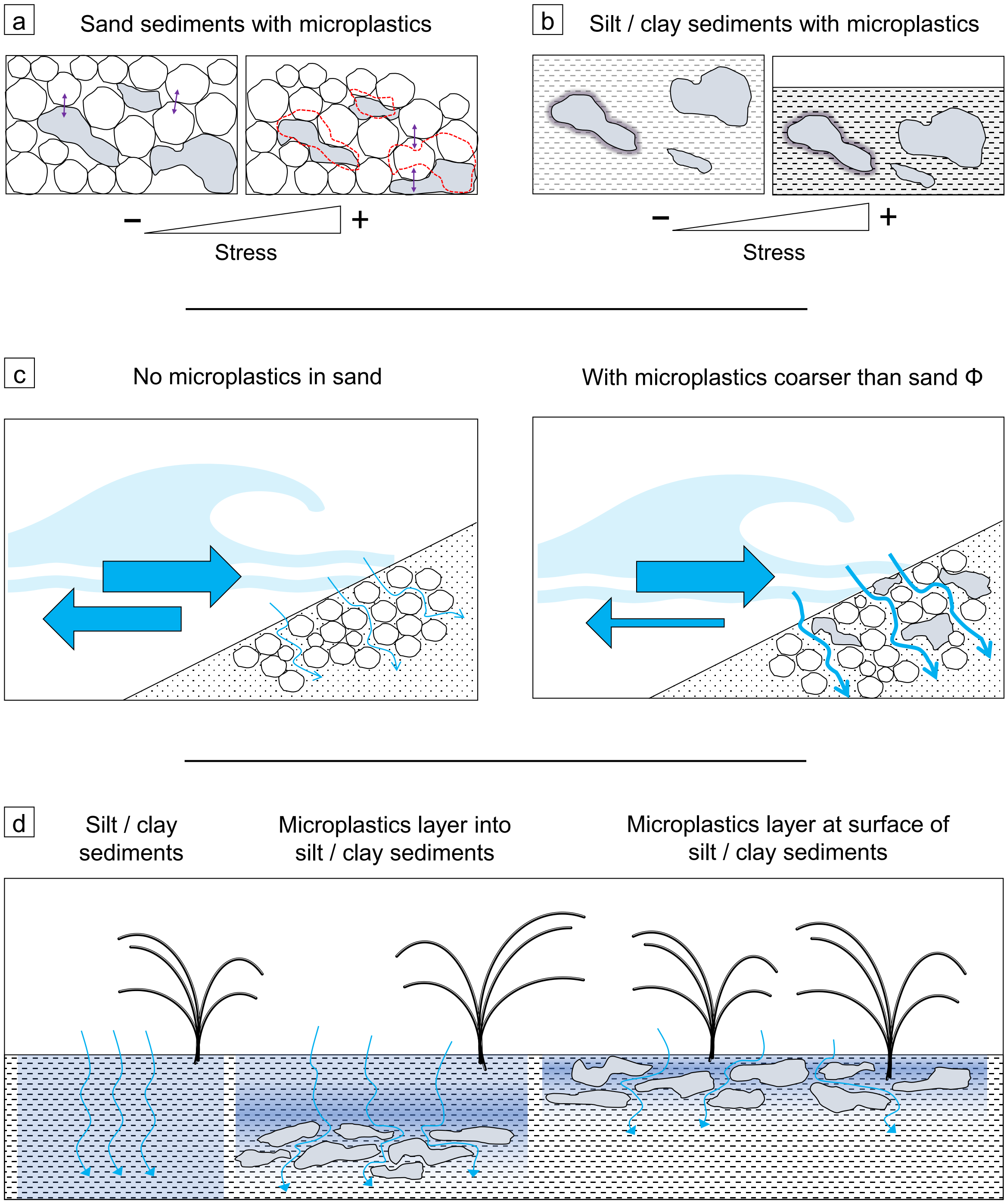

Figure 11. Plastic inclusion in marine sediments implications: (a) load-carrying fraction of sandy sediments evolves with plastic content from sand-to-sand and sand-to-plastic contacts and (b) fine sediments where the load-carrying fraction might remain soil-based due to its inherent large void ratios, (c) hydraulic conductivity increases thanks to large plastic particles in sandy-based sediments in swash zone currents and reduced backwash, and (d) water infiltration modification in a salt marshes: tortuosity factor increase and reduced permeability.

Environmental Implications

Coastal hydro-morphology processes

The activities of cities, ports, and landfills contribute significantly to the release of microplastics (MP): leachate from landfills, whether through aquifers, windblown lightweight plastics, or transported by fauna, can ultimately reach coastal areas making their impact worthy of careful study. Particularly, beach swash zones, and the wrack line are prone to microplastic deposits [22] [68] and accumulate plastic debris. Sediment permeability in the beach swash zone influences water infiltration and consequently the backwash (offshore flow) currents. When sediments are highly permeable, a significant amount of the uprush (onshore flow) quickly seeps through and contributes to weaken the backwash [46]. Our results demonstrate that the addition of plastic fragments in sandy sediments can increase permeability when $PC >$ 10%. Although 10% can be considered very high concentration, it could easily be reached on coasts located near plastic waste sources or with marine currents carrying plastic debris (Figure 11c). Kamilo beach, a Hawaiian island famous for its accumulation of large amounts of marine debris, is an example [24]. Plastic inclusions in fines decreases hydraulic conductivity and create ponds and lagoons (Figure 11d). The low conductivity could severely impact coastal sedimentary environments regarding water infiltration and associated ecosystems. In addition, migration experiments have highlighted the possible formation of plastic layers, a process creating plastic accumulation even with low overall *PC*. Consequently, the formation of MP layers among very fine sedimentary material in salt marshes can be expected.

Marine life

Temperature is a major abiotic factor influencing living organisms. Plastic debris on beaches affect thermal input and outputs, increasing daily extreme temperatures [52]. Our results show a gain in sediment insulation properties with the addition of *PC*. The insulating properties of plastics are therefore an additional stress to consider in the case of significant increase in MP content, particularly for sea turtle hatching [15] [29], corals, algae, crustaceous and nearshore fish [39]. In addition, we anticipate that a change in sediment structure can significantly impact burrowing animals in unknown ways.

Limitations and future work.

The large PVC fragments employed in this study exhibit a uniform sphericity distribution (Figure 3e), ensuring that our results remain unaffected by shape. Moreover, we do not account for the geographical variability of plastic shape and size as well as plastic degradation process that would occur in a natural setting. Consequently, we restrict our findings to these conditions. However, we anticipate that MP composition, size, and shape may yield varied effects: smaller particles could impede the impact on coarse sediments by accumulating in pores; a skewed distribution towards 1D MP fragments could significantly enhance strength in sands through particle interlocking; certain MP materials might develop stiffer skeletons, redirecting contact forces and weakening the overall structure; and rougher MP surfaces could increase the grain-grain friction coefficient, thereby enhancing strength and stiffness. Additionally, the full cycle landfill-transport-marine sediment should be studied to understand the fate of MP in marine environments. Although these aspects fall beyond the current scope of this article, we deem them worthy of exploration in future work.

Conclusions

Plastic pollution has become a major concern to both the environment and humans. Major plastic accumulation in coastal areas can impact marine life, local processes and sediment behavior. To understand better the impact of microplastics on the behavior of marine sediments, we conducted a comprehensive experimental study with two soils (sand and kaolinite) and used large PVC plastic fragments as an analogue of a marine setting. Salient conclusions are:

- The inclusion of plastic fragments forms a new skeleton, the load-carrying fraction changes abruptly once the plastic content threshold is surpassed. Our results show that as low as 1% of plastic content by volume is sufficient to irreversibly modify a sediment matrix behavior. Sediment mechanical deformation, stiffness and strength is impacted by *PC* = 1-3%; however, stiffness experiments in kaolinite-based samples of *PC* can reach 20%. The thermal property threshold is in the order of 1% for sand, but up to 10% in fine mixtures, while for hydraulic conductivity it is in the order of 10%. Shear wave velocity emerges as an excellent monitoring method for skeleton behavior.
- The impact of microplastic properties differs from coarse- to fine-based matrix. In coarse material, we can expect a substantial transfer of load from grain-grain contact to grain-plastic contact at very low plastic content. In fine sediments, plastic fragments 'float' in the fine's matrix. The future of the marine landscape will effectively depend on the amount of MP deposited and its interaction with marine sediments.
- Plastic migration shows that accumulation in layers and at the surface is possible.
- Because the plastic density is composition-dependent, the classical definition of void ratio cannot be used. This is accentuated when *PC* > 1%.
- Published marine sediment *PC* content averages 0.2% in a range of <0.01% to 0.75%, which are very close to the minimum threshold found in this study. Nevertheless, higher *PC* is expected on coastal areas subject to debris accumulation processes or in deep-sea hotspots.
- Coastal processes and marine life will be the most affected: changes in thermal

properties and permeabilities could result in irreversible detrimental consequences.

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