Investigating the Potential Release of Microplastics from Recycled Plastic Modified Asphalt Pavement

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Abstract

Due to the ever-increasing volume of plastic waste, researchers are exploring alternative end destinations for recycling and repurposing, with civil infrastructure systems seen as promising hosts. One area that has seen exponential growth in research interest is Recycled Plastics Modified Asphalt (RPMA) pavement. Despite significant progress in this field, several issues remain relatively underexplored, including the potential release of microplastics from RPMAs under stress conditions. This study attempts to help bridge this gap. RPMAs and control asphalt pavement samples were prepared in the laboratory and mechanically tested using standard performance tests, including the Hamburg Wheel Tracking Test (HWTT) and Moisture-Induced Sensitivity Test (MiST), to simulate long-term aggravated service conditions. RPMAs used an agricultural Low-density Polyethylene (LDPE) as the modifier. Leachate solutions with debris from these tests, along with background solutions and samples of raw materials, were screened for microplastic presence using Laser Direct Infrared Imaging (LDIR) and Attenuated Total Reflectance (ATR). The analysis revealed a variety of polymeric and non-polymeric particles across all tested samples. However, the quality of identification and the percentage of polymeric particles generally remained low. Pervasive polymeric background contamination, coupled with challenges in spectral similarities between different ingredients, complicates efforts to definitively determine whether RPMAs specifically released microplastics, as various types of polymeric particles were detected and identified in the control samples as well. Future studies are recommended to implement more rigorous contamination controls and to incorporate complementary analytical techniques to improve identification confidence.

Key Words: Microplastics, Recycled plastics modified asphalt (RPMA), Leachate, Laser Direct Infrared Imaging (LDIR), Attenuated Total Reflectance (ATR), Hamburg Wheel Tracking Test (HWTT), Moisture-Induced Sensitivity Test (MiST)

1. Introduction

Plastics are widely used because of their favorable properties such as durability, strength, lightweight, and cost-effectiveness (1, 2). However, with a global plastic recycling rate of less than 10% (3), their widespread use has led to significant environmental challenges. Hence, waste plastics are actively becoming a global concern (4–10). Recycling efforts aim to mitigate this issue by identifying sustainable end destinations for waste plastics, including their application in asphalt pavement (1, 9, 11–14). This approach is aligned with the use of other waste-based materials in asphalt pavement such as Reclaimed Asphalt Pavement (RAP) (15, 16), Reclaimed Asphalt Shingles (RAS) (17), and Crumb Rubber (CR) (18–20). Despite recent progress, the use of recycled plastics in asphalt pavement still faces several unresolved challenges (9). These include but are not limited to intermediate and low-temperature performance issues (1), storage stability (21, 22), workability (23), repurposing and recycling of recycled modified asphalt, effect on the asphalt plant operation (24, 25), potential emission of harmful gases during preparation (4, 10, 26), and potential release of microplastics during service (27). While some of these issues are receiving global attention and are being extensively researched, the potential release of microplastics from Recycled Plastics Modified Asphalt (RPMA) remains comparatively underexplored. However, as roads are constantly exposed to weathering and mechanical degradation that generate roadside dust, concerns about the potential release of microplastics from RPMAs are increasing (28). Although microplastics have long been found to accumulate in soil and bodies of water (29), research on the release of microplastics from RPMAs is limited. Likewise, there are no established standards or best practices for evaluating microplastic release from RPMAs. Researchers in this field are exploring various methods to assess this risk potential. Based on the limited literature, the prevailing assumption is that plastic-modified asphalt pavements could shed microplastics (fragments of plastics smaller than 5 mm in size) during their service life and these particles could end up in the aquatic environment by rainfall and surface runoff. Existing studies primarily focus on 1) whether RPMAs release microplastics, and 2) how significant this source is compared to the other road-related sources of microplastics such as particles from vehicle tire wear and polymeric paint used for road markings (27, 30). Typically, road microplastic studies involve collecting random samples of roadside dust and debris from various locations along the study area which are then analyzed for microplastic content using a range of techniques (30–34). However, this approach is less applicable for roads modified with recycled plastics, as such roads are not yet widely implemented. As a result, alternative laboratory-based methods are being developed to assess the potential release of microplastics from RPMAs.

One approach involves the use of Hamburg Wheel Tracking Test (HWTT) samples, where the solution and debris from both control and plastic-modified asphalt samples are collected after the test for quantitative and qualitative analysis of microplastic presence. Duan et al. (27) investigated the potential for the production of microplastic from plastic-modified asphalt pavement using linear low-density polyethylene (LLDPE) as an asphalt modifier. Within the conditions of their test, their results indicate that plastic-modified asphalt pavement could produce microplastics, however, about three orders of magnitude less than microplastics released from vehicular tire wear for a comparable amount of asphalt pavement.

Similarly, several studies have confirmed the presence of significant amounts of microplastics in roadside dust from conventional roads (i.e., roads not modified with plastics) across various countries (31–34). They are primarily associated with wear from vehicle tires, road marking paint, and other plastic materials used on the roads. Therefore, the objective of this research is to

investigate the potential release of microplastics from Recycled Plastic Modified Asphalt Pavements under aggravated service conditions simulated in the lab.

2. Material and Methodology

2.1 Materials

PG64-22 with a specific gravity of 1.028 was used as the base binder to prepare asphalt pavement specimens. Fine and coarse aggregates were sourced from a limestone quarry in central Pennsylvania. Specific gravities and absorption properties of the aggregates were 2.649, 2.655, 1.19%, and 0.60% for fine and coarse, respectively. The RAP used throughout this project was also sourced from projects in central Pennsylvania. An anti-stripping agent of the commercial type KoHere AS-700 was used for all the mixtures. Recycled plastics used in this study were shredded Low-Density Polyethylene (LDPE) from agricultural films. Besides the supplier confirmation, the LDPE type was also verified using infrared (IR) spectroscopy that matched it to a polyethylene (chlorinated) wavenumber fingerprint with a match quality of 87.309% (Major spectral peaks: dominant C-H stretching regions between 2800 cm^{-1} and 3000 cm^{-1}, CH_2 bending at around 1400 cm^{-1} to 1500 cm^{-1} and CH_2 rocking at around 700 cm^{-1}). The IR results with an image of plastic particles are shown in Figure 1. The size of the shredded flakes ranges from plastic dust of a few microns to plastic pieces of up to 1.00 cm of irregular shapes and nonuniform sizes.

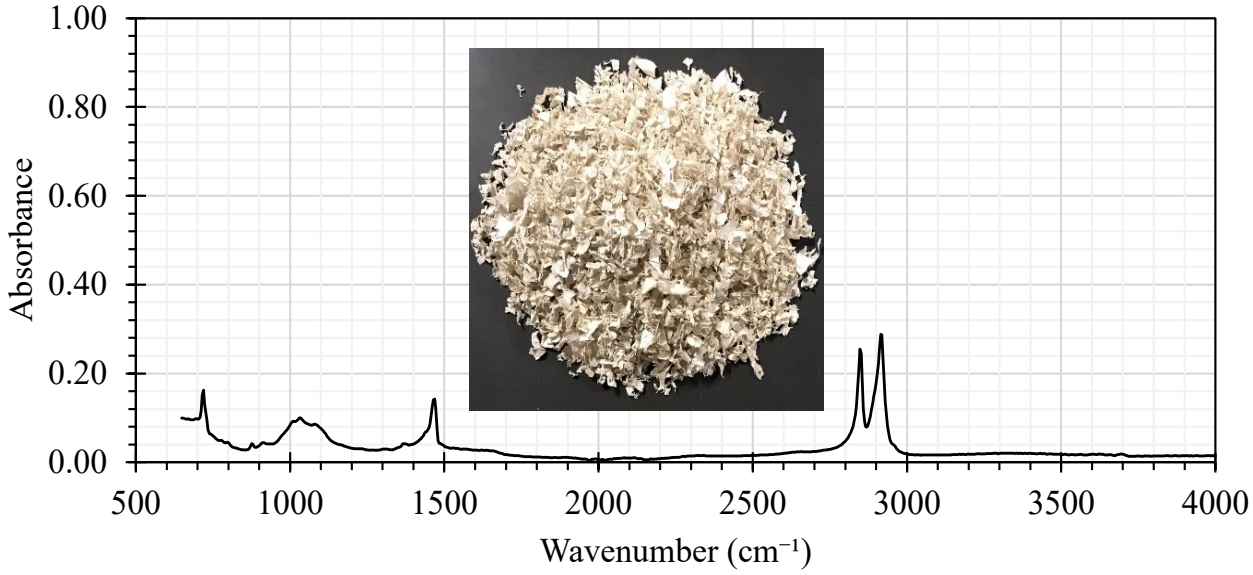

Figure 1: IR spectra and an image of the type of LDPE used for this study

2.2 Methodology

To study the potential release of microplastics from recycled plastic-modified asphalt pavement under service conditions, solutions with debris and sediments (leachate) were collected from conventional asphalt pavement mechanical tests such as the Hamburg Wheel Tracking Test (HWTT), and Moisture-Induced Sensitivity Tester (MiST). While the HWTT method is used by at least one other researcher (*27*), it is likely that MiST is not used for this purpose as of yet and hence introduced as novel procedure in this study. The collected leachate was then evaluated for microplastic presence using microplastic characterization techniques such as Laser Direct Infrared Imaging (LDIR) (Agilent 8700 LDIR Chemical Imaging System with Microplastics Starter 1.0

and Clarity v1.5.58 software) and Attenuated Total Reflectance (ATR) (Cary630 with MicroLab v5.7 software). The overall research methodology is presented in Figure 2.

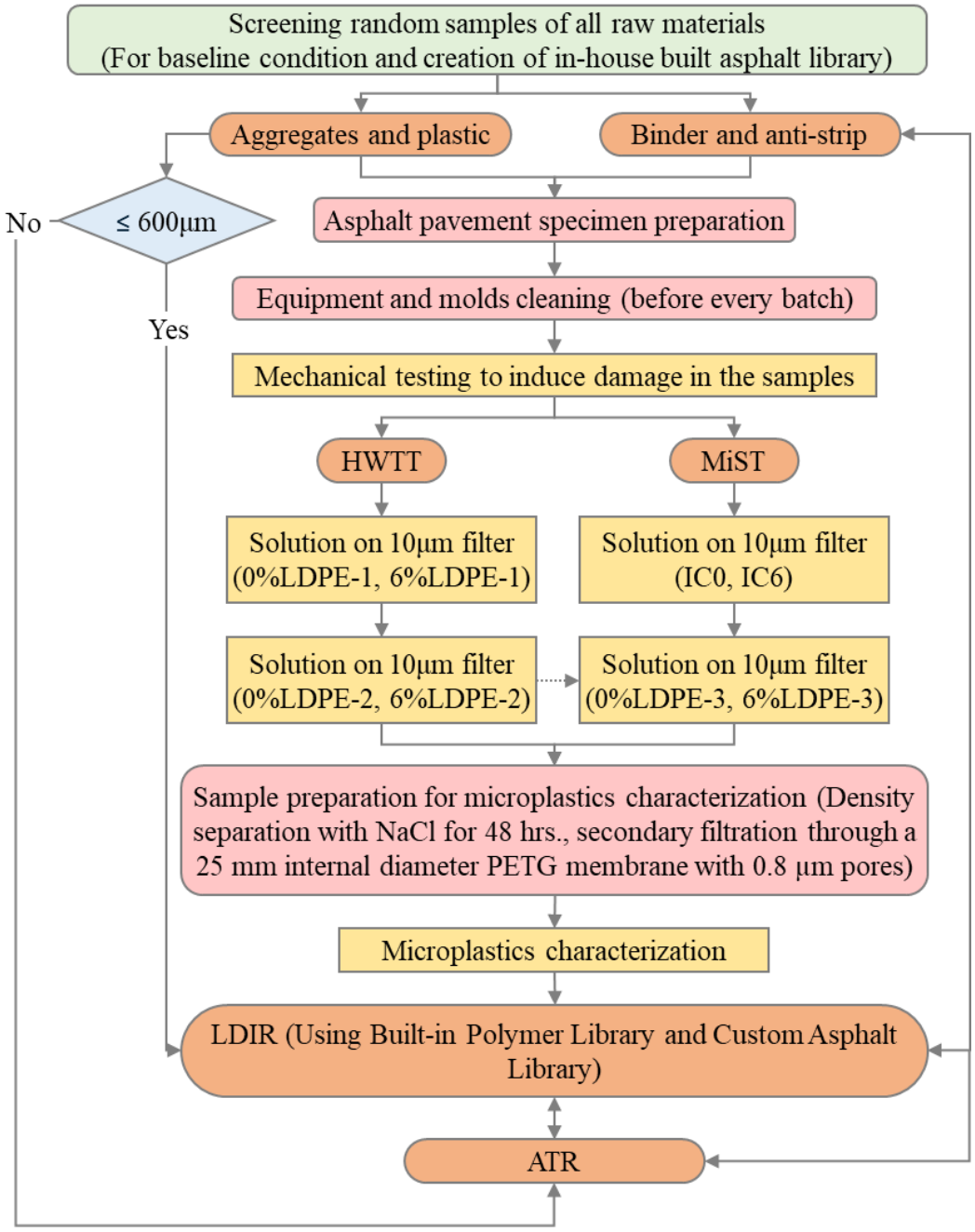

Figure 2: Research methodology flowchart

LDIR analysis was performed using two reference libraries: the built-in polymer library provided by the LDIR instrument and a custom asphalt library developed specifically for this study. All microplastic characterizations were carried out at the Institute of Energy and the Environment at Penn State (PSU-IEE). Spectra for the custom asphalt library were collected using ATR analysis. For each asphalt ingredient (raw material), an average of seven spectra were collected and imported into the LDIR system under the ingredient's name, rather than its chemical composition, as in the built-in polymer library. For example, while the built-in library might identify a 0.075

mm fine aggregate particle as silica, the custom library will identify it as "Sieve #200," reflecting its role in the asphalt mix rather than its chemical identity. As a result, particles matched using the built-in library are reported by their chemical composition, whereas those matched using the custom asphalt library are identified by ingredient name.

2.2.1 Raw Materials Screening

Before the preparation of asphalt pavement specimens for HWTT and MiST tests, random samples from the bins of the raw materials were screened for microplastic presence for the creation of baseline condition and the custom asphalt library. This included samples of PG64-22 binder, anti-stripping agent (ASA), LDPE particles, and aggregates (9.5mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm, 0.075mm and < 0.075mm). PG64-22 and ASA were screened using both LDIR and ATR. On the other hand, while all the aggregates were screened using the ATR, some were not suitable for LDIR testing due to their sizes. Hence, a cutoff was set at Sieve #30 (600 μm) or smaller for LDIR tests. Establishing baseline conditions was essential to determine whether any traces of plastic, particularly polyethylene-based materials, were present in the raw materials before the addition of LDPE as a modifier.

For the LDIR analysis of the aggregates, approximately 1mg of each material from the random samples was transferred to a 2000 μL amber glass vial using a micro spatula which was followed by the addition of 1000 μL of 91% ethanol into the glass vial by a micropipette. Subsequently, about 50 μL of the solution was transferred to Low-E glass slides and was allowed to dry at room temperature for 5 minutes, before it was used for LDIR analysis. On the other hand, for the LDIR analysis of binder and anti-stripping agent, droplets of each material were directly deposited on Low-E glass slides used for the LDIR analysis. The sample with the binder droplets was allowed to cool down before the analysis. In both cases, the sample-containing slides were then attached to a mobile stage and then inserted into the LDIR instrument sample bay. The microplastics characterization processing method was then applied to the selected region of the slides where materials were deposited. The LDIR instrument detected every particle in the selected region and measured their physical attributes such as width, height, diameter, aspect ratio, area, perimeter, eccentricity, circularity, and solidity. Subsequently, it created a spectrum of each particle and identified them by comparing their spectrum to a selected library of a wide range of polymeric and non-polymeric materials and selecting the best match (based on the highest match quality between 0% to 100%).

Likewise, for the ATR analysis of the aggregates and the LDPE, individual particles of each sample were positioned in the center of the ATR machine stage under the diamond crystal. Subsequently, the ATR anvil was lowered to ensure adequate contact between the sample and the diamond during spectrum analysis. For the binder and anti-stripping agent, a droplet of the material was deposited directly on the ATR diamond. To make sure that the intensity of the spectra was not reduced, the entirety of the diamond was covered with the sample liquid. Spectra were collected once adequate distribution of the sample was ensured. In all cases, once the spectra were collected it was then compared against the ATR search library that contains the most common thermoplastic polymers to find a match or several matches with a match quality like LDIR. The ATR machine stage, the anvil and diamond were cleaned with 89-91% ethanol using a cotton-tipped applicator before and after each test. Tests with binder samples required an extra step of cleaning with toluene or a citrus-based solution to completely remove any binder residue from the diamond and recleaning with ethanol solution. It should also be noted that although the aggregates were screened

for microplastics separately based on their sieve sizes, they come from the same limestone quarry. They were sieved in the lab for the preparation of asphalt pavement samples.

2.2.2 Asphalt Samples Preparation

The mix design presented in literature (*23*) with adjustment of 5.9% optimum binder content, 0.25% anti-stripping agent and nominal maximum aggregate size was used to prepare asphalt pavement samples for this research. Before the mixing process, the aggregates and the binder were preheated at 160 °C for 2 hours, while the RAP materials were preheated at 110 °C for 1 hour. Upon completion of the preheating process, the aggregates and the RAP were blended for 90 seconds using an asphalt mixer drum, followed by the addition of PG64-22 and mixing for another 90 seconds. RPMA specimens were prepared using the dry mixing method where 6% shredded LDPE particles were added directly to the mix during the second 90 seconds of mixing time. After mixing, the asphalt mixtures were short-term aged at 135 °C for 2 hours following AASHTO R30 standards and subsequently compacted using a Superpave Gyratory Compacter (SGC) into cylindrical disks of 60 mm thick and 150 mm in diameter, intended for HWT and MiST tests.

2.2.3 Hamburg Wheel Tracking Trest

The Hamburg Wheel Tracking Test (HWTT) was conducted following AASHTO T324. However, the objective of the HWTT in this study was not to evaluate the rutting resistance or moisture sensitivity of the specimens but rather to create road-like extreme damage to the specimens to induce microplastic leaching, if any. The HWTT is designed to subject the test samples to an aggravated aging and loading condition that simulates the wear and tear experienced by asphalt pavements over several years in the field but within hours in the lab. This is achieved by repetitive loading of steel wheels, moving back and forth for up to 20,000 passes on the test samples, which typically results in measurable and visible damage, often releasing debris and sediments. All the HWT tests were conducted in the water bath to maintain the testing temperature at 50 °C. The HWTT equipment with its molds and fixtures was washed and cleaned thoroughly before every test with a commercially available detergent for stainless steel applications. An image of the cleaning process is presented in Figure 3.

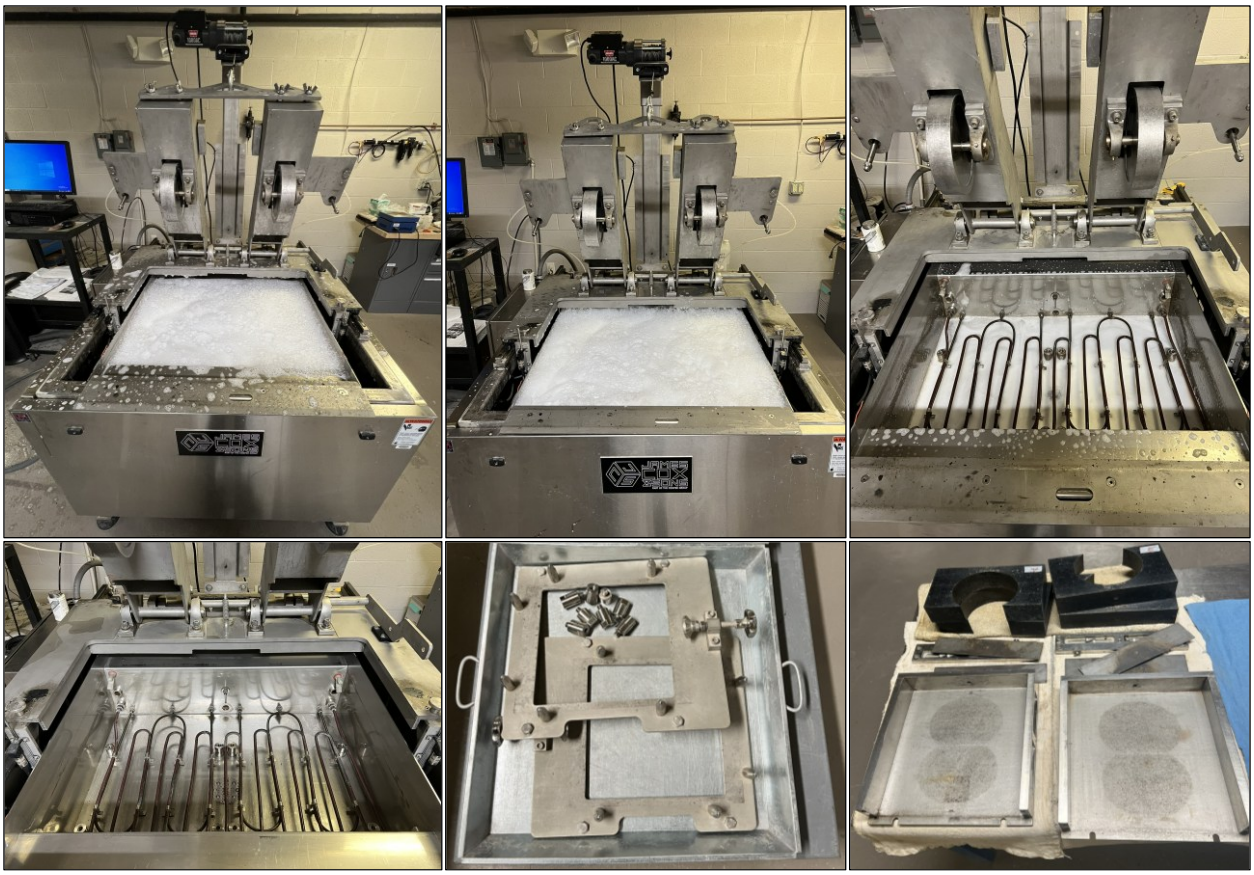

Figure 3: Cleaning process of the HWTT equipment with its fixtures

Before HWTT with asphalt pavement samples, the machine was allowed to run for 10 minutes with empty upside-down molds and other fixtures that were used during a typical test. This was conducted to obtain a baseline condition for HWTT samples. After completion of the test, the water solution with the debris was collected using a 10µm filter (Figure 4a and 4b) at the end of the outlet pipe of the HWTT machine. In addition to the test water that drains naturally, the machine bath was flashed with room temperature water with a continuous pressure hose for approximately 10 minutes until the water was cleared. The collected debris and sediment were immediately transferred to a glass jar along with the filter and sealed (Figure 4c) until it was characterized for microplastics. The solution collected before the HWTT for unmodified samples is named 0% LDPE-1 while that for the modified samples is named 6% LDPE-1. The same procedures were followed to collect sample solutions after the HWTT test with asphalt pavement samples. The solution collected after the HWTT for unmodified samples is named 0% LDPE-2 while that for the modified samples is named 6% LDPE-2.

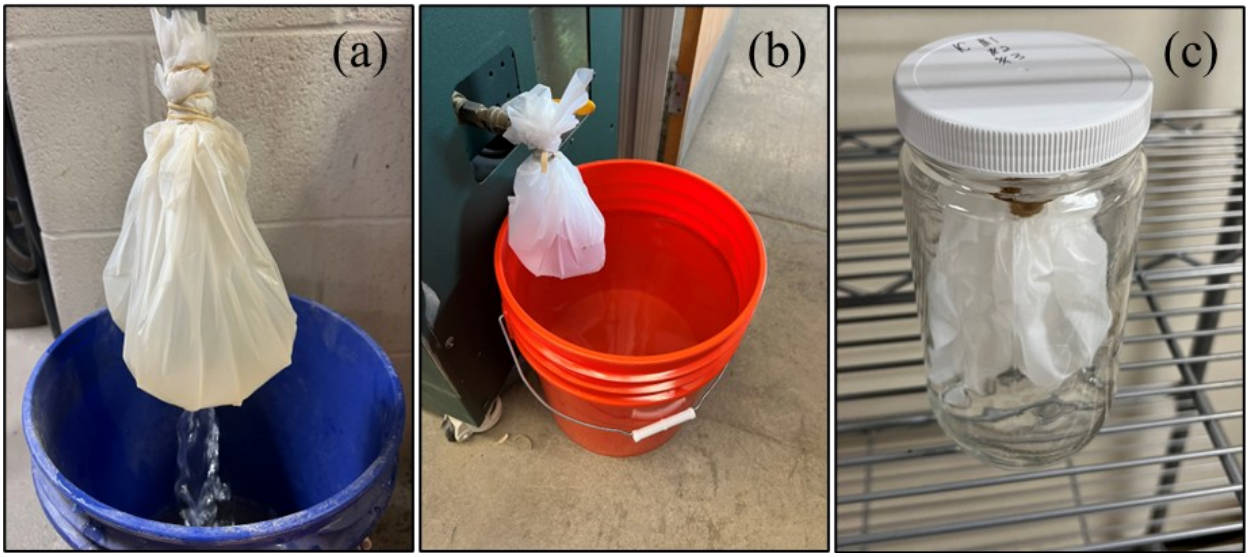

Figure 4: Sample collection from (a) HWTT, (b) MiST, and (c) sample transferred to a jar

2.2.4 Moisture Induced Sensitivity Test

The Moisture-Induced Sensitivity Test (MiST) was conducted following AASHTO TP 140 and ASTM D7870. MiST test subjected compacted asphalt samples to a hydrostatic pore pressure in a confined chamber and high temperature to determine cohesion and adhesion strength of compacted asphalt mixture specimens in aggravated conditions (3500 cycles of 40 psi confined hydrostatic pore pressures at 60 °C, for 20.5 hours in the equipment's pressure chamber). Like HWTT, MiST was not used for its intended purpose but created a condition to induce the release of microplastics from the samples, if any. In addition to intact asphalt pavement samples, the tested HWTT samples that were already damaged were used for MiST in this research. The intact samples are named IC0 for the unmodified and IC6 for the modified conditions. Likewise, the HWTT-damaged unmodified samples evaluated with MiST are called 0% LDPE-3 while that of the modified sample is named 6% LDPE-3. Each MiST subjected two compacted asphalt pavement samples to the mentioned aggravated condition. Sample solution (leachate) from MiST was collected in the same manner as in HWTT (Figure 4b). The 10µm filter was attached at the end of the outlet pipe for debris collection. In addition to the test water, the samples in the MiST equipment were flashed with an extra five gallons of room-temperature water.

2.2.5 Microplastic Characterization

After screening samples of the raw materials for microplastics, the following procedures were used to evaluate the collected solutions from mechanical tests. Initially, each sample filter was quantitatively transferred into a respective chemical sample jar using DI water. Then, the sample jar was decanted and extensively rinsed into a separatory funnel for density separation using NaCl for a minimum of 48 hours, and the densest constituents were extracted after this interval. Samples were then quantitively transferred and filtered through a 25 mm internal diameter, 0.8 µm pore, polyester gold coated (PETG) filter membrane. The filter membrane with the particles was carefully transferred and secured to the LDIR sample stage and the stage was inserted into the LDIR instrument and analyzed using a particle analysis method (Microplastic Starter 1.0). For each sample, the LDIR detected and counted the total number of particles present on the PETG with their physical attributes, chemical spectrum, images of the individual particle, and an overall false image of the PETG membrane with deposited particles. Parameters such as Area,

Identification, and Quality of the identification for each particle were used for further analysis in this study. An image of this process with a false image of one of the samples is presented in Figure 5.

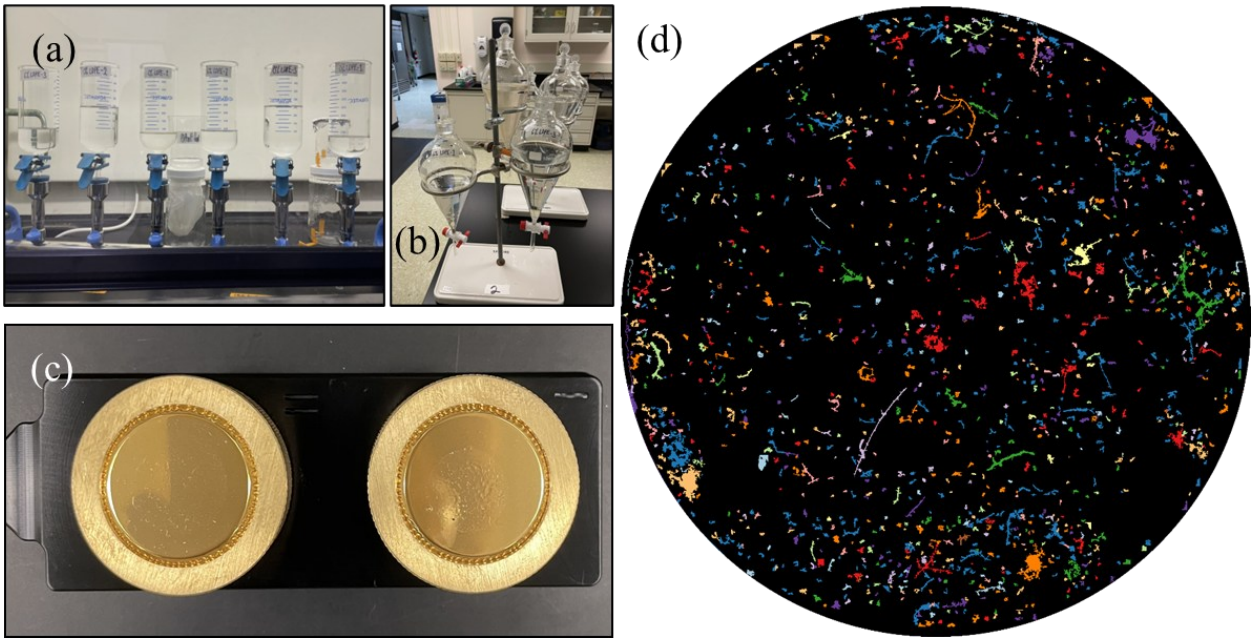

Figure 5: LDIR samples preparation process (a) and (b) density separation of the particles, (c) particles on the PETGs, and (d) and false image of one of the samples for this study (Photos courtesy of PSU-IEE)

3. Results and Discussions

Microplastic characterization using the LDIR built-in library revealed the presence of a wide range of polymeric and non-polymeric particles across all tested samples, including asphalt raw materials, background water solutions, and leachates from both modified and unmodified asphalt specimens. None of the detected particles were positively identified as specific microplastics and polymeric particle counts remained consistently low. However, their widespread and random presence across all samples introduced significant complexity in determining whether recycled RPMA specimens released microplastic.

Importantly, the only polymer used in the modified samples was agricultural LDPE, which is the primary material of interest (Figure 1). While the LDIR did not identify any particles explicitly as LDPE, it did detect polyethylene (PE) and chlorinated polyethylene (CPE) across both control and modified samples. These polymers share key spectral similarities with LDPE and are therefore treated in this study as proxy indicators of LDPE-related particles. For clarity, when using the built-in LDIR polymer library, PE and CPE are considered particles of interest; when using the custom-built asphalt library, the relevant particle of interest is labeled LDPE.

As with many infrared spectroscopy-based methods, spectral match quality is a continuous metric, and there is currently no standardized threshold for confirming positive identification of microplastics in recycled plastic-modified asphalt contexts. Confidence levels are typically determined at the discretion of the researcher. Any match below the ideal 100% certainty reflects

varying degrees of uncertainty. In this study, the following confidence scale was adopted to guide interpretation:

- High confidence: Match quality > 95%
- Medium confidence: Match quality between 90% and 95%
- Low confidence: Match quality < 90%

This confidence framework is consistent with broader scientific practice in polymer identification but is not universal. Alternative thresholds may be applied depending on analytical goals, instrumentation, and material complexity.

3.1 LDIR Results of the Raw Materials

Table 1 summarizes the relative abundance of polyethylene (PE) and chlorinated polyethylene (CPE) as a percentage of the total particle count (PPC) in 1 mg of each raw material sample, along with their corresponding spectral match quality scores. While LDIR detected these polymers across several samples, it is critical to interpret these results in the context of the method's limitations.

Although LDIR is a powerful technique for rapid microplastic detection and classification, its effectiveness may be influenced by both the complexity of the material being analyzed and the structure of the reference library. Materials with broad, overlapping infrared absorption spectra, such as petroleum-based binders, modifiers, or mineral aggregates, can lead to ambiguous matches. The LDIR's matching algorithm attempts to assign the best available spectral fit from its library, which may result in misidentifications when the sample's actual composition is not well-represented or falls outside the library's spectral content.

Table 1: PE and CPE content of the raw materials evaluated with LDIR

Sample of Material (LDIR)	Random mass from bin (g)	Mass for test (mg)	PE PPC (Match Quality) (%)	CPE PPC (Match Quality) (%)
Pan dust (<0.075)	62.1	1.0	0.91 (66)	0.08 (72)
0.075mm	64.4	1.0	1.92 (66)	0.00 (N/A)
0.150mm	119.7	1.0	13.95 (72)	0.00 (N/A)
0.300mm	128.1	1.0	0.00 (N/A)	5.00 (66)
0.600mm	131.2	1.0	3.76 (68)	6.02 (70)
Anti-stripping agent	37.4	1.0	12.12 (66)	3.03 (64)
PG64-22	42.3	1.0	63.6 (93)	0.00 (N/A)

As an example, consider the LDIR results for the PE and CPE content in the asphalt binder (PG64-22), summarized in Table 1. These results are based on microdroplets (~0.016 mm² average area) of binder sprayed onto a glass slide, as described in the raw material screening methodology. Of the eleven analyzed droplets, LDIR identified seven (64%) as polyethylene (PE), with an average match quality of approximately 93%. The remaining four droplets (36%) were identified as rubber with similar match quality scores (not shown in the table).

Although a 93% match falls within the "medium confidence" range defined earlier, this identification is likely a misclassification, a limitation of LDIR's spectral matching algorithm. LDIR assigns identities by comparing particle spectra to those in its reference library. However,

complex, undefined mixtures like asphalt binders are difficult to classify with confidence. PG64-22 is composed of saturates, aromatics, resins, and asphaltenes, collectively known as SARA fractions, which do not have fixed molecular structures and instead represent a continuum of hydrocarbon compounds. Therefore, it does not make sense if the LDIR identifies it as anything.

These SARA fractions, especially the saturates and resins, contain long hydrocarbon chains that produce IR spectra like polyethylene. This spectral overlap likely explains why the binder droplets were misidentified as PE. Similarly, the resin fraction's structural and functional resemblance (*35*–*37*) to certain rubbers may account for the rubber classification observed in 36% of the microdroplets.

Further characterization methods, such as Raman spectroscopy, pyrolysis-GC/MS, or detailed SARA fraction analysis, would be required to conclusively validate these identifications. However, such analyses were beyond the scope of this study.

Similarly, for the aggregate samples presented in Table 1, the detected PE and CPE content was minimal and associated with low match quality and very small particle counts. More than 85% of the total particles were identified as a diverse mix of non-polymeric materials, including cellulosic substances, chitin, coal, natural polyamides, calcium carbonate-based particles, and silica. This composition is consistent with the expected mineral and organic content of aggregates sourced from limestone quarries and is further supported by ATR results discussed in the following section.

Notably, some of the identified substances, such as cellulose and chitin, are among the most abundant natural organic compounds on Earth. Their presence in the raw materials, and consequently in the prepared asphalt mixtures, is unsurprising and not considered relevant to the detection of microplastics in this study. As such, they are not analyzed further.

Despite the limitations and high sensitivity of the LDIR method, the detection of microplastics in raw materials is consistent with a growing body of literature. Numerous studies have documented microplastics in natural environments, with one recent review calling their presence a threat to "every sphere of the planet" (*38*, *39*). Microplastics have also been detected in and around mining operations (*40*, *41*) such as aggregate quarries. In these settings, the presence of microplastics is often attributed to the abrasion and degradation of polymer-based mining equipment such as tires, conveyor belts, vehicle parts, storage containers, and ventilation systems. Additionally, airborne and waterborne transport can introduce microplastics from external sources. In the context of this study, where aggregates were sourced from a limestone quarry, the detection of PE, CPE, and other polymeric particles is therefore not unexpected. For example, after passing through crushers, the aggregates are conveyed via long polymer-based belts to storage piles. These belts frequently wear down and are replaced, shedding fine polymeric debris in the process. Even if such material comprises a small fraction of the total mined volume or in trace amounts, they will still be detected in an LDIR characterization.

3.2 ATR Results of the Raw Materials

Table 2 presents the ATR results for the aggregate samples with the highest spectral match quality. In all cases, the aggregates were identified as polysulfide caulking and high calcium carbonate (CaCO3) filler with a spectral match quality exceeding 80%. Although the aggregates are not polysulfide caulking material, the principal component of both polysulfide caulking and the limestone (e.g., aggregates used for this research) are CaCO3. Hence, the ATR device matches the aggregates to the closest available polymer in its library, in this case, polysulfide caulking.

Table 2: ATR results for the raw materials

Sample of Material (ATR)	IR Spectra Best Match (ATR Library)	Match Quality (%)
Pan dust (<0.075)	Polysulfide Caulking, high $CaCO_3$ filler	86.638
0.075mm	Polysulfide Caulking, high $CaCO_3$ filler	89.798
0.150mm	Polysulfide Caulking, high $CaCO_3$ filler	90.297
0.300mm	Polysulfide Caulking, high $CaCO_3$ filler	90.312
0.600mm	Polysulfide Caulking, high $CaCO_3$ filler	88.151
1.180mm	Polysulfide Caulking, high $CaCO_3$ filler	90.011
2.360mm	Calcium Carbonates ($CaCO_3$)	84.943
4.750mm	Polysulfide Caulking, high $CaCO_3$ filler	83.935
9.500mm	Polysulfide Caulking, high $CaCO_3$ filler	85.304

3.3 LDIR Results of the Particles Collected from the Solutions Before the HWTT

LDIR analysis of the water solution samples collected prior to the Hamburg Wheel Tracking Test (HWTT) (0% LDPE-1 and 6% LDPE-1) revealed the presence of various polymeric and non-polymeric particles. Figures 6a and 7a display the results based on the LDIR's built-in polymer library, while Figures 6b and 7b present the same samples analyzed with the custom asphalt library.

Across all four analyses, several types of particles were detected, including those chemically similar to the target polymers (PE, CPE, and LDPE). However, the identifications were generally of low confidence and represented a small proportion of the total particle count. While the sample labels reference LDPE content (0% and 6%), it is important to clarify that these solutions were collected before HWTT of specimens with 0% and 6% LDPE content, respectively. The solutions did not contain added LDPE themselves. Furthermore, the two solutions were collected on different days under independent conditions.

In Figures 6a–7b, particle identification quality is represented by a dot-whisker plot on the left y-axis (mean ± standard deviation), and the relative abundance of each unique particle type is shown as a percentage of total particle count (PPC) on the right y-axis. Particles of interest (PE, CPE, and LDPE) are highlighted and labeled for ease of reference.

The consistent detection of PE and CPE in both pre-test samples suggests the influence of background contamination, which may originate from the HWTT apparatus itself. Components such as plastic molds (often made from high-density polyethylene, HDPE) and piping (commonly LDPE) are potential sources of leached or abraded particles. Despite thorough cleaning between tests, residual contamination is plausible, particularly given that the HWTT equipment had previously been used for RPMA testing involving the same type of agricultural LDPE. In addition, the shared laboratory environment, where various recycled plastics are stored and handled, further increases the likelihood of airborne or surface-borne contamination, which could have affected both equipment and other materials in the lab.

While background solutions were collected before each HWTT and the suspended particles were characterized for microplastics, their values were not meant to be subtracted from post-test measurements due to uncontrolled variations in lab use, equipment exposure in between these solutions collection, and timing of the collection. Instead, these data are used qualitatively to show the pervasive presence of microplastic contamination across this testing environment.

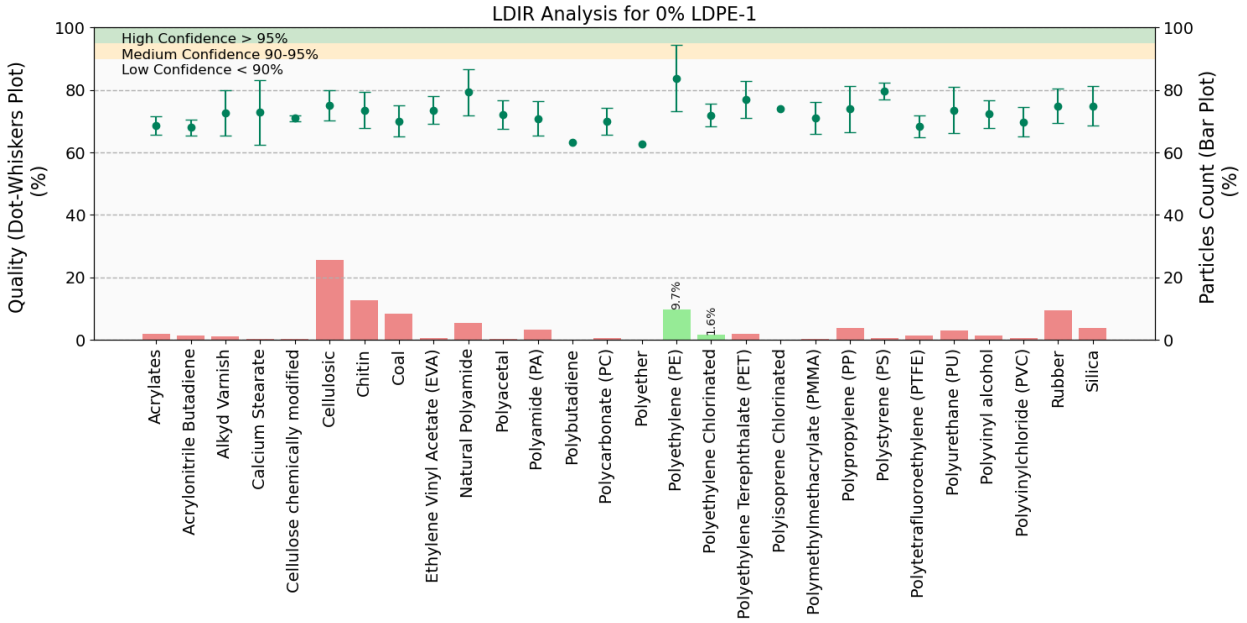

Figure 6a: LDIR analysis results for 0% LDPE-1 (built-in library)

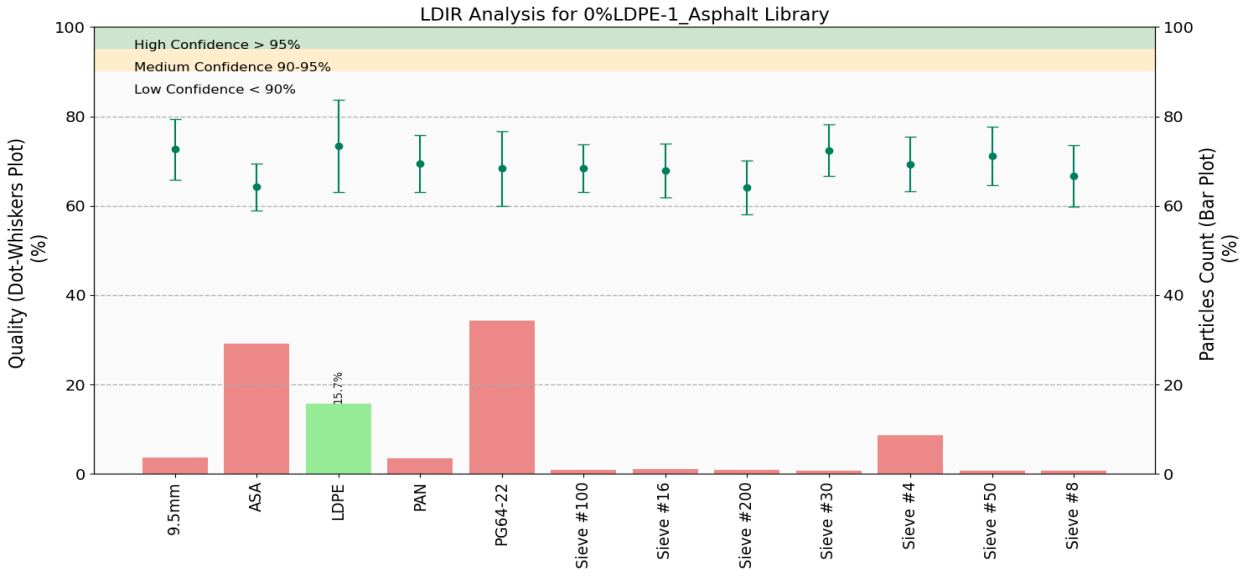

Figure 6b: LDIR analysis results for 0%LDPE-1 (custom-built asphalt library)

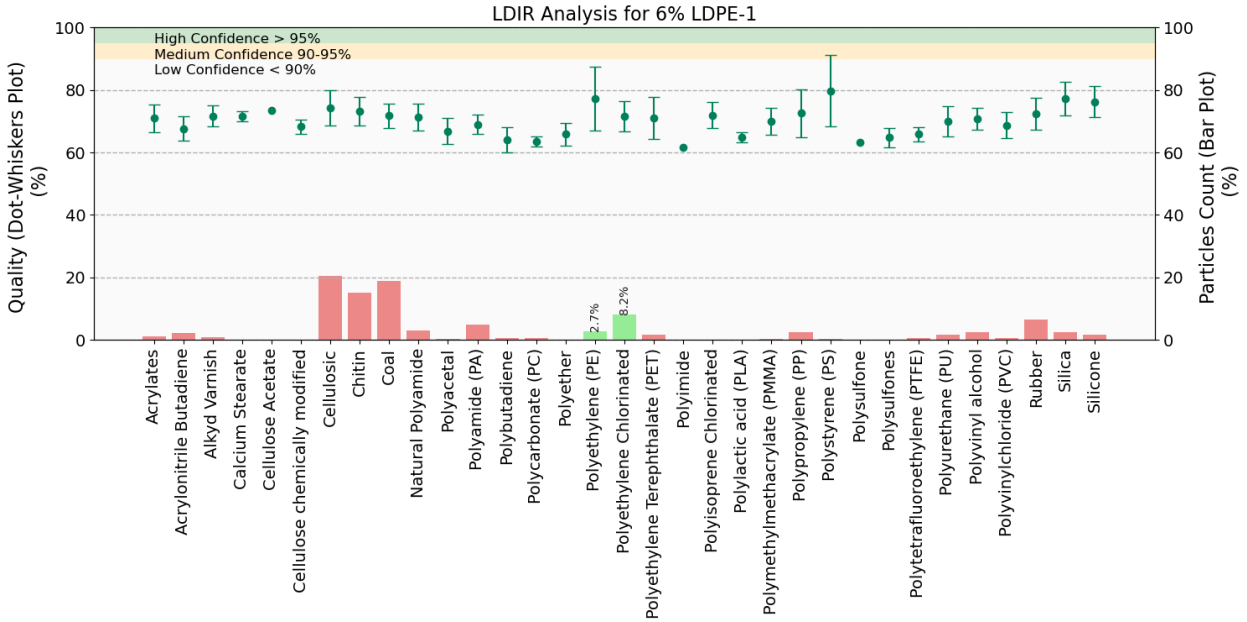

Figure 7a: LDIR analysis results for 6% LDPE-1 (built-in library)

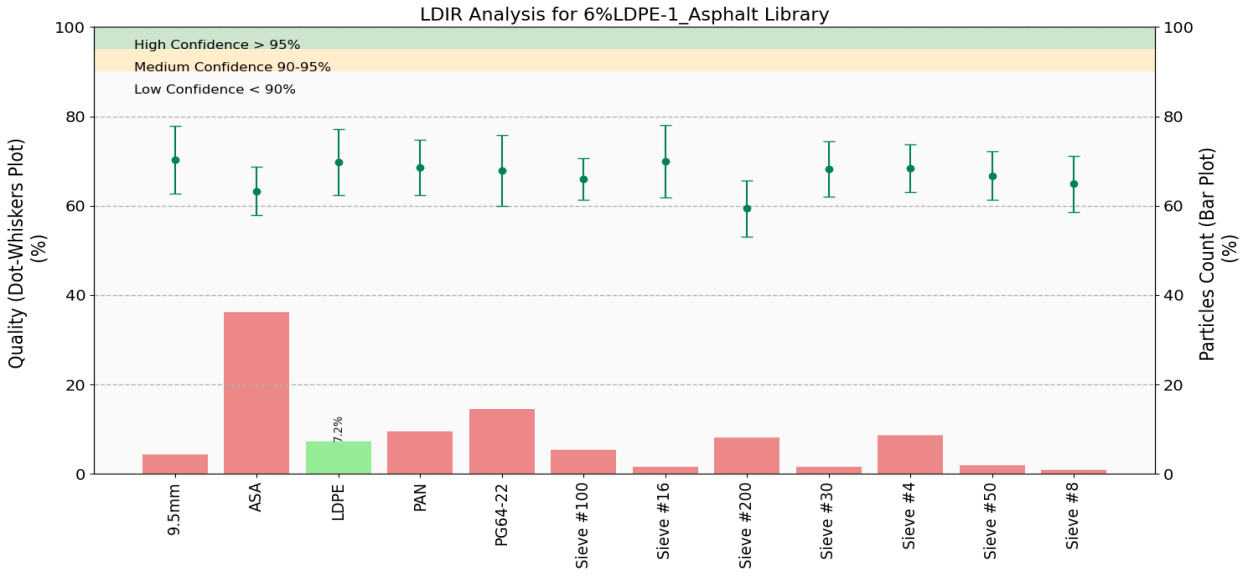

Figure 7b: LDIR analysis results for 6%LDPE-1 (custom-built asphalt library)

3.4 LDIR Results of the Particles from the Asphalt Pavement Samples

Given the wide range of particles detected in both the raw materials and background solutions, several analytical strategies were employed to assess whether recycled plastic-modified asphalt samples released more polymeric particles, particularly microplastics, than unmodified controls, irrespective of the particles of interest.

An initial exploratory data analysis was conducted using the physical attributes of particles detected via the LDIR using its built-in library. These attributes included width, height, diameter, aspect ratio, area, perimeter, eccentricity, circularity, and solidity. However, no single variable showed a consistent or distinguishable pattern between modified and unmodified samples.

Hence, to explore whether combinations of these features might reveal underlying structure, Principal Component Analysis (PCA), a commonly used linear dimensionality reduction technique, was applied. The first round of PCA grouped all particles across the six test conditions according to their material identification (Figure 8). The goal was to determine whether particles linked to plastic modification, particularly those identified as PE or CPE, exhibited distinct clustering behavior.

Although both PE and CPE were detected across all test cases, the PCA revealed no consistent separation or clustering based on identification type alone, suggesting that individual particle classifications were insufficient for distinguishing modification conditions.

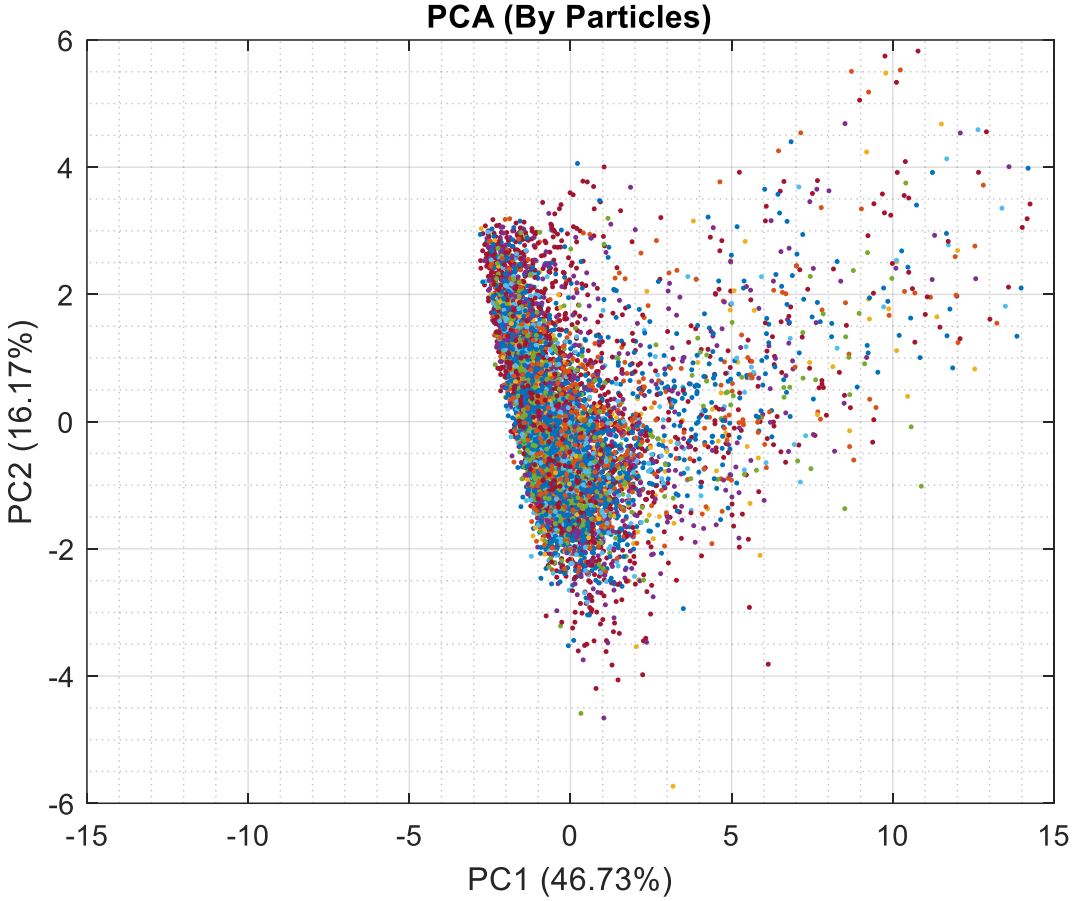

Figure 8: PCA by particles type (legend is not shown as it includes ~ 35 unique material)

PCA was then applied based on the six distinct sample cases (Figure 9). Although some visual dispersion and partial grouping were observed, the results did not reveal any definitive clustering patterns that could reliably distinguish the samples by case.

It should be noted that, while other data science techniques, such as nonlinear dimensionality reduction or machine learning-based clustering could be applied that might uncover subtle patterns, they were not pursued in this study, as the primary objective was to assess observable differences under realistic laboratory conditions using interpretable, conventional methods.

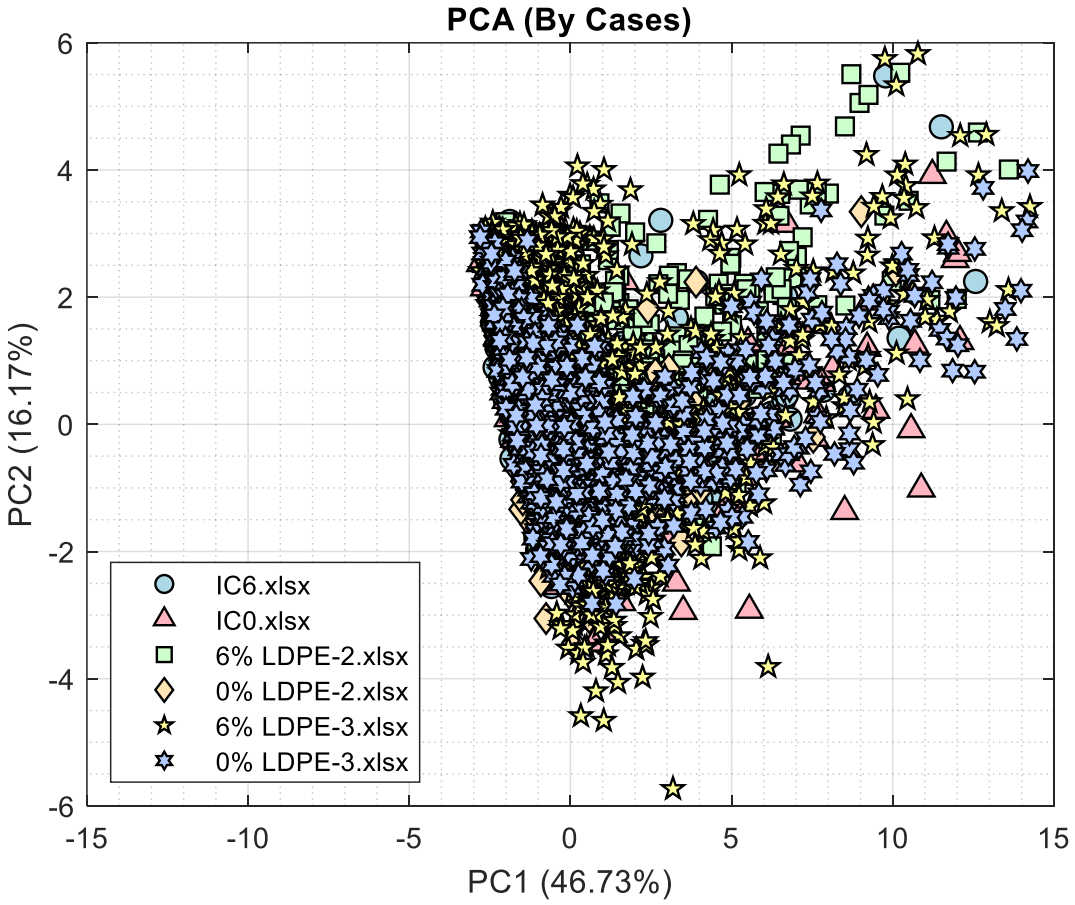

Figure 9: PCA by case (IC6, IC0, 6% LDPE-2, 0% LDPE-2, 6% LDPE-3, and 0% LDPE-3)

Next, PCA was conducted by grouping particles according to modification conditions, either modified or unmodified, as shown in Figure 10. This approach produced a clearer clustering pattern: the unmodified samples formed a relatively compact cluster, while the modified samples exhibited greater dispersion, spatially surrounding the unmodified group.

This behavior aligns with the material composition. The unmodified set, denoted as:

u = {aggregates, binder, anti-stripping agent}, which represents the base mix, while the modified set can be expressed as:

m = u ∪ {LDPE particles}.

Both groups share the same foundational materials, but the inclusion of LDPE in the modified samples introduces additional particle types and morphological variability, leading to broader feature distributions in the PCA space.

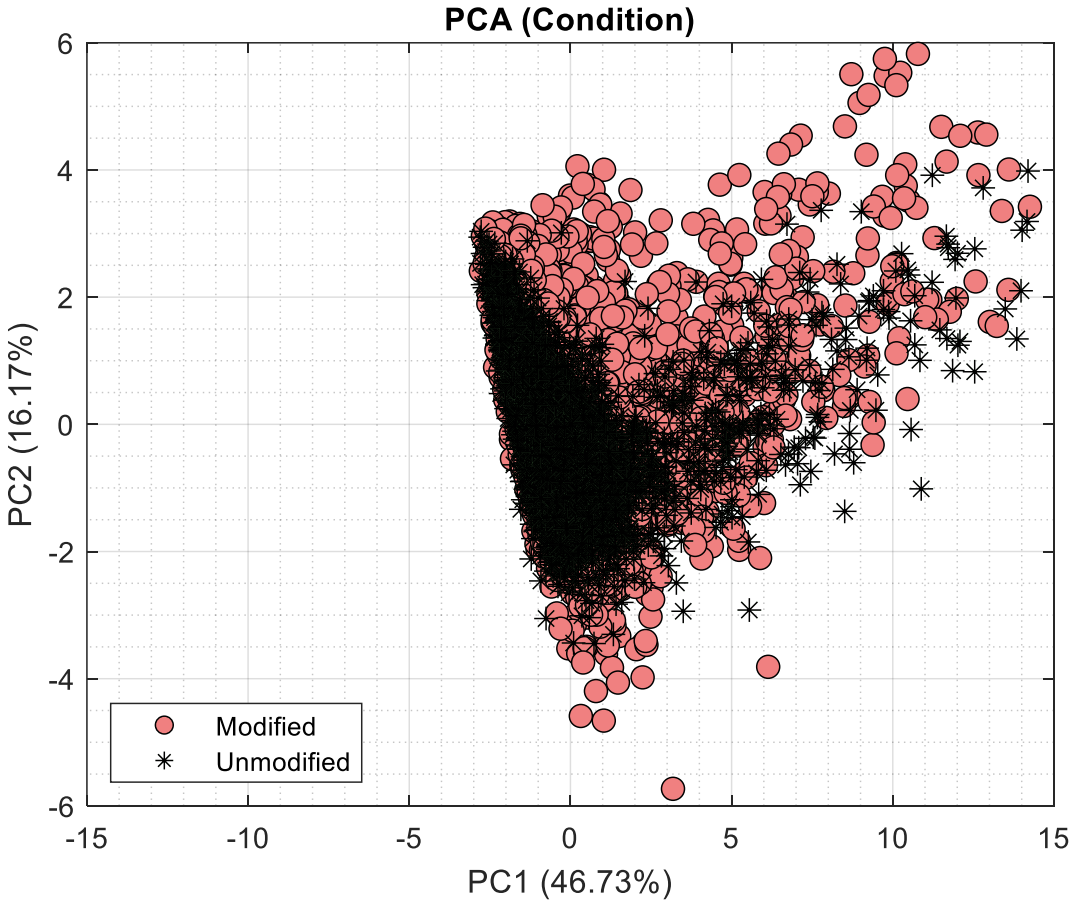

Figure 10: PCA by modification condition (modified vs unmodified)

Since PCA revealed a distinct separation between modified and unmodified samples, a loading analysis was conducted to identify which particle attributes contributed most to the principal components (Figure 11). The analysis showed that Principal Component 1 (PC1) was dominated by size-related variables, including area, width, height, diameter, and perimeter, while Principal Component 2 (PC2) was primarily influenced by shape-related characteristics, such as solidity, circularity, and eccentricity.

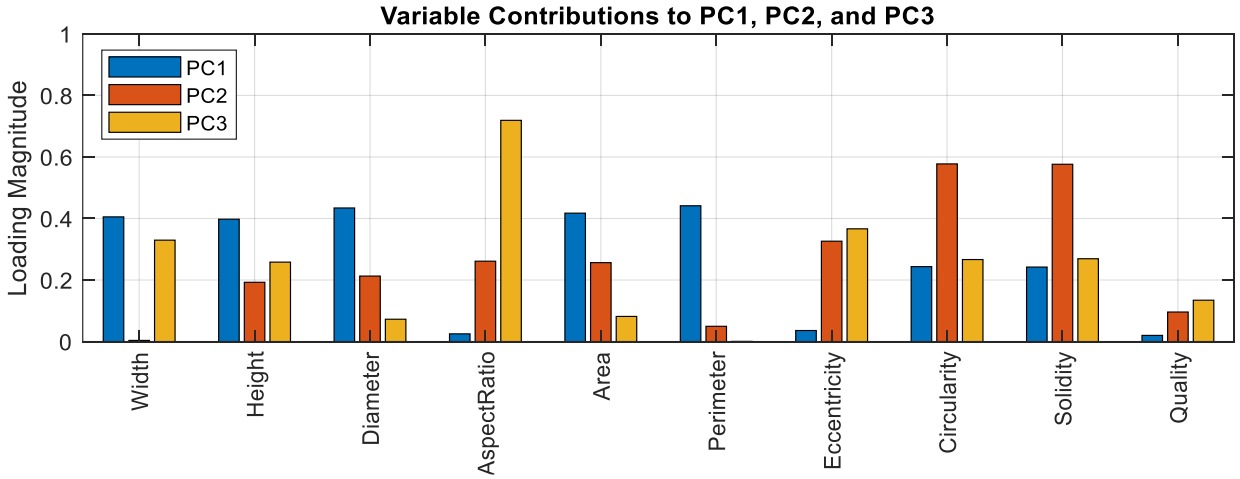

Figure 11: PCA loading contribution of each variable to the first three principal components

Consequently, size-related parameters of the detected particles were selected for further analysis. Distributions of these parameters, grouped by modification conditions, are shown in Figures 12 through 16. While all size-related variables contributed comparably to PC1, particle area was chosen as the primary variable for quantitative comparison in this study, due to its broad representativeness of particle size. That said, the same analytical framework could be applied using other features, particularly when particle shape (e.g., fibers, pellets, spheres, or fragments) is of specific interest for classification or environmental behavior modeling.

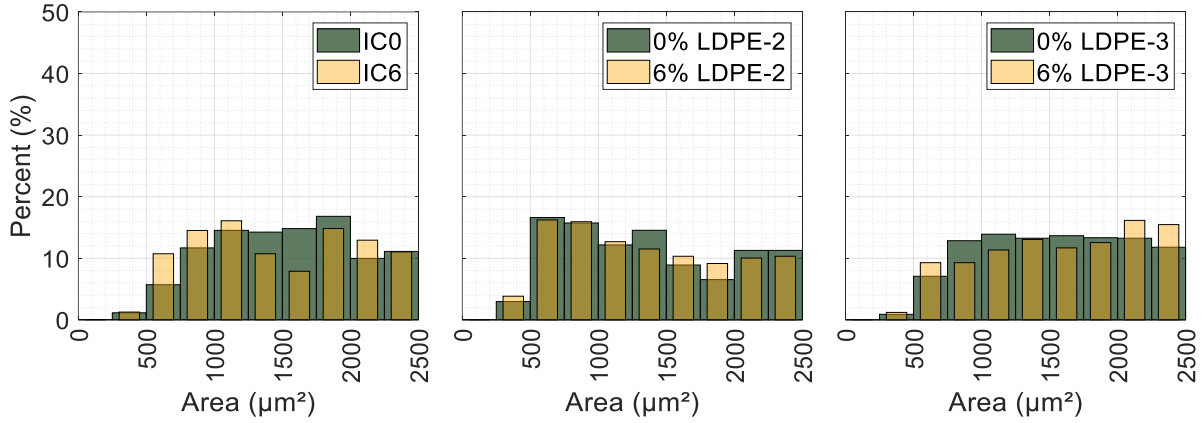

Figure 12: Area distribution of the particles from different cases

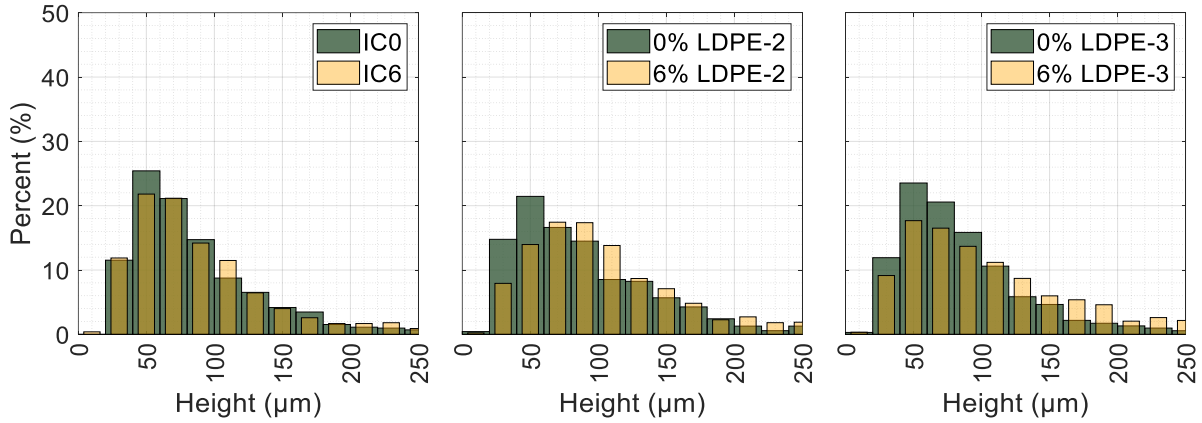

Figure 13: Characteristic Size (Height) distribution of the particles from different cases

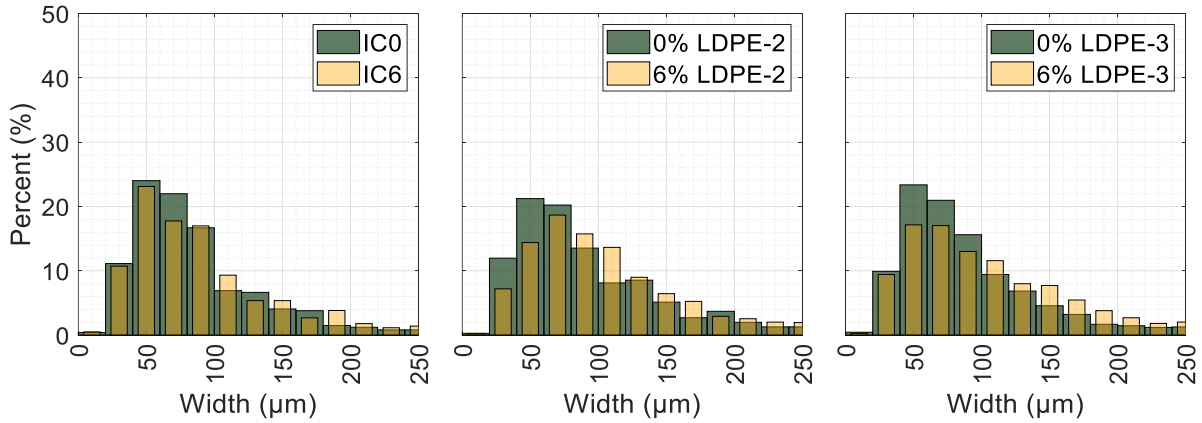

Figure 14: Width distribution of the particles from different cases

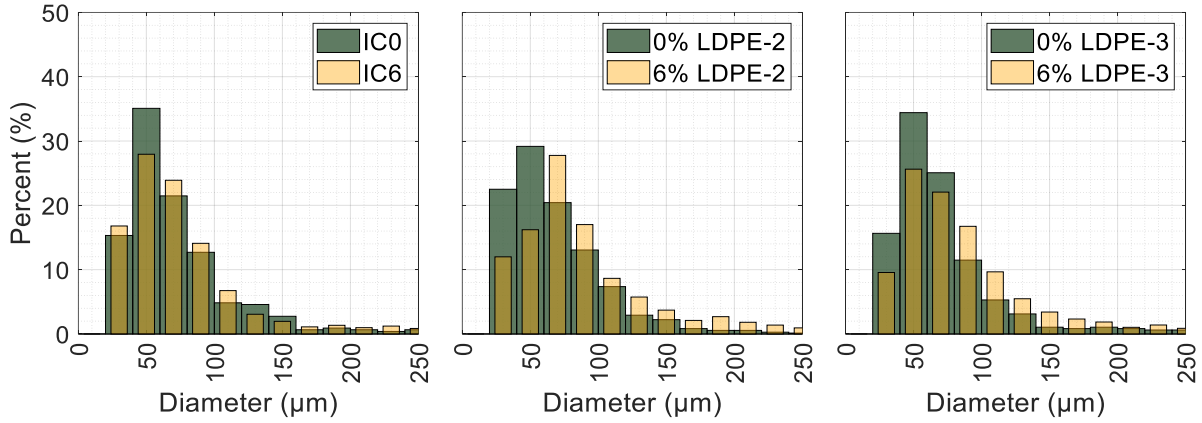

Figure 15: Diameter distribution of the particles from different cases

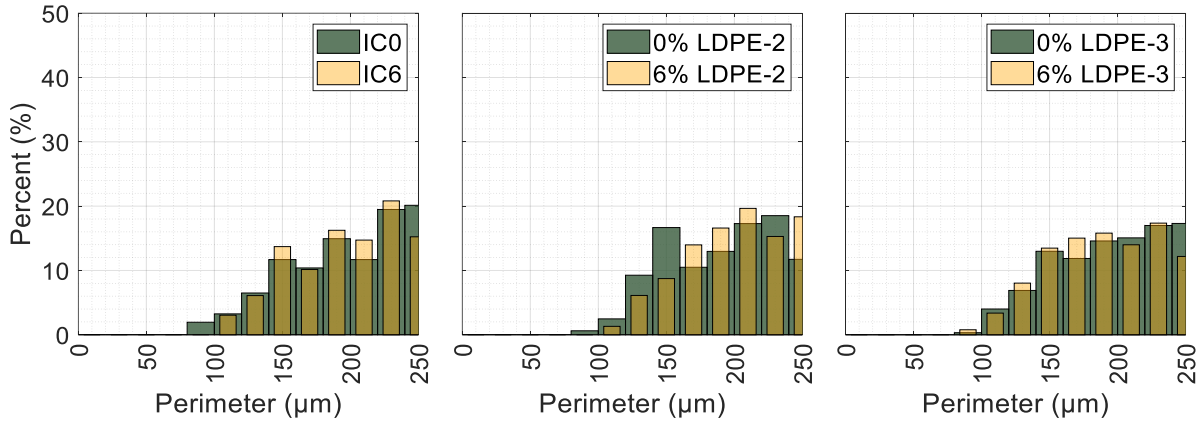

Figure 16: Perimeter distribution of the particles from different cases

To quantitatively compare the release potential of microplastic-like particles across different samples, a Normalized Area Index (NAI) was developed. For each test case, the total area of detected particles was normalized by the mass of the corresponding asphalt pavement specimen, resulting in a metric expressed in µm²/g. This allowed for a standardized comparison of particle load between samples with differing test masses.

The NAI is defined as:

$$NAI = \frac{\sum A}{m}$$

where:

A is the sum of area of all the particles for a sample in µm²

m is the total mass of the corresponding asphalt pavement sample in grams

Higher NAI values may indicate an increased potential for the release of microplastics or related micro polymer particles. While the metric captures all detected particles, subsequent interpretation in this study focuses specifically on the particles of interest (PE, CPE, and LDPE).

Sample mass values used for normalization are provided in Table 3. The two water solution samples (0% LDPE-1 and 6% LDPE-1) were excluded from this analysis, as they were not associated with measured sample masses and were collected prior to HWTT exposure.

Table 3: Mass and number of particles for each case

Specimen	Type of Specimens	No. of Specimens	Total Mass (g)	No. of Particles
IC0	Uncut Disks	2	5033.3	796
IC6	Uncut Disks	2	5037.7	831
0% LDPE-2	HWTT	4	9750.30	723
6% LDPE-2	HWTT	4	9760.60	1433
0% LDPE-3	HWTT and MiST	2	4848.7	2847
6% LDPE-3	HWTT and MiST	2	4869.3	2029

3.4.1 LDIR Results of the Particles from the Intact Condition MiST Test

The NAI values for samples collected after the Intact Condition MiST test (IC0 and IC6) are shown in Figures 17a and 18a (based on the LDIR built-in library) and Figures 17b and 18b (based on the custom asphalt library). While the primary discussion in this section focuses on the built-in library results for consistency and broader comparability, the custom library results are included to provide a complete representation of the data.

In these figures, the NAI values of individual particle types, including the highlighted particles of interest (PE, CPE, and LDPE, shown in bright green), are plotted on the right y-axis. The left y-axis displays both the mean identification quality (± standard deviation) and the percentage of each particle type relative to the total particle count for that case, with both metrics expressed as percentages.

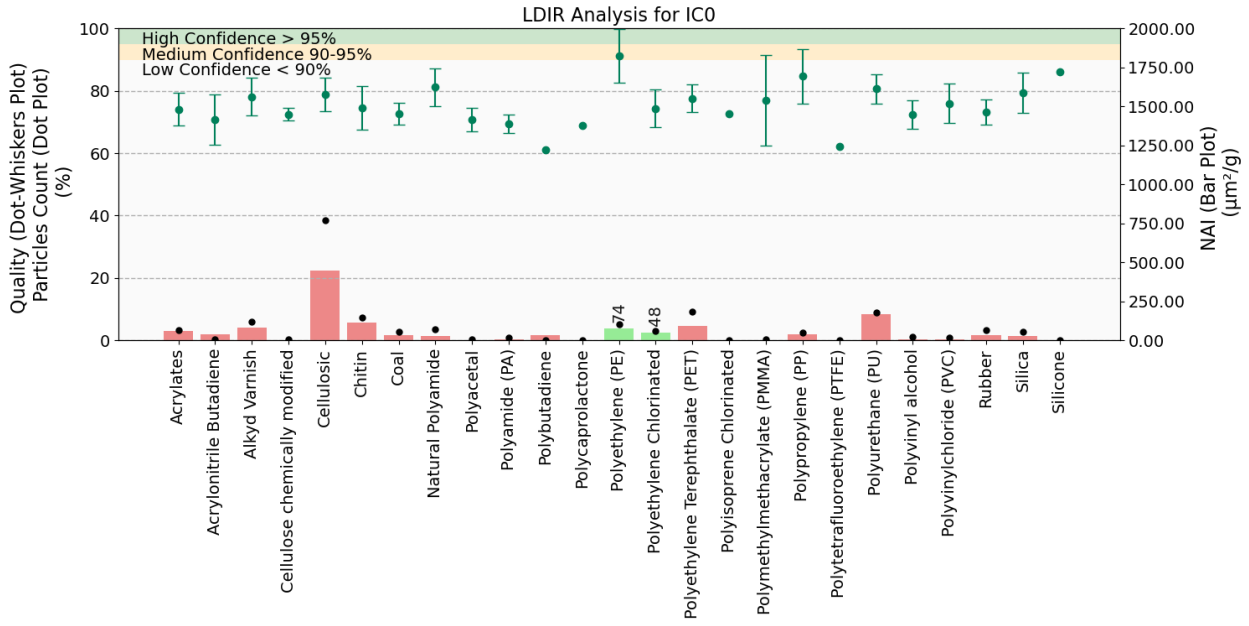

Figure 17a: LDIR analysis results for IC0 (built-in library)

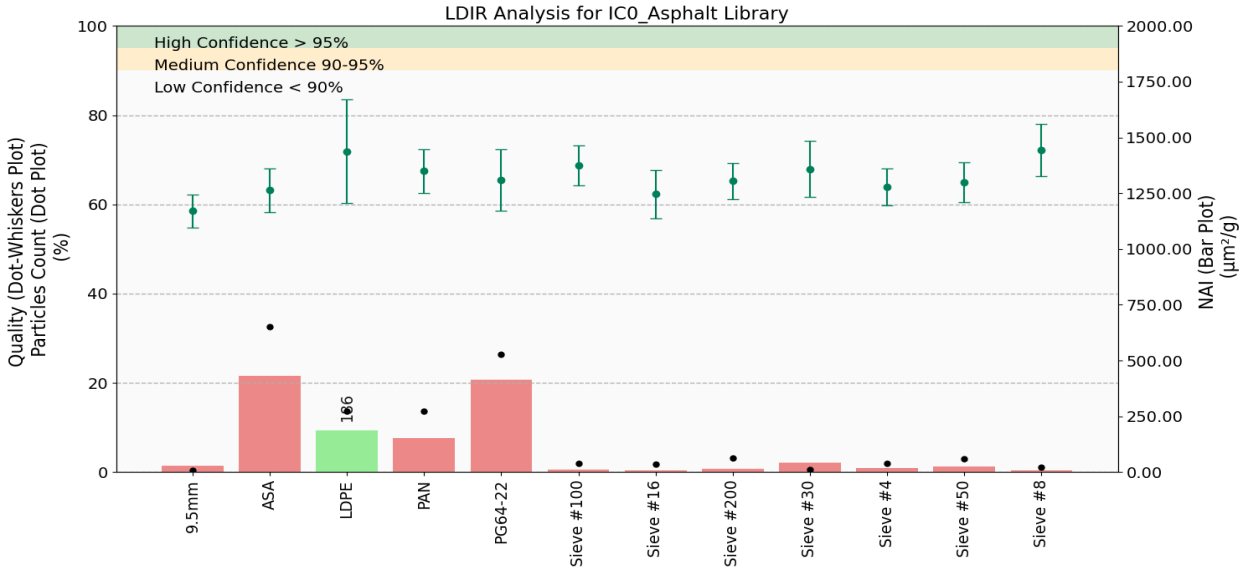

Figure 17b: LDIR analysis results for IC0 (custom built asphalt library)

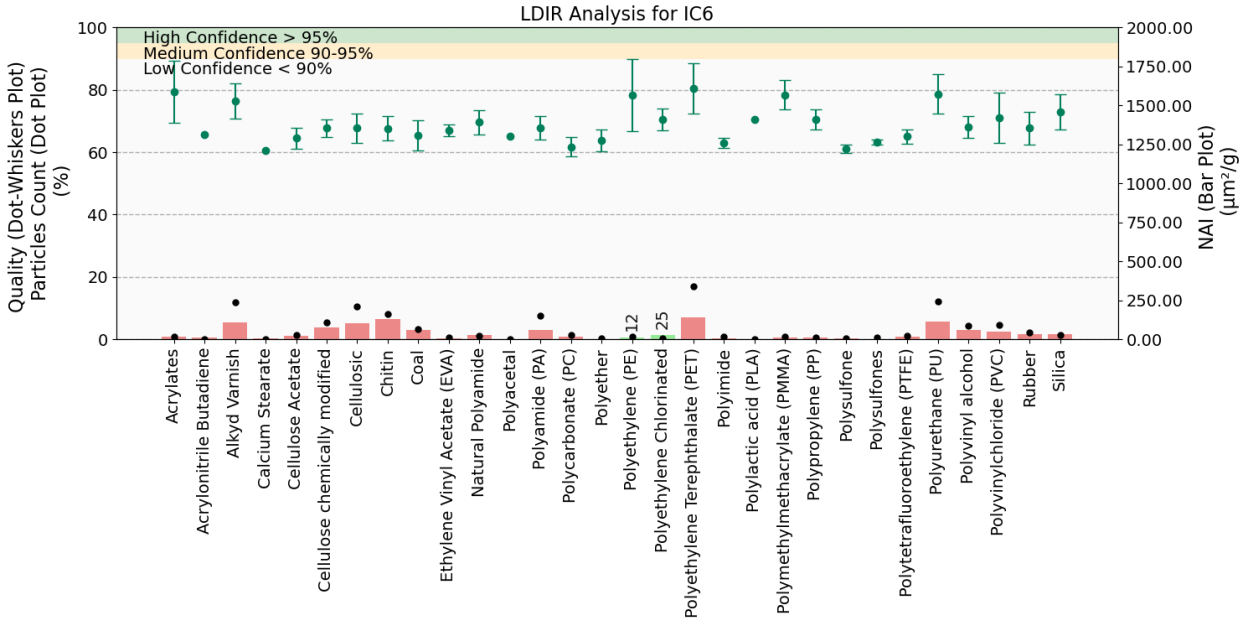

Figure 18a: LDIR analysis results for IC6 (built-in library)

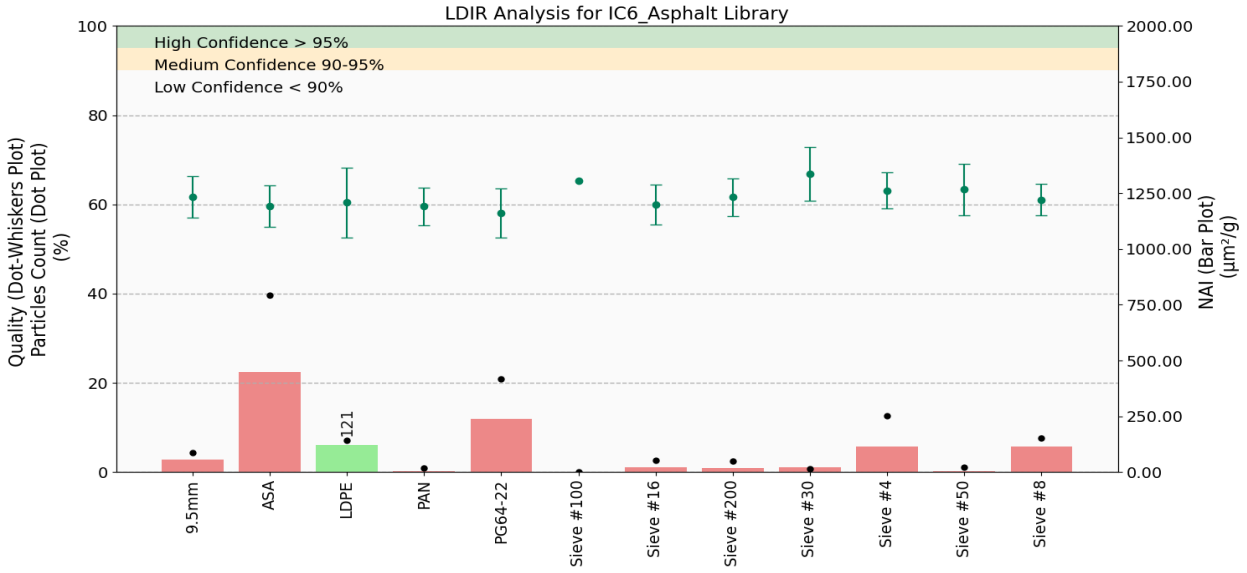

Figure 18b: LDIR analysis results for IC6 (custom built asphalt library)

Comparing IC0 and IC6, it is observed that despite having nearly identical sample masses (5033.3 g vs. 5037.7 g) and total particle counts (796 vs. 831), the normalized area index (NAI) for the particles of interest, PE and CPE, is higher in the unmodified sample (IC0) than in the modified sample (IC6). While this may initially seem counterintuitive, it likely results from a combination of factors.

First, as shown in Table 1, the asphalt binder is often identified by LDIR as PE with high match quality, due to overlapping IR spectra. Therefore, it is expected that both IC0 and IC6 which contain the same binder, would show strong PE-like signals. However, the classification dynamics may shift in IC6 due to the addition of actual LDPE particles, which the LDIR may also interpret as PE. In this case, the instrument may be attributing PE identifications in IC6 to LDPE particles rather than to binder (closer spectral match between LDPE and PE compared to PG64-22 and PE), which could reduce the number of PE-classified particles overall, especially given the low dosage of LDPE (6% of the 5.9% binder content). In contrast, IC0 contains no LDPE, so a higher fraction of particles may be classified as PE due solely to binder exposure.

Second, a potential coating or encapsulation effect may also influence the results. In IC6, LDPE particles might be entirely or partially coated with binder during mixing. Since LDIR identifies materials based on their surface infrared characteristics, the system may interpret these coated particles as binder, or binder-like substances, instead of LDPE or PE.

Finally, particle morphology may also play a role. As shown in Figure 12, the IC0 sample contains a slightly greater proportion of larger-area particles compared to IC6. Since the NAI is area-based, this could further elevate the normalized values for IC0, despite both samples having comparable particle counts.

3.4.2 LDIR Results of the Particles from the Damaged Condition MiST Test

The NAI values for samples tested under damaged conditions, that is, MiST testing conducted after HWTT exposure (0% LDPE-3 and 6% LDPE-3), are shown in Figures 20a and 21a for the built-in library analysis, and Figures 20b and 21b for the custom asphalt library.

As with the intact condition samples, both modified and unmodified damaged specimens released polymeric particles, including those of interest. However, the NAI values for these damaged samples were substantially higher than their intact counterparts (IC0 and IC6). Although the damaged specimens had slightly lower masses, due to section chipping during HWTT preparation, they were structurally weakened and thus released more particles during MiST testing. This increased instability under hydrostatic pressure likely contributed to the larger overall particle output, including a higher count of particles of interest.

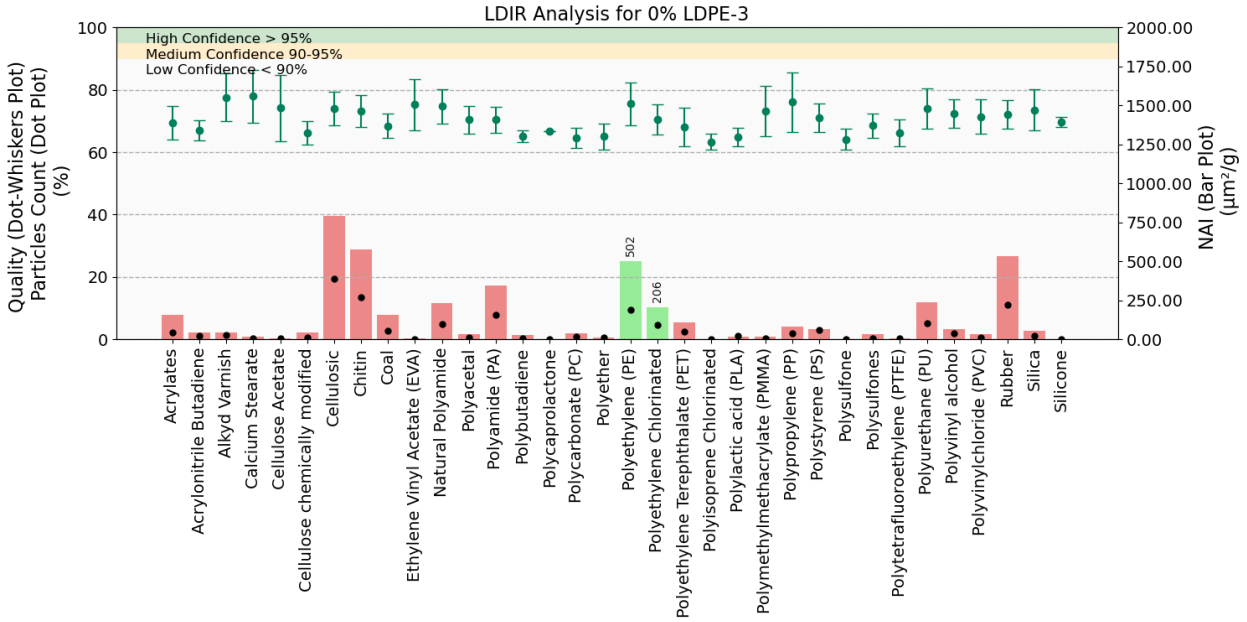

Figure 20a: LDIR analysis results for 0% LDPE-3 (built-in library)

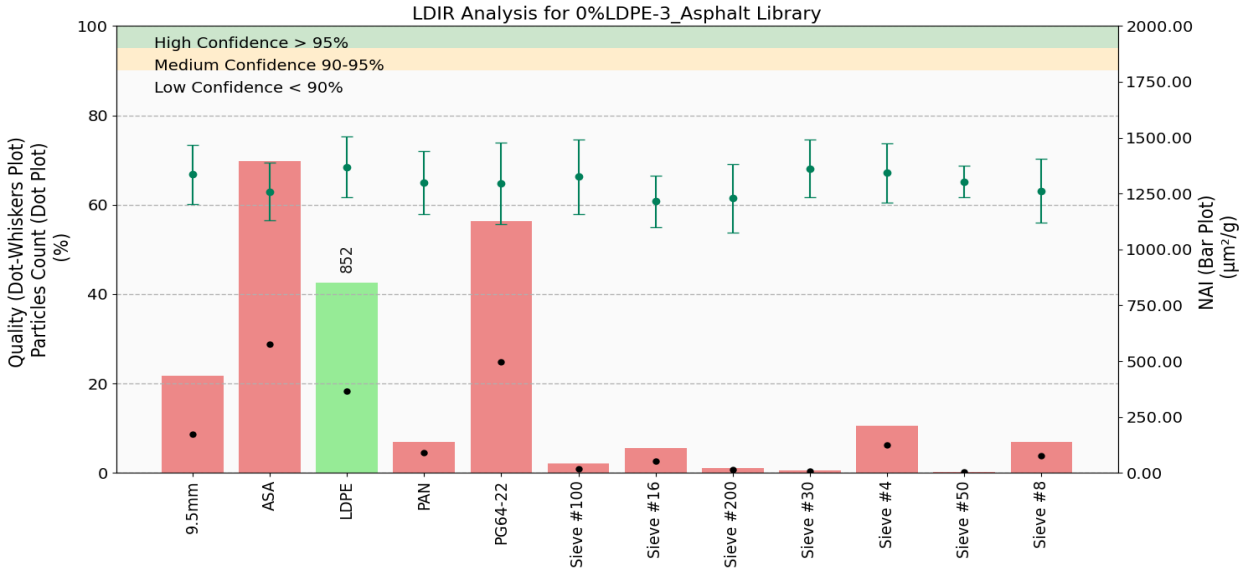

Figure 20b: LDIR analysis results for 0% LDPE-3 (custom-built asphalt library)

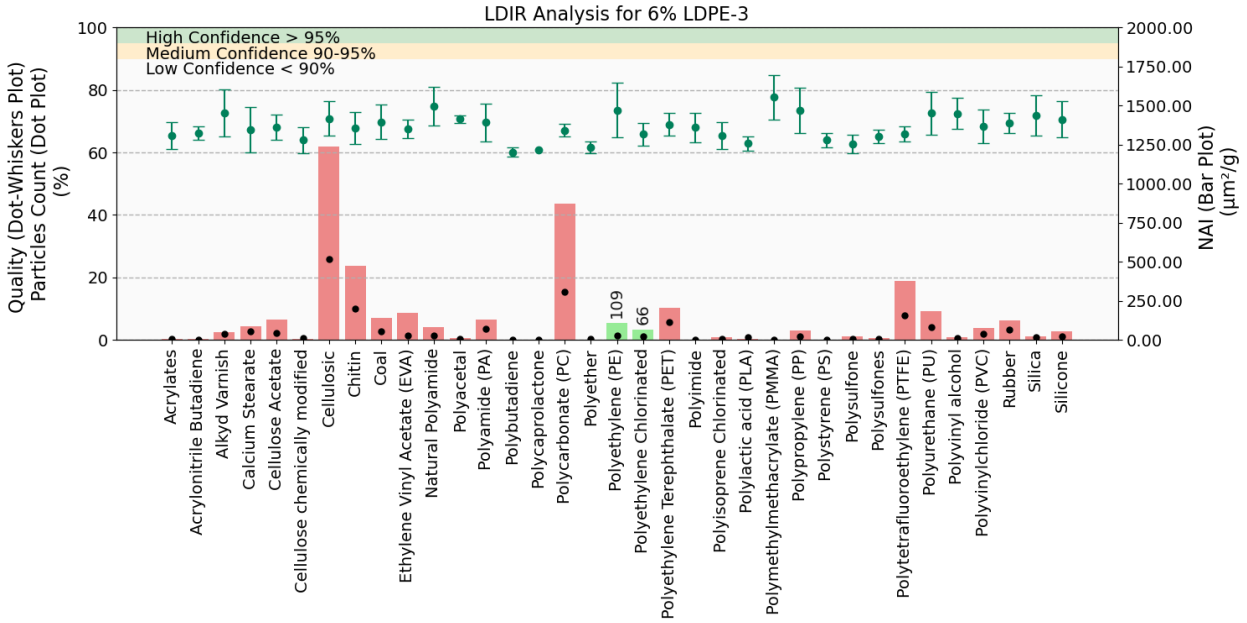

Figure 21a: LDIR analysis results for 6% LDPE-3 (built-in library)

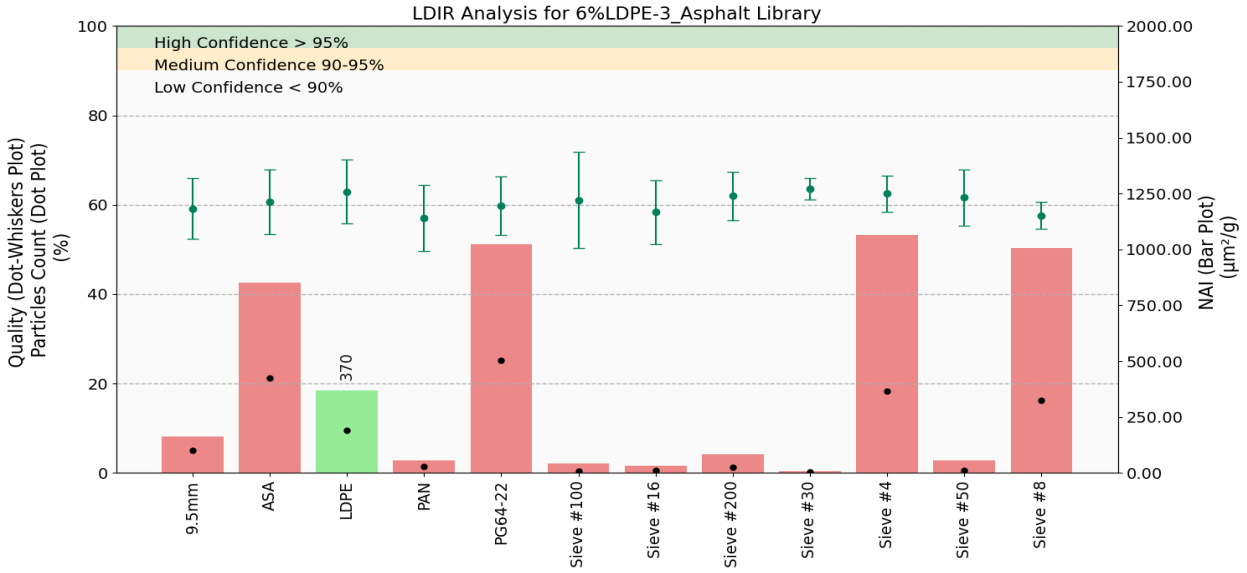

Figure 21b: LDIR analysis results for 6% LDPE-3 (custom-built asphalt library)

3.4.3 LDIR Results of the Particles from HWTT

The NAI values for samples collected after Hamburg Wheel Tracking Test (0% LDPE-2 and 6% LDPE-2) are shown in Figures 22a and 23a for the built-in library and in Figures 22b and 23b for the custom asphalt library.

Comparing these cases, both contain particles of interest, but unlike the results from the MiST tests, the modified sample (6% LDPE-2) exhibited higher NAI values than the unmodified sample. This suggests that under the specific mechanical loading and water exposure conditions of the HWTT, the inclusion of LDPE may result in greater particle shedding or at least higher detection of LDPE-like fragments.

One possible explanation is that HWTT's repeated wheel loading and immersion may create surface wear or abrasion patterns that preferentially affect LDPE domains in the modified asphalt. Unlike MiST, which uses cyclic hydrostatic pressure with limited mechanical contact, HWTT involves direct physical deformation, which may fragment LDPE into more detectable particles. This could account for the increased presence of PE/CPE in the modified sample after HWTT.

Moreover, unlike the MiST tests, where binder-related misclassification may obscure differences between samples, the harsher mechanical damage in HWTT may have exposed or dislodged LDPE particles more directly, leading to stronger signal attribution in LDIR.

That said, the number and area of particles of interest remain relatively low in absolute terms, and the match confidence scores are still below the threshold for definitive material identification. These findings should therefore be interpreted with caution and within the broader context of background contamination and material complexity discussed previously.

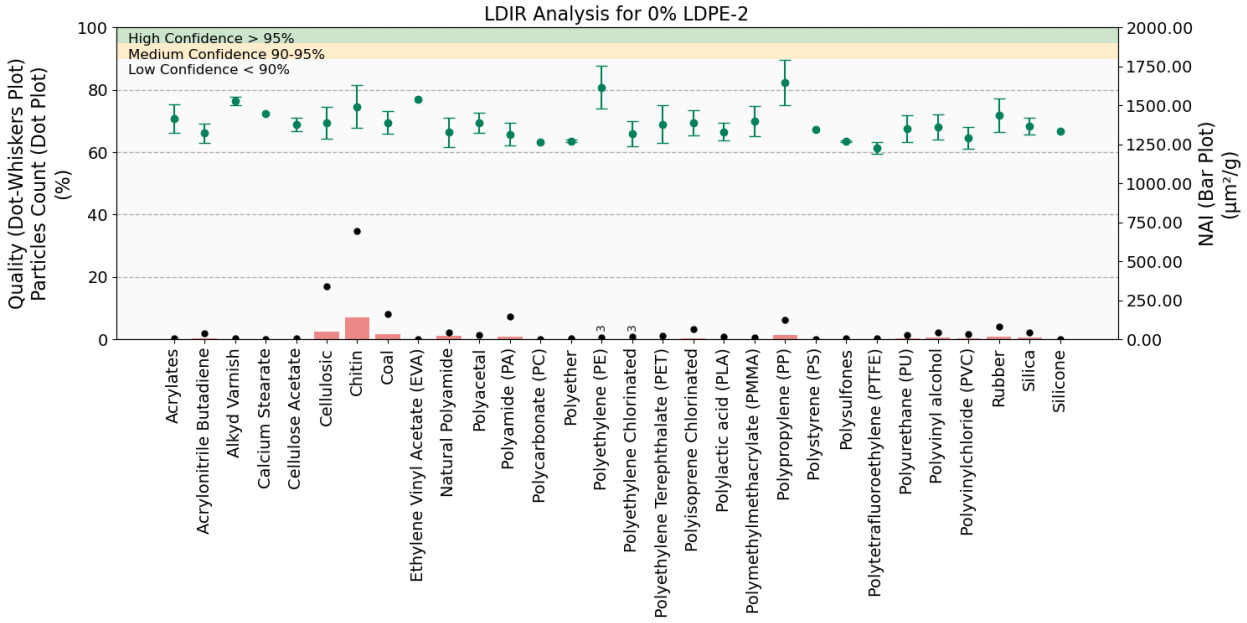

Figure 22a: LDIR analysis results for 0% LDPE-2 (built-in library)

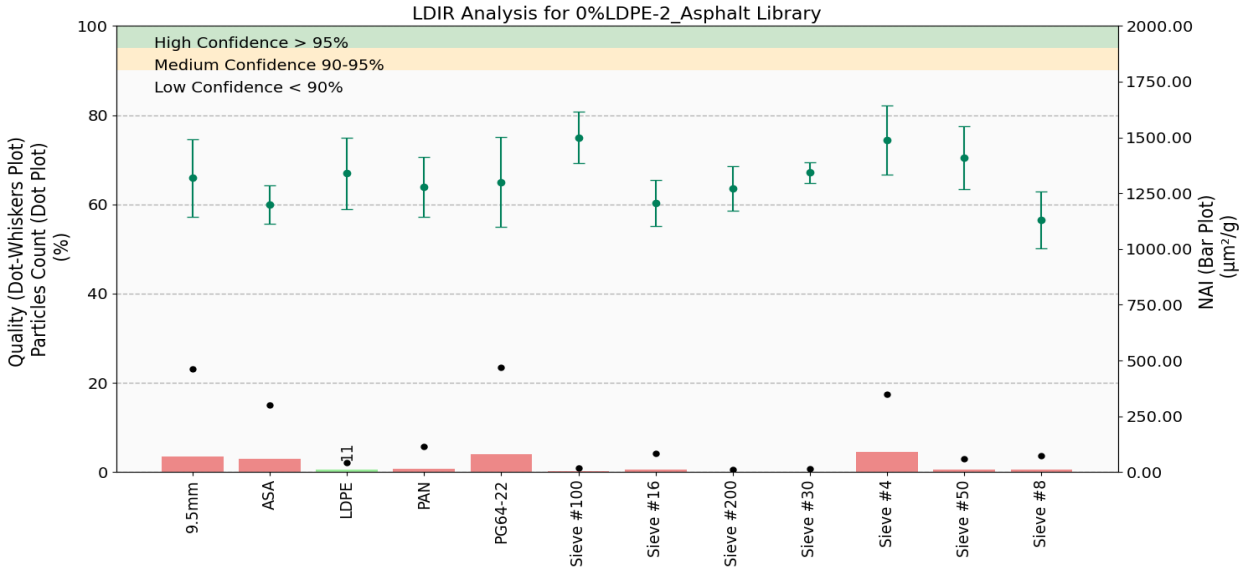

Figure 22b: LDIR analysis results for 0% LDPE-2 (custom-built asphalt library)

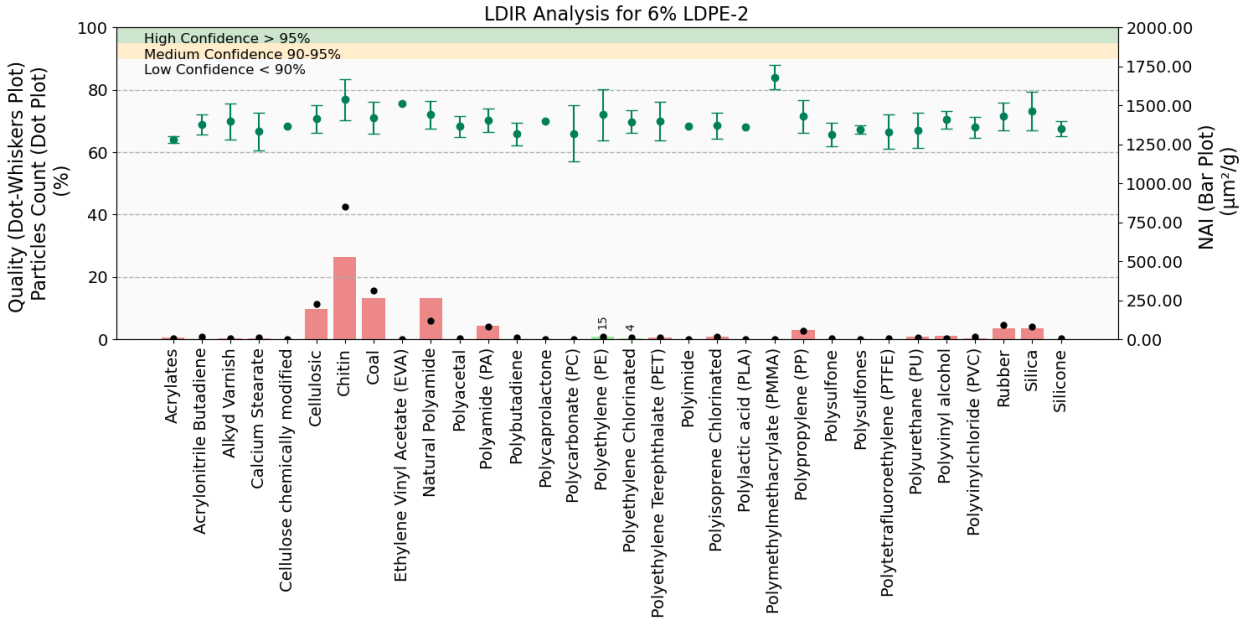

Figure 23a: LDIR analysis results for 6% LDPE-2 (built-in library)

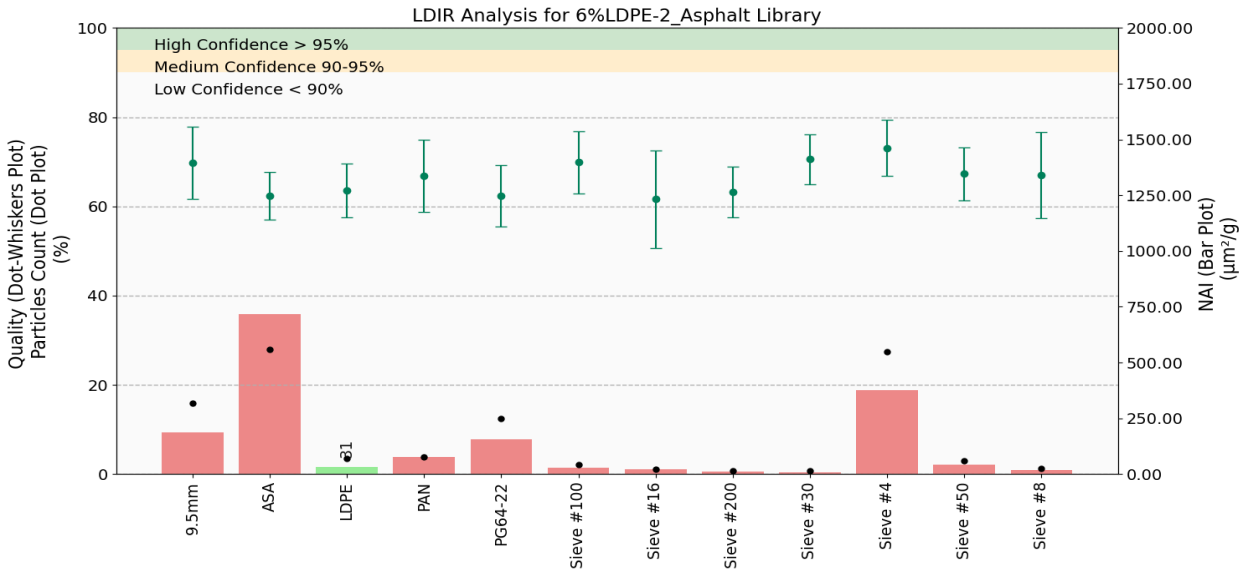

Figure 23b: LDIR analysis results for 6% LDPE-2 (custom-built asphalt library)

Furthermore, it is important to note that the comparisons above between modified and unmodified samples were based exclusively on the particles of interest (PE, CPE, and LDPE). However, given the pervasive background contamination observed throughout the study, affecting raw materials, equipment, and even pre-test solutions, it was necessary to extend the analysis to include all detected particles, both polymeric and non-polymeric. Hence, when the Normalized Area Index (NAI) is recalculated on this broader basis, the modified samples consistently exhibit equal or higher NAI values across test conditions, as shown in Figure 24. This trend is also supported by the Principal Component Analysis, which revealed greater dispersion of particle features in the modified samples relative to the unmodified ones.

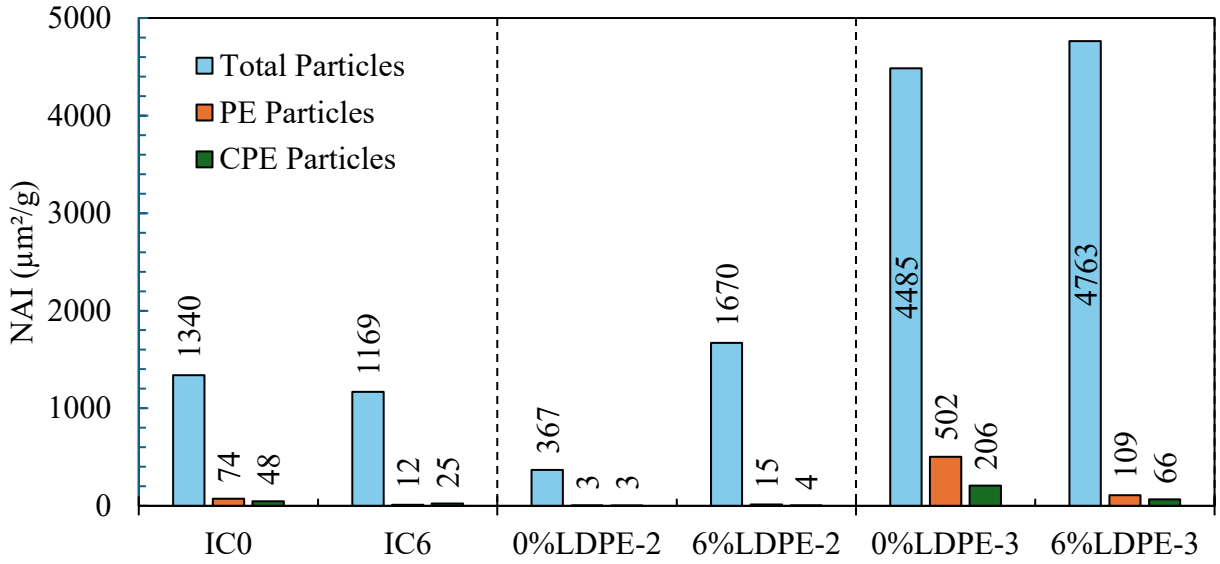

Figure 24: NAI values based on total particles compared with particles of interest for each case

4. Conclusions and Recommendations

This study investigated the potential release of microplastic particles from Recycled Plastic Modified Asphalt (RPMA) using agricultural Low-Density Polyethylene (LDPE) film as a modifier. Modified and unmodified asphalt pavement samples were subjected to Hamburg Wheel Tracking Test (HWTT) and Moisture Induced Sensitivity Tester (MiST), with leachate samples analyzed using Laser Direct Infrared Imaging (LDIR) and Attenuated Total Reflectance (ATR). Raw materials and background solutions were also screened to establish a baseline and develop a custom asphalt spectral library.

Across all samples, including raw materials, background solutions, and unmodified controls, a wide range of polymeric and non-polymeric particles were detected. PE and CPE particles, which share spectral similarities with LDPE, were found inconsistent in both modified and unmodified samples, often at low particle counts and with match quality below thresholds for definitive identification. Notably, the LDIR system did not positively identify any particles as LDPE.

The pervasive detection of these particles, even in unmodified samples and background water, underscores a broader challenge in microplastic research where contamination appears ubiquitous, even in controlled laboratory settings. This contamination, coupled with the spectral similarity between various particles, complicated the efforts to isolate the specific contribution of recycled LDPE to microplastic release.

While some patterns emerged, these results should be interpreted with caution. Limitations in spectral resolution, overlapping material signatures, and the absence of more definitive chemical identification techniques (e.g., pyrolysis-GC/MS or Raman spectroscopy) prevented conclusive attribution of microplastic release to the add LDPE modifier.

Ultimately, the study highlights both the analytical potential and the interpretive limitations of current microplastic detection tools when applied to complex construction materials such as asphalt pavement. Future research should aim to refine analytical protocols, control background contamination more rigorously, and incorporate complementary techniques to validate microplastic presence and identity with higher confidence.

Artificial Intelligence Disclaimer

This manuscript was edited and subsequently ai-peer reviewed using OpenAI's ChatGPT, using the following prompt designed to emulate a rigorous, multi-perspective scholarly review. The AI-generated feedback was incorporated by the author, and this document reflects the final revised version.

The Prompt:

You are assigned to conduct a comprehensive academic peer review of the attached manuscript, emulating the role of three independent expert reviewers. Each reviewer should assess the paper from a distinct disciplinary perspective:

- **Reviewer #1 – Materials Science**
  A researcher with a broad background in materials science, evaluating the manuscript for technical rigor, experimental clarity, novelty, and contribution to the discipline.
- **Reviewer #2 – Recycled Plastics Modified Asphalt Pavement (RPMA)**
  A domain specialist assessing methodological soundness, relevance of findings to pavement engineering, and alignment with existing knowledge and industry practices.
- **Reviewer #3 – Environmental Sustainability & Microplastics**
  An expert focused on environmental risk, sustainability, and microplastic behavior within infrastructure systems. This reviewer emphasizes unintended consequences and lifecycle impacts.

Each reviewer was instructed to:

1. Evaluate the manuscript according to established peer review criteria, including:
   - Originality and significance
   - Clarity of objectives and coherence of argument
   - Methodological appropriateness and transparency
   - Quality of results and interpretation
   - Engagement with literature
   - Validity of conclusions
   - Societal and ethical implications
2. Identify strengths and weaknesses constructively, and provide specific, actionable recommendations for improvement.
3. Maintain a formal academic tone and offer high-level feedback appropriate for a peer-reviewed, high-impact journal.
4. Deliver final recommendations (e.g., Accept, Minor Revision, Major Revision, Reject), each justified by the preceding review.

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Version 2

Two Appendices are added to this version, Appendix A and Appendix B.

References

1. Xu, F., Y. Zhao, and K. Li. Using Waste Plastics as Asphalt Modifier: A Review. *Materials*, Vol. 15, No. 1, 2021, p. 110. https://doi.org/10.3390/ma15010110.
2. Hopewell, J., R. Dvorak, and E. Kosior. Plastics Recycling: Challenges and Opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 364, No. 1526, 2009, pp. 2115–2126. https://doi.org/10.1098/rstb.2008.0311.
3. OECD. *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. United Nations OECD, 2022.
4. Li, C.-T., H.-K. Zhuang, L.-T. Hsieh, W.-J. Lee, and M.-C. Tsao. PAH Emission from the Incineration of Three Plastic Wastes. *Environment International*, Vol. 27, No. 1, 2001, pp. 61–67. https://doi.org/10.1016/S0160-4120(01)00056-3.
5. Gu, L., and T. Ozbakkaloglu. Use of Recycled Plastics in Concrete: A Critical Review. *Waste Management*, Vol. 51, 2016, pp. 19–42. https://doi.org/10.1016/j.wasman.2016.03.005.
6. Oehlmann, J., U. Schulte-Oehlmann, W. Kloas, O. Jagnytsch, I. Lutz, K. O. Kusk, L. Wollenberger, E. M. Santos, G. C. Paull, K. J. W. Van Look, and C. R. Tyler. A Critical Analysis of the Biological Impacts of Plasticizers on Wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 364, No. 1526, 2009, pp. 2047–2062. https://doi.org/10.1098/rstb.2008.0242.
7. Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. H. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada. Transport and Release of Chemicals from Plastics to the Environment and to Wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 364, No. 1526, 2009, pp. 2027–2045. https://doi.org/10.1098/rstb.2008.0284.
8. He, P., L. Chen, L. Shao, H. Zhang, and F. Lü. Municipal Solid Waste (MSW) Landfill: A Source of Microplastics? -Evidence of Microplastics in Landfill Leachate. *Water Research*, Vol. 159, 2019, pp. 38–45. https://doi.org/10.1016/j.watres.2019.04.060.
9. Wu, S., and L. Montalvo. Repurposing Waste Plastics into Cleaner Asphalt Pavement Materials: A Critical Literature Review. *Journal of Cleaner Production*, Vol. 280, 2021, p. 124355. https://doi.org/10.1016/j.jclepro.2020.124355.
10. Verma, R., K. S. Vinoda, M. Papireddy, and A. N. S. Gowda. Toxic Pollutants from Plastic Waste- A Review. *Procedia Environmental Sciences*, Vol. 35, 2016, pp. 701–708. https://doi.org/10.1016/j.proenv.2016.07.069.
11. Yin, F., R. Moraes, and A. Anand. *Recycled Plastics in Asphalt Part B: Literature Review*. Greenbelt, MD, 2020.
12. Willis, R., F. Yin, and R. Moraes. *Recycled Plastics in Asphalt Part A: State of the Knowledge.* 2020.
13. Willis, J. R., and F. Yin. "Road-Grade" Recycled Plastics: A Critical Discussion. In *Plastic Waste for Sustainable Asphalt Roads*, Elsevier, pp. 43–59.
14. New End Market Opportunity (NEMO) for Film Project. , 2022.
15. Pouranian, M. R., and M. Shishehbor. Sustainability Assessment of Green Asphalt Mixtures: A Review. *Environments - MDPI*, Vol. 6, No. 6, 2019. https://doi.org/10.3390/environments6060073.

16. Zhou, F., S. Hu, G. Das, R. Lee, T. Scullion, and G. Claros. Successful High RAP Mixes Designed with Balanced Rutting and Cracking Requirements. *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*, Vol. 81, 2012, pp. 477–505.
17. West, R. C. Best Practices for RAP and RAS Management - NAPA, Quality Improvement Series 129. *National Asphalt Pavement Association (NAPA)*, 2015, pp. 1–44.
18. Picado-Santos, L. G., S. D. Capitão, and J. M. C. Neves. Crumb Rubber Asphalt Mixtures: A Literature Review. *Construction and Building Materials*, Vol. 247, 2020, p. 118577. https://doi.org/10.1016/j.conbuildmat.2020.118577.
19. Zhang, F., and C. Hu. The Research for Crumb Rubber/Waste Plastic Compound Modified Asphalt. *Journal of Thermal Analysis and Calorimetry*, Vol. 124, No. 2, 2016, pp. 729–741. https://doi.org/10.1007/s10973-015-5198-4.
20. Piao, Z., M. Bueno, L. D. Poulikakos, and S. Hellweg. Life Cycle Assessment of Rubberized Semi-Dense Asphalt Pavements; A Hybrid Comparative Approach. *Resources, Conservation and Recycling*, Vol. 176, 2022, p. 105950. https://doi.org/10.1016/j.resconrec.2021.105950.
21. Costa, L. M. B., H. M. R. D. Silva, J. Peralta, and J. R. M. Oliveira. Using Waste Polymers as a Reliable Alternative for Asphalt Binder Modification – Performance and Morphological Assessment. *Construction and Building Materials*, Vol. 198, 2019, pp. 237–244. https://doi.org/10.1016/j.conbuildmat.2018.11.279.
22. Haji Seyed Javadi, N., A. Hajimohammadi, S. Heydari, J. J. Kien Chung Ng, J. E. Kypreos, and N. Khalili. Investigating the Applicability of Storage Stability Test for Waste Plastic Modified Bitumen: Morphological Analyses. *Construction and Building Materials*, Vol. 441, 2024, p. 137451. https://doi.org/10.1016/j.conbuildmat.2024.137451.
23. Yu, S., J. A. Musazay, C. Zhang, P. Hu, and S. Shen. Workability of Low-Density Polyethylene Modified Asphalt Mixtures: A Statistical Analysis of Particle Kinematics. *Journal of Cleaner Production*, Vol. 447, 2024, p. 141564. https://doi.org/10.1016/j.jclepro.2024.141564.
24. Tarsi, G., P. Tataranni, and C. Sangiorgi. The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials*, Vol. 13, No. 18, 2020, p. 4052. https://doi.org/10.3390/ma13184052.
25. Hicks, R. G., J. R. Lundy, R. B. Leahy, D. Hanson, and J. Epps. *CRUMB RUBBER MODIFIER (CRM) IN ASPHALT PAVEMENTS: SUMMARY OF PRACTICES IN ARIZONA, CALIFORNIA, AND FLORIDA*. Publication FHWA-SA-95-056. Oregon State University, Oregon, 1995, p. 120.
26. Boom, Y. J., M. Enfrin, S. Grist, and F. Giustozzi. Recycled Plastic Modified Bitumen: Evaluation of VOCs and PAHs from Laboratory Generated Fumes. *Science of The Total Environment*, Vol. 832, 2022, p. 155037. https://doi.org/10.1016/j.scitotenv.2022.155037.
27. Duan, Y., K. Wu, C. Serrat, F. Arteaga-Larios, H. Brown, C. J. DuBois, W. G. Buttlar, and B. Deng. Assessment of Microplastics Production from Waste Plastics-Modified Asphalt Pavement. *Resources, Conservation and Recycling*, Vol. 202, 2024, p. 107329. https://doi.org/10.1016/j.resconrec.2023.107329.
28. Enfrin, M., R. Myszka, and F. Giustozzi. Paving Roads with Recycled Plastics: Microplastic Pollution or Eco-Friendly Solution? *Journal of Hazardous Materials*, Vol. 437, 2022, p. 129334. https://doi.org/10.1016/j.jhazmat.2022.129334.

29. Sharma, S., S. Basu, N. P. Shetti, M. N. Nadagouda, and T. M. Aminabhavi. Microplastics in the Environment: Occurrence, Perils, and Eradication. *Chemical Engineering Journal*, Vol. 408, 2021, p. 127317. https://doi.org/10.1016/j.cej.2020.127317.
30. Monira, S., M. A. Bhuiyan, N. Haque, and B. K. Pramanik. Road Dust-Associated Microplastics from Vehicle Traffics and Weathering. In *Plastic Waste for Sustainable Asphalt Roads*, Elsevier, pp. 257–271.
31. Su, L., B. Nan, N. J. Craig, and V. Pettigrove. Temporal and Spatial Variations of Microplastics in Roadside Dust from Rural and Urban Victoria, Australia: Implications for Diffuse Pollution. *Chemosphere*, Vol. 252, 2020, p. 126567. https://doi.org/10.1016/j.chemosphere.2020.126567.
32. Patchaiyappan, A., K. Dowarah, S. Zaki Ahmed, M. Prabakaran, S. Jayakumar, C. Thirunavukkarasu, and S. P. Devipriya. Prevalence and Characteristics of Microplastics Present in the Street Dust Collected from Chennai Metropolitan City, India. *Chemosphere*, Vol. 269, 2021, p. 128757. https://doi.org/10.1016/j.chemosphere.2020.128757.
33. Abbasi, S., B. Keshavarzi, F. Moore, A. Turner, F. J. Kelly, A. O. Dominguez, and N. Jaafarzadeh. Distribution and Potential Health Impacts of Microplastics and Microrubbers in Air and Street Dusts from Asaluyeh County, Iran. *Environmental Pollution*, Vol. 244, 2019, pp. 153–164. https://doi.org/10.1016/j.envpol.2018.10.039.
34. Yukioka, S., S. Tanaka, Y. Nabetani, Y. Suzuki, T. Ushijima, S. Fujii, H. Takada, Q. Van Tran, and S. Singh. Occurrence and Characteristics of Microplastics in Surface Road Dust in Kusatsu (Japan), Da Nang (Vietnam), and Kathmandu (Nepal). *Environmental Pollution*, Vol. 256, 2020, p. 113447. https://doi.org/10.1016/j.envpol.2019.113447.
35. Ghasemirad, A., N. Bala, and L. Hashemian. High-Temperature Performance Evaluation of Asphaltenes-Modified Asphalt Binders. *Molecules*, Vol. 25, No. 15, 2020, p. 3326. https://doi.org/10.3390/molecules25153326.
36. Huang, G., Z. Chen, J. Zhang, Z. Hu, and A. C. Falchetto. Investigation of SARA Fractions Transformations and Molecular Weight Distribution During Adhesion of Crumb Rubber Modified Asphalt Binder and Aggregates. In *Proceedings of the 10th International Conference on Maintenance and Rehabilitation of Pavements* (P. Pereira and J. Pais, eds.), Springer Nature Switzerland, Cham, pp. 329–338.
37. Jiang, J., F. Lu, X. Guo, P. Hao, W. Wang, and J. Yu. Effect of SARA Fractions on Fatigue Properties of Hard Asphalt. *Materials*, Vol. 17, No. 11, 2024, p. 2713. https://doi.org/10.3390/ma17112713.
38. Debraj, D., and M. Lavanya. Microplastics Everywhere: A Review on Existing Methods of Extraction. *Science of The Total Environment*, Vol. 893, 2023, p. 164878. https://doi.org/10.1016/j.scitotenv.2023.164878.
39. Ziani, K., C.-B. Ioniță-Mîndrican, M. Mititelu, S. M. Neacșu, C. Negrei, E. Moroșan, D. Drăgănescu, and O.-T. Preda. Microplastics: A Real Global Threat for Environment and Food Safety: A State of the Art Review. *Nutrients*, Vol. 15, No. 3, 2023, p. 617. https://doi.org/10.3390/nu15030617.
40. Brožová, K., J. Halfar, K. Čabanová, O. Motyka, S. Drabinová, P. Hanus, and S. Heviánková. The First Evidence of Microplastic Occurrence in Mine Water: The Largest Black Coal Mining Area in the Czech Republic. *Water Research*, Vol. 244, 2023, p. 120538. https://doi.org/10.1016/j.watres.2023.120538.

41. Tajwar, M., S. S. Shreya, M. Hasan, Md. B. Hossain, Md. Y. Gazi, and N. Sakib. Assessment of Microplastics as Contaminants in a Coal Mining Region. *Heliyon*, Vol. 8, No. 11, 2022, p. e11666. https://doi.org/10.1016/j.heliyon.2022.e11666.

APPENDIX A

The following images (Appendix A) were extracted from data reports provided by the Environmental Contaminants Analytical Laboratory (ECAL) and/or the Energy and Environmental Sustainability Laboratories (EESL) at Penn State's Institute of Energy and the Environment. I have made minor edits to adjust size, improve relevance and arrangement, or to add images of the actual materials on the spectral figures for ease of visualization.

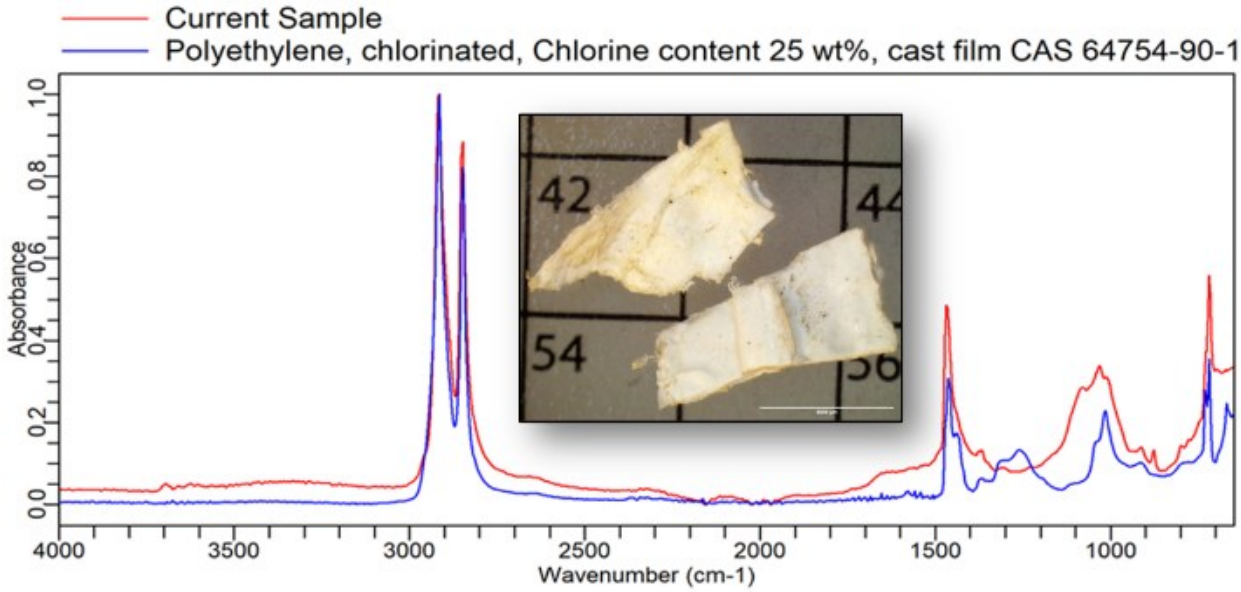

Figure A1: IR results and an image of a sample of the LDPE used for this study (Match Quality=0.87309) (ECAL)/(EESL)

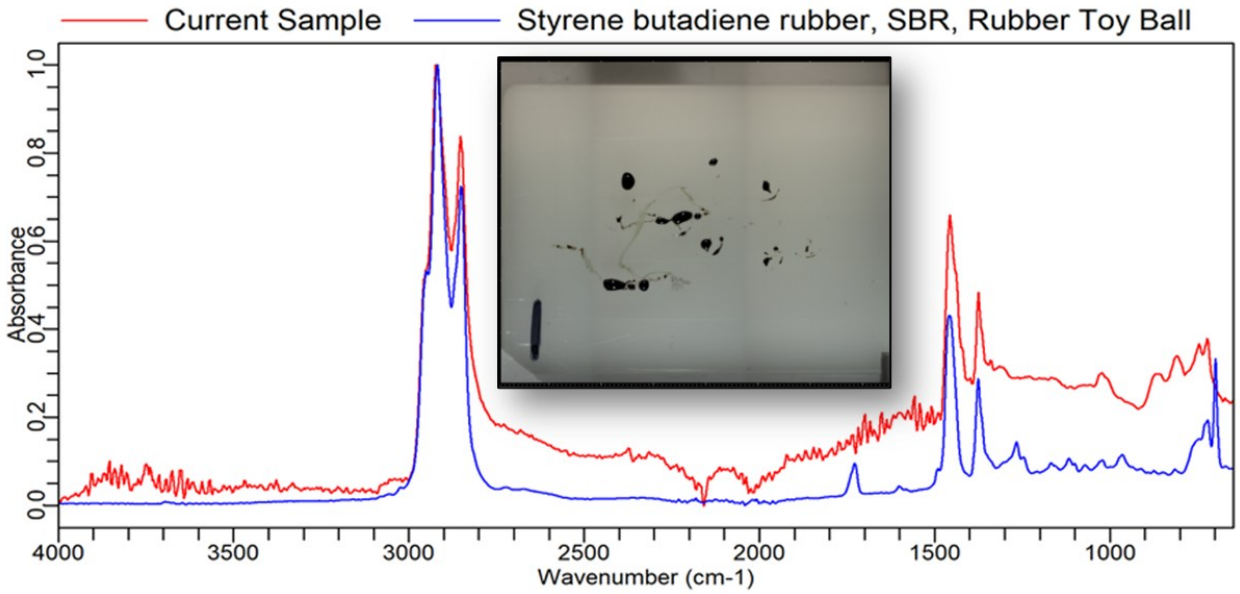

Figure A2: IR results and an image of a sample of the PG64-22 (Match Quality=0.81565) (ECAL)/(EESL)

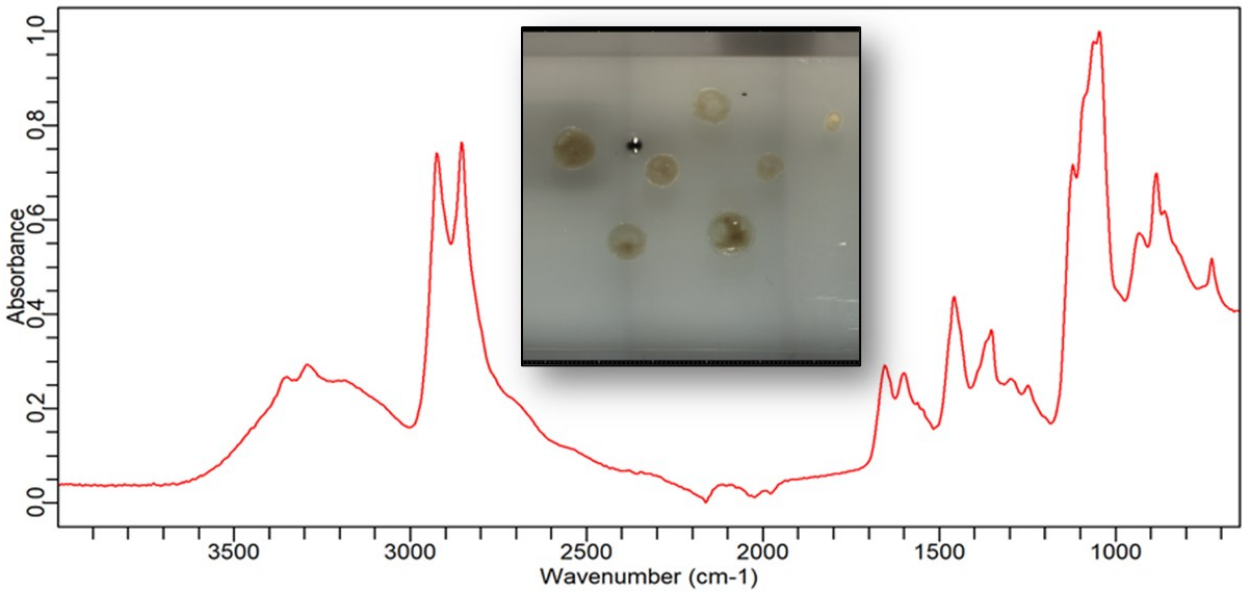

Figure A3: IR results and an image of a sample of the anti-stripping agent (Match Quality=could not match with its library) (ECAL)/(EESL)

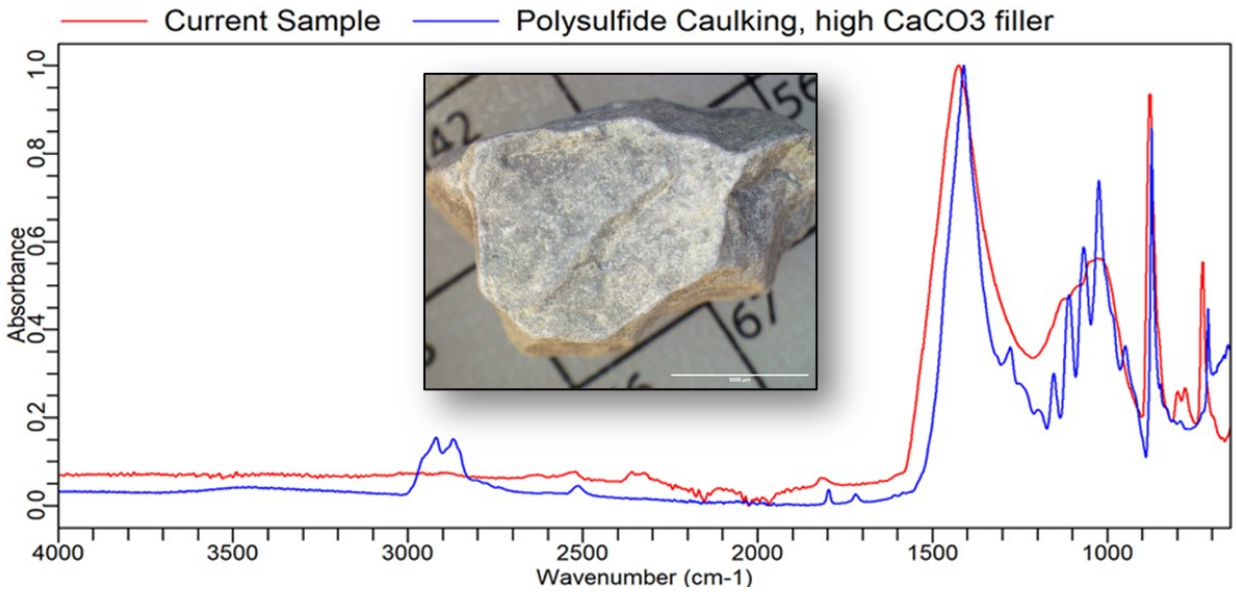

Figure A4: IR results and an image of a sample of 9.5 mm aggregate (Match Quality=0.85304) (ECAL)/(EESL)

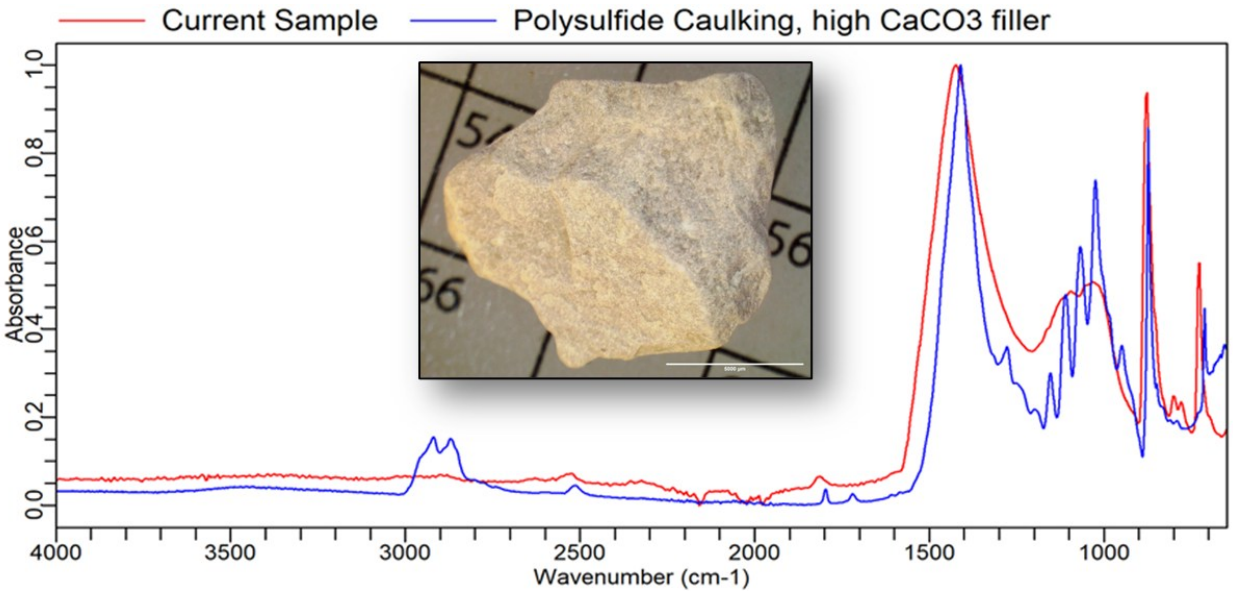

Figure A5: IR results and an image of a sample of 4.75 mm aggregate (Match Quality=0.83935) (ECAL)/(EESL)

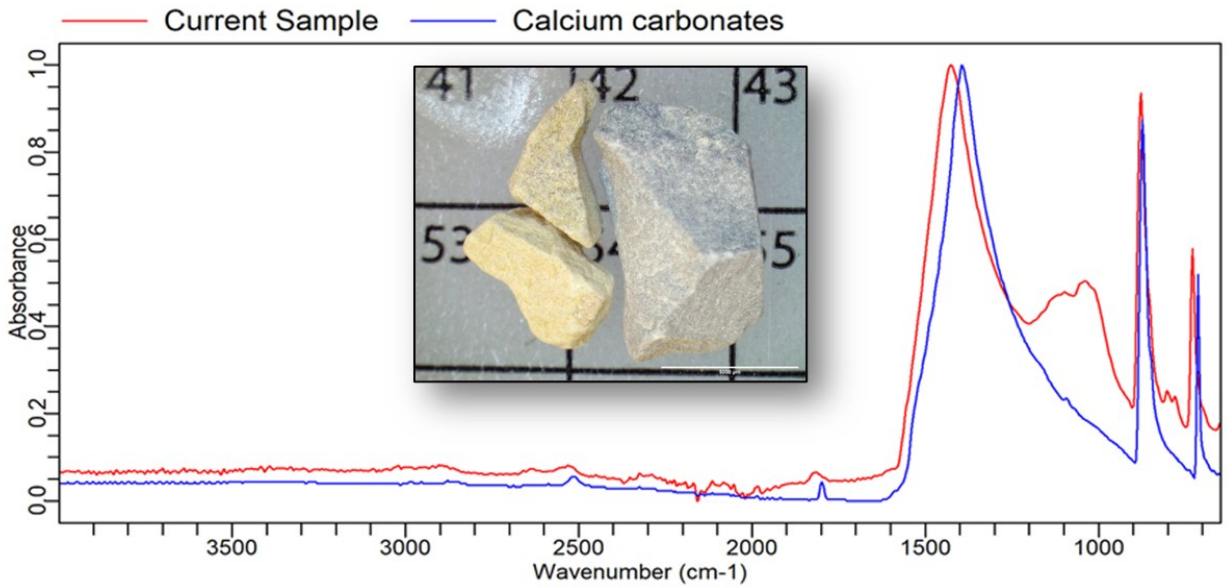

Figure A6: IR results and image of samples of 2.36 mm aggregates (Match Quality=0.84943) (ECAL)/(EESL)

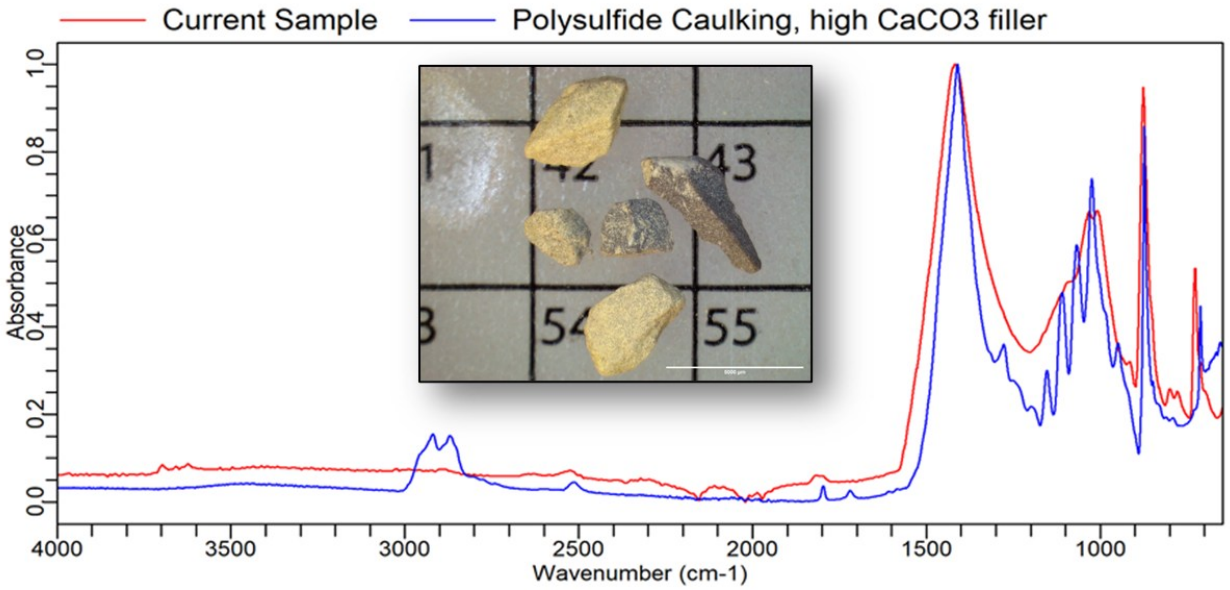

Figure A7: IR results and image of sample of 1.18 mm aggregates (Match Quality=0.90011) (ECAL)/(EESL)

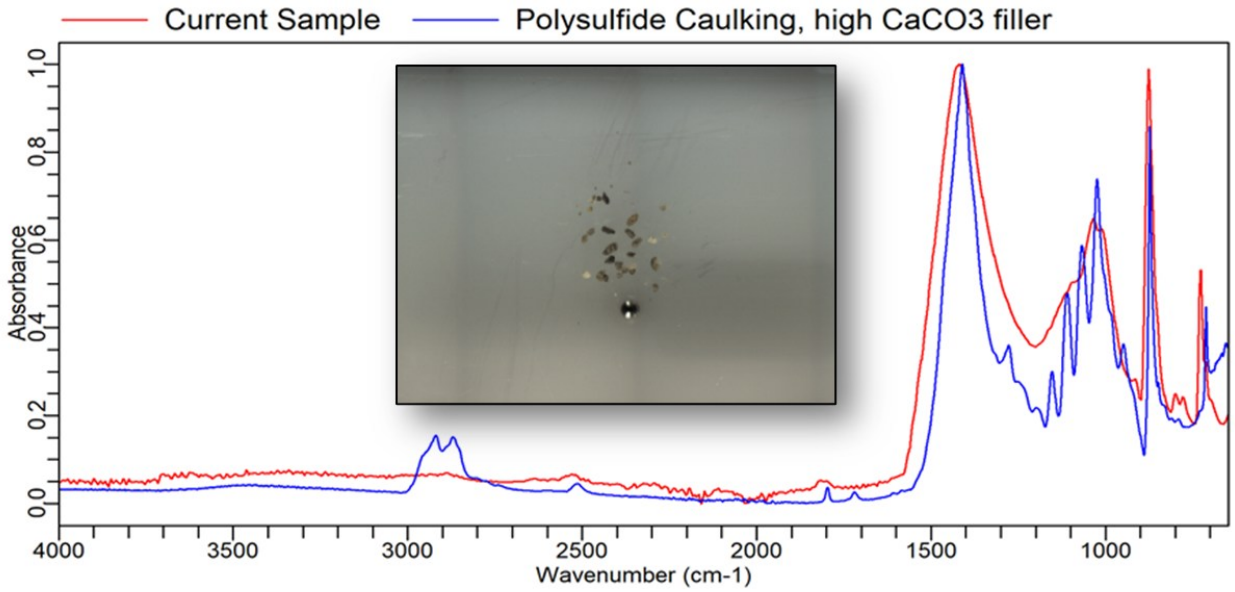

Figure A8: IR results and image samples of 0.6 mm aggregates (Match Quality=0.88151) (ECAL)/(EESL)

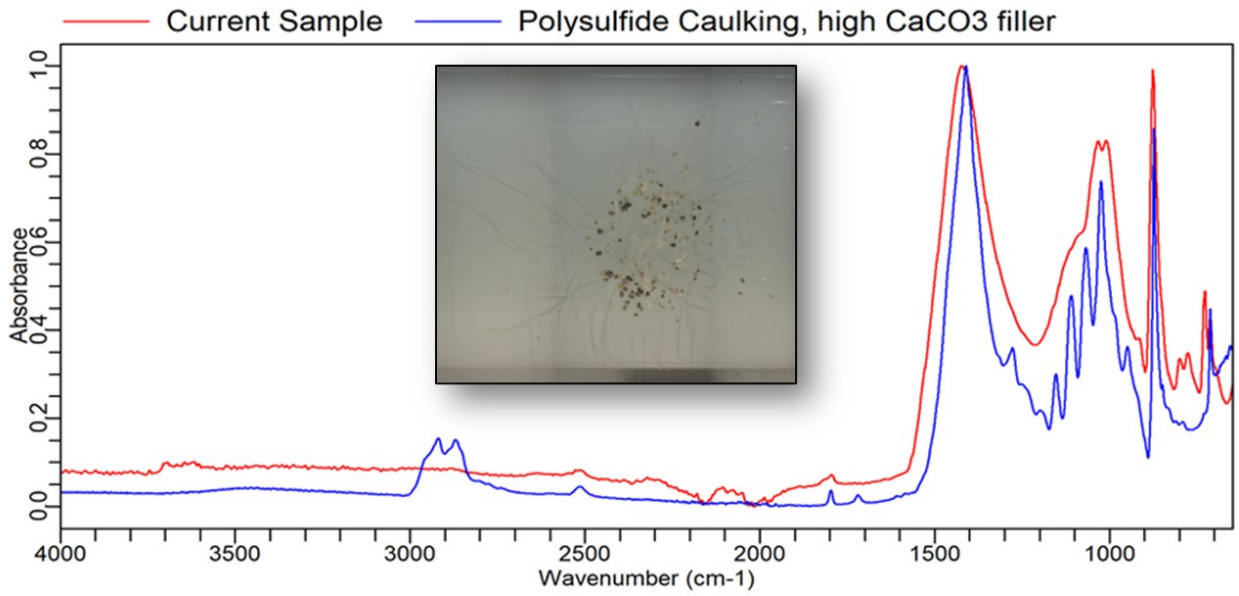

Figure A9: IR results and an image of samples of 0.3 mm aggregates (Match Quality=0.90312) (ECAL)/(EESL)

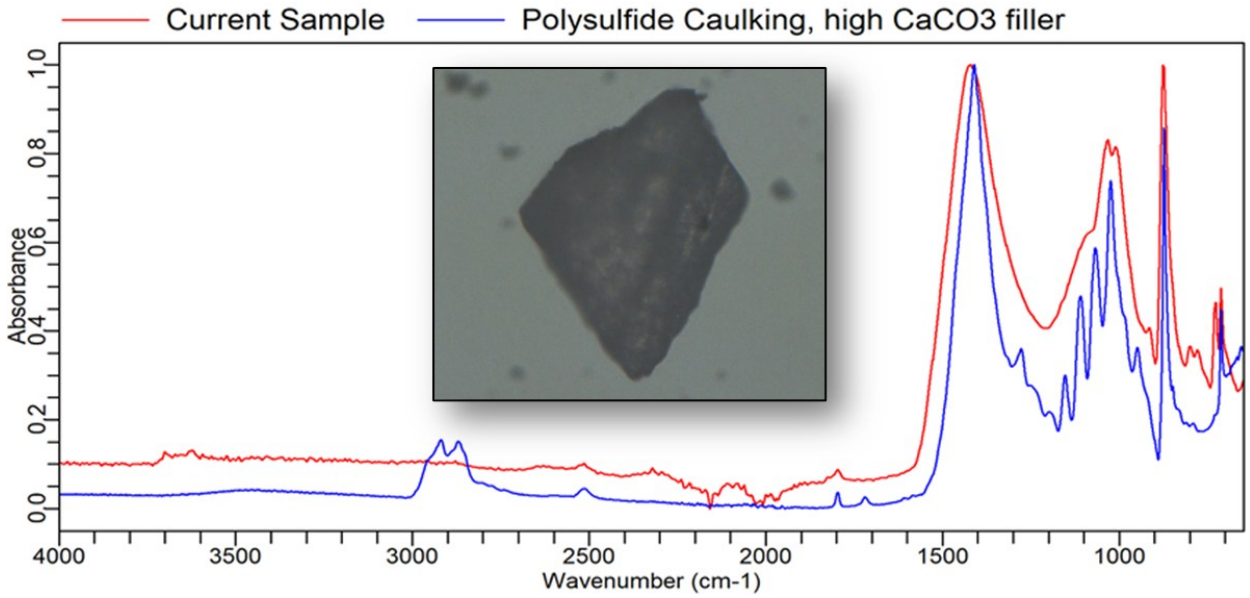

Figure A10: IR results and an image of sample of a magnified 0.15 mm aggregates (Match Quality=0.90297) (ECAL)/(EESL)

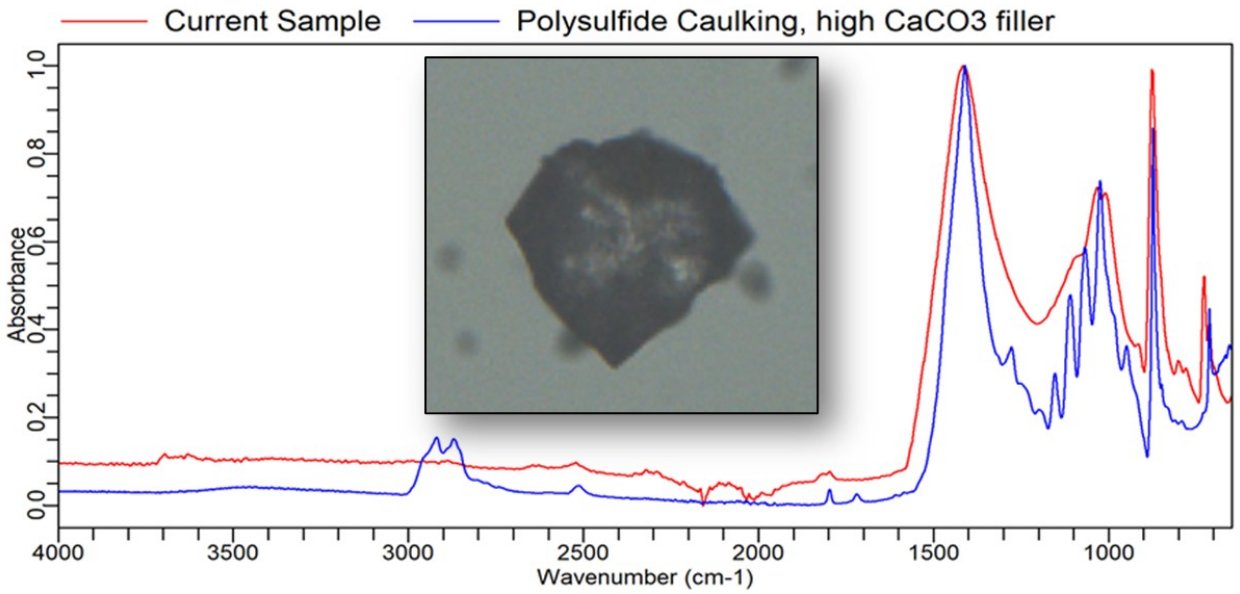

Figure A11: IR results and an image of sample of a magnified 0.075 mm aggregates (Match Quality=0.89798) (ECAL)/(EESL)

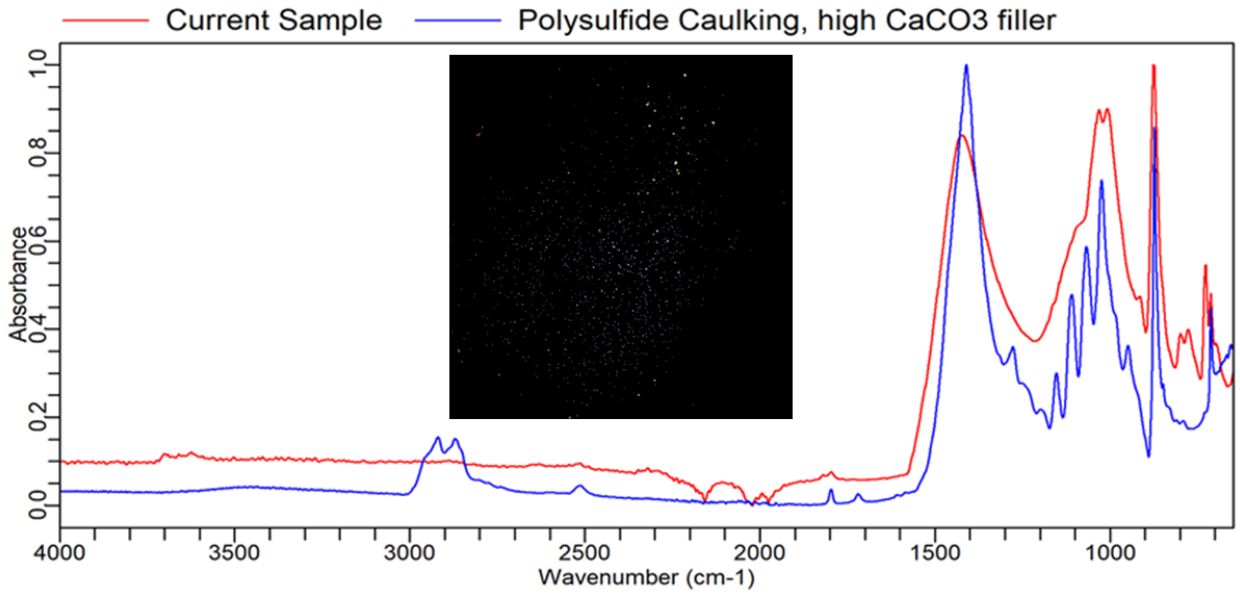

Figure A12: IR results and image of sample aggregates smaller than 0.075 mm (pan materials) (Match Quality=0.86638) (ECAL)/(EESL)

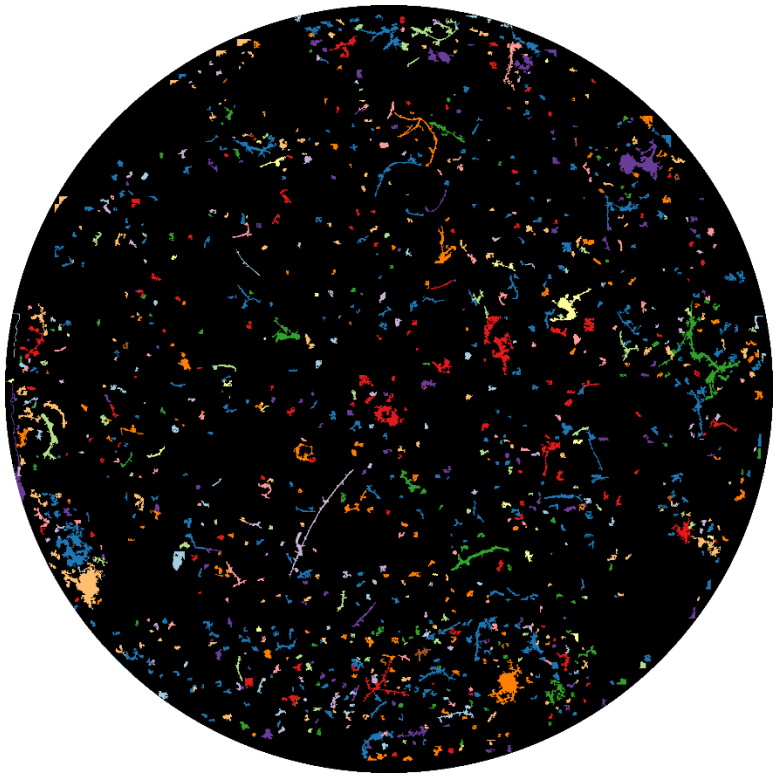

Figure A13: A false image of the particles identified for the 0%LDPE-1 samples (ECAL)/(EESL)

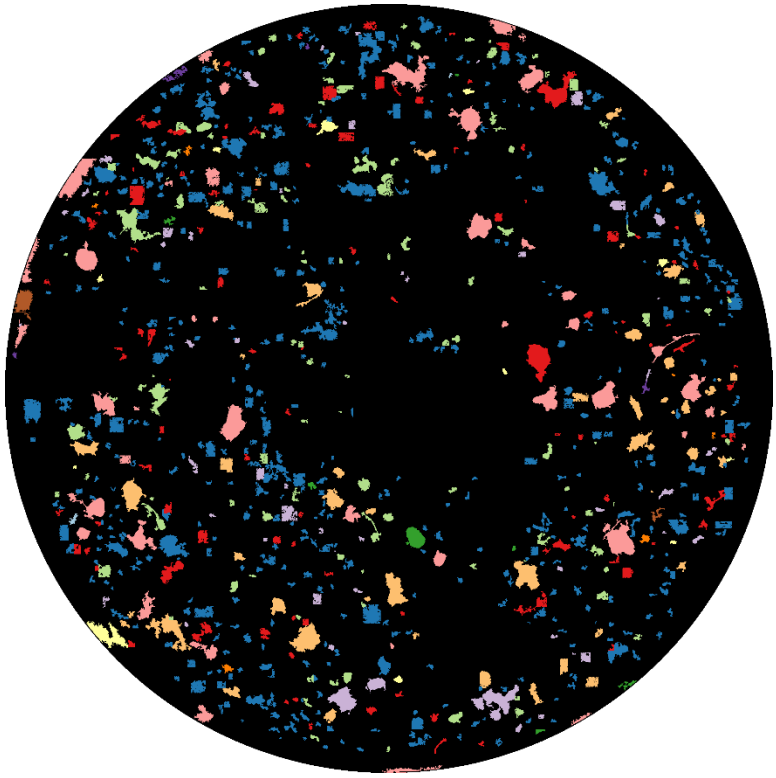

Figure A14(a): A false image of the particles identified for the 0%LDPE-2 samples (#1) (ECAL)/(EESL)

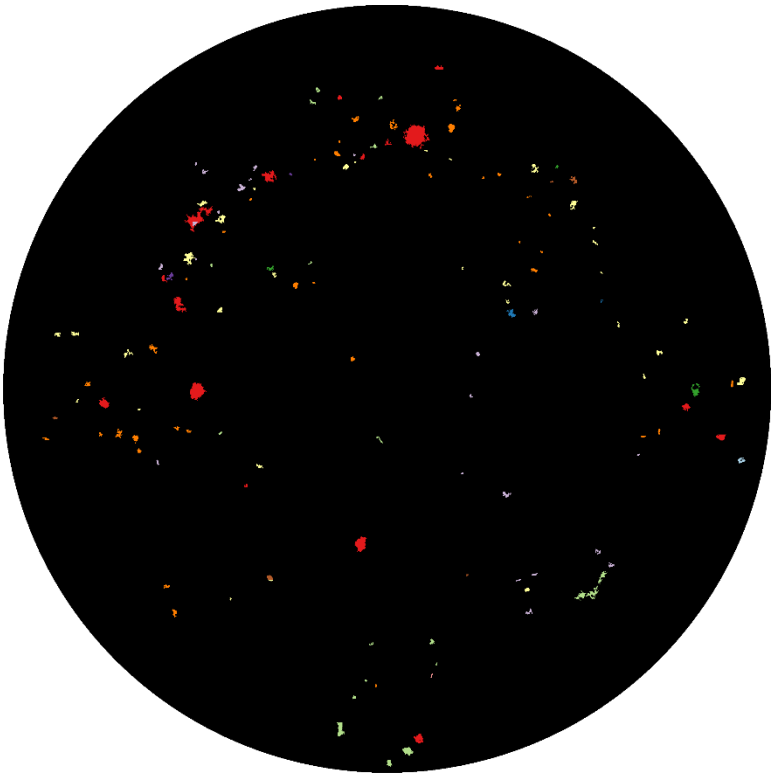

Figure A14(b): A false image of the particles identified for the 0%LDPE-2 samples (#2) (ECAL)/(EESL)

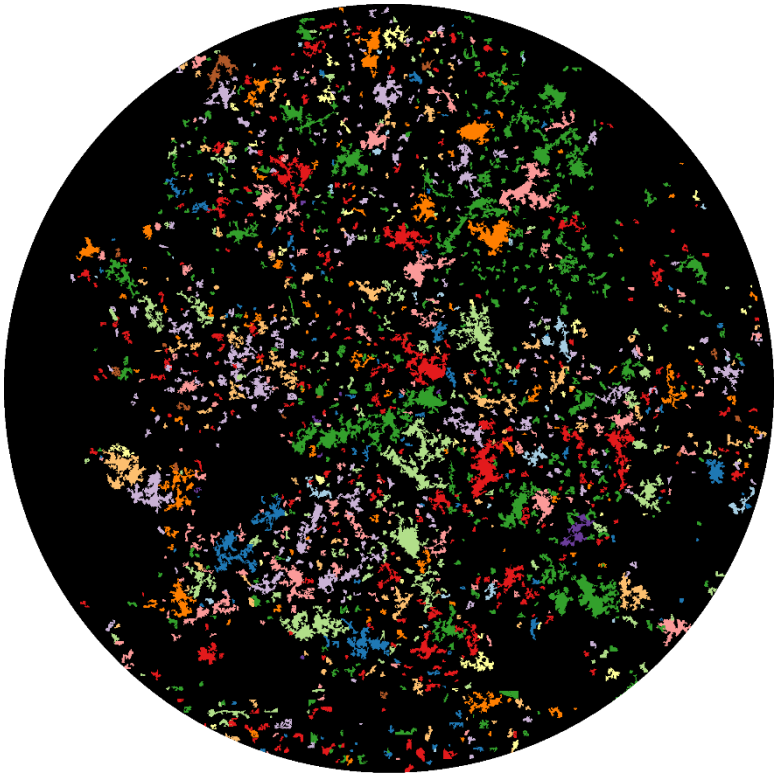

Figure A15(a): A false image of the particles identified for the 0%LDPE-3 samples (#1) (ECAL)/(EESL)

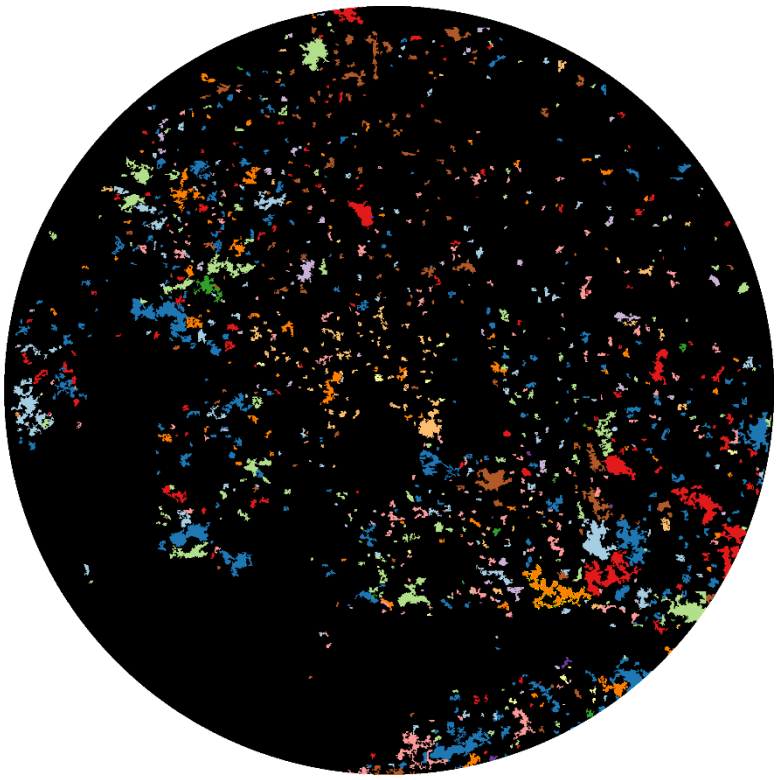

Figure A15(b): A false image of the particles identified for the 0%LDPE-3 samples (#2) (ECAL)/(EESL)

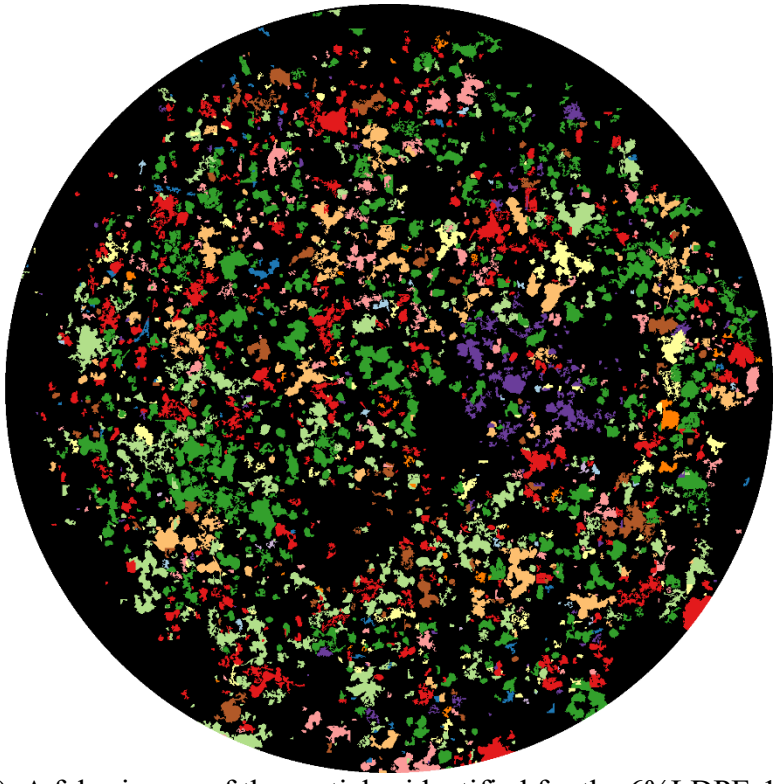

Figure A16(a): A false image of the particles identified for the 6%LDPE-1 samples (#1) (ECAL)/(EESL)

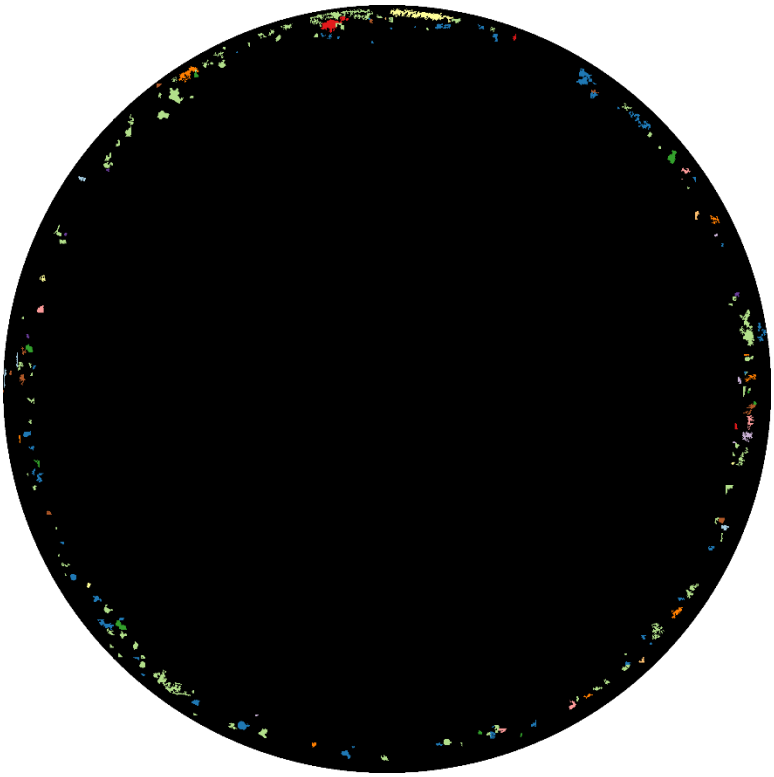

Figure A16(b): A false image of the particles identified for the 6%LDPE-1 samples (#2) (ECAL)/(EESL)

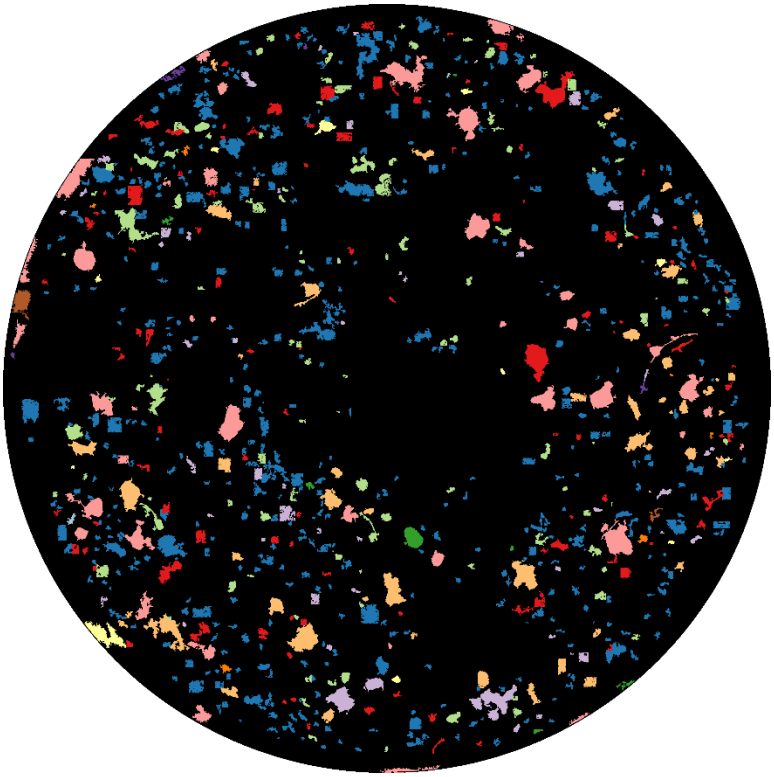

Figure A17(a): A false image of the particles identified for the 6%LDPE-2 samples (#1) (ECAL)/(EESL)

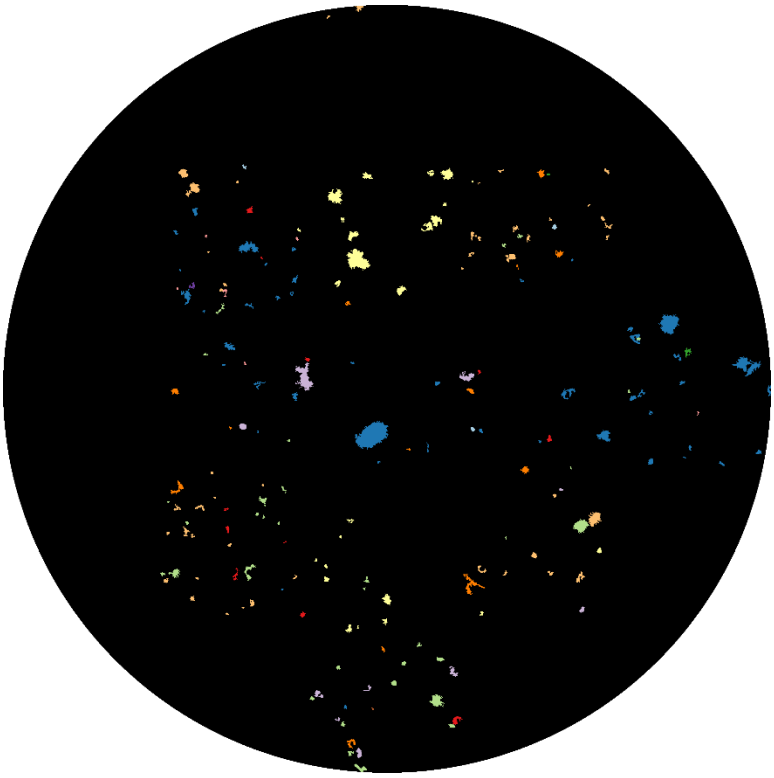

Figure A17(b): A false image of the particles identified for the 6%LDPE-2 samples (#2) (ECAL)/(EESL)

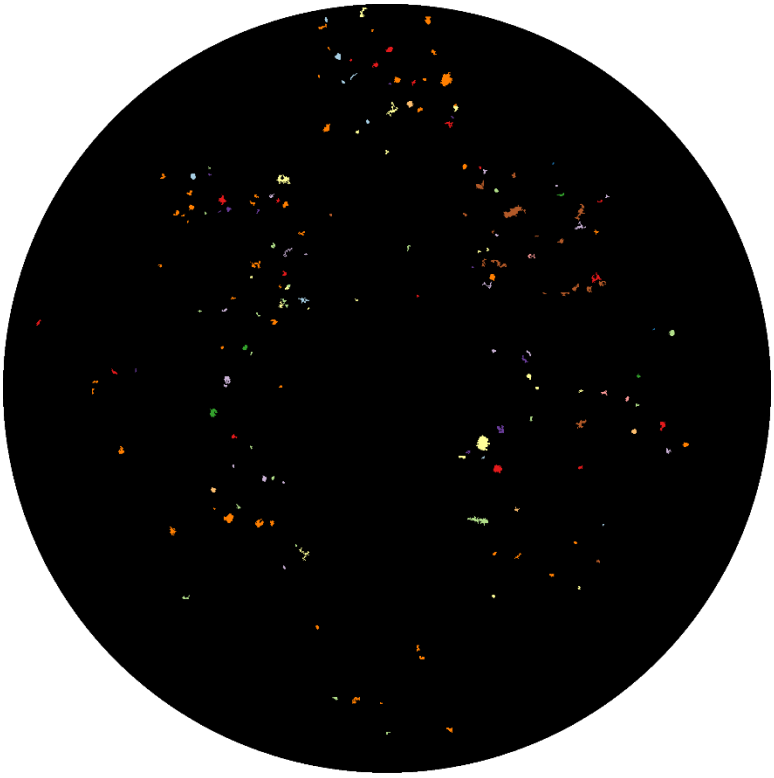

Figure A17(c): A false image of the particles identified for the 6%LDPE-2 samples (#3) (ECAL)/(EESL)

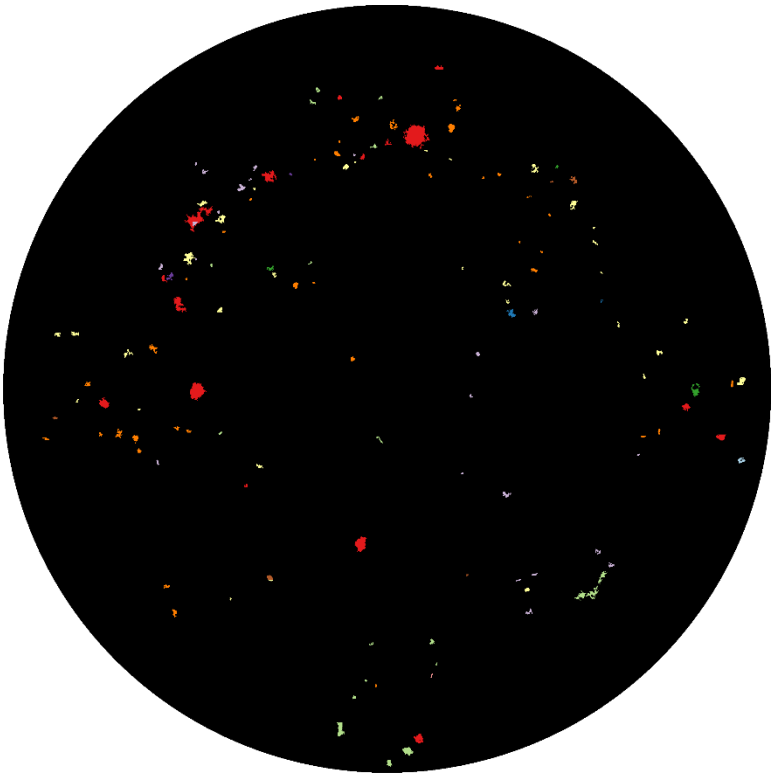

Figure A17(d): A false image of the particles identified for the 6%LDPE-2 samples (#4) (ECAL)/(EESL)

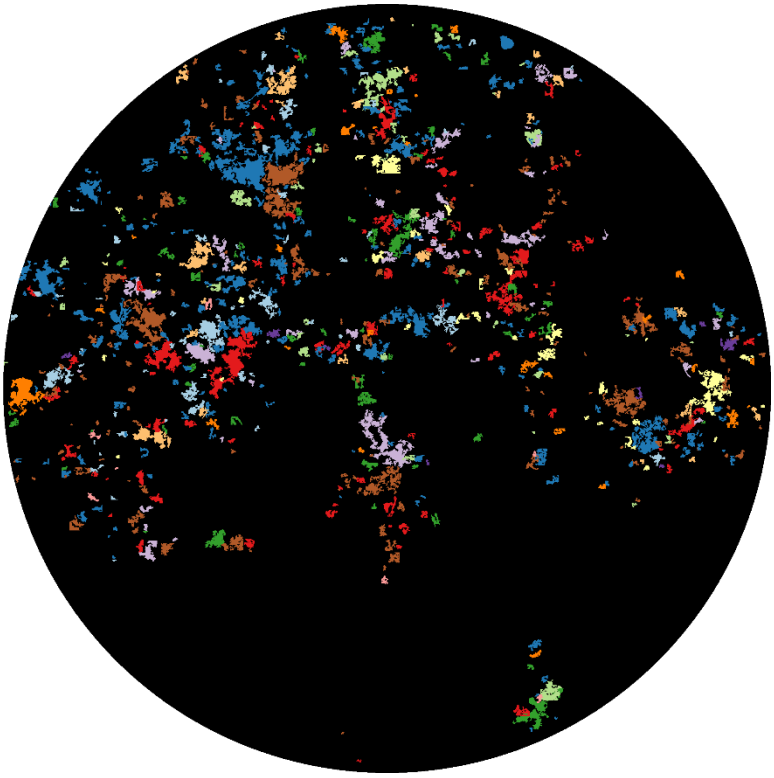

Figure A18: A false image of the particles identified for the 6%LDPE-3 samples (ECAL)/(EESL)

APPENDIX B

Table 1 in the report shows the percentage of particles count (PPC) and average identification quality for PE and CPE in the raw materials characterized by LDIR. The PPC and a quality distribution for the rest of the particles detected in the sample of raw materials are presented in this Appendix.

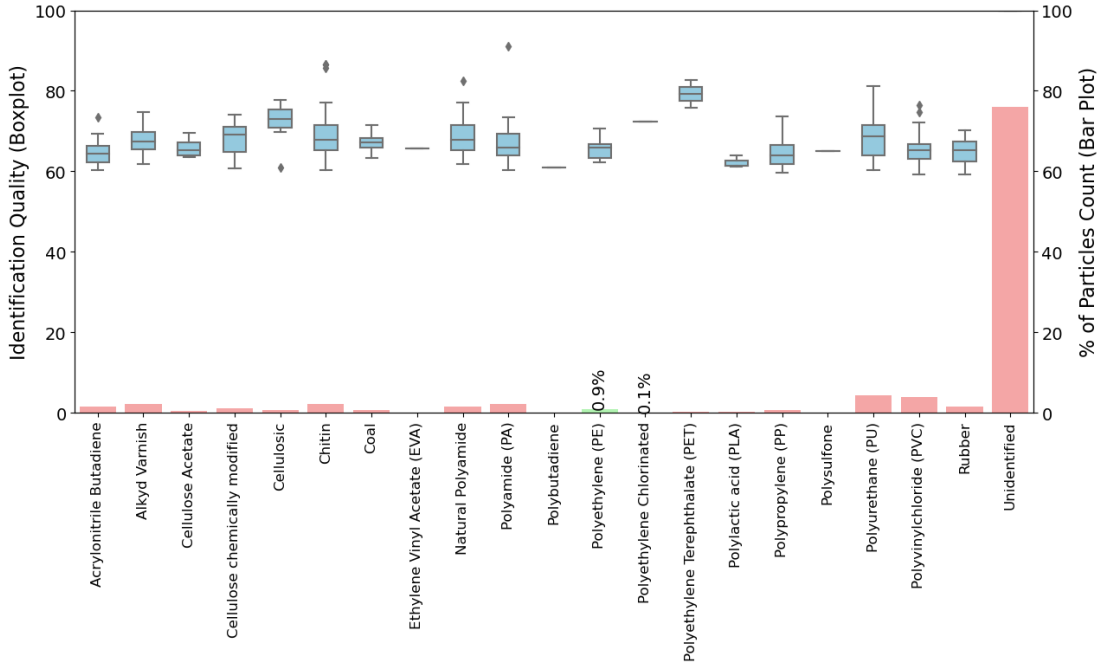

Figure B1: Distribution and chemical composition of a sample of the pan dust using LDIR

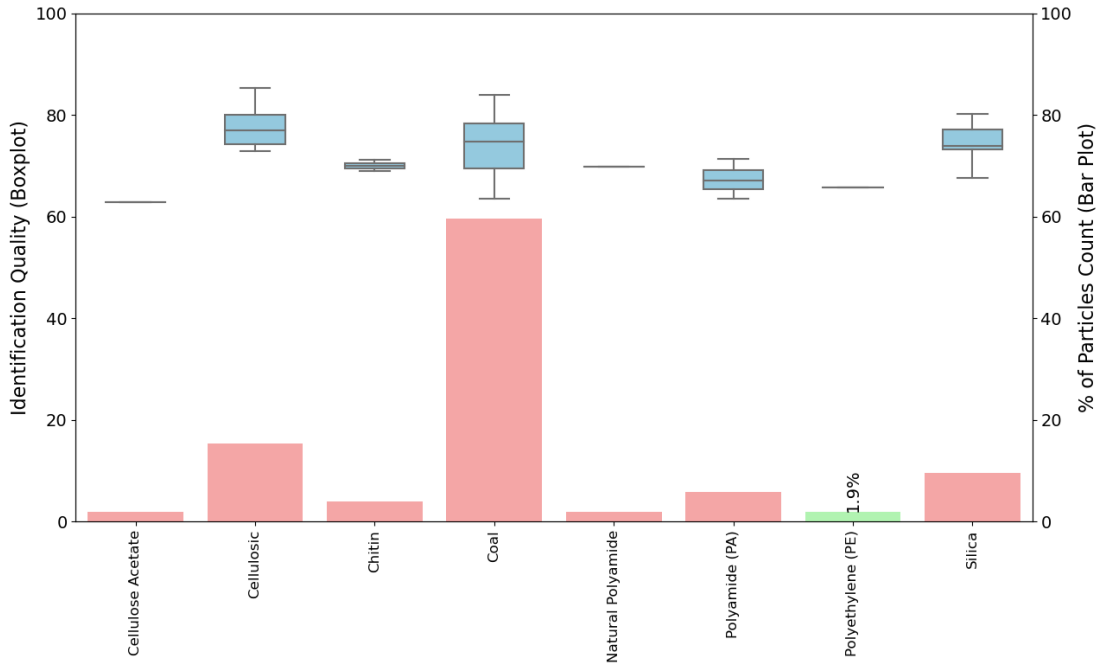

Figure B2: Distribution and chemical composition of a sample of the 0.075 mm aggregates using LDIR

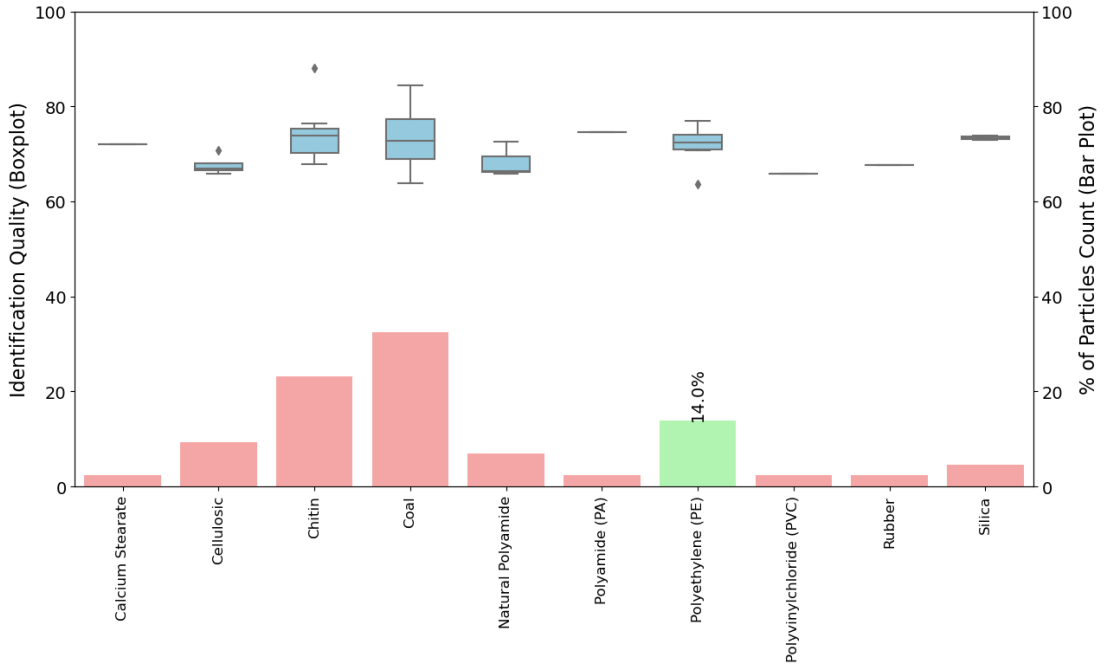

Figure B3: Distribution and chemical composition of a sample of the 0.15 mm aggregates using LDIR

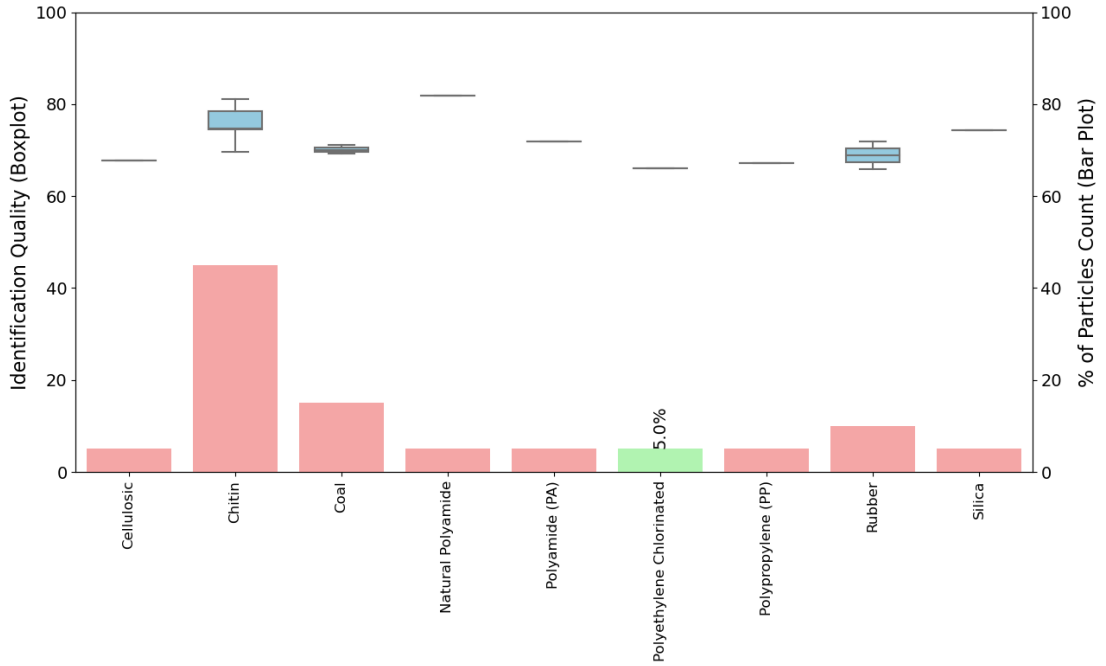

Figure B4: Distribution and chemical composition of a sample of the 0.3 mm aggregates using LDIR

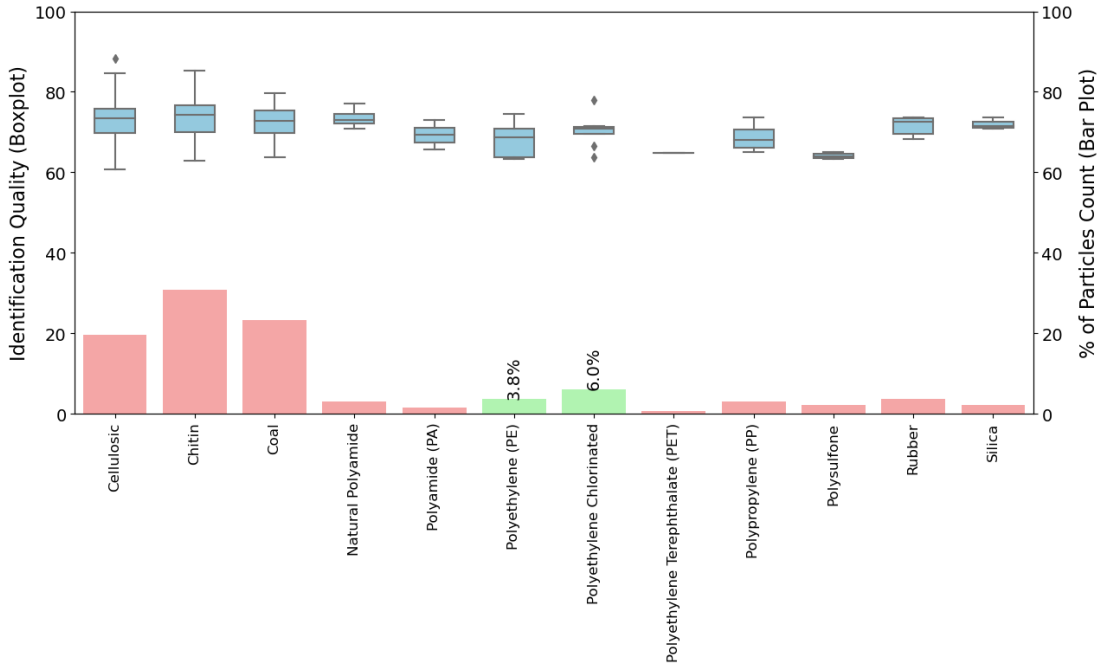

Figure B5: Distribution and chemical composition of a sample of the 0.6 mm aggregates using LDIR

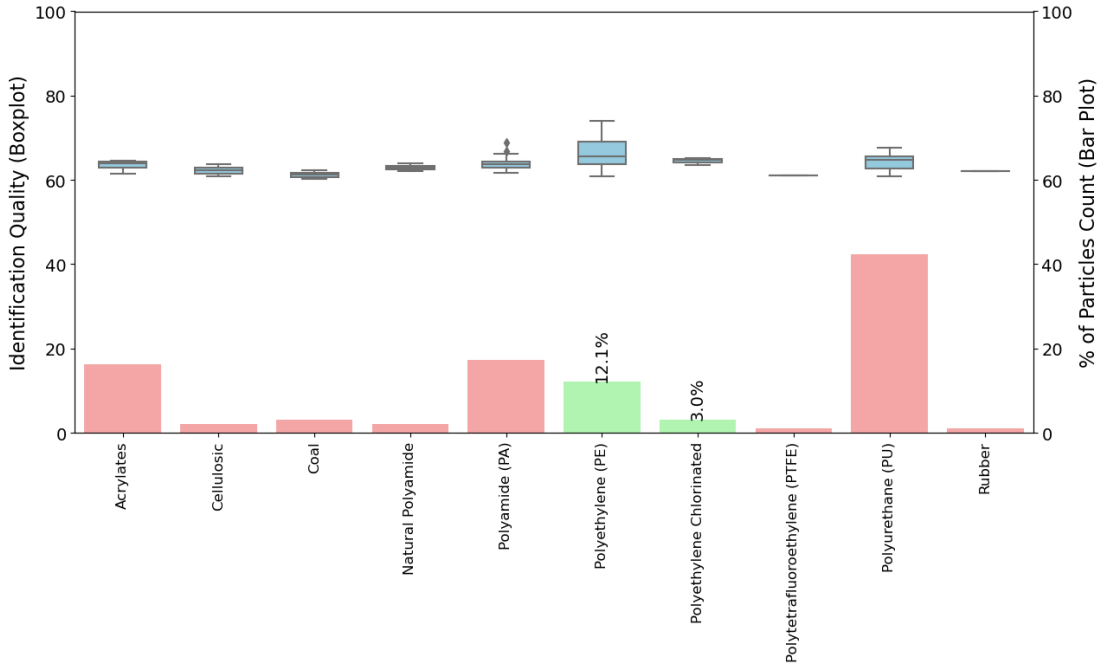

Figure B6: Distribution and chemical composition of a sample of the anti-stripping agent

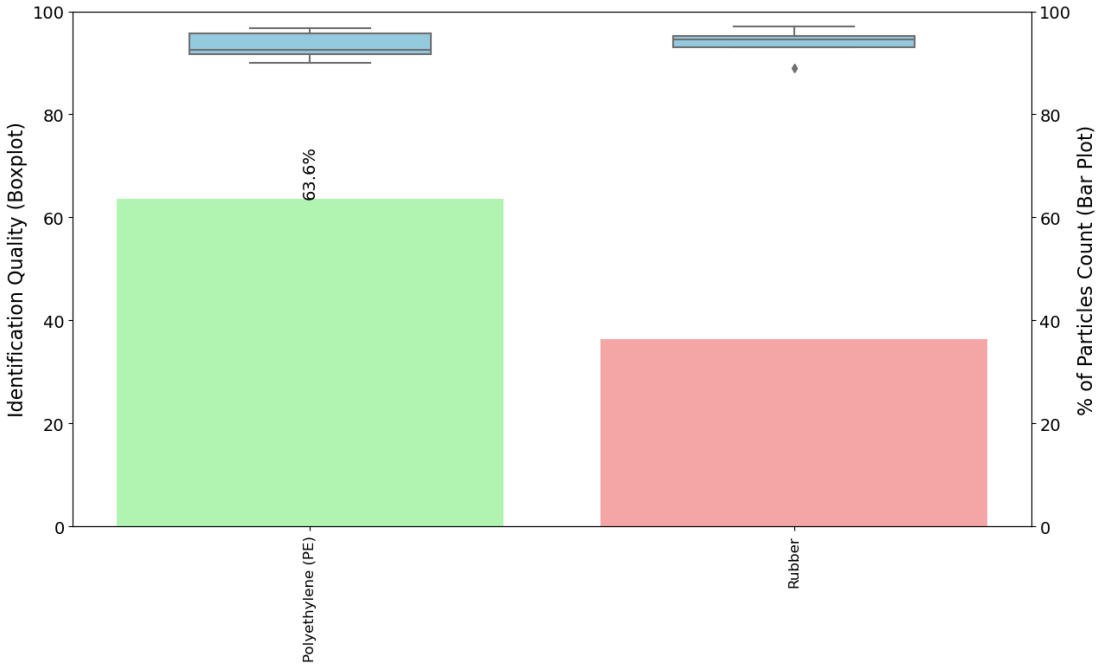

Figure B7: Distribution and chemical composition of a sample PG64-22