Comparison of Advanced Hydraulic Properties between Microplastic and Fines in Sands

Brandon De Jesus[1], Gustavo Menezes[2], and Wing Shun Kwan*[,3]

[1]*Graduate Research Assistant, Dept. of Civil Engineering, California State University, Los Angeles*
[2]*Professor and Chair, Dept. of Civil Engineering, California State University, Los Angeles*
[3]*Associate Professor, Dept. of Civil Engineering, California State University, Los Angeles*

**Corresponding author's email:* wkwan4@calstatela.edu

<u>Abstract</u>: Advanced hydraulic characteristics of sands mixed with microplastic and fines are studied and compared using a Steady-State Centrifugation (SSC) Unsaturated Flow Apparatus (UFA). The concentration levels of microplastics are rapidly increasing in urban areas, and wildfires in urban-forest interface areas can increase the generation and distribution of microplastics, amplifying the environmental contamination and potential health hazards associated with these persistent pollutants. Currently, there is limited literature focused on the impact of microplastics on the hydrological impedance of soils, which can potentially impact landslides and aquifer recharging. This study utilizes California State University Los Angeles centrifuge facilities for the development of Soil Water Retention Curves (SWRC) for Microplastic-Sand mixtures to characterize the unsaturated hydraulic properties of the sand-microplastic mixtures and compare responses from sand-kaolin mixtures. We considered sands with five and ten percent microplastic and sands with the same proportions of Kaolin fines, and a special test of sand-microplastic-kaolin mixture. The generated SWRC curves with various percentages of microplastic will be useful for future numerical studies on the effects of microplastics on rainwater infiltration and on urban resilience from natural hazards like wildfires. The results suggest that while small amounts of microplastic powder alone have minimal impact on soil properties, their combination with kaolin fines can alter unsaturated hydraulic conductivity and matric suction.

Introduction

Microplastics have become a growing environmental concern, especially in areas that use large amounts of plastics, such as growing urban areas. The growing reliance on plastic eventually drastically increases the quantity of microplastics, and these degrade over time. The large amount of microplastics entering the soil has not been well studied, and while most concerns with microplastics are the potential health and environmental impacts, the effect on the properties of soils has not been clearly studied. Along with this, an effective technique to quantify the amount of microplastic in the soil is yet to be established [1]. Changes in soil hydraulic properties due to microplastics can impact water infiltration rates, potentially leading to increased runoff, soil erosion, and reduced plant water availability. Some previous cases, such as the ones discussed by Polito and Martin [2], have focused on saturated soils, and these conditions may not be fully represented in the vadose zone, considering that unsaturated conditions could better represent them. To investigate the effects of microplastics on the hydraulic properties and matric potential of unsaturated soil mixtures, a centrifuge apparatus can be employed, building upon the theoretical and experimental results of centrifuge testing for unsaturated soils demonstrated by Zornberg and McCartney [3].

Furthermore, the interactions between microplastics and unsaturated soil are limited, and studies such as the one by Shafea et al. [6] have observed that microplastics can reduce the hydraulic conductivity of fully saturated topsoil samples by clogging soil pores reducing pores spaces, leading to lower hydraulic conductivity and changes in water retention in the soil. However, it is crucial to explore unsaturated conditions since some instances would be more relevant to the condition. Due to the large variety of microplastic shapes and sizes as they degrade, this study will focus on a range from 50 to 100 microns, which is similar to the clay particles. Previous studies have found that differences in the size of plastic would have different effects on the hydraulic conductivity of soil [7]. Xie & Wang noted that 500 μm microplastics would drastically increase the hydraulic conductivity of compacted soils, while smaller particles ranging between 50 -150 μm decreased it. Given the variability in microplastic shapes and sizes, this research aims to contribute to a more comprehensive understanding of how these particles affect unsaturated soil hydraulic properties. This paper will focus on the effects of microplastics on the unsaturated hydraulic properties of soils by testing samples containing pure Ottawa sand, various fines, and microplastics with varying particle size distributions. This study is validated using ASTM D6527-00 [4] to develop the hydraulic conductivity functions from a UFA centrifuge. Furthermore, a centrifuge is also used to build water retention curves. Previous steady-state centrifuge testing with the same research instrumentation had been conducted to analyze the difference between treated and untreated bauxite residue by developing hydraulic conductive and water retention curves [5].

Material and Equipment

This research investigated the effects of kaolin fines and microplastics on the hydraulic conductivity and matric potential of sand. A control test was performed using lab-grade Ottawa sand saturated with distilled water. Subsequent samples were prepared by incorporating varying amounts of kaolin fines and microplastic particles into the sand matric. The microplastics consisted of polyethylene terephthalate (PET) powder with a particle size range of 50–100 microns, sourced from Nanochemazone. The kaolin fines, classified as Edgar Plastic Kaolin (EPK) powder, were obtained from R.T. Vanderbilt Holding Company, Inc., with a particle size range of 0.2–200 microns. The kaolin clay had a liquid limit (LL) of 60 and a plastic limit (PL) of 30, classifying it as a high-plasticity clay (CH) according to the Unified Soil Classification System (USCS).

Hydraulic conductivity and matric potential tests were conducted using the Steady-State Centrifuge (SSC) Unsaturated Flow Apparatus (UFA) located at California State University, Los Angeles (Figure 1). The centrifuge apparatus consists of a UFA rotor (rotational speed up to

4000 rpm) and two high-precision infusion pumps that provide water flow as low as 3.7×10^{-9} cm/s. Material imaging was performed using a KEYENCE VHX-7000 4K High-Accuracy Digital Microscope at the Cal State LA Materials Characterization Laboratory. Figure 2 presents images of the microplastic and kaolin particles, while Figure 3 displays the tested materials, including Ottawa sand mixed with microplastic particles and mixtures of microplastics with kaolin powders. Two specimens were tested during each centrifuge run, with all specimens prepared to a target relative density of 50%.

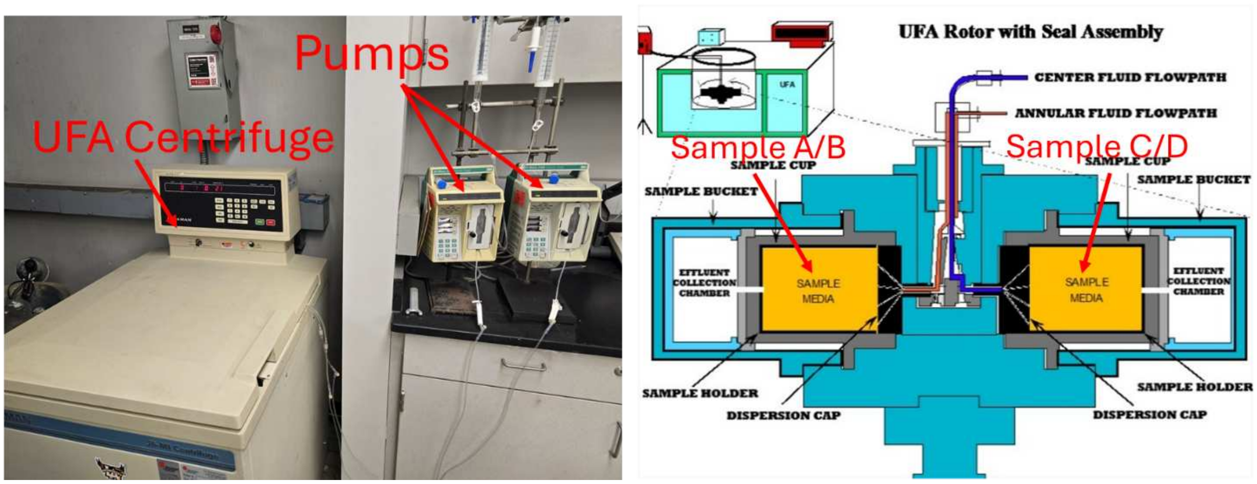

Figure 1: Overall Setup of Cal State LA SSC - UFA (left) and Rotor Scheme (ASTM D6527) (right)

Testing Procedures

Material Characterization

At the start of the specimen preparation process, water equivalent to the total dry mass of sand and contaminants (microplastic and/or kaolin powder) was measured and thoroughly mixed with the dry materials.

Figure 2: Images of microplastic (left) and Kaolin (right)

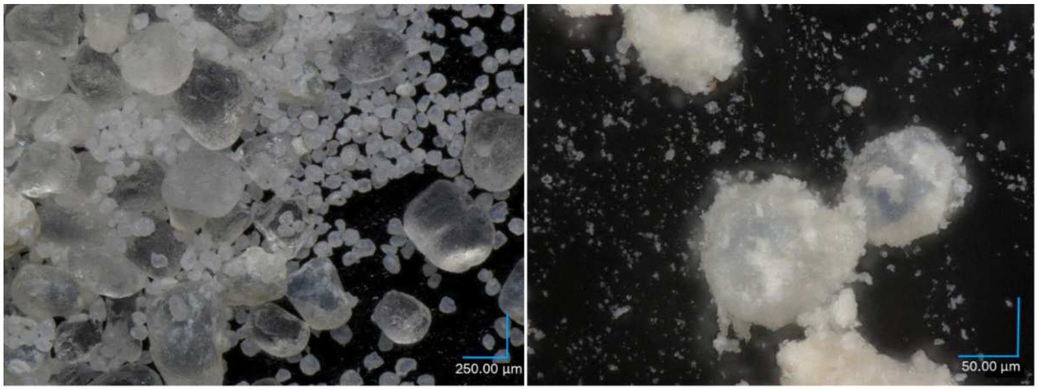

Figure 3: Images of microplastic with Ottawa Sand (left) and Kaolin with Microplastic (right)

Material properties, including maximum unit weight (γ_{max}), minimum unit weight (γ_{min}), and grain size distribution of Ottawa sand, were determined following ASTM D4253-13 [8] and D4254-16[9]. A summary of these properties and the USCS classification of the materials, ASTM D2487-17 [10], is provided in Figure 1, along with the grain size distribution curve.

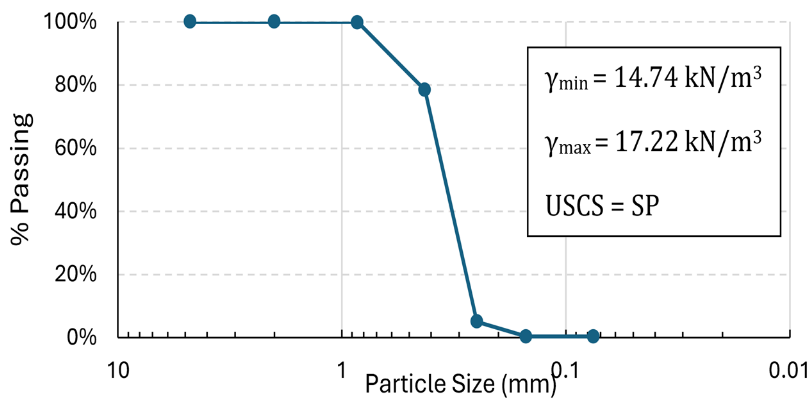

Figure 4: Grain Size Distribution and Index Properties of the Ottawa Sand

<u>Sample Preparation</u>

Afterward, the prepared soil mixtures were compacted into small cylindrical containers with dimensions of 3.3 cm in diameter and 4.85 cm in height using the moist tamping method described by [11]. This process involved calculating the precise mass of the mixture required in each container to achieve the target relative density of 50%. The required mass was divided into four layers, with each layer carefully placed and compacted to the appropriate height. To ensure uniformity, minor surface scratches were introduced at the top of each layer (except the topmost layer) to improve inter-layer bonding. The mass and height of each layer were recorded during placement to verify that the target relative density was achieved. The relative density calculations for all specimens, including those containing kaolin and microplastics, were based on the same minimum and maximum unit weights. Sand mixtures were prepared with 5% and 10% by weight of kaolin and microplastic powders as additives, along with a special case containing a combination of 5% kaolin and 5% microplastic powders Conducting separate tests to determine these values for the sand-kaolin and particularly, sand-microplastic mixtures, was deemed economically unfeasible due to the high cost and limited availability of the microplastic powders. Pure Ottawa sand samples were used as a baseline and to better compare samples with the different contamination levels.

The moist mixtures (Figure 5a) were sealed in a mixing bowl to maintain moisture content and stored for at least 12 hours to ensure homogeneity. After the two specimens required for each trial were prepared, they were submerged in distilled water for 48 hours to ensure full saturation (Figure 5d). Following saturation, the samples were removed, and their masses were recorded for final density calculations. The plastic containers holding the specimens were subsequently encased in metal containers (Figure 6b), which were designed to be mounted on the centrifuge. These containers included an effluent chamber to collect water expelled during testing. Once the entire assembly was prepared, a final mass measurement of the soil was taken to confirm accuracy before centrifuge testing began. The two tests conducted were the hydraulic conductivity test and the matric potential test.

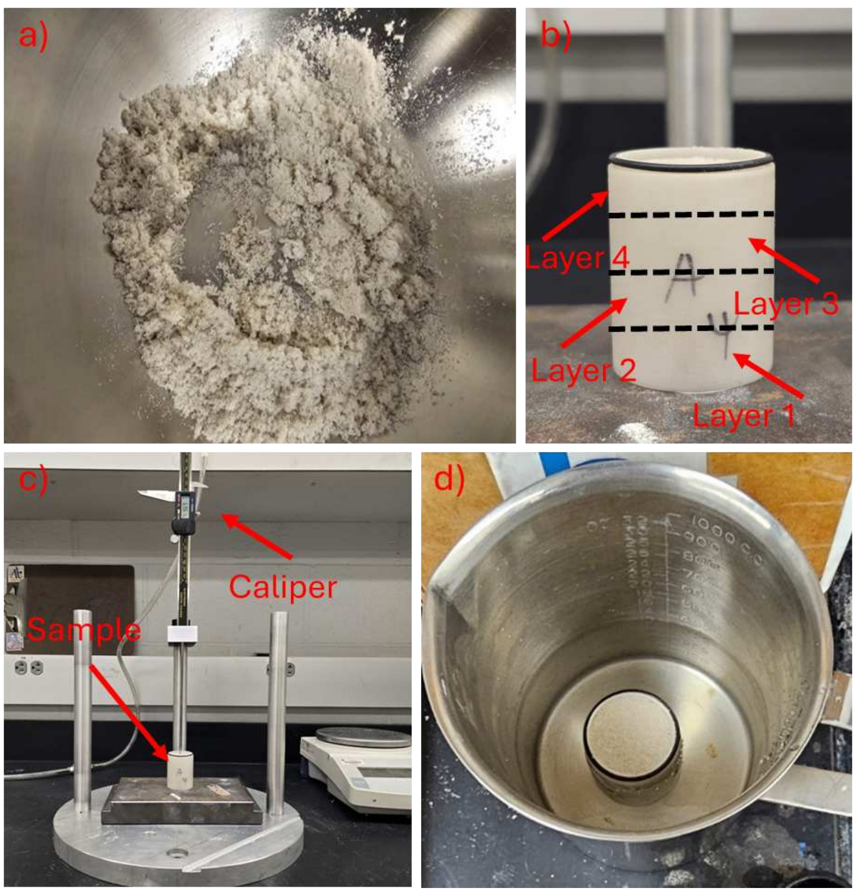

Figure 5: (a) Sand-water mixture with 5% water content; (b) Sample split into 4 equal layers (c) Moist Tamping sand reconstitution procedure setup; and (d) 48-hour specimen saturation procedure

Hydraulic conductivity

The Hydraulic conductivity test would require a known flow rate provided by the pumps into the centrifuge. This would be repeated at a specific increasing rotation per minute as the flow decreases per ASTM standards. The ability to control rotation and flow rate allowed us to set a hydraulic conductivity. In other words, the hydraulic conductivity is imposed by adjusting the flow rate, q, and the angular velocity, and the level of saturation changes to meet the imposed hydraulic conductivity until a steady-state is reached. This Procedure followed the ASTM D6527 standard to ensure a wide range of hydraulic conductivity was tested.

$$K(\theta) = \frac{q}{\rho\omega^2 r} \quad (1)$$

Where $K(\theta)$ is the hydraulic conductivity (cm/s); q is the flow rate (mL/h); ρ the fluid density (g/cm^3); ω is the angular velocity (rad/min); r is the distance from the rotation axis to the sample's middle (cm). The imposed hydraulic conductivities are shown below in Table 1.

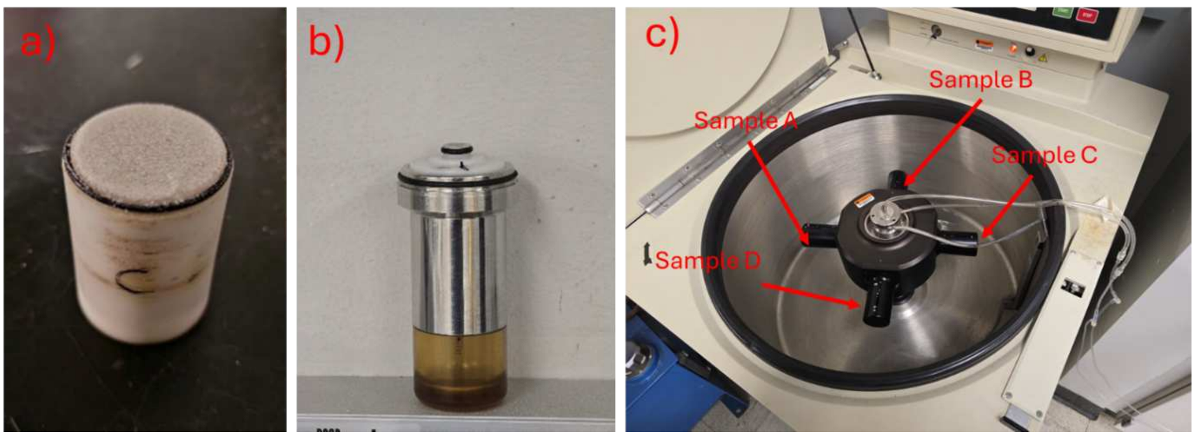

Figure 6: a) Sand a microplastics sample; (b) Samples casing and effluent chamber; and (c) Centrifuge rotor along with corresponding location of samples.

Matric Potential

When conducting the matric potential test, a set of new samples was created following the previous steps stated. The samples were then placed into the centrifuge to conduct the matric potential test to obtain the water retention curves. These tests did not require any flow rate to be pumped into the samples. The centrifuge was set to a specific time and speed to obtain the desired pressure on the sample. In other words, for a given angular velocity, water starts to flow out of the sample, increasing the matric potential. At some point, the matric potential equals the pressure applied by the centrifuge, and the water stops flowing out. At that point, it is possible to record the matric potential for the steady-state volumetric water content, which is obtained by measuring the sample weight. The pressure applied to the sample results from acceleration in a rotating field. Under a centripetal acceleration, the force is a function of rotation speed, distance from the axis of rotation, and fluid density [12] and [13].

$$\psi = \frac{\rho\omega^2}{2g}(r_1^2 - r_o^2) \quad (2)$$

Where ψ i s the average matric potential (bar); g is gravitational acceleration (cm/sec^2); ρ the fluid density (g/cm^3); ω is the angular velocity (rad/min); r_1 is the average radius of the sample (cm), and so is the radius of rotation of the outer sample face (cm). The corresponding matric potential with respect to rotation speed is shown in Table 2.

Table 1: Imposed Hydraulic Conductivity

Pump Rate (mL/hr)	Speed (rpm)	Hydraulic Conductivity (cm/s)
50	300	1.81E-04
50	600	4.54E-05
50	1000	1.63E-05
50	1500	7.26E-06
40	2000	3.27E-06
15	2000	1.22E-06
5	2000	4.08E-07
1	2000	8.17E-08
0.5	2000	4.08E-08
0.2	2300	1.23E-08
0.1	2500	5.23E-09

Table 2: Matric Potential Controls

Rotation Speed (rpm)	Matric Pressure (bars)	Matric Potential (kPa)
300	0.04	4
600	0.20	20
800	0.30	30
1000	0.47	47
1200	0.68	68
1500	1.10	110
1800	1.50	150
2100	2.10	210
2500	3.00	300
2800	3.75	375

Results and Discussion

A total of six tests were conducted, with two samples prepared and placed in the centrifuge for each test. Each test included Ottawa sand as the baseline material, with specific distributions of kaolin and/or microplastic. Table 3 provides a summary of the mix proportions and densities for the hydraulic conductivity samples, while Table 4 details the corresponding information for the matric potential samples. Across all 24 samples, the densities were consistent, averaging 1.703 g/cm^3 with a standard deviation of 0.007 g/cm^3. Two samples were tested for each run, and a detailed list of each test and sample is shown in the following figure.

Hydraulic Conductivity:

The results for all six hydraulic conductivity tests are presented in Figure 7. Ottawa sand was used as a control to facilitate comparison with specimens containing kaolin clay, microplastics (MP), and their combinations. Since all tests were conducted at similar densities, the observed variations in hydraulic behavior (Figure 7) can be attributed to the introduction of contaminants. When the MP content was 5%, the hydraulic behavior was nearly identical to the baseline test, suggesting that this concentration was insufficient to cause significant changes. However, increasing the MP content to 10% resulted in an average of 31% higher volumetric water content at equivalent hydraulic conductivity values.

Table 3: Hydraulic Conductivity Samples

Test (#)	Sample	Density (g/cm^3)	Kaolin %	MP %
(1) Sand	A	1.69	0	0
Only	C	1.69	0	0
(2) 5%	A	1.70	5	0
Kaolin	C	1.71	5	0
(3) 10%	A	1.71	10	0
Kaolin	C	1.71	10	0
(4) 5%	A	1.70	0	5
MP	C	1.70	0	5
(5) 5%	A	1.71	0	10
MP	C	1.71	0	10
(6) 5%	A	1.70	5	5
Kaolin + 5% MP	C	1.70	5	5

Table 4: Matric Potential Samples

Test (#)	Sample	Density (g/cm^3)	Kaolin %	MP %
(7) Sand	B	1.70	0	0
Only	D	1.70	0	0
(8) 5%	B	1.71	5	0
Kaolin	D	1.71	5	0
(9) 10%	B	1.71	10	0
Kaolin	D	1.71	10	0
(10) 5%	B	1.70	0	5
MP	D	1.70	0	5
(11) 5%	B	1.71	0	10
MP	D	1.71	0	10
(12) 5%	B	1.70	5	5
Kaolin + 5% MP	D	1.69	5	5

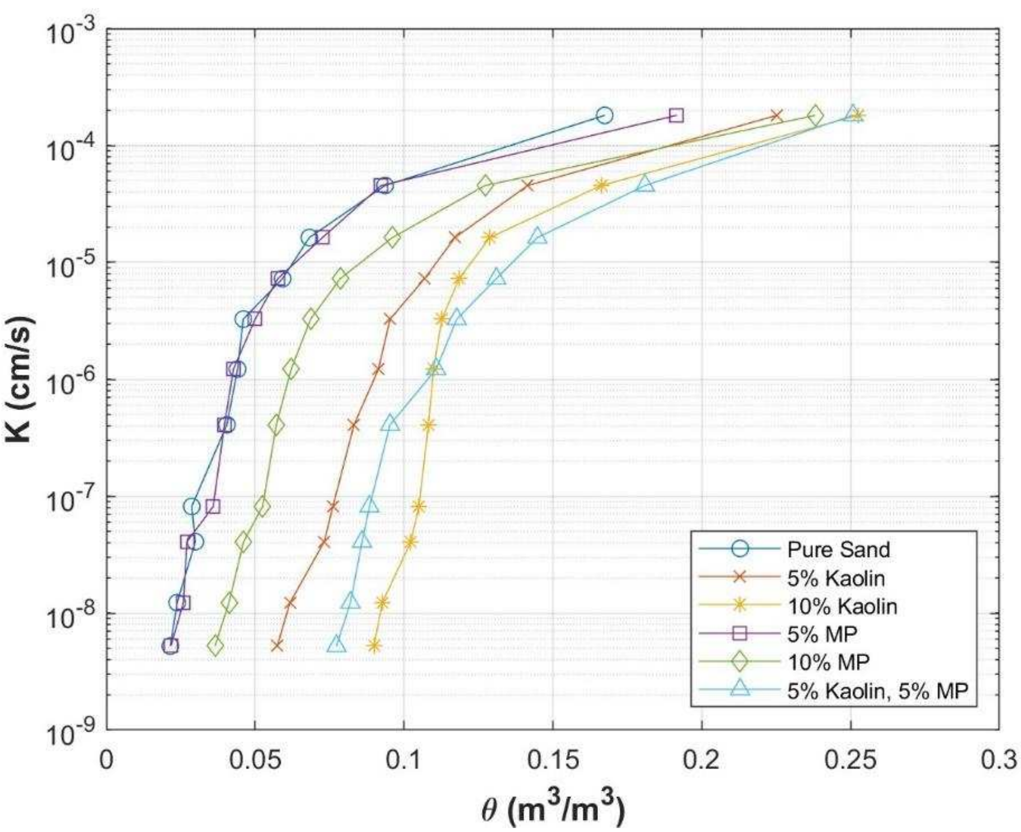

Figure 7: Hydraulic Conductivity Curves for Five Different Sand Mixtures Compared to the Baseline Sand-Only Test.

For specimens with kaolin fines, the hydraulic conductivity decreased as expected due to the lower permeability of clay compared to granular materials. At 5% kaolin content, the volumetric water content required to achieve the same hydraulic conductivity increased by an average of 44.8% compared to sand alone and was approximately 20 times greater than that of sand with 10% MP. The addition of 10% kaolin fines further reduced the unsaturated hydraulic conductivity, aligning with predictions. For the specimen containing 5% MP and 5% kaolin, the hydraulic behavior closely resembled that of the specimen with 10% MP. This suggests that combining MP with kaolin fines may impede water flow more effectively than MP alone, as demonstrated in the 10% MP case.

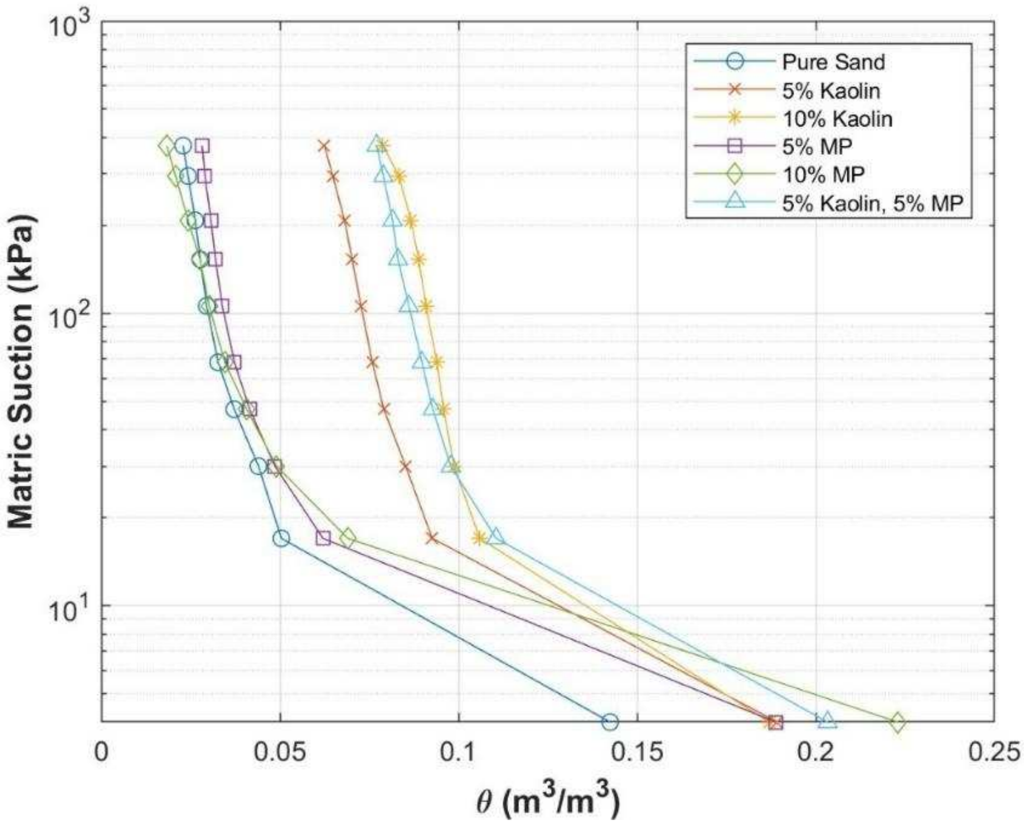

Figure 8: Soil Water Retention Curves for Five Different Sand Mixtures Compared to the Baseline Sand-Only Test.

Matric Potential

As for developing water retention curves, an additional six tests were conducted, replicating all samples tested in the hydraulic conditions testing. Two samples (B and D, Table 4) were created and placed into the centrifuge during each test. Matric potential testing was performed at the same microplastic and fines concentrations as the hydraulic conductivity tests (Figure 8). The matric suction curves for specimens with 5% and 10% MP are similar to the baseline sand curve, except at the lower pressure level of 4 kPa. For the two kaolin tests, the matric suction pressures are significantly higher than those of the baseline sand and sand with MP, which is consistent with the behavior of clayey soils. In the specimen containing 5% MP and 5% kaolin, the suction response closely resembles that of the 10% MP test, aligning with the observations in the hydraulic response tests.

Conclusion

This study evaluated the effects of microplastic (MP) powder and kaolin fines on unsaturated hydraulic conductivity and matric suction in sand using a steady-state centrifugation device. The results indicated that the addition of a small amount of MP powder (5–10%) had negligible to minor effects when compared to the clean sand baseline. Further studies will be required to ensure that microplastics have a negligible effect or if the MP particle and being washed away as sample moisture content decreases. However, when MP was combined with kaolin fines, such as the 5% MP and 5% kaolin mixture tested in this study, the overall unsaturated hydraulic and matric suction behavior resembled that of a specimen containing 10% fines. Other interesting effects of microplastics would include the fact that microplastics have a lower saturation in the clay sample than in the baseline sand. A noticeable difference can be observed when looking at the microplastic curves in the hydraulic conductivity plot, unlike when looking at the matric potential curve. It could indicate that the microplastics are physically blocking passages for water to get through. These findings suggest that MP has the potential to impede water flow. Future studies are needed to investigate the effects of wildfire-induced MP contamination on groundwater recharge, particularly in urban-forest interface areas prone to wildfires.

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