Extracting Microplastic from Anhydrous Beach Sediment Utilizing Relative Terminal Velocities

Grace Robertson

Jackson Schuler

Background

Through the uproar of plastic utilized in manufacturing processes, primary and secondary microplastics have been created as a byproduct in vast quantities. By definition, microplastics are less than 5mm in maximum diameter. Primary microplastics are created intentionally and are often found in abrasive materials or cosmetics. Secondary microplastics are created unintentionally and are a byproduct of larger plastic products decaying (Cole, Lindeque, Halsband, & Galloway, 2011).

A literature review indicated that primary research into the creation and effects of microplastics began in 2011. Awareness of the prominence of the issue has grown due to this research, thus feeding inspiration into subsequent research.

In consideration of prior research, a United States patent was filed in 2015 to remove microplastic from beach sediment using a fine, polymer-coated mesh intended for manual use in sifting plastic particles from sand (Ward). The intention of the developed extraction method in this research is for use onboard an autonomous system, thus mitigating the need for human motivated extraction efforts.

Through extensive research, as published in the Marine Pollution Bulletin, Environmental Pollution, Environmental International, and others, it is shown that microplastics are potently common in all marine environments, as the particles are carried by international sea currents, deposited on shorelines, and carried throughout inland bodies of water. This poses a threat to the natural world, as the plastic particles are consumed by wildlife and disturb local vegetation. As an example of the extremes of this problem, microplastics have been found in snow and stream samples on Mount Everest, which was previously considered to be one of the most pollution-free locations (Napper et al., 2020).

Introduction

Literature review before, and throughout research, indicated that there was no method specifically developed for microplastic extraction from anhydrous beach sediment.

The scope of this research includes microplastics commonly found in anhydrous beach sediment. These range in size from 1mm to 20mm in maximum diameter. Since some plastics considered are larger than the 5mm microplastic definition, they are considered to be mesoplastics. These were considered in the scope of research because they are commonly found in beach sediment and therefore pose a threat to the natural environment.

Through iterative testing methods, potential extraction methods were identified including the use of electrostatics, and the use of chemical compounds, such as ferrofluids or zinc chloride solution. All other separation methods were deemed ineffective or unfit for use onboard an autonomous system, as is the design intent with the developed proof of concept outlined in this paper.

Methodology

Previously considered separation methods include the use of electrostatics, vibrational separation, and separation using relative densities inside a fluid compound. The vibrational separation method included an oscillating table, which would vibrate the low-density sediment off the sides while the higher-density plastic would continue into a collection bin. The use of fluids to separate via relative densities used a sodium chloride aqueous solution, in which the higher density plastic would sink to the bottom, while the sediment would float to the top. The use of a mesh screen was also considered, in which the sediment would pass through the screen, leaving only plastic particles behind. These methods were initially considered but, due to design and practical limitations, they were all abandoned for the method as discussed in this paper.

The method of separation via electrostatics was further considered through preliminary testing. This method utilized a Van de Graff generator to induce an electric charge onto a belt, which would be hovered over the sediment and plastic aggregate. The induced electric charge was theorized to polarize the plastic, attracting the plastic only to the belt, thus separating the plastic from the aggregate. Initial research and literature review indicated that the most common form of beach sand would not polarize, and thus would not be attracted to the charged moving belt. However, through initial testing using sediment from Daytona Beach, FL, the testing environment, the sediment polarized more strongly than microplastic and therefore the sediment would be picked up by the moving belt. This refuted initial hypotheses that only the microplastics would be picked up using the electro-static method and instead confirmed that both the sediment and plastic would be picked up, defeating the intended purpose, and so this method was also put to the side.

The successfully proven concept of microplastic extraction exploits the fact that the sediment, being much smaller than the microplastics, can be carried with airspeed at too slow of a velocity to carry the plastics. This is due to the differences in aerodynamic drag characteristics and weights of the microplastics and sediment particles. The separation device, as named the Controlled Airspeed Regulatory and Operational Tunnel (CAROT), features a change in shape such that the airflow through the tunnel remains constant from inlet to outlet. The concepts that prove this possible include Bernoulli's Principle and the Continuity Equation.

The Continuity Equation is given by

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 \quad [1]$$

For a constant-area, dynamically-shaped nozzle, such as the CAROT, these equations can be applied to the flow given that the flow is potential. Calculated values for terminal velocity were found for both microplastic and anhydrous sediment using the equation

$$u_t = \sqrt{\frac{4gD_p(\rho_p - \rho)}{3C_D\rho}} \quad [2]$$

The calculated terminal velocities for sediment and microplastic are 6.32 meters per second and 14.28 meters per second, respectively. These values were obtained by using equation [2] in a MATLAB script, which also factored in the shape, size, and density of each particle. The script averaged each terminal velocity value for the range of particle sizes for microplastic and sediment and outputted the magnitudes as aforementioned. These calculated terminal velocities were used in equation [1] to ensure that the area remained constant throughout the design, so as not to create any pockets of accelerated or decelerated air. This constant velocity ensures that both sediment and plastic continue through the system without getting stuck in one of these pockets.

The nozzle design, as used in the proof of concept testing, is shown in *Figure 1*. The CAROT design is split into 3 main sections: the distributor, the convergence tube, and the particle diffuser. The distributor, shown in *Figure 2*, intakes the sediment-plastic aggregate via an auger system, which then falls down the slopes and into the airflow along the sides. The sediment, which has a terminal velocity lower than the airflow, moves with the airflow upwards into the convergence section (*Figure 3*), whereas the microplastic, which has a higher terminal velocity than the airflow, fall through the particle diffuser (*Figure 4*) and into a collection bin. The sediment, after traveling through the convergence section, would continue through the sediment diffuser and into a separate bin, though in final application this would flow directly back onto the beach.

While developing the test procedure, a margin of 60% separation was deemed the success parameter. A set quantity of microplastics was inserted into the aggregate so that the quantity removed could be quantified, thus giving the percent separation rate. For all particle size tests, only ten plastic particles were inserted into the aggregate. Particles were introduced to anhydrous sand samples such that the mixture was heterogeneous before being fed into the airflow via the auger. For all density loading tests, the number of particles inserted into the aggregate is as indicated in the testing procedure as undermentioned.

Figure 1: Testbed set-up

Figure 2: Aggregate distributor

Figure 3: Flow convergence section

Figure 4: Particle diffuser section

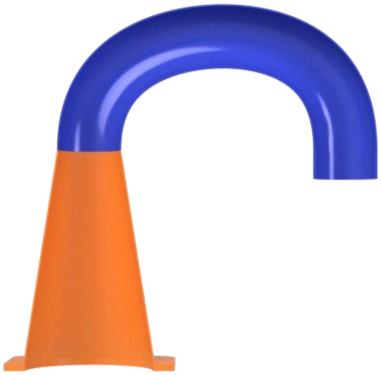

Figure 5: Sediment diffuser section

A sample collection of microplastic particles was obtained from Daytona Beach, FL. Plastic particles in the sample collection were categorized by their maximum diameter as measured by a digital caliper. Large microplastics are categorized in this consideration as greater than or equal to 4.0 mm but less than 5.5 mm in maximum diameter. Small particles are categorized as less than 4.0 mm in maximum diameter. Particles greater than 5.5 mm are excluded from consideration in this proof, though they most likely could also be extracted using the described method with adjustments to the CAROT reflecting the necessary larger particulate size flowing through the system.

Two primary sets of tests were conducted to explore the effectiveness of the testbed with different microplastic particle sizes and through different density loadings. For all tests, the motor used was set to its maximum revolutions per minute to target an airspeed through the nozzle matching the terminal velocity of sediment at 6.32 m/s.

To test the CAROT's effectiveness in extracting different microplastic particle sizes, the particles as previously labeled large or small were tested separately first, then in a mixed test. To obtain control data for airspeeds through the CAROT, three tests were run with only sand injected into the airflow. Following the control trials, six trials each were conducted for large-only particles, small-only particles, then an equal part mix of small and large particles.

Density loading tests were conducted to see if there was a point of overload to which the test setup could no longer remove the target 60% of injected microplastics. The control test, as conducted before the particle test, was used as a comparison trial set in this case also. Two trials each were conducted for five, seven, ten, and fifteen particles of mixed sizes injected into the flow. These particles were also mixed into the sand such that the mixture was heterogeneous before being fed into the flow via the auger.

The five, ten, and fifteen number of particles represented a low, medium, and high density of particles inserted, respectively. Seven particles inserted represents the target density. This target density was identified using the number of particles in a kilogram of sand, as experimentally defined along the Florida Atlantic coast Baruch Institute of Coastal Ecology & Forest Science to be 146 particles per kilogram. At a smaller scale for testing purposes, the number of particles was recalculated to be seven particles per 50 grams of sand, which was the amount used during tests.

Results

Completion of tests as described in Methodology yielded collected results as displayed in *Tables 1-8*. The control test, in which no microplastics were inserted, has data that is shown in *Table 1*. All particle size test data is shown in *Tables 2-4*. All density loading data is shown in *Tables 5-8.*

Table 1: Raw data results from control trials with no microplastics inserted.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
6.2	0	0
6.3	0	0
6.3	0	0

Table 2: Raw data results from large particle size testing.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
6.5	10	8
6.2	10	6
6.5	10	6
6.5	10	7
6.0	10	7
6.2	10	6

Table 3: Raw data results from small particle size testing.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
7.0	10	7
6.8	10	6
6.9	10	6
7.1	10	7
6.8	10	8
7.0	10	8

Table 4: Raw data results from mixed particle size testing.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
6.8	10	10
7.0	10	10
6.9	10	10
6.5	10	8
7.0	10	10
6.8	10	9

Table 5: Raw data results from low particle number density loading tests.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
7.1	5	5
6.9	5	5

Table 6: Raw data results from medium particle number density loading tests.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
7.1	10	10
6.8	10	9

Table 7: Raw data results from high particle number density loading tests.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
6.8	15	14
7.2	15	13

Table 8: Raw data results from the target particle number density loading tests.

VELOCITY [M/S]	PARTICLES IN	PARTICLES OUT
6.9	7	6
7.2	7	7

Discussion

For these control trials, an average airspeed of 6.26 m/s was obtained through the operation of the CAROT with only sand injected into the flow. This value matched the target airspeed as calculated by the developed MATLAB script. This success of the control trials indicated to the test team that the testbed set-up was working as intended, and therefore was cleared to be tested with the aggregate.

There is no average separation rate indicated for the control trials, as there were no particles inserted into the flow, thus there were none to be separated. The average separation rate for the large particle tests was 67%, 70% for small particle tests, and 96% for mixed particle tests. The success parameter for separation was 60% and since all particle size tests indicated a greater separation rate, these tests are deemed successful. The mixed particle tests were the most similar to the blend of plastic particles that are prevalent in the beach environment. For research purposes, different particle sizes were isolated so that it could be identified if certain particle sizes were less likely to be separated from the airflow. The mixed particle size tests showed a 36% increase in separation above the 60% minimum separation parameter. This high average separation rate of 96% indicates that the developed method will be successful when experiencing a variety of particle sizes that occur.

The highest separation rate for particle size testing was observed in the mixed particle tests. During the two prior trial sets for large and small particles, some plastic particles injected into the flow were unidentifiable at the end of the test trial. For some trials in those sets, some plastic particles were unrecoverable, meaning that they were not clogged in the CAROT, were not in the sediment diffuser section, and were not in the collection receptacle underneath the CAROT. However, since the particles were not found inside the CAROT or the sediment diffuser section, it is likely that they were separated, but did not fall into the collection receptacle underneath the CAROT. These unidentified and unrecovered particles may have negatively affected the percent separation achieved during these trials. For future trials and further development of proof of concept, the small and large particle size testing will be reconducted to mitigate any errors in post-test particle identification. While the large and small particle size tests showed a separation margin of at least 60%, their actual separation rate may be higher than what was experimentally measured.

The average separation rate was 100% for the low-density test, 95% for the medium density test, 90% for the high-density test, and 93% for the target density test. The success parameter for separation was 60% and, since all density loading tests indicated a greater separation rate, these tests are deemed successful.

The highest separation rate for the density loading tests was observed in the low-density tests. This indicates that fewer particles injected into the flow make it more likely that a higher number of particles will be separated. It can be deduced that this may occur because, as fewer particles are injected into the flow, the testing system is less overwhelmed. Similarly, lower separation rates may be reflected in the high-density tests since the testing system may be overwhelmed with high numbers of plastic particles. This will be considered in future design modifications such that the flow rate of aggregate into the airflow can be limited to maximize potential separation.

The target density test showed 93% extraction. This specific test being successful is essential because, if the current test setup were used with an unaltered sample that was taken directly from the beach, the separation rate would be successful.

Conclusion

Future testing will include more trials, with design adjustments to the CAROT to make the device capable of handling a wider range of plastic particle sizes. From the sample microplastic collection obtained from Daytona Beach, particles up to 20mm in maximum diameter were found. This indicates that in the environment, there is a range of plastics beyond the defined range of microplastics. By adjusting design features to the CAROT, these larger plastics will be able to be processed and therefore also separated from sediment.

The CAROT is intended to be used on an autonomous vehicle platform. The design has been created in such a way that mitigates human interference and thus also limits the potential breakdown of a long term beach cleanup system. By implementing this autonomous system, a municipality may decrease its local environmental detriment by directly reducing the number of plastics embedded in the beach sand. The separation device itself can be replicated for a relatively low cost being that it is majorly comprised of 3D printed parts, in addition to other hardware commonly found at retail hardware retailers.

The use of such devices widely and regularly is key to the success of a larger mission intended to mitigate negative environmental effects due to industrial manufacturing processes. Through continued research in this application, carefully engineered solutions will continue to contribute to that mission.

https://www.sciencedirect.com/science/article/abs/pii/S0048969717324427

References

Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin, 62(12), 2588-2597. Doi:10.1016

Napper, I. E., Davies, B. F., Clifford, H., Elvin, S., Koldewey, H. J., Mayewki, P. A., . . . Thompson, R. C. (2020). Reaching New Heights in Plastic Pollution—Preliminary Findings of Microplastics on Mount Everest. *One Earth*, *3*(5), 621-630. Retrieved December 8, 2020, from https://www.sciencedirect.com/science/article/pii/S2590332220305509

Sagawa, N., Kawaai, K., & Hinata, H. (2018). Abundance and size of microplastics in a coastal sea: Comparison among bottom sediment, beach sediment, and surface water. *Marine Pollution Bulletin*, *133*, 532-542. doi:https://doi.org/10.1016/j.marpolbul.2018.05.036

Ward, M. (2015). *U.S. Patent No. US 8,944.253 B2*. Washington, DC: U.S. Patent and Trademark Office.

Yu, X., Ladewig, S., Bao, S., Toline, C. A., Whitmire, S., & Chow, A. T. (2018). Occurrence and distribution of microplastics at selected coastal sites along the southeastern United States. *Science of the Total Environment*, *613-614*, 298-305. Retrieved 2020, from