

MICROPLASTIC RISK CHARACTERIZATION OF PLASTIC ROAD

by

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## **ABSTRACT**

### **MICROPLASTIC RISK CHARACTERIZATION OF PLASTIC ROAD**

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In recent past, the act of waste recycling has been diversified in manifolds across the world leading to evolution of newer recycling technique and fresh recycled product. Albeit plastic is one of those waste materials which is getting extremely difficult to get substantially recycled because of its record-breaking production, consumption, and its wide range of variations in properties ultimately leading to substandard recycling status of plastics globally. This seemingly poor status of waste plastics recycling against the gargantuan amount of fresh plastic products being added to consumer stream gives rise to a menacing one directional problem: Plastic Pollution, which is getting worse day by day. Having said that, designing a viable way for repurposing large scale plastic wastes instead of traditional recycling could divert that one directional problem to a more prosperous circular economy. One such way to repurpose large scale waste plastics is construction of an integrated plastic road incorporating shredded waste plastics in multiple layers of a flexible pavement.

Concept of integrated plastic road would not only ensure macroscale use of plastic waste but also refrain the plastics being accumulated in the landfills eventually minimizing the worldwide waste plastics crisis.

For this study, different types of plastics (HDPE, LDPE, PP, PET) have been incorporated with other recyclable components like Recycled Crushed Concrete Aggregate (RCCA) and regular pavement material like bitumen for base and surface course of a flexible pavement. However, introduction of plastics as a roadway material gives rise to the potential environmental hazard, and most importantly microplastic risk which itself is an emerging global concern. This study aims at identifying, quantifying, and characterizing microplastic risk associated with a plastic road from an ecotoxicological point of view. Moreover, a number of common environmental leaching tests (COD, TDS, TSS, Specific Conductance) have also been carried out and compared against the USEPA urban stormwater runoff benchmarks. Microplastic risk has been assessed with respect to the toxicity parameter called Predicted No Observed Effect Concentration (PNEC). PNEC is the maximum allowable microplastic concentration that could be tolerated by microorganisms without having any adverse physiological impacts. Microplastic concentration has been quantified using an optical microscope and qualified by using Fourier Transform Infra-Red (FTIR) spectroscopy to corroborate the presence of microplastic in experimented sample. Measured concentration was then divided by PNEC to get the Risk Characterization Ratio (RCR). If RCR value is less than 1, the corresponding microplastic concentration does not pose any threat to the ecological system. RCR values have been measured for two different weathering cases of base course and surface course of a plastic road.

For case I, where base course cylindrical representative specimens are kept submerged in contained water for 28 days to collect the leaching sample, average RCR has been observed as 0.103 which is significantly lower than 1. In case I, samples incorporating PP plastic type exhibit relatively more RCR values ranging from 0.063 to 0.253. Case II also represent base course yet a different weathering condition where the cylindrical specimens were subject to cyclic loading before 28 days water submergence. This case resembles the long term microplastic risk characteristics. For this case, average RCR obtained is 0.735 which is higher that of case I, yet lower than the RCR threshold 1. In this case, however one incidence attributes to a RCR more than 1 involving PP type of plastic. The final case is representative of surface course incorporating shredded plastics. Leaching samples for this case are collected from submerged cylindrical specimen exerted by repetitive wheel passing in a Hamburg rutting test setup. For this case, average RCR observed is 0.186 which is the lowest of all three cases. Regardless of the case, weathering condition, plastic type, constituent percentage, this study shows that RCR value remains less than 1 implying that plastic road does not pose any ecological threat in terms of microplastic toxicity. And finally, this study also envisages Multiple linear Regression (MLR) models for both base and surface course to predict the RCR value based on primary constituent parameters and resulting predictor variables.

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## Chapter 1

### **INTRODUCTION**

#### **1.1 Background**

In consonance with the worldwide population growth, not only the amount of waste being generated has been on the rise, but also the type of waste has been diversified. Many of the wastes produced today will remain in the environment for thousands, if not hundreds of years. The creation, and subsequent consumption of nondecaying waste materials, combined with a growing population, has resulted in an ever-increasing waste disposal crisis all over the world. One solution to this crisis can be attributed to reusing (recycling and/or downcycling) waste in useful, and conventional operation. Research into new and innovative uses of waste materials is continually advancing to introduce reusable materials to replace ever exhausting traditional virgin materials. Many highway agencies, private organizations, and individuals have completed or are in the process of completing a wide variety of studies and research projects concerning the feasibility, environmental suitability, and performance of using recycled products in highway construction. Albeit, Recycled Crushed Concrete Aggregate (RCCA), Recycled Asphalt Pavement (RAP) or other sorts of Construction & Demolition Materials (CDM) are most conventional, and widely used recyclable materials to be used in pavements, several unorthodox yet potentially efficacious nondecaying reusable materials have also been tried. Fly ash, scrap rubber tires, glasses are few of the nonconventional options to be considered for pavement base materials. However, one potential option has been knowingly or unknowingly been overlooked as a viable alternative to traditional pavement base materials,

and that is recycled plastic. Since the very first production of synthetic plastic back in 1907, the incredible increase of its production, and consumption has been posing a diabolical threat on the global environment. It took until the 1950s for plastic production to experience a rapid increase. The annual manufacturing of plastics expanded roughly 200-fold over the following 65 years, reaching 381 million tons in 2015. To put this into perspective, this is approximately equal to the mass of two-thirds of the world's population (ourworlddata.org). Prior to 1980, there was almost no recycling or burning of plastic; all of it was dumped. Rates climbed on average by around 0.7 percent year from 1980 for incineration and 1990 for recycling. Around 55 percent of plastic garbage worldwide was thrown in 2015, while 25 percent was burned, and 20 percent was recycled (ourworlddata.org). In 2018, plastics generation was 35.7 million tons in the United States, which was 12.2 percent of MSW generation. According to USEPA, in 2018, landfills received 27 million tons of plastic. This was 18.5 percent of all MSW landfilled. The holistic plastic pollution scenario in the USA has been lately exacerbated due to the much talked about Chinese ban on importing recycled plastics from the USA. On January 1st of this year, China formally blocked its borders to the importation of 24 different categories of solid waste, including scrap plastic. The effects of this new program, known in China as National Sword, spread to the United States, which now had more waste than could possibly be recycled or even disposed of in landfills. This sudden onus embedded on an already existent problems of recycling materials has led many research institutions across the USA to envisage ideas which could effectively solve the problem ensuring no harms to the environment. However, with the proposition of using non-conventional recyclable materials in place of virgin materials for pavement construction, environmental concern automatically comes into play. Since, plastic is by nature is deemed to be potentially threatening to geo-environment either in the form of unfiled state, or in the form of more complex microplastic structure, it is customary

to scrutinize all possible potential hazards associated with plastic use, and ensure a safe, reliable, environmentally sustainable measure to use recycled plastics as an alternative to virgin materials in pavement construction. Environmental assessment could be performed through a set of leaching tests to determine the parameters; i.e. pH, COD, TDS, TSS, Specific Conductance and compare the results with the stipulated benchmark (Hoyos et al., 2008). U.S. Environmental Protection Agency (2005) has set the benchmark of storm-water sampling as derived from the pavement runoff, and seepages. (“Benchmarks for storm-water sampling.” Business Environmental Resource Center, City of Sacramento, California).

While using a few well-known characteristics to assess the environment is a simple strategy that is subject to predetermined standard experimental procedures, characterizing the risk of microplastics in plastic roads is a more involved process. It is natural that research involving microplastic risk assessment is scarce because the practice of reusing recycled plastic in pavement engineering is still in its infancy. However, in recent years, the global concern over microplastic contamination has grown. Microplastic waste in freshwater and marine ecosystems has grown in importance during the past ten years. Given that the effects of microplastics on aquatic animals are still not well understood, there is a growing interest in understanding these effects (Thompson et al., 2004, Browne et al., 2007). Spherules in plankton tows off the coast of New England were the first signs of microplastics in North America in the 1970s (Carpenter et al., 1972). Microplastics have since been discovered in the majority of significant bodies of water (oceans, seas, lakes, and rivers). According to Arthur et al. (2009), microplastics are plastic particles with a size of less than 5.0 mm, while the exact size range for microplastics is not known. Primary and secondary microplastics are the two main ways that microplastics are created and enter a body of water (Arthur et al., 2009). Primary

microplastics are created raw plastic materials that enter the ocean by runoff from land, such as virgin plastic pellets, scrubbers, and microbeads (Browne et al., 2007, Arthur et al., 2009). (Andrady 2011). When bigger plastic objects (meso- and macro-plastics) reach a beach or ocean and degrade mechanically, chemically, or biologically, this results in secondary microplastic introductions (Thompson et al., 2004, Browne et al., 2007, Cooper and Corcoran 2010, Andrady 2011). The larger bits are reduced by this degradation into progressively smaller plastic fragments that are eventually invisible to the human eye. At the moment, it is unclear how microplastics affect wildlife. However, it has been discovered that a number of creatures, including both vertebrates and invertebrates, absorb microplastics. These illustrations illustrate several creatures with various modes of feeding, such as detritivores, deposit feeders, and filter feeders. Examples include fish (Carpenter et al., 1972), scleractinian corals (Hall et al., 2015), mussels (*Mytilus edulis*; Browne et al., 2007), lugworms, amphipods, and barnacles (Thompson et al., 2004). Ingesting plastic waste could expose organisms to toxins that have bonded to the plastic, which worries scientists (Teuten et al., 2007).

## **1.2 Problem Statement**

Successful and sustainable use of alternative materials to be used in any type of construction depends on three components; popularly termed as three E's; i.e. Engineering, Economics, and Environment. Highway and/or pavement constructions are no exceptions. Albeit, in many cases environmental impacts associated with the construction is overlooked. Since, this research work accentuates on using the combination of Recycled Crushed Concrete Aggregates (RCCA), and recycled plastics as alternative pavement materials, environmental assessment against the set standard will be taken care of with utmost importance. Since, repurposing recycled plastic in pavement engineering operation is still in its nascent period, it

is quite understandable that research works incorporating microplastic risk evaluation for plastic road is almost nonexistent. Which inspired us to carry out this study to characterize the risk associated with microplastic alongside the conventional environmental assessment.

In this research work, Recycled Crushed Concrete Aggregates (RCCA), and shredded recycled plastics will be mixed in different proportions, and will be stabilized with Portland cement in multiple dosages to prepare the samples which would prototype the pavement base, whereas for the pavement surface course different grades of bitumen will be mixed with shredded plastics in different proportions. Prepared samples then will be subject to the environmental assessment tests, designed microplastic detection test and subsequent microplastic risk characterization.

### **1.3 Research Objective**

The principal objective of this current study is to characterize the risk associated with microplastic from the plastic road. The specific tasks to accomplish the objective of the study include:

1. Collecting, sorting, cleaning, shredding of waste plastics
2. Collecting Recycled Crushed Concrete Aggregates (RCCA), cement, bitumen
3. Development of an experimental program
4. Preparation of samples
5. Leachate tests for environmental assessment
6. Microplastic detection and risk characterization
7. Qualitative FTIR analysis to confirm the presence of Microplastics
8. Development of statistical model to predict Risk Characterization Ratio (RCR)



## **1.4 Dissertation Organization**

The dissertation is organized into six chapters. Following is the summary of each chapter being presented in this dissertation.

Chapter 1 presents the background, problem statement, and research objective of the current study.

Chapter 2 presents a literature review on basic pavement structure, previous studies on use of alternative recycled materials in pavement. Plastic pollution across the globe, and a possible way of using recycled plastics as alternative pavement materials are also discussed. Results from previous studies on acceptable limits of multiple environmental attributes with the use of alternative pavement materials are also portrayed. Most importantly, this chapter highlights the basic concept of microplastics and its potential risk as well as the quantitative, and qualitative analysis.

Chapter 3 describes the experimental program, sample and specimen preparation, experiments methodology to conduct multiple environmental tests, microscopic detection of microplastic, and FTIR technique to corroborate the presence of microplastics.

Chapter 4 presents test results, and the subsequent analyses and discussion based on the tested results.

Chapter 5 provides an outline for developing a statistical model to predict the value of microplastic Risk Characterization Ratio (RCR), using

Chapter 6 summarizes the major conclusions from laboratory test results and statistical analysis. Finally, recommendations for further studies are presented.

## Chapter 2

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This chapter presents a literature review on basic pavement structure, use of alternative pavement materials to replace the virgin materials in pavement construction. Global emergence of plastic production and uncontrolled pollution and a possible way of using recycled plastics as alternative pavement materials to address this global issue are also discussed in this chapter. This chapter deals with the results from previous studies on acceptable limits of multiple environmental attributes in correspondence with the use of alternative pavement materials. Most importantly, this chapter highlights the basic concept of microplastics, and potential risk associated with microplastics along with the quantitative analysis done by the optical microscope. This chapter also highlights the basic concepts of Risk Characterization Ratio (RCR) which deems to be the primary indicator of microplastic contamination. Standard baseline to calculate RCR is also explained in detail based on previous studies conducted on fresh water and marine microorganisms wantonly exposed to microplastics. Finally, this chapter delineates about FTIR (Fourier-Transform Infrared spectroscopy) technique to qualify the microplastic type and corroborate the presence in consonance with the already conducted optical microscope investigation.

#### **2.2 Pavement Structure**

The primary function of a pavement is to reduce the stress to an acceptable level for the subgrade. A generic pavement structure constitutes layers where every layer convey load from

the upper layers and dispatch them to the lower layers. Principal purpose of the upper layers is to ensure that the transmitted stresses due to wheel load do not exceed the bearing capacity of the subgrade. From the structural point of view, pavements can be classified in correspondence with the load distribution pattern. The three main forms of pavement are flexible pavement, rigid pavement, and composite pavement. Base and/or subbase course, surface course, and prepared or stabilized sub-grade are typically included in flexible pavement. The deflection of flexible pavement is often stronger near the borders and lower in the middle. On the other hand, rigid pavement is made up of a concrete slab, base and/or base course, and a prepared subgrade. It makes sense that composite pavement combines hard and flexible pavement. A flexible portion is placed on top of a rigid part to operate as a conventional wearing course, a heat and moisture blanket, and to prevent deflection.

### **2.2.1 Surface Course**

The pavement's topmost layer is known as the surface course. This layer, which is on top and over the base course, is in direct touch with the wheels of the moving traffic. As a result, this layer is skillfully made to endure traffic loads, allow for adequate drainage, resist road abrasion and skidding, and survive the effects of changing natural phenomena and climatic conditions.

### **2.2.2 Base Course**

To provide a stable structural support, the base course, the second layer of pavement, is built just below the surface course and above the conditional base if one is present. If not, it is placed directly on the subgrade. In general, base materials consist of virgin aggregates. To minimize the heavy reliance on natural aggregates, recovered crushed concrete aggregates (RCCA), recycled asphalt pavement processed with Portland cement, lime, or other binder

components, are also utilized as base course materials. The stabilization of the foundation layer is crucial for the pavement structure's performance and overall thickness.

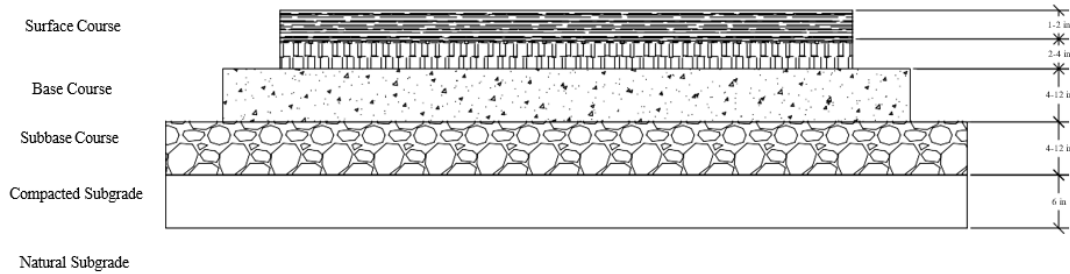


Figure 2-1 Typical Pavement Structure

### 2.2.3 Subbase course

This layer serves as a support for the surface and base course and is often built beneath the base layer. It typically comprises of stabilized or unstabilized compacted granular materials. It prevents fine particles from entering the base layer from the subgrade. If the base layer's strength is sufficient to support the weight of the wheels, the subbase layer is skipped, resulting in a more cost-effective design.

### 2.2.4 Subgrade

The subgrade course normally consists of natural soil and selected aggregate particles that have been compacted to a specified degree to withstand the relative stress caused by the weight of the course above. As a result, the road is supported by the poor soil, and if the road is built on an embankment, the imported fill materials (embankment) serve as the subgrade. Any weight or load stress communicated from the courses above can (or should be able to) be absorbed by this course. A typical cross section of pavement structure is shown in Figure 2-1 (Ordonez, 2007).

## **2.3 Use of Recycled Materials in Pavement**

The significant push to incorporate waste materials into the road construction industry aims to reduce the negative effects of processing natural materials on the environment, to alleviate the already existing burden on authorities in both developing and developed countries in designing new landfills and establishing provisions for such wastes, and to reaffirm the industry's commitment to improved road infrastructure and transportation efficiency. In addition, the scarcity of natural resources is an obvious justification for the need for proper usage of nondecaying, recyclable residual materials. Several experimental and research investigations have investigated the potential incorporation of waste materials in the field of road construction. Numerous studies have demonstrated the viability of reusing and recycling certain compositions of these waste materials in pavement structures, while others are still undergoing extensive research to shed light on the benefits of their recycling in pavement constructions. Due to a lack of knowledge and funds for an in-depth investigation of utilizing waste materials in the most advantageous manner, waste material is a central concern for governmental institutions and transportation law authorities in many parts of the world. International collaboration is essential for protecting the environment by reducing greenhouse gas emissions and conserving natural resources by incorporating feasible recycled materials into the construction industry and reviewing methods for employing these materials (M. Bassani et al., 2009).

### **2.3.1 Types of Recycled Materials for Pavement**

Recycled materials used in the construction of roadways can be largely divided into two categories: conventional and unconventional. These include Recycled Crashed Concrete Aggregates (RCCA), Recycled Asphalt Pavements (RAP), Construction & Demolition

Materials (CDM), bio asphalt, etc. In contrast, uncommon materials include discarded tires, recycled shingles, used motor oil, and recycled glass, among others.

Unconventional material is material that does not possess the required attributes according to the customary specifications. This is the definition of unconventional material (L. R. de Rezende et al. 2015). Secondary materials and waste by-products have become an urgent necessity in the field of road construction as a result of the growing demand for aggregates material in road construction, the scarcity of accepted quality material, and the urge in preserving natural resources. This has created an urgent necessity for the inclusion of secondary materials and waste by-products. The incorporation of several waste recyclable materials into a variety of projects across the world has revealed the ability to not only save money but also to protect the environment. These projects can be found in every region of the world. Because the responses of roads and their long-term performance are so dependent on the characteristics of the materials that are used in the compositions of the structure, it is essential to have a comprehensive understanding of the behavior and pattern of these materials as well as the effects of their transformation when these materials are used in road pavement structure either on their own or in combination with other materials. It is believed that the responses to the enormous demand for alternatives to natural materials in road construction have been effectively responsive. This is a reflection of the fact that a significant amount of research has been devoted to carrying out feasibility studies on using this substitute material with an eye toward sustainability from both an environmental and an economic perspective. (M. Pasetto & N. Baldo 2012).

### *2.3.1.1 Recycled Crushed Concrete Aggregate (RCCA)*

The most popular non-traditional paving material is undoubtedly RCCA. Concrete paving is the main source of RCCA. The key characteristics of RCCA are its angles constructed from natural aggregates and anchoring mortar, as well as its stiffness. When water is added, fines from the mortar component might cause "self-cementing" or "re-cementing." An even tougher layer is created as individual particles bind together. To satisfy the general standards of AASHTO M147 or ASTM D2940, RCCA must be crushed and screened. RCCA has an adsorption rate that is 4-8% higher than natural aggregate. Due to the inclusion of mortar, RCCA aggregates have a somewhat lower specific gravity (varying from 2.0 for tiny particles to 2.5 for coarse particles) than natural aggregates. The friction angle of the RCCA is often larger than 40 degrees. Excellent stability and minimal settling after compaction. Ground RCCA has a pronounced angular form. Comparable to crushed limestone aggregates, the California Bearing Ratio (CBR) values range from 90 to over 140. In general, RCCA aggregates demonstrate exceptional weather resistance and erosion resistance. RCCA is plastic-free and not susceptible to frost. RCCA (predominantly coarse fraction) is more freely drainable and permeable than conventional granular materials due to its low fines concentration.

The experiences and studies of transportation authorities have demonstrated that, under certain conditions, Recycled Crushed Concrete Aggregate (RCCA) can create strong, durable materials suitable for use in the highway system. The RCCA coarse aggregate component does not significantly alter the workability of the mixture or the quantities that are desired. When employed, recycled fines make up no more than 30% of the fine-aggregate component (FHWA State of the Practice National Review September 2004).

### *2.3.1.2 Reclaimed Asphalt Pavement (RAP)*

Reclaimed Asphalt Pavement (RAP) is, like RCCA, an extensively utilized non-conventional pavement material. Essentially, RAP is crushed or milled asphalt pavement. In other words, RAP can be characterized as natural aggregate coated with aged asphalt binder that is generally clean and contains negligible noxious elements. In general, asphalt binder is a viscoelastic-plastic substance that can increase rigidity and strength, but is sensitive to rutting. RAP can be treated to meet AASHTO M147 or ASTM D2940 aggregate criteria and should be. RAP and other aggregates are combined to produce the base. The bearing capacity of the mixture is highly dependent on the ratio of recycled asphalt pavement to conventional aggregate. The bearing capacity diminishes as RAP content increases. When the percentage of RAP approaches 20 to 25 percent, the California Bearing Ratio (CBR) falls below the level expected for traditional granular foundation. Due to the asphalt cement covering on RAP aggregate, which prevents compaction, the density of blended granular material tends to decrease as RAP percentage increases. Due to the greater fines content and absorptive potential of these fines, the optimal moisture content for RAP blended aggregates is stated to be higher than for typical granular material, particularly for RAP from pulverizing operations. Permeability of blended granular material with RAP is comparable to that of ordinary granular base course material. Since the quality of virgin aggregates used in asphalt concrete typically exceeds the standards for granular aggregates, there are typically no durability concerns associated with the use of RAP in granular base, particularly if the RAP comprises less than 20 to 25 percent of the base.



RAP can, if practicable, be combined with RCCA or other demolition debris and used as an alternative pavement base material. In this situation, the mixing proportion will be determined by a number of variables, such as the availability of materials in the area in question.

### *2.3.1.3 Recycled Pavement Material (RPM)*

Recycled pavement material (RPM) is more often than not a composite product that can be produced by grinding up the bound layers and a portion of the unbound foundation of the existing pavement. Depending on the quantities, the properties of RPM may act more like RAP or more like ordinary mineral aggregate. RPM can be ground on-site or using conventional techniques. Gradation can be difficult to describe because the original aggregate, depth of cut, and crushing processes all influence it. Frequently, there is a maximum size restriction, such as 97% passing 50 mm (2 in) mesh. If performed ex situ, aggregate requirements can adhere to AASHTO M147 or ASTM D2940 specifications. The bearing strength is dependent upon the ratio of RAP to other aggregates and the percentage of fine particles. Due to the fines, there appears to be a tendency for the CBR of material pulverized on-site to be lower than that of material mixed, pulverized, and screened off-site.

Typically, RPM is stabilized with a binder to increase its strength. Due to the addition of RAP and perhaps RCA, the compacted density will typically be lower. As with RAP mixtures, the optimal moisture content for RPM is typically more than for ordinary granular material, especially for in place material, which tends to contain more particles. Permeability of compacted RPM is dependent on its ingredients and stabilizer addition. In general, however, the permeability through the compacted layer is minimized, hence reducing moisture problems.

Again, the durability is dependent on the original aggregate, as well as the quantities of RAP and other aggregates, as well as stabilizers. RPM can be crushed to create a robust base, though stabilizers are frequently added to increase durability.

#### *2.3.1.4 Construction & Demolition Materials (CDM)*

CDM is a readily available alternative to standard paving materials. CDM consists mostly of crushed concrete from the demolition of industrial buildings and accompanying infrastructure. Stone, brick, asphalt, porcelain, and decorative concrete can be included in CDM. Also may have a greater soil component. Gradation is dependent on processing, but often contains more fines. However, the majority of transportation organizations do not suggest CDM as an alternate pavement base material due to the increased costs associated with removing and handling demolished concrete reinforcements. CDM must be crushed and screened to meet AASHTO M147 or ASTM D2940 criteria for aggregate. Depending on the relative quantities of concrete, rock, RAP, etc., CDM absorbs more than natural aggregates. Because of this, CDM is more prone to moisture and more susceptible to freeze-thaw conditions. Due to the mortar fraction and RAP, the specific gravity of CDM aggregates (range from 2.0 for fine particles to 2.5 for coarse particles) is slightly lower than that of natural aggregates. CDM Due to the crushed material, the angle of friction is often medium to high. The CBR values are comparable to RCA (>90), but decline when RAP is included. Additionally, brick tends to reduce CBR, particularly wet CBR.

In general, CDM aggregates are durable and resistant to weathering and erosion. Presence of clay-based aggregates may increase moisture sensitivity and deterioration. BDC is often free draining because the fines are usually screened off. Like RCA, the initial pH of pore water in

the can high but drops with time. Since BDC comprises a somewhat greater proportion of non-concrete material, pH concerns are not as significant.

#### *2.3.1.5 Recycled Road Surface Gravel (RSG)*

RSG is not as well known as RCCA or RAP. RSG is appropriate for use as the road surface material for unpaved roads. If the road needs to be upgraded, RSG can also be referred to as a mixture of gravel (or aggregate), sand, and fines that will compact for create a hard crust that can be stabilized into a base layer for hot mix asphalt. Compared to other road aggregates, RSG typically has a finer gradation, with more than 50% passing the 6.3 mm (0.25") mesh. Instead of being recycled and used as unbound foundation, this material would be stabilized. The base performance may be enhanced by the addition of coarser aggregates. Depending on the fines concentration, CBR values are on the order of 50 lower than for coarse aggregates. RSG can be made stronger by adding coarser material and by including binders to give it more rigidity and strength. Based on past performance with stable base and base layers, durability is anticipated to be good. It has a poor gradation trend and produces weaker strength attributes than RCCA, RAP, or even RPM due to its generally more uniform particle textures. However, it is less expensive than RCCA and RAP in comparison. RSG may therefore be a good substitute for pavement foundation intended for medium to low traffic.

#### *2.3.1.6 Scrap Tires*

The more popular, widely accessible non-conventional recyclable materials utilized in pavement building have been explored so far. On the other hand, a small amount of scrap tires are employed in the construction of pavement layers. The crumbed rubber used in asphalt surfacing applications, whether it is produced using a wet or dry method, provides a number of additional benefits in addition to better skid resistance. Additionally, it offers asphalt mixtures

with high shear strengths, which are advantageous in withstanding traffic loads and reducing rutting in the pavement's sublayers (Y. Huang et al. 2007). Additionally, the inclusion of scrap rubber in the compositions of the beneath layer compositions plays a critical function in lowering the frost penetration level during freezing and thawing cycles in cold weather circumstances. In addition to reducing temperature sensitivity, fostering rutting and fatigue resistance, increasing stability, reducing flow value (up to a rate of 10% of crumb rubber), and enhancing stripping resistance are some additional advantages of employing crumbed rubber in road building applications (A. Modarres & P. Ayar 2016). Significant improvements in qualities like weathering and stripping resistance have been made when up to 30% of the asphalt binder is applied.

#### *2.3.1.7 Foundry sands*

It is a by-product of the ferrous and nonferrous metal casting industries and is categorized as a fine-grained material made of high-quality, uniform-sized silica. According to the literature, sand is reused at foundries until it becomes impracticable to continue doing so, at which point it is discarded as waste sand. When considering it for road maintenance, it is at this point (Y Zhang et al., 2021). This material has been used as flowable fills in HMA, base, embankments, and backfill. Due to its high clay content, it cannot be used in areas with poor drainage or high water levels. Due to the high concentration of heavy metallic elements, nonferrous foundries are not advised for HMA. Another research demonstrated that the OMC or MDD were unaffected by the addition of 5-15% to base-base. However, the resilient modulus values were significantly lower than those of the cited base mixtures, and it was advised that more research be done on the functionality of modified base-base materials (D. H. Kang et al. 2011).

### *2.3.1.8 Coal Combustion Products*

This comprises oil-contaminated soil, fly ash, bottom ash/boiler slag, pond ash, oil sand, oil shale ash, and brake shoes fine. The feasibility of using fly ash as a mineral filler in HMA (Hot Mixed Asphalt) is based on the low concentration of heavy metals and the extremely small particle size. Type C, which has a high calcium level, or type E, which has a lower calcium concentration, are the two options. The addition of 2 to 12% fly ash is intended to enhance the subgrade characteristics. It is feasible that base and base course materials for light traffic pavements might be created by adding 40% fly ash to the RAP modified mixture with 20% fresh aggregates (S. Saride et al. 2015). To maintain the necessary compressive strength in compliance, a rate of 25% of 12% cement should be maintained in cement stabilized base (S. Dimter et al. 2011). When inferior quality aggregates were combined with standard PG binder, it was discovered that it developed significantly more moisture-damage resistance than when superior quality aggregates were combined with polymer modified PG binder.

Due to its angular glassy surface, bottom ash/boiler slag has the advantage of having a strong resistance to sliding. Furnace bottom ash is the name given to the ash that comes from the blast furnace. According to the literature, fly ash is chosen over bottom ash while building roads (Y. R. Kim et al. 2012). However, the use of bottom ash outweighs the use of fly ash in terms of the immediate boost in resilience. This ash has a leaching problem, and vitrification has been suggested as a solution. The vitrified ash, which has a glassy quality, will be used as aggregates in asphalt pavement. Because it hates water, less asphalt cement would be required to obtain the desired performance characteristics. With the addition of bottom ash, tensile strength and resistance to deformation increase. Additional investigation is required to determine the properties of resistance to stripping (M. Bassani et al. 2009).

Pond ash, which is a mixture of water and ash dropped at lagoons, is distinguished by its lack of crystalline structure. To improve the characteristics, it is typically treated with additional additions like lime and fiber. Vertical compressive strain and horizontal tensile strain placed on the base course and subgrade layers reduced as the rate of fiber and lime combined with the ash rose. As a result, the pace at which fiber and lime were added enhanced the rigidity of the pavement (M. Fall & S. Samb 2008). Once more, it makes sense to look into how utilizing pond ash affects the CBR value of the underlying material.

As a by-product of the crude oil refining process, oil, tar, or bituminous sand naturally accumulates as deposits of sand, clay, water, and an extremely viscous asphalt cement that reaches 13% in Utah. Alberta is home to the largest known source of oil sand waste in the world. The quantity of the deposits, the availability of water for the extraction process, and the makeup of the deposits are some of the barriers preventing the US from fully utilizing this oil sand. In Canada, this substance was first used in 1913. Results showed poor rutting resistance when utilized in Gap HMA, and the mixing temperature, which was 104oC, was lower than it was for traditional HMA (O. Nasir & M. Fall 2008). Ash from the extraction of oil shale is regarded as a valuable ingredient to enhance the rheology of asphalt cement. Through the use of rotating viscometer and dynamic shear rheometer tests at high temperatures, the inclusion of 0 to 20% at a 5% increment was examined. With an increase in usage rate, shear modulus rose. However, as shown by the findings of the phase angles, the modified binder's elastic behavior was stagnated. Therefore, shale ash had no effect on the virgin binder's low-temperature performance. In order to achieve the performance requirements at lower temperatures, it was advised to examine various binder grades (M. Saltan & F. S. Fndk 2008).

In China, brake shoe dust from the automobile industry was tested as a filler in HMA at rates ranging from 0 to 7.5% with a 2.5% increment. A 40°C hot temperature caused the dynamic modulus to increase, and a 5°C low temperature caused it to fall. The IDT showed that the tensile strength only increased at a rate of 2.5%. Although no discernible resistance to deformation was found, a conclusion was reached about the use of 2.5% of powdered brake shoe material as a filler in HMA (M. Fall et al. 2010).

#### *2.3.1.9 Glass Waste*

Waste glass that has been crushed and sorted can be included in the fine aggregate used in asphalt formulations. Hot mix asphalt pavements with 10-15% crushed glass in the wear surface mix have shown satisfactory performance. These pathways were occasionally referred to as "grasfalt." Base or binder course combinations could potentially employ higher mixtures, possibly up to 25%. The separation of the bitumen-cement binder from the waste glass can cause harm to overlays constructed with hot mixed asphalt having more than 15% waste glass. The leftover glass that has been sorted and crushed can be used as a granular raw material. Due to the angular form of the crushed glass particles, glass that has been crushed to a fine aggregate size fraction (less than 4.75 mm in size; #4 sieve) acts as a fine aggregate or gritty material. strong stability It typically needs to be blended with other traditional coarse-grain materials to match the standards needed for granule-based grading.

Expect a rather large size range in the crushed glass that is collected from material recovery facilities. Gradation variations are largely influenced by the kind of glass crushing machinery utilized. The majority of the time, crushed glass can be counted on to be a well-graded material, and with the right sizing, cullet or cullet-aggregate blends can produce engineering qualities that are quite equivalent to those of natural aggregates used in granular

base applications. To create a product that satisfies the grading criteria of granular base specifications, such as AASHTO M147, waste glass should be crushed and screened. Density when compacted and unit weight The unit weight of crushed glass is roughly 1120 kg/m<sup>3</sup> (70 lb/ft<sup>3</sup>), which is less than that of traditional aggregate. The size, grade, and level of contamination of the glass, as well as the compacted density of broken glass, will vary (extraneous debris, such as paper, plastic caps, and soil). The maximum dry density, which is likewise a little lower than that of typical granular material, has been reported to be between 1800 and 1900 kg/m<sup>3</sup> (111 and 118 lb/ft<sup>3</sup>). The moisture-density curve for crushed glass is rather flat, which suggests that the compacted density is not sensitive to moisture content. For broken glass with top diameters of 19 mm (3/4 in) and 6.4 mm (1/4 in), relatively high angles of internal friction (compared to ordinary aggregates) of higher than 50 degrees have been found. Crushed glass and conventional aggregate tested under the California Bearing Ratio (CBR) test showed values ranging from 42 to 125 percent for blends including 50% glass and crushed rock. Lower glass additions of 15% were discovered to display values that were nearly equal to the crushed rock employed in the testing (approximately 133 percent). According to the Los Angeles Abrasion test, larger glass particles show minimal durability, with values between 40 and 45 percent. In order to eliminate the bigger, less durable glass percentage, it would seem desirable to process (crush) the waste glass more thoroughly. Depending on the glass gradation, crushed glass is a free-draining substance with permeabilities ranging generally from 10<sup>-1</sup> to 10<sup>-2</sup> cm/sec.



## 2.4 Plastics and Plastic Waste

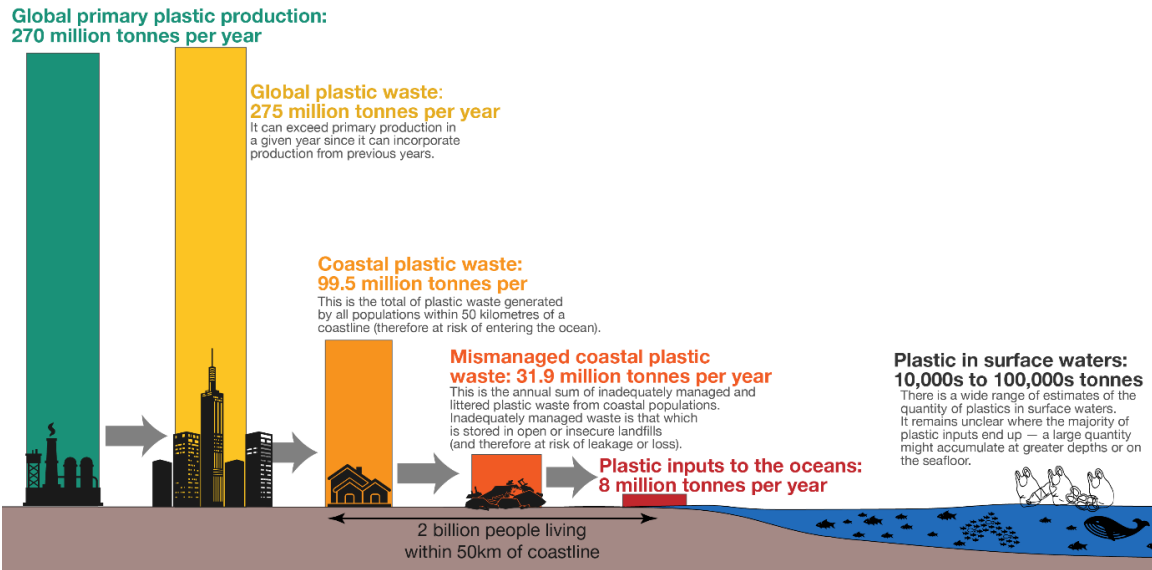
Plastics have grown so essential to our society that we are unable to function properly without them. The amount of plastic that is used each year has been gradually increasing, and the amount of plastic that is used everywhere in the world has also been steadily increasing. Plastic's phenomenal rise in popularity can be attributed to a variety of reasons, including the material's low density, strength, user-friendly design and construction, simple accessibility, affordable price, portability, and other attributes. They are used extensively not just in packaging, automobiles, and other industrial uses, but also in medical delivery systems, artificial implants, and a wide variety of other healthcare applications. This is in addition to the fact that they are utilized extensively in industrial applications. Plastics are used in so many different ways to maintain the freshness of food and transport it to consumers that it would be impossible to list them all here. Whether they are utilized in the production of chips, printed circuit boards, or computer cases, plastics that have been specially formulated have long been an essential component of the global communication and electronics industries. They are also essential components in the production and distribution of alternative energy systems such as fuel cells, batteries, and even solar electricity. Plastic is widely used not only because its production is inexpensive, but also because it possesses numerous helpful features, such as being light, resistant to chemicals, and flexible. This has contributed to the material's widespread adoption. In addition, the adaptability of plastic makes it simpler to develop new technologies, which has proven particularly useful in the domains of medical, construction technology, and the manufacture of automobiles and airplanes. However, the overconsumption of plastics contributes to a wide variety of difficulties. A significant portion of the plastic is

immediately discarded or deposited in landfills. Because typical plastic does not degrade, any rubbish made of plastic that is not disposed of in an appropriate manner might remain in the environment for decades or even centuries. Since people continue to use a significant amount of plastic, we urgently want solutions to this issue that are both comprehensive and long-term.

Trash made of plastic and the pollution that it generates may now be found on every beach in the globe, even those that see relatively few people and those that are popular tourist destinations. Researchers have recently discovered little bits of plastic buried deep within the Arctic ice. There were 2.5 billion people living on the planet in 1950, and they produced 1.5 million tons of plastic during that time. In the year 2016, there were over 7 billion people on the planet, and together they produced over 320 million tons of plastic. By the year 2034, this will have increased by a factor of 2. Every single day, almost 8 million individual pieces of waste plastic make their way into our oceans. It is estimated that there are currently roughly 5.25 trillion large and small fragments of plastic floating in the open ocean. The majority of these bits are likely microplastics. Heavy, weighing up to 269,000 tons at its maximum capacity. Plastics always make up between sixty percent and ninetieth percent of all the waste that is discovered in the water. This percentage is always consistent. Recent studies have found evidence of the presence of plastic in the bodies of each and every species of marine turtle, as well as in 59% of whales, 36% of seals, and 40% of seabirds. [Citation needed] Plastic contamination in the ocean is responsible for the deaths of one million seabirds and another 100,000 marine creatures and turtles every single year.

# The pathway by which plastic enters the world's oceans

Estimates of global plastics entering the oceans from land-based sources in 2010 based on the pathway from primary production through to marine plastic inputs.



Source: based on Jambeck et al. (2015) and Eriksen et al. (2014). Icon graphics from Noun Project.  
Data is based on global estimates from Jambeck et al. (2015) based on plastic waste generation rates, coastal population sizes, and waste management practices by country.  
This is a visualization from OurWorldInData.org, where you will find data and research on how the world is changing. Licensed under CC-BY-SA by the authors.

Figure 2-2 Comprehensive data of worldwide plastic pollution (Our World in Data)

## 2.4.1 Plastic Waste in USA

The United States produced 34.5 million tons of plastic in 2015, which accounts for 13.1% of the country's municipal solid garbage. The Environmental Protection Agency (EPA) conducts research on the production of municipal solid waste plastics as well as their recycling, composting, burning (including energy recovery), and disposal. In 2015, recycling rates in the United States barely reached 9.1% of total plastic production. As a result, the amount of recycled plastic was 3.1 million tons. In 2015, the total volume of plastics burned in municipal solid waste was 5.4 million tons. This figure represents the entire volume of plastics burned. During that year, 15.9 percent of municipal solid waste was incinerated for the purpose of energy recovery. The amount of plastic that was thrown away in landfills in 2015 was 26 million tons. This accounted for 18.9 percent of the total amount of municipal solid trash that

was thrown away in landfills. Figure 2-3 illustrates the management of plastic garbage in the United States.

## Total MSW Generated by Material, 2018

292.4 million tons

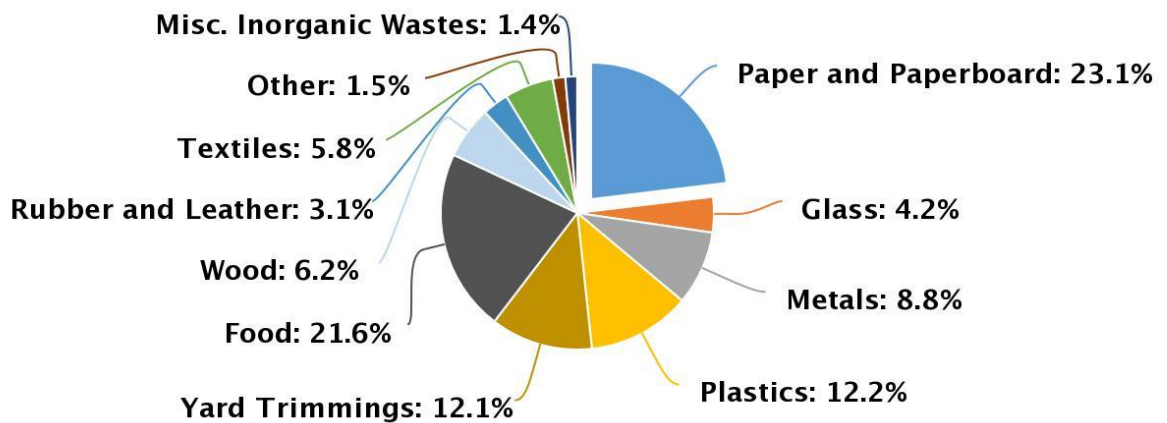


Figure 2-3 Total MSW generation in USA (EPA 2018)

Plastics constitute a continually expanding portion of municipal solid waste (MSW). While plastics are included in all main MSW categories, the category with the highest plastic tonnage in 2015 was containers and packaging, with over 14 million tons. This category contains polyethylene terephthalate (PET) bottles and jars, high-density polyethylene (HDPE) natural bottles, and other containers. While the total volume of recycled plastics in 2015 was just 3,1 million tons, with a recycling rate of 9.1 percent, the recycling of specific types of plastic containers was more significant. 2015 saw a 29.9 percent recycling rate for PET bottles and jars and a 30.3 percent recycling rate for HDPE natural bottles. However, there are extremely few or no facilities for recycling LDPE products such as supermarket bags and plastic wraps.

### Plastics Waste Management: 1960–2018

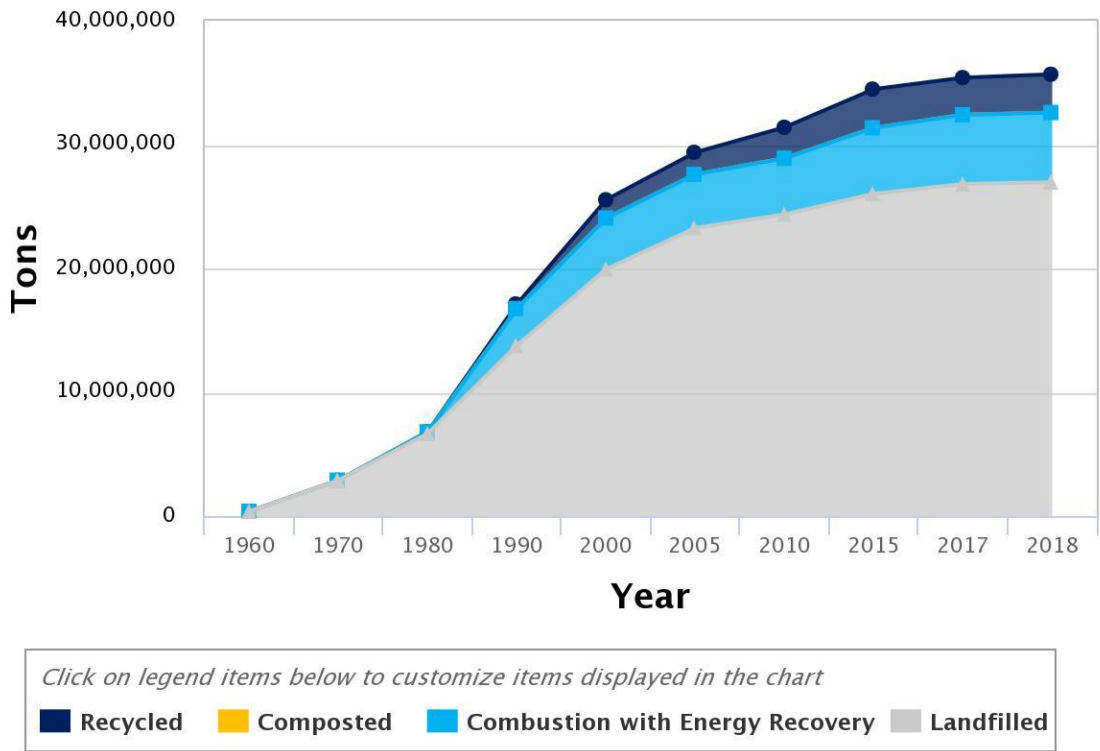


Figure 2-4 Plastic Waste Management (American Chemistry Council)

USEPA projects that between 2015 and 2018, plastic waste generation in the United States will increase by 3.8% each year, from 34.5 million tons in 2015 to 38.5 million tons in 2018. Jan Dell, a chemical engineer in 2018, used U.S. Environmental Protection Agency (EPA) data and industry data to project the U.S. plastic recycling rate and found that it will decline from 9.1% in 2015 to 4.4% in 2018. If further Asian nations impose plastic rubbish import bans in 2019, Dell (2018) predicted the recycling rate could fall as low as 2.9%. The United States' plastic waste generation and recycling rates are summarized in Table 2-1.

Table 2-1 Summary of US plastic waste generation and recycling amount (in thousands U.S. tons) (Source: American Chemistry Council)

| Management Pathway                     | 1960 | 1970  | 1980  | 1990   | 2000   | 2005   | 2010   | 2015   | 2017   | 2018   |
|--|------|-------|-------|--------|--------|--------|--------|--------|--------|--------|
| <b>Generation</b>                      | 390  | 2,900 | 6,830 | 17,130 | 25,550 | 29,380 | 31,400 | 34,480 | 35,410 | 35,680 |
| <b>Recycled</b>                        | -    | -     | 20    | 370    | 1,480  | 1,780  | 2,500  | 3,120  | 3,000  | 3,090  |
| <b>Composted</b>                       | -    | -     | -     | -      | -      | -      | -      | -      | -      | -      |
| <b>Combustion with Energy Recovery</b> | -    | -     | 140   | 2,980  | 4,120  | 4,330  | 4,530  | 5,330  | 5,590  | 5,620  |
| <b>Landfilled</b>                      | 390  | 2,900 | 6,670 | 13,780 | 19,950 | 23,270 | 24,370 | 26,030 | 26,820 | 26,970 |

Ocean and animal health are also negatively impacted by plastic pollution. Numerous examples of marine impacts exist. The weight of plastic in the oceans will surpass that of fish by 2050. (Jambeck et al. 2015). The United States ranks twenty-first on the list of nations that contribute to plastic pollution in the ocean, creating an estimated 88 to 242 million pounds of plastic marine debris annually. In 2017, 209,643 volunteers gathered more than 3.7 million pounds of trash, the majority of which was plastic, in a single day as part of the annual International Coastal Cleanup. This demonstrated the occurrence of plastic contamination along the beaches of the United States.

## 2.4.2 Classification of Plastics

In 1988, the Society of the Plastics Industry (SPI) created a classification system to enable consumers and recyclers to distinguish between various forms of plastic. Manufacturers typically mold an SPI code or number onto the bottom of each plastic product. This guide provides an overview of the many plastic varieties corresponding to each code number.

### 2.4.2.1 Polyethylene terephthalate (PET or PETE)

When John Rex Whinfield combined ethylene glycol and terephthalic acid in 1941, he created a brand-new polymer. Polyethylene terephthalate made up the condensate (PET or

PETE). A thermoplastic called PET can be drawn into films and fibers (like Dacron) (like Mylar).



Polyethylene  
terephthalate



Sometimes, the odors and flavors of the foods and beverages that are stored in them are absorbed by polyethylene terephthalate. This plastic is frequently recycled in products. PET is transparent, durable, and has effective gas and moisture barriers. commonly found in bottles of soft drinks. These containers occasionally pick up smells and scents from the foods and beverages that are kept inside of them. However, this plastic is still often used for a variety of household goods and necessities. In the US currently, recycling accounts for 25% of PET bottles.

#### 2.4.2.2 High Density Polyethylene (HDPE)

Karl Ziegler polymerized ethylene in the presence of several metals in the 1950s. Most of the components of the final polyethylene polymer were linear polymers. High-density polyethylene, now known as this linear form's product, developed structures that were more compact, ordered, and tight (HDPE). Products made of high-density polyethylene are extremely safe and are not known to leach chemicals into food or beverages. Petroleum is used to create the thermoplastic polymer known as High Density Poly Ethylene (HDPE). One of the most adaptable plastic materials on the market, HDPE plastic is utilized in a number of products, including milk jugs, shampoo bottles, cutting boards, piping, and plastic bottles. HDPE plastic is well-known for its exceptional tensile strength and high strength-to-density ratio. It also has a high melting point and impact resistance. FDA, NSF, and USDA-approved

industrial-grade food HDPE (High Density Polyethylene) boards are designed to be durable, safe, and minimal maintenance. They provide a gripping surface with roughness that makes holding food secure. A few of the key benefits of HDPE plastics include, but are not limited to, their strong corrosion resistance, high strength to density ratio, and simplicity in recycling. HDPE has a density that can range from 0.93 to 0.97 g, but it is just slightly higher than LDPE (low-density polyethylene). The linear structure of HDPE, however, means that it has no branching when viewed under a microscope, giving it more tensile strength and intermolecular forces than LDPE. Because of this, a 60-gram HDPE container can securely transport more than one gallon of liquid or about eight pounds of weight. Given how much plastic we consume on a daily basis, plastic recycling should be one of the most significant considerations when choosing a material. HDPE plastic, fortunately, is easily recycled, preventing non-biodegradable trash from ending up in landfills and assisting in the up to 50% reduction in plastic production! If you're searching for a reasonably priced, environmentally friendly material. Due to its resistance to decay, mildew, and mold, HDPE is the best material for water delivery subterranean piping.



**High-density  
polyethylene**



**Milk containers,  
cleaning agents,  
shampoo bottles,  
bleach bottles**

Products made of HDPE are often recycled. Containers for milk, motor oil, shampoo and conditioner bottles, soap bottles, detergents, and bleaches are among the products created from this plastic. However, if an HDPE bottle did not initially contain specific types of edible materials, it is unsafe to reuse it as a food or drink container due to the possibility of contamination. Every year, 30–35% of the HDPE plastic used in America is recycled.



### 2.4.2.3 Polyvinyl Chloride (PVC)

Dow produces Saran resins, which are created by polymerizing molecules of vinylidene chloride ( $\text{CH}_2=\text{CCl}_2$ ). Flexible and rigid materials can be used to categorize the wide range of vinyl products. Major rigid markets include bottles and packaging sheet, but it is also extensively utilized in the construction industry for items like pipes and fittings. After polyethylene and polypropylene, polyvinyl chloride (PVC) is the synthetic plastic polymer that is produced the most widely worldwide. Each year, about 40 million tons of PVC are produced. PVC is available in two basic types: rigid (also known as RPVC) and flexible. PVC in its rigid form is employed in pipe construction as well as in profile applications, such doors and windows. Additionally, it is used to create bottles, non-food packaging, food cover sheets, and greeting cards (such as bank or membership cards). Plasticizers can be added to make it softer and more flexible; phthalates are the most popular choice. It is used in this form to make canvas, which is utilized in many applications where rubber is replaced with cotton or linen, including plumbing, imitation leather, flooring, signage, phonograph records, and inflatable items. White and brittle solids make up pure polyvinyl chloride. Tetrahydrofuran makes it slightly soluble but alcohol makes it insoluble.



Polyvinyl  
chloride



The polymer can be formed into wraps and films that are resistant to odors from food. This type of plastic should not come into contact with food since it contains a harmful, hazardous chemical. Although PVC is used in many common items, it is primarily used in the

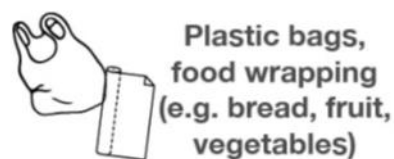
plumbing and building industries. The amount of PVC that is recycled is under 1%. Compatible plasticizers that reduce PVC's crystallinity are added to PVC to create flexible PVC. These plasticizers behave as lubricants, making the plastic much clearer and more flexible. PVC-P is another name for this kind of PVC.

#### 2.4.2.4 Low Density Polyethylene (LDPE)

Polyethylene, which is produced from ethylene monomers, is the most prevalent polymer in plastics ( $\text{CH}_2=\text{CH}_2$ ). In 1934, the first polyethylene was created. As a result of its ability to rot in a solution of alcohol and water, it is now referred to as low-density polyethylene (LDPE). Because the polymer strands in LDPE are intertwined and loosely arranged, it is flexible and soft. As implied by the name, LDPE is less "dense" than HDPE. As a result, it merely deviates slightly in mass from its volume. Although they have certain similar uses, including packaging, LDPE and HDPE have relatively distinct qualities because of their lower density and branching molecules. LDPE and HDPE are often collected for recycling separately due to their variances. LDPE is resistant to chemicals, moisture, and impact (doesn't break easily) (can stand up to many hazardous materials). The American Chemistry Council (ACC) asserts that LDPE is largely utilized in film applications due to its durability, flexibility, and relative transparency. Some flexible lids and bottles, as well as applications for wire and cable, are also made using LDPE. According to the ACC, LDPE offers exceptional resistance to bases, acids, and vegetable oils. It works well for packaging applications that call for heat-sealing due to its durability, flexibility, and relative transparency.



Low-density  
polyethylene



Many thin, flexible products, including rubbish bags, newspapers, bread, frozen foods, fresh vegetables, and plastic bags for dry cleaning, are made from LDPE. The majority of shrink-wrap and stretch film, as well as coatings for paper milk cartons and single-use beverage cups, are also manufactured of LDPE. LDPE is also used by manufacturers to make several toys, squeezable bottles, and thin container lids. According to the ACC, recycled LDPE can be used to make shipping envelopes, trash can liners, floor tiling, paneling, furniture, compost bins, and trashcans in addition to landscaping timber and outdoor lumber.

#### *2.4.2.5 Polypropylene (PP)*

Karl Ziegler and Giulio Natta created polypropylene from propylene monomers on their own in 1953 ( $\text{CH}_2=\text{CHCH}_3$ ) and received the Nobel Prize in Chemistry in 1963. The melting temperatures and toughness of the different polypropylene forms vary. Occasionally, polypropylene is recycled. Strong and often able to endure greater temperatures is PP. Thermoplastic polymer polypropylene (PP), commonly referred to as polypropene, is employed in a wide range of applications. It is created from the monomer propylene using chain-growth polymerization. Polypropylene is a non-polar, partly crystalline member of the polyolefin family. Although it is a little stronger and more heat resistant than polyethylene, it has qualities that are similar. It is a white, strong mechanical material with a high level of chemical resistance. The second-most common commodity plastic made is polypropylene (after polyethylene). (PP) has a density of 0.89 to 0.92 grams per cubic centimeter. PP is the commodity plastic with the lowest density as a result. A greater number of components can be made from a given quantity of plastic by molding parts with a lower density. Contrary to polyethylene, the density of the crystalline and amorphous areas barely varies. Fillers, however, can drastically alter the density of polyethylene. PP has a Young's modulus ranging from 1300

to 1800 N/mm<sup>2</sup>. The melting point of polypropylene is found by finding the maximum temperature on a differential scanning calorimetry chart since the melting point fluctuates. The melting point of perfectly isotactic polypropylene is 171 °C (340 °F). Depending on the atactic material and crystallinity, commercial isotactic PP has a melting point that ranges from 160 to 166 °C (320 to 331 °F). The melting point of syntactic PP with a 30% crystallinity is 130 °C (266 °F). PP becomes brittle below 0 °C.



Polypropylene



Polypropylene has good chemical resistance, is strong, and has a high melting point making it good for hot-fill liquids, and packaging for catch-up and margarine. PP can be recycled but is not as accepted as PETE or HDPE. It is used to make lunch boxes, margarine containers, yogurt pots, syrup bottles, prescription bottles. Plastic bottle caps are often made from PP. This type of plastic is strong and can usually withstand higher temperatures. About 3% of PP products are currently being recycled in the USA.

#### 2.4.2.6 Polystyrene (PS)

Styrene molecules combine to produce polystyrene. In order to make a link with nearby styrene molecules, the double bond that connects the CH<sub>2</sub> and CH portions of the molecule rearranges, creating polystyrene. Styrofoam is created when polystyrene is heated, and air is pushed through the mixture. Styrofoam is a great insulator and is lightweight and moldable.

The synthetic aromatic hydrocarbon polymer known as Polystyrene (PS) is created from the styrene monomer. Solid or foamed polystyrene are both possible. Polystyrene for general use is transparent, rigid, and somewhat brittle. Per unit weight, it is a reasonably priced resin. It has a relatively low melting point and a weak barrier to oxygen and water vapor. One of the most often used polymers is polystyrene, which is produced at a rate of several million tons annually. Uses for protective packaging include constructing models, containers, lids, bottles, trays, tumblers, and jewel cases used to store optical discs like CDs and occasionally DVDs. Packing peanuts are another example. When heated above around 100°C, the glass transition temperature, polystyrene, a thermoplastic polymer, flows from its solid (glassy) state at room temperature. After cooling, it returns to being rigid. Since it can be precisely cast into molds, this temperature behavior is used for extrusion (as in Styrofoam), as well as for molding and vacuum shaping.



Polystyrene



Food takeaway containers, plastic cutlery, egg tray

A material with many uses, polystyrene can be rigid or foamed. Polystyrene for general use is transparent, rigid, and brittle. Its melting point is relatively low. Protective packaging, containers, lids, cups, bottles, and trays are examples of common usage. PS can be recycled, but not efficiently; recycling it takes a lot of energy.

## **2.5 Scope of Plastic as Pavement Material and Plastic Road**

Finding a way to use recycled plastic wastes as an alternative solution to the ever-more-sumptuous virgin materials used for pavement construction is probably one of the most exciting marvels of the current day's transportation geotechnics research. This research is being conducted in the United States. If we could find a way to use plastic in a sustainable way, it would serve two important purposes: 1. It would lessen the burden of irresponsible exploitation of virgin materials, and 2. It would reduce the number of plastics that are piled up in landfills, opening the door to a new door of circular economy. Both of these goals would be accomplished by paving the way for the use of plastic in a sustainable way. These days, the issue of plastic pollution in every region of the world is receiving a lot of attention. No matter how much effort is put in to decrease the production of plastic and, as a result, the consumption of plastic, the amount of plastics that have already been made and the amount of plastic-induced items that are currently existing is more than enough to cause significant concerns. As a potential solution to this issue, the designed utilization of waste plastic in the creation of pavement could be a glimmer of light at the end of the tunnel.

The majority of the plastic that has been strewn is high in polymers. It is possible to use it either as a soil stabilizing agent, as a direct element of base/base applications, or as an additive to aggregates mixes in hot mix asphalt pavement. All of these uses are possible thanks to its versatility. When using the wet method, it is added to the binder in the form of pellets at a rate ranging from 0.25-0.5% of the binder's weight. When using the dry method, it is added to the aggregates (Y. Huang et al., 2007). The concept of using used plastics in the building of roads is a relatively recent one, and to date, no roads have been built entirely out of plastic garbage. Because of this, the concept of an integrated plastic road does not exist. However,

according to a review that was conducted by Huang et al., (2007), recycled plastics have the potential to either take the place of aggregates or act as a binder modifier. The addition of waste plastic in small doses (about 5-10% by weight of bitumen) has been shown to significantly improve the stability, strength, fatigue life, and other desirable properties of bituminous mixes. This, in turn, leads to improved longevity and pavement performance. There is a good potential for using waste plastic in the construction of bituminous roads (Kalantar et al., 2012; Vasudevan et al., 2012; Indian Road Congress, 2013). According to reports from laboratory and field performance studies, the addition of waste plastic to bituminous mixes improves durability and results in higher resistance to deformation and water-induced damage, which indirectly contributes to increased levels of user satisfaction and a reduction in the number of accidents (Bale, 2011; Behl et al., 2012; Vishnu and Singh, 2017; Manju et al., 2017). When waste plastic is incorporated into the bituminous mix, it leads to a reduction in the amount of bitumen that is consumed, which in turn results in a reduction in expenses (Vasudevan and Rajasekaran, 2006; Behl et al., 2012). The utilization of discarded plastic in the construction of roads also contributes to an increased road service life (Sojobi et al., 2016).

India is one of the world's leaders when it comes to research and experiments on the exploitation of plastics in the building of pavement. This research and experimentation can be found in India. India has approved the use of waste plastic in bituminous mixes as the default mode of periodic renewal with hot mixes for roads that are less than 50 kilometers away from urban centers that have a population of more than 500,000 people. India has also encouraged the use of waste plastic in bituminous mixes for the building of its national highways and rural roads. These roads are located within the country (National Rural Roads Development Agency, 2019; Government of India, 2015). The National Rural Roads Development Agency (2019)

sets precise rules for the use of waste plastic in the development of rural roads. These instructions pertain to the utilization of recycled plastic. The Indian Road Congress (2013) and the Indian Road Congress (2013) have both established guidelines regarding the use of waste plastic in hot bituminous mixtures. These rules may be found here and here. The Indian Road Congress (2013) has issued guidelines for the exploitation of waste plastic in hot bituminous mixtures. These guidelines may be found here. You may find both sets of rules and guidelines on the specific websites of the organizations that were in charge of establishing them in the first place. Since 2002, waste plastic has been employed in the construction of over 2500 kilometers of roads, and ten years later, those roads appear to be free of potholes, raveling, and rutting. The reason for this phenomenon is unknown. This is because the roadways were constructed out of recycled plastic, which contributed to this effect. This is as a result of the removal of the compounds in the waste plastic that were before accountable for the formation of potholes (Vasudevan et al., 2010; Indian Road Congress, 2013). (Table 2-2). During the typical process of creating roads, it is possible for there to be insufficient adhesion between the aggregates and the bitumen, which is one of the problems that can develop. This can result in a variety of difficult situations. The adhesion that is present in ordinary building procedures is far weaker than the adhesive that is present between plastic-coated aggregate and bitumen. This adhesive is significantly stronger (Vasudevan et al., 2012; Mishra and Gupta, 2018).

According to Vasudevan et al. (2012), the utilization of one ton of waste plastic was used to create one kilometer of road, which resulted in a reduction of three tons per kilometer of carbon dioxide emissions when compared to the emissions produced by conventional construction methods. In other words, the use of waste plastic was able to reduce the amount of carbon dioxide emissions by three tons per kilometer. In other words, the utilization of



discarded plastic was able to bring about a reduction of three tons per kilometer in the amount of carbon dioxide emissions. To put it another way, the exploitation of discarded plastic was able to bring about a reduction in the amount of carbon dioxide emissions of three tons per kilometer.

Table 2-2 Roads constructed in India using waste plastic and their condition (Vasudevan et al., 2012)

| <i>Road</i>  | <i>Year laid</i>    | <i>Unevenness (mm/km)</i> | <i>Skid number</i> | <i>Texture depth (mm)</i> | <i>Field density (kg/m<sup>3</sup>)</i> | <i>Rebound deflection (mm)</i> |      |
|--|---------------------|---------------------------|--------------------|---------------------------|---|--------------------------------|------|
| <b>Design standard (acceptable values)</b>             | –                   | <4000                     | <65                | 0.6 – 0.8                 |   | 0.5 – 1                        |      |
| <b>Typical construction method: plain bitumen road</b> | 2002                | 5200*                     | 76*                | 0.83*                     | 2.86                                    | 1.55*                          |      |
|  | Jumbulingam Street  | 2002                      | 2700               | 41                        | 0.63                                    | 2.55                           | 0.85 |
| <b>Roads constructed using waste plastics</b>          | Veerabadhra Street  | 2003                      | 3785               | 45                        | 0.7                                     | 2.62                           | 0.6  |
|  | Vandiyur Road       | 2004                      | 3005               | 41                        | 0.66                                    | 2.75                           | 0.84 |
|  | Vilachery Road, Mai | 2005                      | 3891               | 45                        | 0.5                                     | 2.89                           | 0.86 |
|  | Canteen Road, TCE   | 2006                      | 3100               | 45                        | 0.65                                    | 2.86                           | 0.86 |

\*Values outside acceptable design parameters shown in red

Some data on the costs associated with the use of waste plastic for the construction of roads in India are presented in Table 2-3.

Table 2-3 Road construction cost data using waste plastic in India

|   |            |
|---|------------|
| Cost of Bitumen   | ~\$670/ton |
| Cost of Waste Plastic   | ~\$230/ton |
| Cost of Shredding Machine and other equipment                   | ~\$955     |
| Optimum amount of waste plastic in the mix                      | ~11%       |
| Cost saved by using waste plastic in road construction (per km) | ~\$670/km  |

\*Source: Vasudevan et al., (2010); Bale (2011); Vasudevan et al., (2012)

MacRebur, a business based in the United Kingdom, has devised a method for incorporating waste plastic into asphalt for road building and surfacing (White and Reid, 2018; White, 2019). Instead of typical bitumen, MacRebur's recycled waste plastic was integrated into asphalt and utilized by Durham County Council in the UK to resurface a portion of the A689 near Sedgfield and the runways and taxiways at Carlisle Airport in the UK. MacRebur was also involved in the development of plastic roads in the United States and Australia (UCSD Guardian, 2018), and is currently building the first plastic road in South Africa (in Kouga Municipality). MacRebur products are the only globally commercialized technique for road construction using waste plastic.

With the help of eight local councils (Buckinghamshire, Bedfordshire, Cumbria, Staffordshire, Kent, Reading, Suffolk, Solihull, and Birmingham), the UK government recently announced an investment of £23 million on plastic road technologies (Department for Transport, 2019). Approximately £1.6 million of this funds will be used to extend a road in Cumbria that is made of recycled plastic mixed with asphalt. A guidance document for the design and specifications of plastic asphalt is another goal of this project (Department for Transport, 2019).

Pavement blocks are made from waste plastic by NelPlast Ghana Ltd, a company that recycles plastic in Ghana. These paving blocks were used to build a road in Accra after receiving approval from Ghana's Ministry of Environment, Science, Technology, and Innovation (AfrikaTech, 2018). Ethiopia, a different African nation, has made significant strides in installing plastic roads. Table 2-4 provides some information on the expenses related to using waste plastic to build roads in Ethiopia.

Table 2-4 Road construction cost data using waste plastic in Ethiopia

|   |           |
|---|-----------|
| Cost of Shredding Machine                                       | ~\$1,545  |
| Cost of Plastic   | \$0.15/kg |
| Optimum amount of waste plastic in the mix                      | 11.5%     |
| Cost saved by using waste plastic in road construction (per km) | 10.06%    |

\*Source: Welegabir et al., (2014)

In the municipality of Zwolle in the Netherlands, a cycle path measuring thirty meters in length that was constructed entirely using prefabricated, modular, and hollow bricks made from recycled plastic is now functioning (Plastic Road, 2018). The municipality of Steenwijkerland is currently hard at work constructing a second route of this kind for cyclists (Plastic Road, 2018). KWS, which is a Volker Wessels firm, Wavin, and Total are currently working on the development of plastic roads for wider applications. They were the ones who came up with the concept, which was created by a consortium (Plastic Road, 2018).

Although the incorporation of plastics into the construction of pavement is a relatively newer concept, it is easily discernible that the use of plastic in road construction across the globe is primarily limited to use in the surface/binder course as a substitute for bitumen. This is the case although the incorporation of plastics into the construction of pavement is a relatively newer concept. The majority of the research projects that have already been carried

out on the viability of using plastic wastes as pavement materials are focused on the prospect of plastics being used as a binder material for the surface course. However, the utilization of recovered plastics on a broad scale can be secured through the utilization of appropriately shredded plastic particles as a substitute material for pavement base or base, even with a small fraction of the material. If added with the traditional constituent base materials in a very limited proportion, i.e., 3%, 5% of shredded plastics replacing same amount of other conventional (gravels, coarse aggregates), or non-conventional (RCCA, RAP, CDM) base materials, even laying the base or base of a small road section can use up a substantial number of shredded plastics. This is the case even if the proportion of shredded plastics added with the traditional constituent base materials is very Having said that, the implementation of a novel alternative inside an existing engineering design always necessitates the provision of a solid justification that is supported by engineering feasibility, economic dividends, and, most significantly, environmental welfare. As a result, the concept of a "Integrated Plastic Road" emerged, which ensures the maximum utilization of waste plastics in pavement construction while simultaneously limiting the negative effects on the surrounding environment.

## 2.6 Environmental Concerns of Using Recycled Materials

Successful and sustainable use of alternative materials to be used in any type of construction depends on three components; popularly termed as three E's; i.e. Engineering, Economics, and Environment. Highway and/or pavement constructions are no exceptions. However, in many cases environmental impacts associated with the construction is overlooked.

Along with the proposition of using non-conventional recyclable materials in place of virgin materials for pavement construction, environmental concern automatically comes into play. Since, plastic is by nature is deemed to be potentially threatening to geo-environment either in the form of undefined state, or in the form of more complex microplastic structure, it is customary to scrutinize all possible potential hazards associated with plastic use, and ensure a safe, reliable, environmentally sustainable measure to use recycled plastics as an alternative to virgin materials in pavement construction. Environmental assessment could be performed through a set of leaching tests to determine the parameters, i.e., pH, COD, TDS, TSS, Specific Conductance and compare the results with the stipulated benchmark (Hoyos et al., 2008). U.S. Environmental Protection Agency (2005) has set the benchmark of storm-water sampling as derived from the pavement runoff, and seepages. (“Benchmarks for storm-water sampling.” Business Environmental Resource Center, City of Sacramento, California).

Table 2-5 Benchmark of Environmental Parameters (USEPA)

| Test                 | Standard Test Method |       | USEPA Acceptable Limit |
|----------------------|----------------------|-------|------------------------|
|                      | ASTM                 | USEPA |                        |
| pH                   | D1293-18             | 150.1 | 9-10                   |
| COD                  | D1252 - 06           | 410.1 | 120 mg/L               |
| TDS                  | D5907 - 03           | 160.1 | 500 mg/L               |
| TSS                  | D5907 - 03           | 160.2 | 100 mg/L               |
| Specific Conductance | D6764 - 02           | 120.1 | 500 $\mu$ mhos/cm      |

In general, most of the past research have been taken notice of the most used recycled materials (Construction & Demolition materials in the form of RCCA, Recycled Asphalt Pavement) (Construction & Demolition materials in the form of RCCA, Recycled Asphalt Pavement). Research efforts on the prospective environmental implications of recycled plastics induced highway pavement materials are nearly nonexistent. Nevertheless, the same method can also be used to examine the potential geo-environmental consequences in the area of recycled plastic-induced pavement materials. Nonetheless, this strategy has a few obstacles, such as the potential variation in leaching behavior between traditional recycled materials and recycled plastics, the difference in surfactants and inherent pollutants, and their separate interactions with the surrounding environment. Evaluation of the environmental impact of recyclable unusual materials used in pavement construction has long been a complicated problem. However, to make things simpler, and less complicated, classic way of measuring the leaching in terms of fundamental criteria (pH, COD, TDS, TSS, Turbidity, Specific Conductance) would be a decent option to have an idea about the margin of the severity.

Incorporating waste plastic into pavement construction increases the risk of microplastics coming from the systematic breakdown of the plastic being utilized or as an intrinsic component of other relevant materials. While environmental assessment in terms of a few known characteristics is a straightforward process according to standard experimental procedures, characterization of the microplastic danger of the plastic road is a difficult operation. Since the practice of reusing recycled plastic in pavement engineering is still in its infancy, it is not surprising that microplastic risk assessment is essentially nonexistent in studies. Detection, quantification, and risk characterization of microplastics are relatively recent areas of scientific study.

## 2.7 Microplastics

Microplastics are so prevalent that many scientists view them as important indicators of recent and current times since they are present everywhere in the world. A new historical era known as the plasticine epoch resulted from this. But it is still unclear exactly what microplastics do to the environment (Claudia et al., 2020). It is difficult to determine how they affect the environment because of their continually varying physical and chemical features, which make them stressors with a wide range of effects. On the one hand, microplastics spread harmful compounds throughout ecosystems. In contrast, they are a complex mixture of hazardous chemicals that are themselves added as additives during production to enhance the polymer's qualities and lengthen its life. Many aspects of the primary additives of concern utilized in the plastics industry, what happens to them when microplastics wind up in the environment, and how they could harm human health are still unknown.

Over the past ten years, the amount of microplastic debris discovered in freshwater and saltwater ecosystems has increased, raising concerns. However, the impacts on human health are still little known. The effects of microplastics on aquatic animals are becoming more interesting (Thompson et al., 2004, Browne et al., 2007). Spherules were discovered in plankton tows off the coast of New England in the 1970s. The first microplastics to be discovered in North America were these (Carpenter et al., 1972). Since then, microplastics have been discovered in the majority of significant bodies of water (oceans, seas, lakes, and rivers).

Polymeric granules smaller than 5.0 mm are referred to as microplastics (Arthur et al., 2009). Although the lowest limit (size) of microplastics is not precisely defined and measured, it is more generally accepted practice to use the neuston nets' mesh size (333  $\mu$ m or 0.33 mm) to gather the samples (Arthur et al., 2009). Primary and secondary microplastics are the two main

types of microplastics that can form and enter a body of water (Arthur et al., 2009). Primary microplastics are made from produced raw materials such virgin plastic granule pellets, scrubbers, and microbeads that are widely used in daily care items and other types of toiletries and enter the ocean via surface runoff from land (Browne et al., 2007, Arthur et al., 2009). (Andrady 2011). When bigger plastic products (meso- and macro-plastics) experience mechanical, photo- (oxidative), biological, and/or weathering deterioration over time, secondary microplastic introductions take place (Thompson et al., 2004, Browne et al., 2007, Cooper and Corcoran 2010, Andrady 2011). The larger pieces of plastic break down into smaller and smaller fragments as a result of this degradation, until they are finally so small and insignificant that they cannot be seen with the unaided human eye.

Microplastics are used in countless applications. For instance, exfoliants in face scrubs, face washes, body lotions, and face creams are among the daily-use personal care items that include microbeads. In some of the frequently utilized medical applications, even microplastics are used to deliver medications (Browne et al., 2007). Additionally, microplastic granules make up the majority of the fibers lost from synthetic rope and clothes (Thompson et al., 2004, Browne et al., 2007), as well as the particles used in the "media blasting" process to clean boat hulls and large appliances (Browne et al., 2007). Many of these minute grains, microplastics, and microbeads are small enough to easily bypass wastewater treatment systems and infiltrate a watershed (Browne et al., 2007). Microplastics have been discussed by several researchers in various ways. The biggest obstacle in the field of microplastic research is the lack of a quantified and sternly accurate lower limit of dimension to define microplastics, despite the fact that it is more widely accepted that plastic granules with any known (longitudinal) dimension of less than 5 mm can be referred to as microplastics. Because a more universal



methodology to identify microplastics has not yet been developed, there is unnecessarily great complexity. In addition, different studies have developed diverse viewpoints when characterizing microplastics. According to several viewpoints, the definition of microplastics is summed up in the following figure.

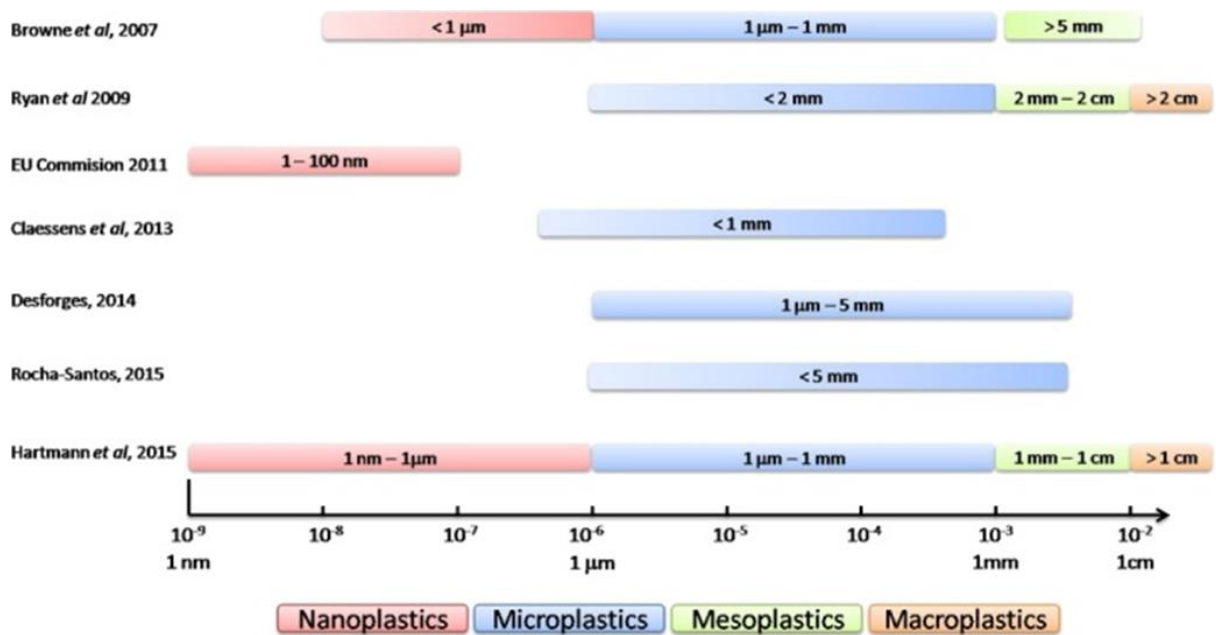


Figure 2-5 Definitions of microplastic (Pico et al., 2019)

Microplastics come in a variety of shapes, including as spheres, pieces, and fibers. The majority of microplastics, with the exception of purposefully created microbeads and granular polymer pellets, are caused by the degradation of bigger plastics (macro-plastics). Over time, microplastics break down into smaller and smaller pieces of trash, eventually taking the form of tiny nano-plastics (1 m; Lambert & Wagner, 2018; Hartmann et al., 2019). Microplastics are, thus, the optimal intermediate quasi-state between macro trash and nanomaterials. According to Besseling et al 2018 .'s analysis, the progressive and long-term fragmentation of spherical microplastics could produce >10<sup>14</sup> times more nano-plastic particles that are ready for exposure to the environment.

### **2.7.1 Nature of Microplastics**

Most of us think that all plastics are made of the same basic materials and will act the same way in the environment because of this. However, this is not true. To fully understand how microplastics behave, where they go, and what happens to them, we need to look at their composition, microstructures, and diversity. Microplastics in the environment are hard to find because they are small and hard to see. This is a multifaceted problem that hasn't been solved with much precision and accuracy yet. Their existential complexity is the same as that of naturally occurring organic particles (Hoellein et al., 2019). Plastics (and, by extension, microplastics) are very different in terms of their chemical structure, size, texture, color, and shape. These things change or get better as they are used and after they are thrown away.

Microbeads in personal care items and industrial abrasives are prominent examples of designated primary microplastics, which also refer to microplastics that are intentionally produced. Microbeads are also widely employed in cleaning agents, coatings, paints, drilling fluids mostly found in the oil and gas industry, and as precursor resins and pellets in the production of final plastic products. The Microbeads Free Waters Act of 2015 was enacted in the United States to exclude microbeads from rinse off personal care products (McDevitt et al., 2017), but not from items that do not require rinsing (e.g., sunscreen and cosmetics) or industrial applications. In several regions of the world, similar restrictions have been implemented. As indicated before in this chapter, secondary microplastics are created by the systematic fragmentation of larger plastic plastics during and/or after use (e.g., tire wear particles) or disposal. However, secondary microplastics are significantly more prevalent in the environment than primary microplastics. The environmental halflives of plastics vary greatly by polymer type and ambient conditions, ranging from days to centuries (Ward et al., 2019).

Andrady (2017) hypothesized that the majority of plastic fragmentation occurs on land as a result of elevated ambient temperatures, frictional forces, and ultraviolet (UV) exposure. Despite growing global concern, the real quantity of plastics (microplastics) in several environmental compartments (terrestrial, marine, freshwater, and air) as well as their biological relevance remain unclear.

### **2.7.2 Microplastics from Degradation of Plastics**

Plastics are generally vulnerable to varying degrees of deterioration. Chemical disintegration of the big polymer particle as a result of exposure to sunshine (the primary source of ultraviolet radiation) is frequently the most significant catalyst (Andrady, 2015). As previously stated, additives can influence the deterioration process. For example, Weinstein et al. (2016) hypothesized that natural or artificial biofilm growth on plastic surfaces could have inhibited UV radiation penetration by as much as 99 percent. In contrast, Khaled et al. (2018) observed that the introduction of brominated flame-retardant chemicals into polystyrene film could have resulted in enhanced UV absorption and subsequent photooxidation of the polymer, leading to a quicker disintegration. The amount of breakdown products potentially leached into water can account for up to 14% of the original polymeric film's weight. UV-induced breakdown of polymers may potentially increase their susceptibility to eventual biodegradation. Most commonly, it is hypothesized that when particle size reduces and surface area increases, environmental reactivity would increase, leading to greater disintegration of bigger plastic particles. Due to increased biodegradation, this process will ultimately result in a large drop in total mass (Hale et al., 2020).

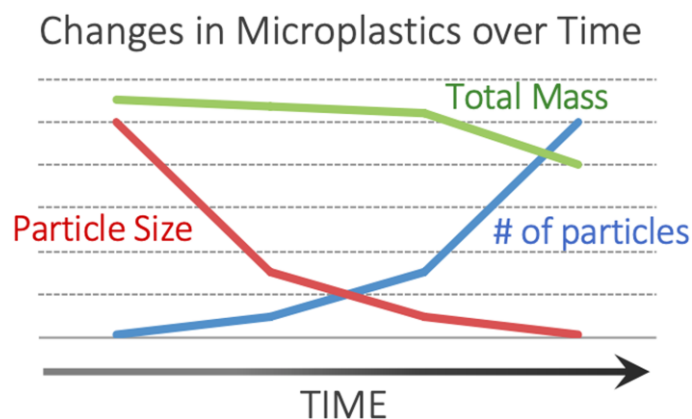


Figure 2-6 Proposed relationship between microplastic size, particle number, and total mass over time (Hale et al., 2020)

Several polymers are composed of uniform monomers derived from renewable, nonpetroleum sources, for example, rayon and cellulose acetate (widely used in regular textiles and cigarette filters). Hartmann et al., (2019) included these as “plastics,” albeit other researchers have agreed upon excluding them owing to their conspicuous cellulose-derived origin. Additionally, polyhydroxyalkanoate present in bacterial precursors and polylactic acid found in plant starch have recently been produced to be more inherently biodegradable (Harrison et al., 2018). The goal is to make sure of complete degradation to CO<sub>2</sub> after the end of product service life, since incomplete breakdown could generate intermediate substances of unknown properties, as well as microplastics. As already stated, polymer biodegradation rate increases as particle size decreases and reverse-proportionately surface area increases (Chinaglia et al., 2018), although this has not been well investigated and scrutinized meticulously under marine conditions. This condition may be an important factor in long-term fate of microplastics in the environment. Characteristics of the surrounding environment are also controlling factors of microplastic presence in the environment. (Dilkes-Hoffman et al., 2016). For example, most of the biopolymers mentioned in the discussion so far are denser than water and hence will sink. There, it may be subject to lower ambient oxygen levels, temperature, and light exposure, ultimately decelerating the subsequent rate of degradation.

It's interesting to note that a number of recent scientific studies suggested that some microbes may be able to break down synthetic polymers derived from petroleum as a necessary physiological function. For instance, Yang et al. (2015) discovered that mealworms' gut bacteria may gradually break down polystyrene, albeit residues are left behind. According to Yoshida et al. (2016), microorganisms exposed to polyethylene terephthalate in a recycling facility may develop enzymes that, in time, may cause the plastic granules to break down into their individual monomers (counter mechanism). This counter-mechanistic method of polymer to monomer transformation may be more resistant to polymers with higher crystallinity, such as polyethylene. However, Brandon et al. (2019) found that active mealworms degraded polyethylene and polystyrene at very similar rates, and they suggested that this was made possible by ongoing microbial adaptation. To combat this transition, several manufacturers have added antibacterial chemicals to their products, such as triclosan. Alternately, additives (such as transition metals) are added to the so-called oxo-degradable polymers to hasten the polymer oxidation and subsequent plastic fragmentation (Ammala et al., 2011). This was initially marketed as an attractive feature for plastic sheeting, which was successfully employed to prevent weed growth and maintain soil moisture and temperature in crop cultivation. Plastic sheeting is also known as plastic mulch or plasticulture (Steinmetz et al., 2016). In light of the fact that the biodegradation of the remaining plastic has been discovered to be remarkably slow and ultimately to release microplastics, the European Union (EU) has proposed limiting their use (European Union, 2018). However, a recently developed polymer known as poly(diketoenamine) was created and was easily disassembled into its component monomers without experiencing any adverse counter-mechanistic effects (Christensen et al., 2019). As a result, reuse is significantly more flexible, and there are more opportunities to remove undesirable additives from previously used applications, as we've already covered.

### **2.7.3 Major Sources of Microplastics**

There is no way to get around the undeniable truth that there are microplastics present everywhere. They are literally there in every single place. It is becoming increasingly difficult, and in some cases even impossible, to avoid being in its presence. They have insidiously and imperceptibly encircled us in a vicious circle from which we are unable to escape. Plastics are made, utilized, and most commonly disposed of on or into soils as their initial disposal location. Plastics that are found at the soil's surface are more susceptible to damage from the sun's ultraviolet rays, recurrent abrasion, and ambient temperatures than materials that are submerged in water (Ng et al., 2018). Microplastics, once they have entered soils, are able to quickly permeate vertically by water movement (O'Connor et al., 2019). This process is further encouraged by wet/dry weather cycles or tilling (Rilling, et al., 2017), as well as by the catalytic actions of soil organisms (Rillig et al., 2017). According to a study that was carried out by the International Union for the Conservation of Nature (IUCN), the majority of the ocean's principal microplastics come from products that are regularly used by consumers. This is something that should be brought to your attention (IUCN). These consumer goods generally consist of manufactured fabrics made from synthetic materials. Abrasion of vehicle tires, city dust, road markings and signs, paints, personal care items, plastic pellets, and other things are also among the most common sources of primary microplastics.

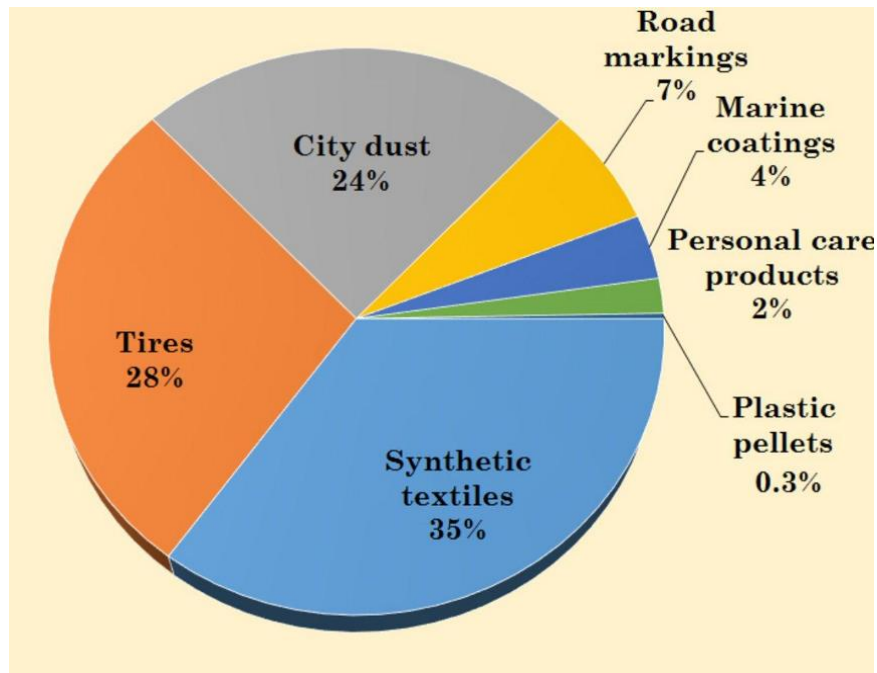


Figure 2-7 Major sources of microplastics (IUCN)

The following image portrays the major sources of microplastics found in the environment. However, this pie chart is not the exclusive one to portray the origins of microplastics but surely delineates the actual scenario.

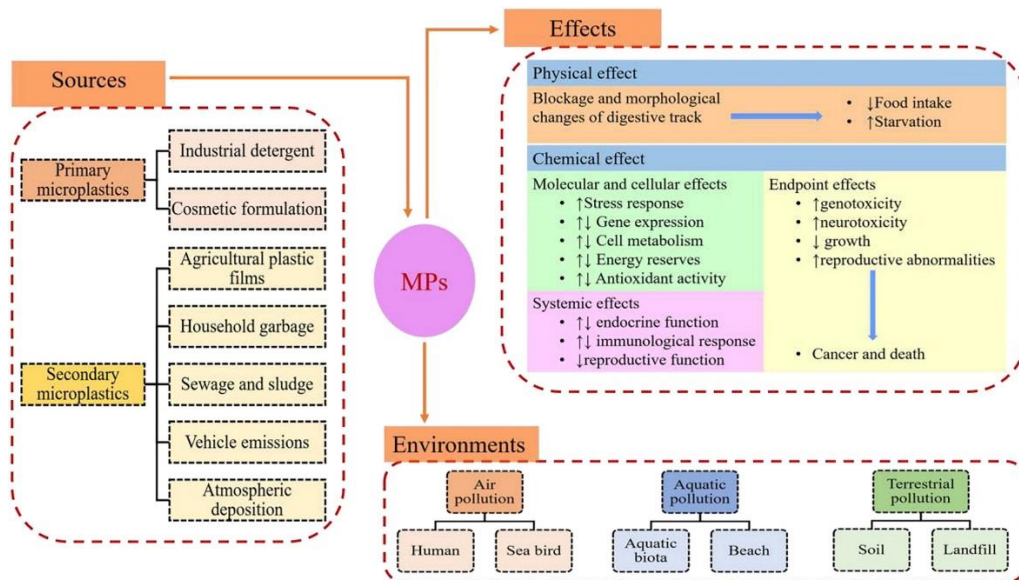


Figure 2-8 Summary of microplastic sources and impacts (Shuo Xiang et al., 2022)

### *2.7.3.1 Landfills and Dumps*

In affluent nations, the majority of plastics end up in landfills via accident or necessity. However, even wealthy nations have had significant problems with off-site trash leakage and improper waste management. In 1987 and 1988, medical waste (the infamous "syringe tide") was spotted on local beaches as a result of activities associated with the New York City-serving Fresh Kills landfill (Sheer & Moss, 2011). In the majority of underdeveloped countries, open dumps are located in lowlying areas, as such lands have low values due to the risk of flooding, and these open dumps are not engineered like landfills in rich countries. As the sea level gradually rises, these areas will become more susceptible to floods and erosion, resulting in the release of extra plastic garbage. Following natural catastrophes such as hurricanes, tsunamis, and wildfires, construction and demolition (C&D) landfills frequently become breeding grounds for debris. However, these dumps are often less precisely designed and monitored than municipal landfills. In comparison to other types of waste, construction and demolition debris (C&D rubbish) is generally regarded to be less harmful to the environment; yet, it may contain significant quantities of plastics (such as insulation and furniture) with high concentrations of additives. The United States produced between 610 and 780 million tons of construction and demolition debris in the year 2002, compared to 214 million tons of municipal solid rubbish (Powell et al., 2015). As a consequence of this, leachates and erosion caused by C&D landfills may also contribute to the presence of microplastics and additives in the environment.

### *2.7.3.2 Burning of Plastics*

In developing countries, and even in developed countries sometimes plastic trash and e-wastes are incinerated under poorly controlled conditions liberating contaminants (Gullett et al., 2007). Releases of microplastics and additives because of these, as well as wildfires, have



been inadequately examined. In the U.S. in 2016, 1.3 million fire incidents took place (<https://www.usfa.fema.gov/data/statistics/#causesR>). A total of 347 fire incidents at waste and recycling facilities were reported in different parts of North America from April 2017 to 2018 alone (Ibrahim, 2022). On top of that, wildfires are increasing in frequency worldwide with the growing surge of worldwide climate change (Keeley & Syphard, 2018). These fires engulf homes, businesses, and vehicles consisting of abundant polymeric materials. The charred, melted, disintegrated plastics may be transported offsite and eventually into waterways. Airborne particulates through these fire incidents may also be produced and understandably include plastic additives. For example, Ni et al., (2016) reported that airborne particulates and residual ash exhibited substantial mg/kg concentrations of flame-retardant polymer particles after plastic wastes were subject to incineration (controlled or uncontrolled). Dust collected from New York City streets following the 2001 World Trade Center terrorist attack quintessentially contained flame retardant polymer additives (Lioy et al., 2002). Resulting particulate matter may be insignificant in size (<2.5  $\mu\text{m}$ : PM<sub>2.5</sub>) and can easily penetrate deeply into respiratory tracts of air breathing organisms, including humans.

#### *2.7.3.3 Abrasion of Tire*

Another important source of microplastics to terrestrial ecosystems is from vehicle tire abraded against the pavement surface. In present days, vehicle tires contain fillers, additives, metallic and polymeric fibers, and natural and synthetic rubbers (most commonly butadiene and styrene-butadiene polymers). Kole et al., (2017) estimated that in the U.S. per capita tire wear microplastics is 4.7 kg/year which is in turn equivalent to 1.8 million metric tons/year. These researchers postulated that tire wear may contribute 5–10% of global ocean plastics loading, as well as 3–7% of PM<sub>2.5</sub> in urban air. Transportation of these polymeric micro-

substances to waterways may transpire via surface runoff, further exacerbated by the impermeability of road surfaces. Alternatively, tire wear fragments can also enter sewer systems and then easily into wastewater treatment plants. Locally, amounts of abraded microplastics released will vary depending on number of vehicles, demographic factors, socio-economic variations, miles driven, climate, and topography. An estimate for the OSPAR catchment (essentially, the European countries bordering the North-East Atlantic Ocean) suggested that the amount of microplastics transported to local marine environments from tire wear can be compared to land-based litter. A recent study (Yale Environment 360, 2021) Published at the Yale School of the Environment opines that the largest source of microplastics on the planet is indeed abrasion of tires which is highly debatable but surely significant.

#### *2.7.3.4 Paint and Coatings*

Paints and surface coatings do contain polymers. Painted surfaces include structures, roadway markings, and vessels and are subject to gradual weathering. Abrasive blasting (occasionally using microbeads) prior to repainting or repairing of surfaces will also generate microparticles. Paint often consists of metal-based pigments (e.g., Cu and Zn). Takahashi et al., (2011) observed that up to 0.2% of the mass of cored sediments from the Plymouth estuary (UK) contained significant polymeric paint particles. Song et al., (2015) investigated and examined microplastics in waters of Jinhae Bay, Korea. They surprisingly reported that the prevalence of paint particles exceeded those of other microplastic types and that size frequencies peaked in the 50 to 100  $\mu\text{m}$  range. They indicated that alkyd ship paint resins and poly (acrylate/styrene) from fiberglass resins were the most common polymer types present there. Chae et al., (2015) published similar findings for the Incheon/Kyeonggi coastal region (Korea) as their Chinese counterparts. They further estimated that such slicks represented only

8.3% of ocean surface habitat in a coastal Hawai'i ecosystem but contained a staggering 91.8% of overall floating plastic present within the scope of the study. They also observed that the paint particles typically were smaller than other types of microplastics, mostly 1 to 50  $\mu\text{m}$ , likely due to their characteristic brittleness.

#### *2.7.3.5 Microplastics from Fabric Washing*

Habib et al. (1998) was one of the first to propose that synthetic fibers, primarily coming from textile washing, may be utilized as tracers of wastewater effluents. It should also be mentioned that, due to discrepancies in collected medium and analytical procedures, researchers are not yet in agreement over the microplastic kinds that dominate the environment. However, the International Union for the Conservation of Nature (IUCN) rated synthetic textile washing as the primary source of microplastics, accounting for 35% of the microplastic burden in the world's oceans (Boucher & Friot, 2017). In their 2016 study, Napper and Thompson found that approximately 700,000 fibers might be liberated from a 6 kilogram wash load of acrylic fabric. Browne et al. (2011) analyzed washing machine wastewater samples and found that a single garment might yield more than 1,900 fibers each wash load. The microplastics can subsequently be introduced into septic systems or transferred to wastewater treatment facilities for further processing. However, in undeveloped and underdeveloped nations, textile wastewater may enter streams without being treated. In a simulated aquatic environment, Zambrano et al. (2019) found that polyester biodegrades more slowly than naturally recognized fibers such as cotton, polyester/cotton, and rayon. In comparison to cotton and polyester/cotton mix fibers, Bajpai et al. (2011) found that microbial adhesion to polyester fibers was low. Schreder and La Guardia (2014) discovered various polymer additives uncommon in garments (e.g., a formulation of PentaPBDE used primarily in polyurethane foam) in laundry wastewater.

Airborne microplastics attaching to garments were determined to be transferable to laundry wash water. In addition, they observed that the removal rates of hydrophilic polymer additives (such as chlorinated phosphate esters) in laundry wastewater were 16% following a process at a wastewater treatment plant. After wastewater treatment, hydrophobic additives (such as PBDEs) were removed at a rate of greater than 86%. Eventually, the hydrophobic additives could be transported to soils via biosolids applied to land.

#### *2.7.3.6 City Dust; Atmospheric Source of Microplastics*

City dust, which roughly accounts for 24 percent of microplastics in the environment comes from a variety of sources. While each is a small contributor, it piles up in a significantly populated area. Weathering, abrasion, and disintegration create city dust from manmade products. City dust consists of losses from the abrasion of objects like synthetic soles of footwear and synthetic cooking utensils, the abrasion of infrastructure like household dust, artificial turfs, harbors, road coatings, demolition of superstructures. Scientists recorded 365 microplastic particles per square meter falling daily from the sky in the Pyrenees Mountains in southern France which is not even a heavily polluted industrial area situated at a place 60 miles from the nearest city.

#### *2.7.3.7 Personal care products*

Many personal care and cosmetic products contain a type of engineered microplastic known as microbeads which in fact the most prevalent primary microplastic present in the environment. These products include scrubbing agents, shower gels, creams, face wash, body lotions etc. Although, the U.S. government banned manufacture and sale, but producers still make and sell these products globally. Microbeads are basically engineeringly manufactured polyethylene primary microplastic. It normally acts as an exfoliant, delivers active ingredients,

and controls the required viscosity in health and beauty care products. Researchers have found that up to 10 percent of some personal care product's weight is plastics which is staggering percentage if we think about the aggregate worldwide production of these kinds of products. Even, some items have several thousand microbeads per gram of product. Once the personal care item is used, it ends up in landfills, open dumps and /or wastewater. These tiny particles readily pass-through water filtration systems and end up in surface waterways.

#### *2.7.3.8 Plastic pellets*

Manufacturers produce several plastics in the shape of pellets or powders, another important primary form of microplastic. These producers then transport the powdery pellets to plastic transformers that make different kinds of plastic products. Pellets can inadvertently find their places in the environment during manufacturing, processing, transport, and repurposing. According to IUCN findings, plastic pellets make up 0.3 percent of the microplastics present in the environment. Recently in 2019, the State of Texas fined a renowned Texas plastic manufacturer of more than \$120,000 after spilling thousands lentil-sized plastic pellets or “nurdles” into a creek and bay on the Gulf Coast. Nurdles can absorb dangerous industrial and consumer chemicals including insecticides, and mercury. The pellets can easily clog the digestive systems of marine animals if ingested for food, and eventually cause them to starve to death. Nurdles can also degrade into smaller sized nano-plastics further down the line.

#### *2.7.3.9 Wastewater Treatment*

Industrial and domestic effluents contain significant amounts of microplastics, and polymer additives derived from consumer products (Schreder & La Guardia, 2014). In developed countries, wastewaters and storm water runoff from urban areas are typically routed to centralized treatment facilities to make it less harmful for the environment before they are

eventually exposed. The treated effluents are eventually then discharged to receiving waters. Even after meticulous treatment, it is not entirely possible to get rid of the microplastic particles. Some effluents, however, particularly in arid areas, are reused for irrigation. Microplastics therein are then easily introduced to soils. To a positive nortion, some wastewater treatment plants have instituted additional cleanup steps and have rebranded themselves “water reclamation facilities”, yet the risk of microplastic contamination is still on the card. Microplastic fate during wastewater treatment is primarily influenced by particle densities and configuration from the microstructure perspectives. Most treatment facilities employ an initial screening of influent to eliminate macro debris and settling to remove dense sand, unwanted macro particles and grit. These byproducts are normally sent to a landfill or open dump. The next step (termed “primary”) typically includes surface skimming and solids settling in an engineered settling pond. Secondary treatment incorporates aerobic digestion of labile organic matter and additional solids settling. A polymeric or inorganic flocculant is often added to improve particle sedimentation as part of the secondary treatment procedure.

Microplastics are sequestered into the settled solids to multiple extents by these steps, with overall treatment removal rates of 90–99% in well-designed systems (Carr et al., 2016). Murphy et al., (2016) noted that most of the buoyant microplastics, including most microbeads from personal care products, were entrained in the floating grease fraction irrespective of the overall efficaciousness of the treatment system. They observed that roughly 78.3% of microplastics were removed during primary treatment, while secondary treatment resulted in removal of 20.1%. Exclusion of oil and grease and primary sludge from land-applied materials would thus significantly lower the amount of microplastics transferred to soils. While facilities rarely implement steps aimed specifically at microplastics removal, interest is increasing. For

example, Talvitie et al., (2017) evaluated several advanced options: disc filter, rapid sand filtration, dissolved air flotation, and membrane bioreactor could be deployed to increase the overall efficiency of the treatment system.

#### **2.7.4 Microplastic Risk Characterization**

Human risk and ecotoxicological risk are the two categories that best describe the risk associated with microplastic pollution. Microplastics are pervasive throughout ecosystems, but the human exposure danger remains uncertain. (Kieran et al., 2019). Measuring the potential detrimental effects of plastics on people is far more challenging than on animals; unlike chickens and fish, human subjects cannot be purposely fed plastics. (National Geographic Year 2022) Microplastics have been found to cause damage to human cells in the laboratory, including allergic reactions and cell death. To date, however, there have been no large-scale epidemiologic investigations showing a link between exposure to microplastics and adverse health effects. Instead, research has been conducted on small groups of individuals, limiting the ability to make conclusions beyond recognizing the presence of microplastics in distinct areas of the body. A 2018 study discovered microplastics in the stool of eight individuals. Another study found microplastics in the placentas of newborn babies. Recent research by Vethaak and colleagues discovered plastics in the blood of 17 of 22 healthy blood donors; the lung investigation discovered microplastics in 11 of 13 lung samples obtained from 11 patients. Virtually nothing is known about either group that would aid in determining the level and duration of exposure, two of the most important factors in determining injury. Therefore, it is understood that there is strong evidence indicating the presence of microplastics in human cells, despite the fact that the degree of the microplastics' adverse physiological effects has yet to be determined.

Contrariwise, hundreds of study articles have been published on the ecotoxicological harm posed by microplastics in the known environment. This remark is supported by the fact that macroinvertebrates and microorganisms are more likely to be exposed to microplastics in the environment and can be cultivated in a microplastic-rich environment for research purposes. In these investigations, microorganisms are indiscriminately exposed to microplastics to determine the unfavorable effects, i.e., reproductive, physiological, metabolic, or a combination of all three, caused by microplastic concentration.

To examine the risk associated with microplastic concentration, a benchmark or standard must be established for measuring the level of contamination. As with any other toxin present in the ecological or natural environment, the presence of microplastics is evaluated based on the Risk Characterization Ratio, abbreviated as RCR. The majority of microplastic risk assessment focuses on the effects on marine microorganisms. No risk evaluation of microplastics in freshwater has been conducted in a comprehensive manner. Despite this, the risk of microplastics to the freshwater ecosystem should be more closely associated with the use of plastics in pavement construction.

In 2019, however, three researchers from the Swiss Federal Laboratories for Materials Science and Technology, namely Veronique Adam, Tong Yang, and Bernhard Nowack, completed a comprehensive risk evaluation of microplastics in freshwater environments. They chose their model microorganism species such that freshwater macroinvertebrates and macroinvertebrates are adequately represented, and so that the experimental population has similar features to their marine counterparts exposed to a particular microplastic concentration (Veronique Adam et. al., 2019).



The primary objective of this investigation is to analyze all known exposure and ecotoxicity data for microplastics in freshwaters and to do a preliminary probabilistic risk assessment. The distribution of exposure likelihood is based on 391 concentrations recorded in Asia, Europe, and North America. Since exposure data are predominantly available in particle number-based metrics while hazard study results are predominantly mass-based, the hazard outcomes were translated to particle number concentrations. A statistical study of the hazard data revealed that neither particle shape nor polymer type significantly affected the No-Observed-Effect Concentration (NOEC). The computed NOEC is then used to determine the Predicted No Effect Concentration (PNEC), which is the foundation for calculating the Risk Characterization Ratio, abbreviated as RCR.

#### *2.7.4.1 Probabilistic exposure assessment*

The analysis comprised of 391 measurements of the presence of microplastic in freshwaters, of which 56% were reported from North American locales, 28% from Asian locations, and 16% from European locations. Within Europe, samples were taken in Germany (10%), Austria, the Netherlands (3% each), Switzerland (25%), France (34%), and Italy (25%). China (86%) and Vietnam (6%), both in Asia, provided the samples. 81% of the samples from North America were taken in the United States, and 19% were taken in Canada. Data were available for the Yangtze River, the river with the worst plastic pollution (Lebreton et al., 2017), but none were available for other severely polluted rivers such the Ganges in India and the Amazon in South America. In a broader sense, it might be argued that the scientific community should prioritize sampling rivers in nations where the waste-management systems are frequently insufficiently effective to handle the volumes produced, resulting in the accumulation of plastic garbage close to water bodies. The likelihood that this improperly

disposed-of plastic debris will end up in freshwater, where it can turn into secondary microplastics, is thus very high (Blettler et al., 2018; Khan et al., 2018).

When studies did reveal variability, it was frequently between replicates obtained at the same site and time. Only the tributaries to the Great Lakes in the United States were studied for temporal fluctuation over a year (Baldwin et al., 2016). Spatial variation was evaluated along the Seine River (Dris et al., 2015). In the Great Lakes, the variability of measurement at a certain period within sample stations was evaluated (United States and Canada; Cable et al., 2017). Even though these measured variabilities could occasionally span several orders of magnitude (Lechner et al., 2014; Cable et al., 2017), 59% of the data points used in the current study were not connected to any variability measurements and therefore could not be assigned to any probability distribution. Figure 2-8 shows a cumulative compilation of all data, whether they were probability distributions linked to measurements or single data points with no related uncertainty or variability. From 10,000 runs, we constructed 10,000 cumulative curves. For each measurement, one value was reported every run, sampled from the corresponding probability distribution. The concentration measured was recorded as such if there was no distribution that could be identified. Then, a cumulative curve was shown on the figure made up of all the data collected from a single run-in ascending order. The ranges of microplastic concentrations corresponding to each probability value are shown in Figure 2-9 after this method was repeated 10,000 times.

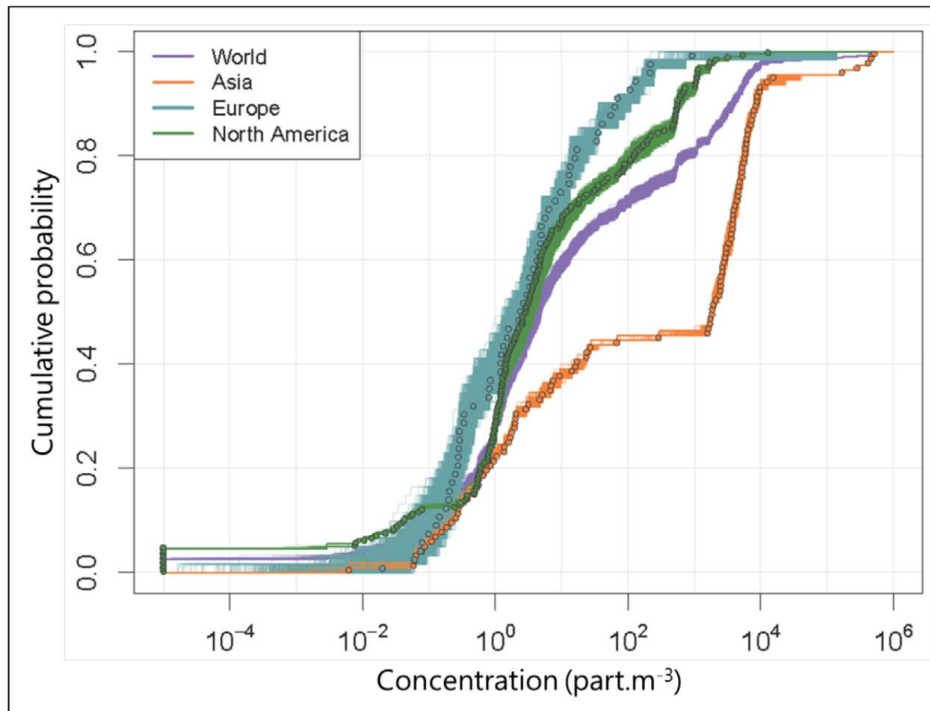


Figure 2-9 Cumulative probability curves of concentrations of microplastics measured in freshwater (Veronique Adam et al., 2019)

Most microplastic concentrations measured were between  $10^{-2}$  and  $10^4$  particles/ $m^3$ . The highest concentrations were found in Asia (up to  $5.2 \times 10^5$  particles/ $m^3$ ). North America presented the lowest concentrations, with many “nondetects,” but also the widest span, with concentrations up to  $1.3 \times 10^4$  particles/ $m^3$ . In Europe, more than half of the concentrations were measured between 0.1 and 10 particles/ $m^3$ .

#### 2.7.4.2 Probabilistic risk assessment

To assess the risk that microplastics might pose in the world’s freshwaters, the probability distribution of the measured concentrations and that of the Predicted No Effect Concentration (PNEC) were plotted on the same graph (Figure 2-10).

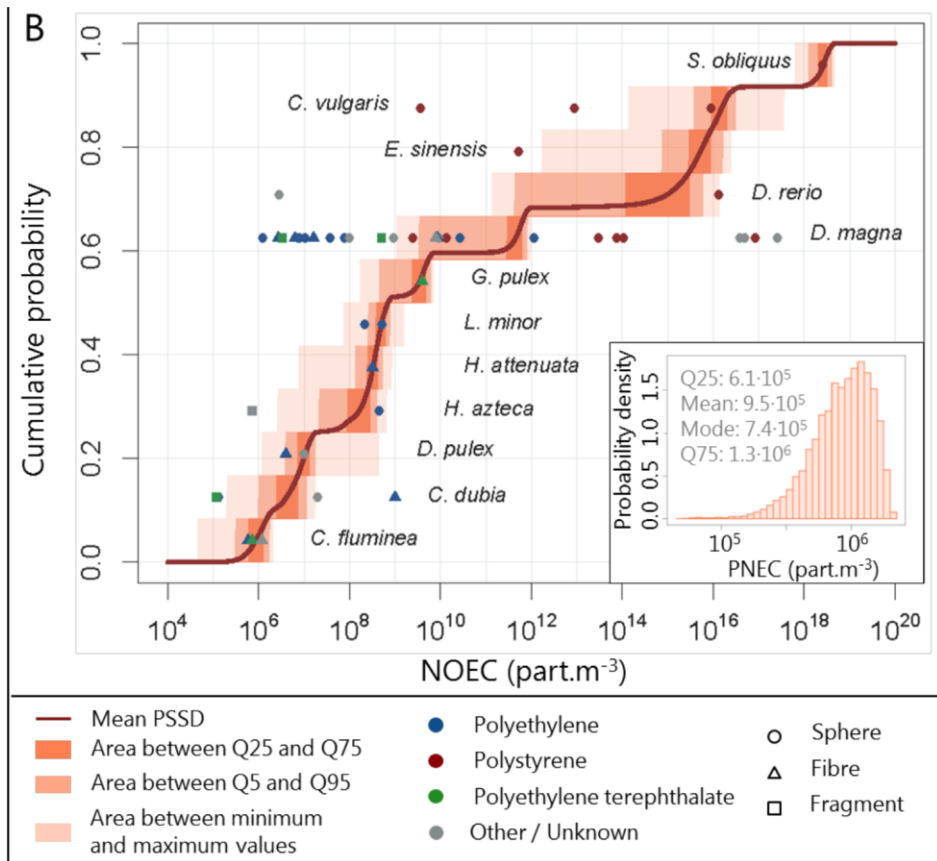


Figure 2-10 Probabilistic species sensitivity distributions and probability distributions of the predicted-no-effect concentration of microplastics in freshwater (Veronique Adam et al., 2019)

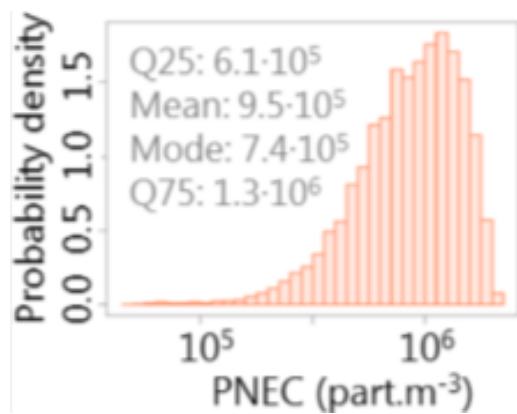


Figure 2-11 Statistical benchmark for PNEC (Veronique Adam et al., 2019)

The probability distribution of the global exposure concentration overlapped to a small extent with the PNEC probability distribution: the range of overlapping values (from the

minimum of the PNEC distribution to the maximum of the measured concentration distribution) represented approximately 23% of the total range of measured concentration and PNEC values combined (from the minimum of the measured concentration distribution to the maximum of the PNEC distribution). Overlapping values ranged from  $3.8 \times 10^4$  (minimum of the PNEC) to  $5.2 \times 10^5$  particles/m<sup>3</sup> (maximum of the measured concentration). Therefore, it cannot be excluded that microplastics represent an ecological risk in freshwater.

#### 2.7.4.3 Risk Characterization Ratio (RCR)

Risk Characterization Ratio acronymically termed as RCR is the fundamental indicator for measuring the toxicity level of any harmful substance present in the natural environment. It is the universal tool used in predicting the risk associated with toxic material. Although, its implications are very diversified depending on the types, quantities, chemical attributes, presence and exposure, the definition of RCR is basically a generalized one.

$$\text{Risk Characterization Ratio (RCR)} = \frac{\text{Measured Concentration (N)}}{\text{Predicted No Effect Concentration (PNEC)}}$$

If  $\text{RCR} > 1$ , measured concentration is likely to pose an immediate or long term ecotoxicological risk (Véronique Adam et al., 2019). In their 2019 study, Veronique Adam and others plotted statistical probability distribution data consisting of the measured concentration, and PNEC concentration on same plot which they used as a benchmark to measure the corresponding Risk Characterization Ratio (RCR).

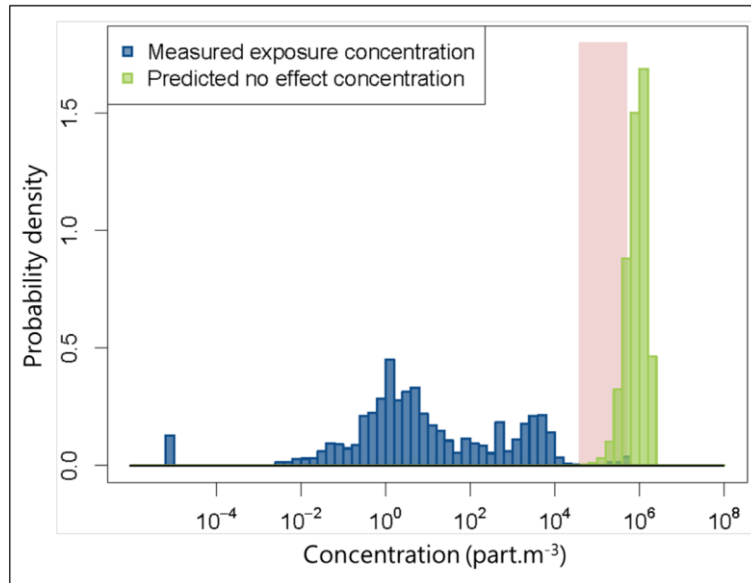


Figure 2-12 Probability distributions of the measured environmental concentration of microplastics and their Predicted No Effect Concentration in freshwater (Veronique Adam et al., 2019)

In the research that Veronique Adam and colleagues carried out, it was found that only a very small percentage of the probability distribution that was estimated for the global RCR was greater than 1. This number was only 0.12%. In Europe and North America, the ranges of the probability distributions were less than one, which indicates that there is now no need for concern in those regions. The mode of the European distribution was found to be  $3.3 \times 10^{-6}$ , while the mode of the North American distribution was  $1.3 \times 10^{-6}$ . However, 0.4% of the RCR probability distribution in Asia was more than one, and this is the reason why the global RCR ranges up to values that are greater than one. Therefore, even though the greatest modal value, which refers to the value with the highest probability of occurring, was significantly lower than 1, an ecotoxicological risk cannot be fully disregarded on this continent.

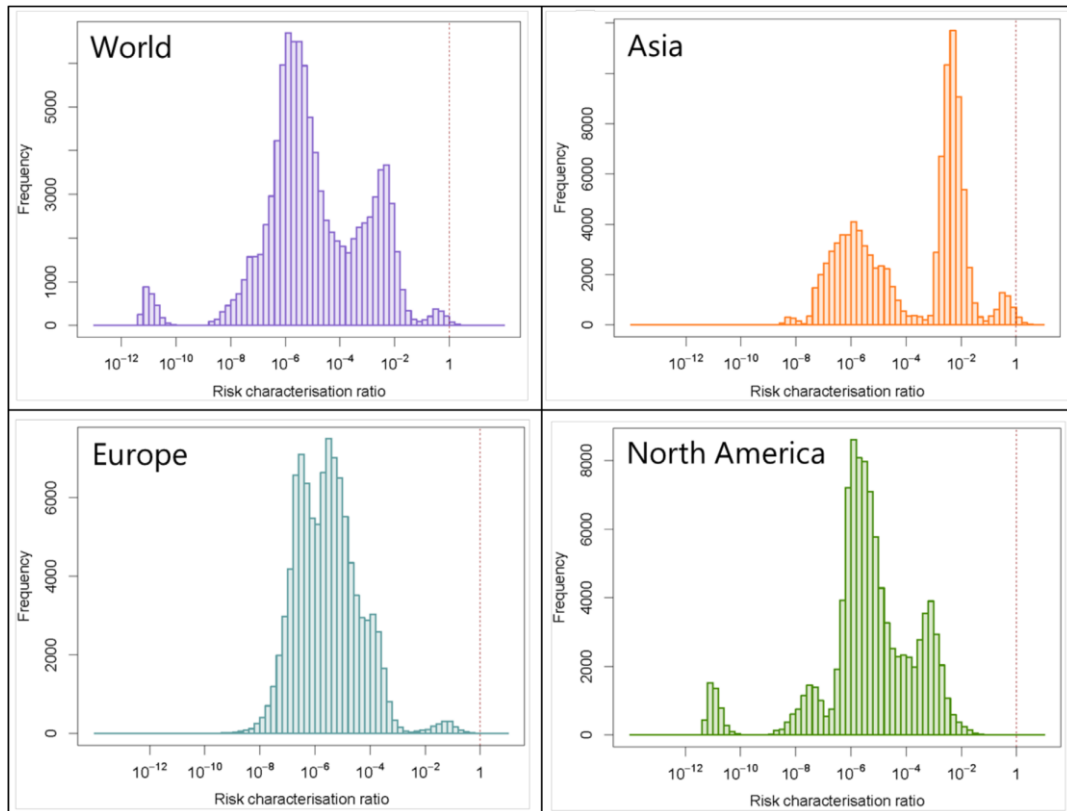


Figure 2-13 Probability distributions of risk characterization ratios in the world, Asia, Europe, and North America (Veronique Adam et al., 2019)

The following table summarizes the statistical distribution of PNEC concentration, and RCR data based on the experimental results measured from the study. (Veronique Adam et. al., 2019).

Table 2-6 Statistical analysis of the predicted-no-effect concentrations and risk characterization ratios associated with microplastics in freshwater

|                          | Unit                              | Q25                  | Mean                 | Mode                 | Q75                  |
|--------------------------|-----------------------------------|----------------------|----------------------|----------------------|----------------------|
| PNEC                     |                                   |                      |                      |                      |                      |
| All data                 | $\mu\text{g} \cdot \text{L}^{-1}$ | $4.4 \times 10^{-2}$ | $8.0 \times 10^{-2}$ | $4.2 \times 10^{-2}$ | $1.1 \times 10^{-1}$ |
|                          | particles $\cdot \text{m}^{-3}$   | $6.1 \times 10^5$    | $9.5 \times 10^5$    | $7.4 \times 10^5$    | $1.3 \times 10^6$    |
| Small particles excluded | $\mu\text{g} \cdot \text{L}^{-1}$ | $4.4 \times 10^{-2}$ | $7.0 \times 10^{-2}$ | $1.0 \times 10^{-1}$ | $1.1 \times 10^{-1}$ |
|                          | particles $\cdot \text{m}^{-3}$   | $6.1 \times 10^5$    | $9.5 \times 10^5$    | $6.3 \times 10^5$    | $1.3 \times 10^6$    |
| RCR                      |                                   |                      |                      |                      |                      |
|                          | Geographical unit                 | Q25                  | Mean                 | Mode                 | Q75                  |
| All data                 | World                             | $9.2 \times 10^{-7}$ | $8.3 \times 10^{-3}$ | $1.8 \times 10^{-6}$ | $3.6 \times 10^{-4}$ |
|                          | Asia                              | $1.7 \times 10^{-6}$ | $2.7 \times 10^{-2}$ | $4.6 \times 10^{-3}$ | $5.7 \times 10^{-3}$ |
|                          | Europe                            | $3.8 \times 10^{-7}$ | $1.2 \times 10^{-3}$ | $3.3 \times 10^{-6}$ | $1.4 \times 10^{-5}$ |
|                          | North America                     | $9.5 \times 10^{-7}$ | $3.3 \times 10^{-4}$ | $1.3 \times 10^{-6}$ | $5.4 \times 10^{-5}$ |
| Small particles excluded | World                             | $9.4 \times 10^{-7}$ | $7.9 \times 10^{-3}$ | $1.9 \times 10^{-6}$ | $3.5 \times 10^{-4}$ |
|                          | Asia                              | $1.7 \times 10^{-6}$ | $2.7 \times 10^{-2}$ | $4.6 \times 10^{-3}$ | $5.7 \times 10^{-3}$ |
|                          | Europe                            | $3.7 \times 10^{-7}$ | $1.1 \times 10^{-3}$ | $3.6 \times 10^{-6}$ | $1.4 \times 10^{-5}$ |
|                          | North America                     | $9.5 \times 10^{-7}$ | $3.5 \times 10^{-4}$ | $1.4 \times 10^{-6}$ | $5.9 \times 10^{-5}$ |

### 2.7.5 Microplastic Analysis

Microplastics research, and microplastic analysis in particular, is still in its infancy. To investigate the fundamental features of microplastics, it is normal practice to harvest MPs from aquatic settings, prepare dry samples, and arrange plastic kinds for identification and chemical investigation. (Kai-Erik Peiponen et. al., 2020). However, it is difficult to recognize plastic particles and measure their size and concentration in the natural environment, outside of a chemistry lab. In natural water bodies, for example, biological tiny particles are also present, and the varying thermodynamic characteristics of water and air can also cause measurement errors.

Microplastic analysis is generally classified into two major categories, i.e., Quantitative Identification, and Qualitative Identification. Irrespective of the identification mode, the sample preparation and pretreatment are similar. Most basic steps to prepare the sample are enumerated as following according to the National Oceanic and Atmospheric Administration (NOAA) protocol for the analysis of microplastics. This guideline is by far the most comprehensive and widely accepted one for any kind of microplastic analysis irrespective of the sources, types, and magnitude.

Microplastic analysis steps-

- Wet Sieving
- Chemical Digestion
- Density Separation (When the sample is collected from multiple sources)
- Filtration
- Microscopic Quantification (Optical Microscope) / Qualitative Characterization (Spectroscopy)



The following image depicts the typical chronology of microplastic analysis (quantitative and qualitative). (Dounia Elkhatab et. al., 2020)



Figure 2-14 Typical chronology of microplastic analysis

### 2.7.5.1 Wet sieving

This phase is the initial separation of visibly existing polymeric or non-polymeric substances with dimensions less than 5 mm in order to satisfy the definition of microplastic as a whole. This stage is primarily suitable for bigger sample sizes. This step is typically omitted when the sample size is limited. Pouring the material through a connected arrangement of 5.6-mm (No. 3.5) and 0.3-mm (No. 50) stainless steel mesh sieves is required for wet screening. The following illustration depicts the sieving procedure (NOAA guideline).



Figure 2-15 Sieving and rinsing field samples (NOAA)

The sample after sieving is rinsed with squirt bottle filled with distilled water to transfer all residual solids to the sieves. Sieved and rinsed sample is then ready for the next step which is chemical digestion.

#### *2.7.5.2 Chemical digestion*

Chemical digestion is the most crucial microplastic detection stage (quantification or chemical analysis). This process is intended to remove any and all possible organic substances from the sample. We do not want the organic substance to interfere with the detection technique during the analysis. In accordance with the preceding discussion, the initial step when dealing with reduced sample sizes is chemical digestion. According to various studies and research, there are several techniques for isolating microplastics from organic matrices. However, no protocol could guarantee the complete eradication of organic matter from a sample. Most common chemical digestion or oxidative digestion method being practiced in different studies is the utilizing hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). That is why, the more common term of chemical digestion in other word is peroxide treatment. Even for the use of hydrogen peroxide as a chemical digester, there are different kinds of conditions being used. For example, conditions vary in terms of the concentration of the peroxide, temperature, and exposure time. In general, it can be observed that hydrogen peroxide provided effective digestion and little degradation in polymers when using lower temperatures (up to 60<sup>0</sup> C) and/or shorter reaction times (up to 24 hours). Therefore, hydrogen peroxide was identified as a viable candidate to be investigated in the study conducted by Mohammed S. M. Al-Azzawi et. al., 2020.



Figure 2-16 Chemical digestion (peroxide treatment) (NOAA)

A good alternative to hydrogen peroxide is the Fenton reaction, which usually takes less time to work. Fenton reagents were used in different ways, just like hydrogen peroxide. Depending on the protocols used, the reaction times ranged from 20 min to 24 h. Mohammed S. M. Al-Azzawi and others found in their study from 2020 that Fenton can break down microplastics effectively while having little effect on them.

Acids like hydrochloric acid (HCl) and nitric acid (HNO<sub>3</sub>) have been used for a long time to break down biological samples like fish tissues. Studies have shown that some polymers are affected by acids and could be changed or broken-down during treatment. But in some previous studies, acid digestions were tested in preliminary experiments, and it was found that they broke down microplastics. Because of this, modern methods of analyzing and classifying microplastics try to avoid acid-based digestion as much as possible.

Biological samples were also often treated with alkaline chemicals like potassium hydroxide (KOH) and sodium hydroxide (NaOH). Some studies found that alkaline digestion,

especially with NaOH, could change the color or damage the microplastics they looked at. Hurley et al., on the other hand, tested a digestion method with 10% KOH at 600C. They got around 57% of the organic matter out of the sludge, but the microplastics didn't change much. In this study's preliminary tests, alkaline digestions were tried, and a protocol based on KOH (10%) was chosen as a possible candidate to be investigated further.

Table 2-7 Protocols of chemical digestion

| Protocols   | Temperature | Time                    |
|---|-------------|-------------------------|
| Fenton (30% H <sub>2</sub> O <sub>2</sub> + 20 g/L FeSO <sub>4</sub> ) [17] | Unregulated | 10 min + 10 min cooling |
| KOH (10%) [22]  | 60 °C       | 24 h                    |
| H <sub>2</sub> O <sub>2</sub> (30%) [7]                                     | 60 °C       | 24 h                    |

Chemical digestions can sometimes be substituted by enzymatic digestions, particularly for biological tissues like those from fish or plankton. They have also been used to treat wastewater samples in combination with other treatment techniques. The issue with such regimens is typically the lengthy time (days) necessary for thorough digestions. Additionally, using this digestion may be expensive or result in an incomplete digestion, especially for wastewater samples, for which a subsequent application of additional chemical reagents may be necessary for a full digestion. Enzymatic digestion is not a practical alternative to chemical digestion to get rid of the inorganic materials before microplastic analysis because of this.

#### 2.7.5.3 Density separation

It has been mentioned briefly in previous section that the step density separation is appropriate for microplastic analysis of sample from multiple sources, where there is a chance of coexistence of plastics of varied types, properties. sizes, and shapes i.e., from regular large plastic fragments to macro-plastics (having a dimension more than 5 mm) to even visually detectable microplastics. Density separation ensures the exclusion of larger plastic fragments

to make it easier for the further analysis. In this step, sodium chloride or zinc chloride solution is used to increase the density of the liquid phase. This allows the low-density MPs to float, and the high-density particles to settle to the bottom. Then, the solution is filtered through mesh sizes varying from 0.7 to 125  $\mu\text{m}$ .



Figure 2-17 Density separation (NOAA)

This step is skipped for the microplastic analysis of single known source and smaller sample size.

#### 2.7.5.4 Filtration

Filtration is the penultimate step of microplastics analysis which incorporates sample after chemical digestion, and conditional density separation being directly through membrane filters or after passing through sieves and then filtering with a vacuum. The samples were transferred with DI water into glass containers and filtered using a vacuum pump after passing through a stack of sieves with a mesh size of 20–500  $\mu\text{m}$ . However, it should be reminded that only filtration skipping either chemical digestion or density separation or both would not differentiate the potential microplastics present in the sample from other organic particles.

Hence, depending on the situation density separation can be excluded, but the step of chemical digestion or popularly termed as peroxide treatment can not be omitted in microplastic analysis/detection method.

#### *2.7.5.5 Microplastic detection*

It is clear that the detection process is the last stage in the examination of microplastics. There are primarily two fundamental forms of microplastic detection: quantitative and qualitative. Finding the number of microplastics in each sample size and converting the result to a standard unit (particles/m<sup>3</sup> or particles/L) are the first steps in quantitative detection. Weight-based definitions of the quantitative analysis are another option. The microplastic particles are weighed in micrograms, and the results are subsequently reported in g/m<sup>3</sup> or g/L. These two various depictions of quantitative detection, however, frequently contradict one another. For example, the comparable number for a detected sample that was similarly weighed could differ. Therefore, when comparing two different samples, the sample with the highest concentration of microplastic particles is not necessarily the one that is heavier in terms of g/L or g/m<sup>3</sup>.

Visual inspection under an optical microscope is the most typical method of quantitative analysis of microplastics. The target microplastic particles are quantified using an optical microscope after the sample has been processed by sieving, chemical digestion, and optional density separation. This technique largely depends on the chemical digestion step and cannot guarantee accuracy of 100 percent. It is largely predicated on the idea that the chemical digestion (peroxide treatment) of the provided sample has completely eliminated all organic components. Any type of microplastic detection/analysis method is subject to some degree of error and is not 100% accurate because chemical digestion, regardless of the protocol used,

does not guarantee an all-out removal of organic component. On the other hand, qualitative analysis of microplastic is a diversified research aspect. Popular techniques for qualitatively identifying microplastics in lab settings currently rely on well-proven optical measurement techniques. Among these, Raman spectroscopy and Fourier-transform infrared (FTIR) spectroscopy have recently shown some extremely encouraging results. These methods can offer the distinctive spectral signature of the plastics' constituent polymers, enabling the screening of microplastics. In order to prevent spectrum abnormalities caused by organic or inorganic particles other than microplastics, samples must undergo extensive preprocessing in the lab. Kai-Erik Peiponen and colleagues, 2020.

## Chapter 3

### **METHODOLOGY**

#### **3.1 Introduction**

The principal objective of this study is to characterize the risk associated with using recycled plastics as alternative materials for different pavement components, i.e., base, surface course. This chapter concentrates on developing an experimental program that would help meet the objective of this current study. The experimental program itself was developed to determine the basic environmental parameters and microplastic concentrations along with the risk characterization ratio of the leaching sample generated from cement-treated Recycled Crushed Concrete Aggregate (RCCA) mixed with different kinds of recycled plastics (PP, HDPE, PET) as pavement base materials. For base, two different conditions were taken into considerations. Firstly, the base representative cylindrical specimens were subject to submergence in stagnant water and secondly representative base specimens were subject to cyclic loading in resilient modulus setup before submergence in water. Then the leaching samples were collected for environmental test and microplastic detection. However, for surface course additionally bitumen as asphalt binder was used along with three different types of plastics (PP, LDPE, and HDPE) in multiple proportions to prepare the representative surface course specimens. Then the leaching samples were directly collected from the rutting test procedure and environmental leachate tests and microplastic detection test were conducted. This chapter discusses



elaborately about the material collections, processing, development of experimental program, specimen preparation for both base and surface course, leaching sample collection under different circumstances, and finally conductance of leachate tests, and microplastic detection test for all pertinent samples.

### **3.2 Material Collection**

Materials required for preparing the samples incorporate Recycled Crushed Concrete Aggregate (RCCA), different types of shredded plastics, Ordinary Portland Cement (OPC), Bitumen (asphalt binder) and water. In this section, collection, and preparation of the materials to be suited for making the testing samples will be described. Readily available Ordinary Portland Cement has been used for this study for stabilization purpose. For pavement base/base, crushed concrete aggregates (RCCA), and three types of recycled plastics (HDPE, PET, PP) were mixed at different prescribed proportions. Cement treatment was undertaken in multiple doses (4%, 6%, 8%, and 10%). On the other hand, two different types of bitumen (PG 70-22 and PG 64-22) have been used in four different doses of plastic (4%, 8%, 12% and 16%). In case of surface course, three grades of plastics (PP, HDPE, and LDPE) have been used.

#### **3.2.1 Collection of Recycled Crushed Concrete Aggregate (RCCA)**

Recycled Crushed Concrete Aggregate (RCCA) were collected from the site of Big City Crushed Concrete located in Dallas, Texas. This company is one of the TxDOT approved companies which supplies recycled flex base materials in Dallas – Fort Worth (DFW) area in accordance with TxDOT specifications. The Recycled Crushed Concrete Aggregate (RCCA) and Recycled Shredded Plastic base materials will be tested in cement treated condition. According to ITEM 247, there are total 12 types of base materials specified in standard specification. Among them Grade 1 is recommended for condition that do not provide its own

stability and used for high to moderate traffic. Grade 2 has the unconfined compressive strength lower than Grade 1.



Figure 3-1 RCCA sample collection from Big City Crushed Concrete in Dallas, Texas

### 3.2.2 Bitumen Collection

As mentioned briefly in this chapter, two different types or grade of bitumen are used in this study for surface course. Bitumen is used as the binder materials for the asphalt. In simple words, asphalt is the prescribed mix of aggregate and bitumen and is the principal component of the pavement wearing course. In that way, bitumen is one of the most important constituent materials of pavement structure. There are different grades of bitumen available in the market. Bitumen grade is mostly characterized by two parameters: performance grade, and viscosity grade. Depending on the specifications in terms of performance and viscosity, there are

multiple combinations of bitumen. For this study, performance grade bitumen is used to prepare the surface course representative specimen. Performance grade bitumen commonly known as PG bitumen is designed by its performance at a temperature range (highest and lowest possible temperature endurance). There is an algorithm used to obtain the temperature of the pavement by the air temperature. This algorithm which is dictated by Long-Term Pavement Performance (LTPP) calculates the highest and lowest pavement temperatures. Bitumen grade consists of two parts in notation, the first number depicts the highest pavement temperature while the second number depicts the lowest one endured by the pavement in 7 days exposure. For example, bitumen grade PG X-Y means in 7 days, this bitumen grade meet maximum of  $X^0$  C and minimum of  $-Y^0$  C hence it can be used in both hot and cold conditions.



Figure 3-2 Bitumen collected from Austin Paving Co., Goodnight Lane, Dallas

In this current study, two different bitumen grades have been used as binder materials. PG 70-22 and PG 64-22. It is of no wonder that PG 70-22 has got higher performance grading compared to that of PG 64-22 in terms of larger temperature variances. Both bitumen grades were collected from Austin Paving Co. located in Goodnight Lane, Dallas.

### 3.2.3 Collection, Sorting, and Shredding of Recycled Plastic

As mentioned earlier, collection of recycled plastic, transporting them to the research facility, and subsequent sorting, shredding was one of the most challenging parts of the experimental program. Recycled plastic is introduced as a novel material for this experimental work. Seven types of plastics are established by The Society of the Plastics Industry (SPI) those are identified by their SPI code or number. In this study, Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE) and Polypropylene (PP) are used for base and additionally Low-Density Polyethylene (LDPE) is used for surface course.

Shredded plastic is considered as flex base material as a replacement of recycled aggregates. Transforming recycled plastic to a more suitable shredded state is cumbersome, and meticulous process. Without having a commercially large-scale plastic shredding machine, it was difficult to have the desired shred size using a small-scale plug and play shredder.

#### 3.2.3.1 Collection of Recycled Plastic

Three types of plastic (HDPE, PET, and PP) were collected from Republic Services Material Recovery Facility, Fort Worth, Texas. Republic Services collect the plastics from nearby cities and bring them to the facility for further sorting and processing.





Figure 3-3 Plastic collection and preliminary shredding

Each type comes with a bale weighing about one thousand pounds of plastic as shown in Figure 3-4. These bales are plastics are subject to cleaning for further steps. On the other hand, LDPE plastics were collected from households, and within the University of Texas, Arlington campus.



Figure 3-4 Collected plastic bales and plastic bags

### 3.2.3.2 *Sorting, Cleaning, and Drying of Recycled Plastic*

Plastic containers and bottles are handpicked and sorted manually. Sorting from a large bale is crucial due to the contamination of other materials like paper, dirt, and other types of unwanted impurities. To avoid the contamination, these materials were cleaned by a dilute solution of sodium hypochlorite known as liquid bleach commercially. Mixing ratio of liquid

bleach and water was 1:20. Plastics were drenched in the large bin and left 2 hours for deep cleaning. Plastics are rinsed with clean water later. Cleaned plastics are air dried for 24 hours and ready for shredding.

### 3.2.2.3 Plastic Shredding

Shredding is one of the most significant operations of this entire research approach. Cleaned and dried plastics were transported to a shredding facility for first stage shredding. Balcones Shred, Dallas shredded the plastics into heterogeneous mesh size ranges from 0.5 inch to 3 in. The second stage of shredding was performed in civil engineering laboratory building using small scale shredder. For this research study we used INTBUYING 220V Heavy Duty Plastic shredder.



(a) Plastic Shredder



(b) Shredded Plastic

Figure 3-5 Plastic Shredding using heavy duty plastic shredder

However, LDPE plastics were shredded manually with scissors in the lab. Because of its highly flaky and pliable characteristics, it is not possible to shred LDPE plastics using a heavy-duty shredder.



Figure 3-6 Manually shredded LDPE plastics

### **3.2.4 Cement Collection**

For the experimental purpose, readily available Ordinary Portland Cement (OPC) has been used to prepare the samples. To be precise, TXI manufactured type I/II OPC has been selected for treating the samples.

### **3.3 Experimental Program**

This study incorporates both base course, and surface course of a plastic road. Understandably, the proposed experimental program will cover the experiments pertinent to both components of the plastic road. For, base course two different conditions are applied. Firstly, the base representative cylindrical specimens were subject to submergence in stagnant water and secondly representative base course specimens were subject to cyclic loading in resilient modulus setup before submergence in water to represent a possible worst-case condition. Whereas, for pavement surface course, the leachate has been directly collected from the rutting test setup where the prepared samples have been subject to 15,000 equivalent wheel passes already been submerged in the water to prototype the worst-case scenario.

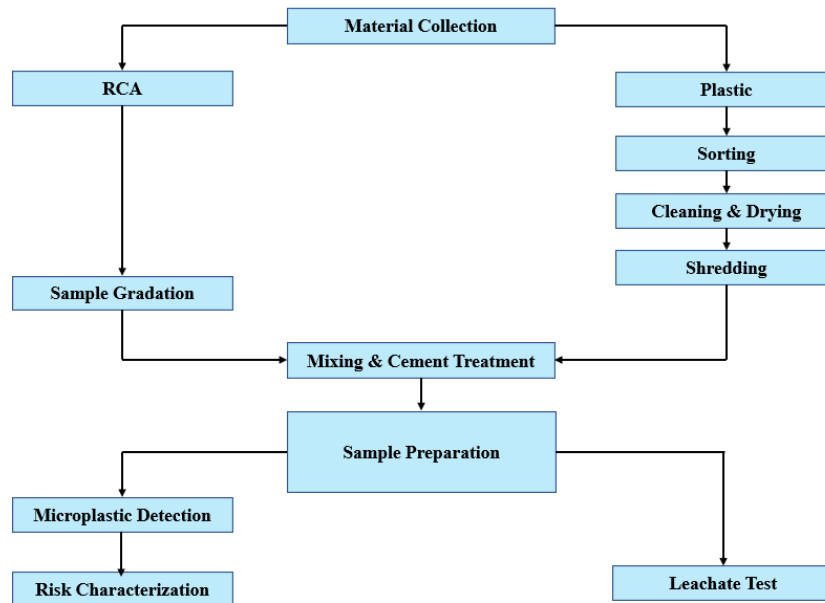


Figure 3-7 Experimental flow chart for base course

Experimental program is prepared to fit three different cases i.e., two cases for base course, and one for the surface course. Two cases for base course represent two different weathering conditions of the representative cylindrical base specimen. One condition is subject to submerge the cylindrical specimen in stagnant water, and the collect the leaching liquid for environmental and microplastic detection test. The other condition refers to the cyclic exposition of the cylindrical specimen in a resilient modulus setup, and then submergence and subsequent collection of leachates for similar tests. Final case is suited for surface course of a plastic road where the prepared samples have been subject to 15,000 equivalent wheel passes already been submerged in the water in a Hamburg rutting test setup to prototype the worst-case scenario.

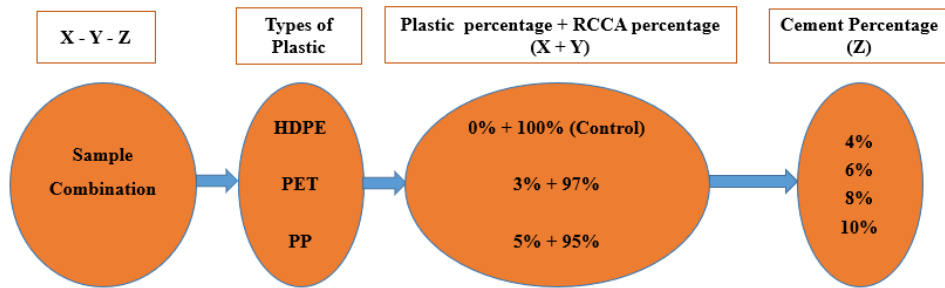
Case I: Base Course; specimen submerged in stagnant water

Case II: Base Course; specimen subject to cyclic loading followed by submergence in stagnant water

Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion Rutting test setup



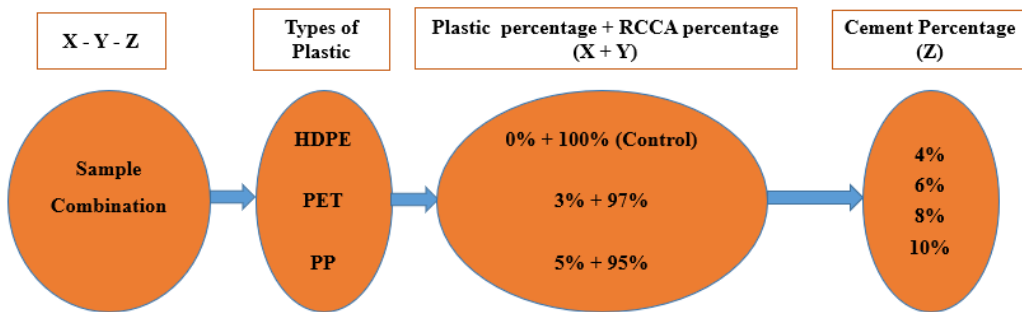
Following are the three experimental programs expressing the total number of respective tests type for three different cases.



X = % Plastic    No. of Control Sample combinations =  $1 * (1+1+1+1) = 4$   
 Y = % RCCA    No. of Experimental Sample combinations =  $3 * (1+1) * (1+1+1+1) = 24$   
 Z = % Cement    Total no. of Sample combinations =  $4 + 24 = 28$   
 Total no. of leachate tests =  $(28 * 4) = 112$   
 Total no. of microplastic tests =  $(28 * 2) = 56$   
 Total no. of tests = 168

\*Leachate tests: COD, TDS, TSS, Specific Conductance  
 \*Microplastic tests: Optical microscopy, FTIR spectroscopy

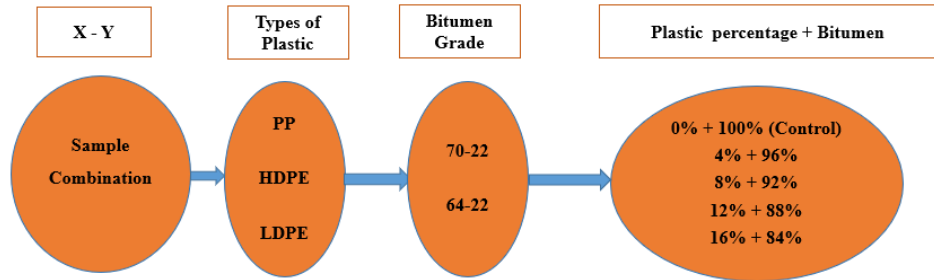
Figure 3-8 Experimental program (case I)



X = % Plastic    No. of Control Sample combinations =  $1 * (1+1+1+1) = 4$   
 Y = % RCCA    No. of Experimental Sample combinations =  $3 * (1+1) * (1+1+1+1) = 24$   
 Z = % Cement    Total no. of Sample combinations =  $4 + 24 = 28$   
 Total no. of leachate tests =  $(28 * 4) = 112$   
 Total no. of microplastic tests =  $(28 * 2) = 56$   
 Total no. of tests = 168

\*Leachate tests: COD, TDS, TSS, Specific Conductance  
 \*Microplastic tests: Optical microscopy, FTIR spectroscopy

Figure 3-9 Experimental program (Case II)



X = % Plastic    No. of Control Sample combinations =  $1 * (1+1) = 2$   
Y = % Bitumen    No. of Experimental Sample combinations =  $3 * (1+1) * (1+1+1+1) = 24$   
Total no. of Sample combinations =  $2 + 24 = 26$   
Total no. of leachate tests =  $(26 * 4) = 104$   
Total no. of microplastic tests =  $(26 * 2) = 52$   
Total no. of tests = 156

\*Leachate tests: COD, TDS, TSS, Specific Conductance

\*Microplastic tests: Optical microscopy, FTIR spectroscopy

Figure 3-10 Experimental program (Case III)

### 3.4 Sample Preparation

Sample preparation for this study is primarily divided into two categories. One category is suited for base course and the other one is for the wearing/surface course of a plastic road. Again, as mentioned in the previous section there are two different cases for base course sample preparation. For these two cases, all the basic sample preparation steps are identical except the size/dimension of the respective cylindrical specimen for two cases. Following subsections, detailed sample preparation steps will be discussed representing all the different cases mentioned by far.

#### 3.4.1 Sample Preparation for Base Course

For plastic road base course, crushed concrete aggregates (RCCA), and three types of recycled plastics (HDPE, PET, PP) were mixed at different prescribed proportions. Specific amount of water was added to the mix based on the derived Optimum Moisture Content (OMC). Cement treatment was undertaken in multiple doses (4%, 6%, 8%, and 10%). Basic steps including mixing of ingredients, compacting, extruding and subsequent curing for both

case I, and Case II are identical. Only differences are the height of the specimen prepared, and the mode of compaction. The specimens were prepared at optimum moisture content (OMC) and compacted at maximum dry density (MDD) with the values obtained from the respective tests according to the guidelines of TxDOT (Reference TEX-113-E).



Figure 3-11 Materials mixing

Specimen for case I were 6” in diameter 8” in height. They are compacted in a specific mold. Before starting to fill the mold with ingredients and the compaction, a lubricant is used to polish the inner side of the mold just to make sure the specimen does not get stuck to it and extrusion is done with ease and comfort. They were compacted in 4 lifts and each layer was subjected to 50 blows to achieve the required compaction. Each lift or layer counts for 2” of height. After each lift, partially compacted layer is scratched with a scrubber or spatula to ensure maximum cohesion within the compacted ingredients, and minimum adhesion to the surrounding mold. While conducting the mechanical compaction it is to be assured that ingredients don not spill out the compaction mold, and the mold itself is embedded on the pedestal throughout the compaction procedure to attain near perfect efficiency. If loose or distorted, it is mandatory to refix the mold with the pedestal using a wrench driver.



Figure 3-12 Compaction & specimen extrusion

For case II, cylindrical specimens were prepared having 6” diameter and 12” height. For the purpose of achieving the highest possible dry density, each and every specimen was compacted while maintaining the ideal level of moisture. Each sample specimen was subjected to 50 blows and compacted at six lifts, with each lift being two inches in height. The height of each lift was measured in inches. The height of each lift was automatically controlled by the compactor's automatic mechanism. There was a restriction that the largest size of the particle must not exceed 1.2 inches, which was equal to one-fifth of the largest diameter that the mold could accommodate. The only difference between this approach and the one employed for Case I is the size of the specimens that are being tested.

The test specimens were removed from the mold by using the extruder. After that, they were wrapped in plastic to prevent any disruptions and placed in the humid chamber to cure for a period of seven days. Throughout the seven-day curing process, the temperature in the damp chamber was maintained at 700 degrees Fahrenheit, and the relative humidity was kept at a controlled level of around 100%.



Figure 3-13 Curing for 7 days

After the completion of the requisite curing, specimens were soaked in free water for 28 days in a container (Hoyos et al., 2008). For case I, after removing specimens from the container, the water comprising solid residues, i.e., soluble, insoluble, dissolved, suspended, settleable will be collected as leachate and be subject to the environmental assessment, and microplastic detection testing in accordance with the guideline of ASTM, USEPA, and NOAA (National Oceanic and Atmospheric Administration).

However, for Case II, prepared cylindrical specimens were subject to resilient modulus setup after the 7 days quintessential curing to find out the attributes of leaching samples in a possible worst-case scenario. Resilient modulus test depicts the long-term endurance of compacted base. Cylindrical specimens run through resilient moduli testing represent the base exposed to periodic loading at the threshold point of its design life.



Figure 3-14 Specimen subject to resilient modulus setup

After completion of the resilient modulus test under a periodically cyclic loading condition, specimens were taken out of the resilient moduli chamber and were submerged in contained water for 28 days (like Case I). And following that, the leaching samples were collected in a similar way for conducting environmental testing and microplastic detection as mentioned above.

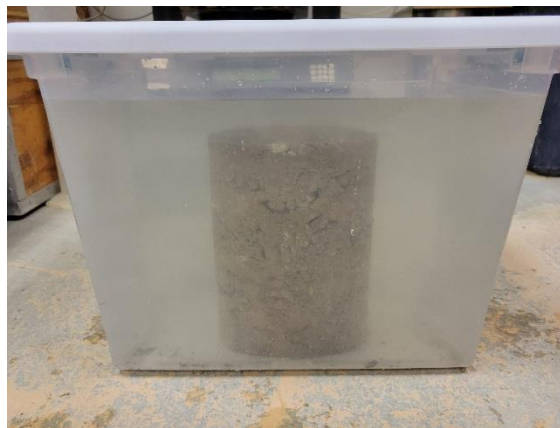


Figure 3-15 Submergence in contained water (Case I & II)

### 3.4.2 Sample Preparation for Surface Course

For case III, surface course samples of plastic road are subject to Hamburg Wheel Tracking Test-HWTT, commonly termed as rutting test because of its primary objective of assessing the rutting potential of Hot Mixed Asphalt (HMA) layer used as the wearing course

of the pavement. A test method called Tex-242-F, "Hamburg Wheel-Tracking Test," was exclusively developed by the Texas Department of Transportation (TxDOT) to evaluate HMA specimens. Test samples for HWTT are typically fabricated using methods Tex-205-F, "Laboratory Method of Mixing Bituminous Mixtures," and Tex-241-F, "Superpave Gyratory Compacting Test Specimens of Bituminous Mixtures." Using the Hamburg wheel tracking device (HWTD), rut depth measurements and corresponding number of passes are recorded for each steel wheel. For this study, HMA specimens already being submerged in stagnant water within the test setup were subject to 15,000 equivalent wheel passes, and the liquid collected after the completion of designed wheel passes was collected directly as leaching sample to carry out the environmental tests and microplastic detection tests.

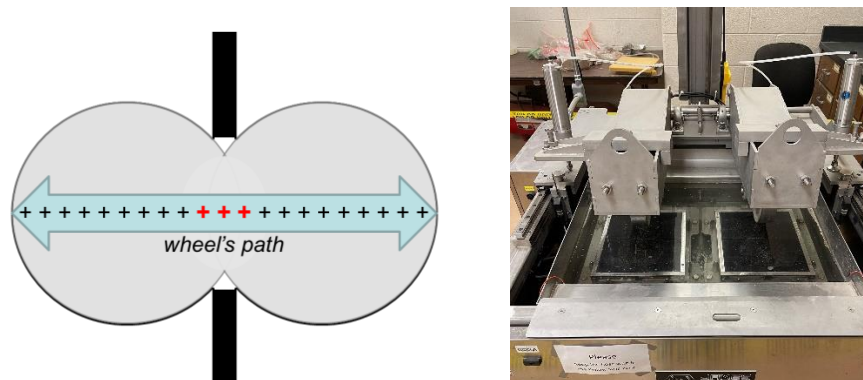


Figure 3-16 Demonstration of wheel passes and ongoing rutting test

### 3.5 Laboratory Testing

Having finalized the experimental program and preparing the samples for three cases, two different sets of laboratory testing were carried out. Several environmental leachate tests were conducted for all three cases to corroborate the leachate characteristics against the set standard of United States Environmental Protection Agency (USEPA) for the pavement stormwater runoff. For case I, and case III four leachate tests were conducted namely Chemical Oxygen

Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and Specific Conductance. However, for case II, only TDS, and TSS tests were conducted. Following table summarizes the list of leachate tests undertaken in this study with their respective ASTM, and USEPA procedure specifications.

Table 3-1 List of environmental leachate tests

| Test                 | Standard Test Method |       | USEPA Acceptable Limit |
|----------------------|----------------------|-------|------------------------|
|                      | ASTM                 | USEPA |                        |
| COD                  | D1252 - 06           | 410.1 | 120 mg/L               |
| TDS                  | D5907 - 03           | 160.1 | 500 mg/L               |
| TSS                  | D5907 - 03           | 160.2 | 100 mg/L               |
| Specific Conductance | D6764 - 02           | 120.1 | 500 $\mu$ mhos/cm      |

On the other hand, irrespective of the cases, two kinds of microplastic detection tests were carried out i.e., Optical Microscopy Test, and Fourier Transform InfraRed (FTIR) spectroscopy. In the following subsections, pertinent procedures for respective tests will be discussed briefly as being carried out for the current study.

### 3.5.1 Chemical Oxygen Demand (COD) Test

A test was conducted in accordance with ASTM D1252 – 06 or USEPA 410.1 to determine the amount of oxygen used by contaminants in the water. First, a calibration curve between COD concentration and COD transmittance was created. The samples were then placed into COD vials and heated for two hours in the COD reactor during the digester phase. The vials were then withdrawn from the digester and cooled to room temperature for 20 minutes. After that, the vials were introduced into the digital reactor and the value of transmittance and absorbance readings were taken from the device.





Figure 3-17 COD test procedure

The absorbance value was then taken as the X coordinate value of the calibration equation, where the derived Y coordinate value depicts the COD value of the sample leachate. For each sample leachate, three vials were set ready for the test to test against one vial of control sample leachate to ensure the authenticity of the COD value for a particular sample leachate.

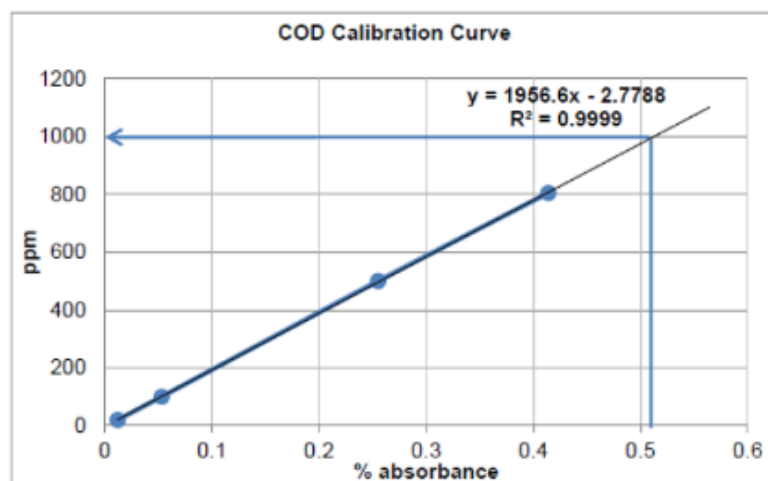


Figure 3-18 COD calibration graph

### **3.5.2 Total Dissolved and Suspended Solids (TDS & TSS) Tests**

Total Dissolved Solids (TDS) test was performed according to ASTM D5907 – 03 or USEPA 160.1 standard method. Total Suspended Solids (TSS) test was performed according to ASTM D5907 – 03 or USEPA 160.2 standard method. From these two tests amount of filterable and non-filterable materials was determined. Glass fiber filter paper is used to remove the suspended solids by passing the water sample through the filter. Suspended solids were retained on the filter paper whereas filtrates were passed through the filter paper. Assuming there is no settleable solids in any of the sample leachates, Total Solids (TS) was also calculated for each sample leachate by adding TDS, and TSS based on the assumption of no settleable solids being present leading to an ideal condition. However, in practical sense, there would be no such case where total solids does not constitute even a trace number of settleable solids.

### **3.5.3 Specific Conductance Test**

Specific Conductance test was performed following the standard of ASTM D6764 – 02 or USEPA method 120.1. Specific conductance (also called specific conductivity or just conductivity) is a measure of the ability of any leaching sample to conduct an electrical current. Specific conductance is an important qualitative measurement because it gives a good idea of the amount of dissolved material in the leaching sample. According to the USEPA benchmark, the favorable limit of specific conductance has been given as 200  $\mu\text{mhos/cm}$ . However, the conductivity of rivers in the United States generally ranges from 50 to 1500  $\mu\text{mhos/cm}$ . Studies of inland fresh waters indicate that streams supporting good mixed fisheries have a range between 150 and 500  $\mu\text{mhos/cm}$ . Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. That is why the allowable limit of specific conductance has been revised to 500  $\mu\text{mhos/cm}$ .

### **3.5.4 Microplastic Detection Test**

The main objective of this study is to characterize risk associated with using recycled shredded plastics as materials for different pavement layers of an integrated plastic road. To microplastic characterize the risk, the first and foremost prerequisite is to detect the concentration of microplastic in the given sample size. Details about the microplastic detection test have been discussed in Chapter 2 with respect to previous studies, and research works. Based on that literature review, it can be noted that there are basically two primary of detection testing: quantitative and qualitative testing. Quantitative testing emphasizes on the numerical values of microplastic in a smaller sample size and then extrapolation to report the numbers in a standard unit. On the contrary, qualitative testing deals with identifying the physical and chemical attributes of the microplastics in terms of spectroscopic wave numbers. In this study, standard optical microscopy has been used for quantitative testing and Fourier Transform InfraRed (FTIR) spectroscopy has been deployed to carry out the qualitative testing.

It is worth mentioning that preliminary preparation steps of the leaching sample obtained from three different cases discussed in the previous section to make it ready for both microscopic and FTIR testing are similar which include screening/sieving, chemical digestion, and filtration. In the following subsections all steps followed by optical microscopy technique and FTIR spectroscopy technique incorporated in thus study will be discussed in detail. Steps for sample composition and optical microscopic detection are conducted in accordance with the guidelines by National Oceanic and Atmospheric Administration (NOAA). FTIR was conducted with respect to the manual of Nicolet iS50 FTIR Spectrometer in the Characterization Center for Materials & Biology (CCMB) laboratory of University of Texas, Arlington.

#### *3.5.4.1 Screening/Sieving*

Screening/wet sieving is the rudimentary step of microscopic detection for microplastic. This step is more appropriate for the condition, where the presence of visually discernible macro-plastics is substantial. This step involves screening of the leachate sample through a #4 sieve having a sieve opening of 4.74 mm. This step is just to corroborate the upper dimensional limit of microplastic since according to the most accepted definition plastic segregate having dimension less than 5 mm could be referred to as microplastic.

In this study, the leaching samples being collected for all three different cases did not exhibit any conspicuous large plastics. On top of that, for this study all kinds of plastics were shredded secondarily using the small-scale shredder in the laboratory to have a uniform size of around 3-4 mm which diminishes the requirement for screening/wet sieving.

#### *3.5.4.2 Chemical digestion*

It is worth mentioning that chemical digestion is the most important step of microplastic detection method regardless of its type: quantitative or qualitative. Chemical digestion is designed for removing all possible organic matters present in the sample. Although, the main objective of this step is to remove all possible organic matter from the leachate sample, it is not possible to attain 100% efficiency should the organic substance removal be concerned. There are various methods available for the chemical isolation of organic matter from the given sample, which have been elaborately discussed in chapter 2. The most common technique of chemical digestion is conducted by using 30% hydrogen peroxide. That is why, the other name of chemical digestion process is peroxide treatment. Mohammed S. M. Al-Azzawi and others in their extensive research on efficiency of different chemical digestion protocol also came up with the statement backed by experimental evidence and corroboration that 30% hydrogen

peroxide is the most efficacious approach to remove possible organic substance from the given leaching sample. In this current study, 30% hydrogen peroxide has been used as the chemical digestion agent. For this step, 30% hydrogen peroxide is uniformly mixed with the leaching sample maintaining a mixing ratio of 5:1 (reagent to sample ratio). For example, 50 ml of sample has been selected as the sample size for this study and 250 ml of 30% hydrogen peroxide has been used as reagent which is 250 ml in volume. However, Mohammed S. M. Al-Azzawi et al., 2020 suggested the reagent to sample ratio be kept as 10:1. Albeit, Veronique Adam et. al. (2021) claimed that reagent to sample ratio 5:1 has almost identical organic matter removal efficiency as 10:1 provided the mixed sample remain heated in an oven for 24 hour.

| Protocols   | Temperature | Time                    |
|---|-------------|-------------------------|
| Fenton (30% H <sub>2</sub> O <sub>2</sub> + 20 g/L FeSO <sub>4</sub> ) [17] | Unregulated | 10 min + 10 min cooling |
| KOH (10%) [22]  | 60 °C       | 24 h                    |
| H <sub>2</sub> O <sub>2</sub> (30%) [7]                                     | 60 °C       | 24 h                    |

Figure 3-19 Protocol used for chemical digestion

To attain maximum possible uniformity of the mix, mechanical magnet driven automated stirrer has been used before 30 minutes of preheat conditioning of the mix at 150 degrees Celsius using hot plate. After the mixing and condition preheating, leaching sample mixed with H<sub>2</sub>O<sub>2</sub> placed in conical flask is placed in an oven for 24 hr.



Figure 3-20 Chemical digestion (peroxide treatment)

### 3.5.4.3 Filtration

Filtration is the penultimate step for optical microscopic detection of microplastics. It involves the filtration of chemically digested target sample using a  $0.1\mu\text{m}$  filter to get ready for the microscopic detection. For the sake of microscopic operation, the entire area of filter used was divided into four quarters to make sure the maximum coverage of the target region under the microscope and to alleviate the chance of potentially misleading double counts of the target constituent, microplastics. There is no set standard for the filter opening size to conduct the filtration. American Chemical Society for one of its studies on the extent of microplastics concentration emanated from urban storm water runoff used a microfiber filter having an opening dimension of  $0.5\mu\text{m}$ . The basic rationale is the less the opening size of the filter, the more the chance of quantifying microplastic particles present in the given sample albeit there is no set regulation for the size of filter to be used. Again, it only matters for quantitative analysis. However, should the sole purpose of any study be qualitative analysis of microplastics, filter size hardly matters in a relative uniform condition of potential microplastics presence. For this study, we used a filter having opening size of  $0.1\mu\text{m}$ . And to make the filtration process more efficient, a pneumatic suction was deployed using a Buchner funnel.

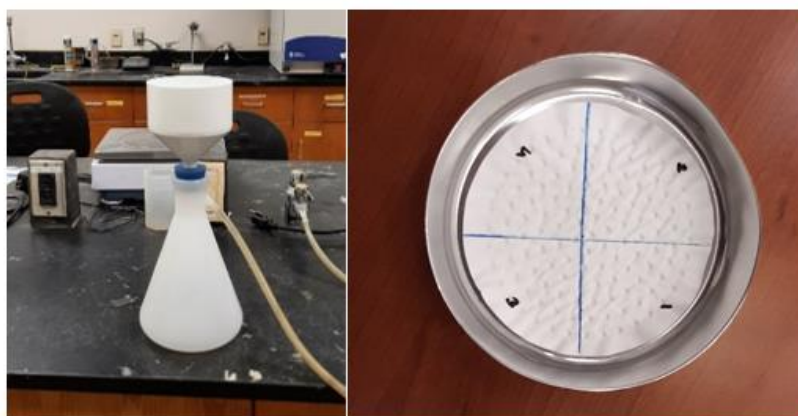


Figure 3-21 Filtration

#### 3.5.4.4 *Optical microscopy*

Optical microscopy is the final step of quantitative microplastic analysis. For this study, an optical microscope equipped with Nikon Eclipse L150 camera (with a combined magnification of 200X) has been used. The detection was carried out in Characterization Center for Materials & Biology (CCMB) Laboratory of the University of Texas, Arlington. The microscope was equipped with multilevel magnifying setup rendering maximum magnification possible. The two directional localizers made sure that there is no repetitive magnification for a certain space coupled with camera with advanced resolution. Computer monitor attached to the microscopic setup facilitates live videography of the target membrane under the microscope. One could select a view, pause accordingly, and count the target constituent with a live snapshot for the reference. Particles found in each of the four target quarters (as mentioned in the previous section) were added up to have the final counts for a specific leaching sample. A same filter was scrutinized twice to crosscheck the particle numbers between each microscopic run. The whole microscopic scrutinization using this optical microscope assumes that the microscopic elements present on the filter surface to be examined are devoid of organic matter. In that way, there is still a possibility that few particles being enumerated through the optical inspection are basically organics yielding in greater numbers.



Figure 3-22 Microscopic detection

#### 3.5.4.5 FTIR spectroscopy

Fourier Transform Infra-Red (FTIR) spectroscopy is one of the most popular and widely used qualitative analysis used to detect the presence of microplastics in a certain leaching sample. It also helps to identify the presence of other substance (substance other than the target microplastics type or microplastics in general). Since, the procedure is entirely based on the chemical compositions of the ingredients in a target sample, it is not dependent on the numerical relative presence of the particulate matters. According to the basic principle of FTIR spectroscopy, a molecule's covalent bonds will selectively absorb radiation of specific wavelengths, which changes the vibrational energy in the bond for that molecule. The type of vibration (stretching or bending) induced by the infrared radiation depends on the atoms in the bond. Since, different bonds and functional groups absorb different frequencies, the transmittance and/or absorbance pattern is different for different molecules. However, transmittance is the reciprocal expression of absorbance. The spectrum is recorded on a graph with wavenumber ( $\text{cm}^{-1}$ ) recorded on the X-axis and transmittance and/or absorbance recorded on the Y-axis. Wavenumber is the reciprocal expression of wavelength and corresponds to the energy of the vibration of the molecular bonds. For instance, each plastic type (even if its micro or nano form) exhibit a specific wavenumber based on which we could identify the plastic type. If there are multiple plastic types being present, through unique wavenumbers one could identify all possible plastic types in that sample.

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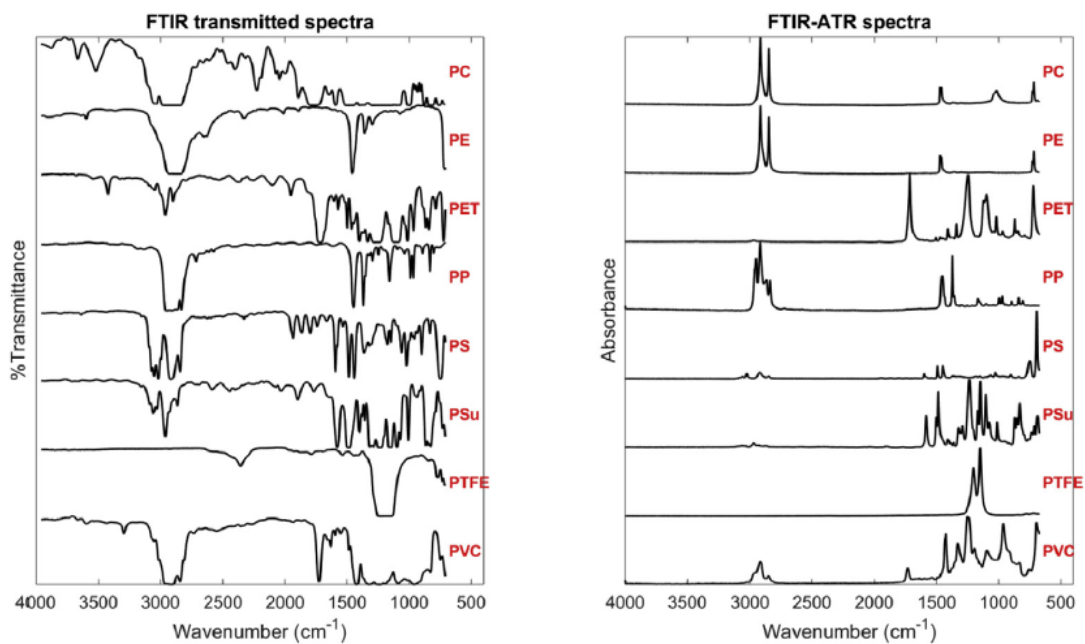


Figure 3-23 FTIR response of different plastic types (Jun-Li Xu et al., 2019)

Raman imaging along with FTIR is also based on the similar kind of principle. However, in this study FTIR spectroscopy has been used. The exact equipment used for this study is a Thermo Scientific Nicolet IS-50 FTIR machine. FTIR analysis was conducted within the facility of in Characterization Center for Materials & Biology (CCMB) Laboratory of the University of Texas, Arlington.

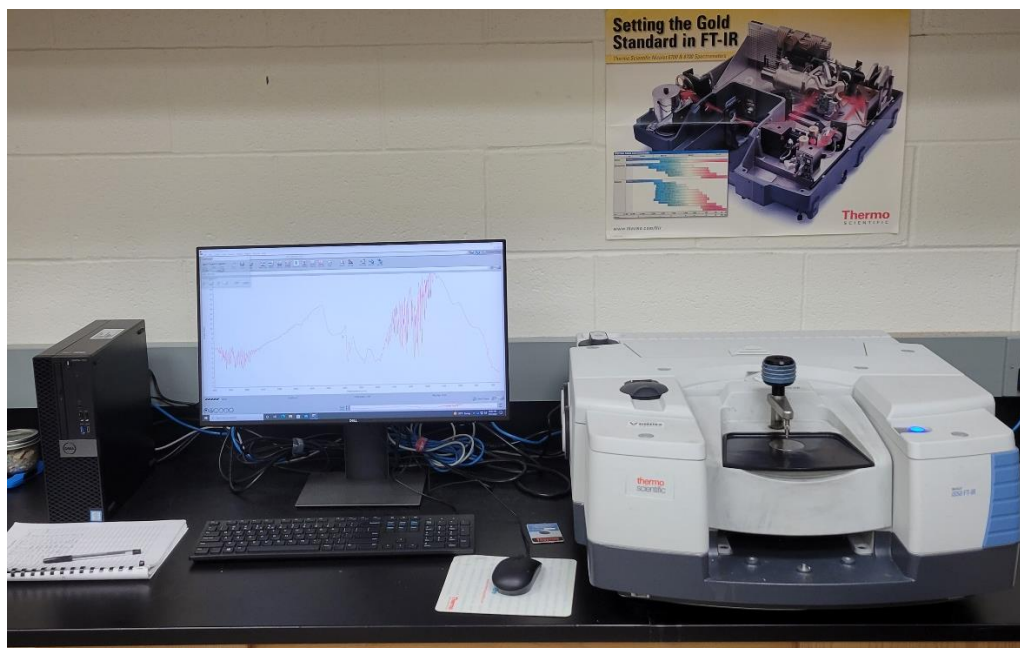


Figure 3-24 FTIR analysis in Nicolet IS-50 spectrometer

Since FTIR stands for Fourier transform infrared, the preferred method of infrared spectroscopy. First step is to place a droplet of sample under the metal presser. When IR radiation is passed through a sample, some radiation is absorbed by the sample and some passes through (is transmitted). The resulting signal at the detector is a spectrum representing a molecular 'fingerprint' of the sample. The usefulness of infrared spectroscopy arises because different chemical structures (molecules) produce different spectral fingerprints which ultimately facilitates identifying the particulate material present in the trace leaching sample. The spectrometer again is linked with a computer which shows the live spectral fluctuation with peak wave numbers. Those wave peak numbers would help us identify different microplastic particles present in the sample. And with a that comes the corroboration of the presence of specific microplastic type with the quantitative data obtained from the optical microscopic detection.

## Chapter 4

# RESULTS AND DISCUSSION

### 4.1 Introduction

Test results and pertinent analysis of the results obtained from environmental leaching tests (COD, TDS, TSS Specific Conductance) and Microplastic detection tests (both optical microscope and FTIR spectroscope) are presented in this chapter. It is important to clarify that tests results are for all three cases mentioned in chapter 3 are presented here. Test results are also analyzed in terms of changing parameters (plastic content, % cement, plastic type). For cases I and II (Base specimen) leaching sample will be denoted as A (X-Y-Z), where A = Plastic type i.e., HDPE, PET, PP or Control mix with 0% plastic) X = % plastic, Y = % Recycled Crashed Concrete Aggregate (RCCA), Z = % Cement. For example, PET (3-97-4) means the leaching sample is representative of cylindrical specimen made of 3% PET plastics, 97% RCCA stabilized by 4% cement. And Control (0-100-8) means it is representative of control sample with 100% RCCA stabilized by 8% ordinary Portland Cement. However, for surface course, samples are identified as A (X/Y), where A = Plastic type i.e., LDPE HDPE, PET or Control mix with 0% plastic and X = % Plastic and Y = Bitumen type. For example, LDPE (12/70-22) means the leaching sample incorporates 12% LDPE plastics and bitumen grade PG 70-22 to prepare the surface course cylindrical specimen and Control (0/64-22) is self-explanatory representing control sample made of 0% plastic and bitumen grade PG 64-22.

## 4.2 Chemical Oxygen Demand

*Case I: Base course; specimen submerged in stagnant water*

Table 4-1 COD test results for Case I

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>COD (mg/L)</i> |
|------------------------|---------------------------|-----------------|-------------------|
| <i>PET</i>             | 3% + 97%                  | 4               | 88.76             |
|                        |                           | 6               | 88.34             |
|                        |                           | 8               | 88.00             |
|                        |                           | 10              | 79.82             |
|                        | 5% + 95%                  | 4               | 72.37             |
|                        |                           | 6               | 72.11             |
|                        |                           | 8               | 70.45             |
|                        |                           | 10              | 70.22             |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 90.26             |
|                        |                           | 6               | 88.34             |
|                        |                           | 8               | 86.91             |
|                        |                           | 10              | 79.31             |
|                        | 5% + 95%                  | 4               | 70.29             |
|                        |                           | 6               | 66.92             |
|                        |                           | 8               | 65.78             |
|                        |                           | 10              | 57.56             |
| <i>PP</i>              | 3% + 97%                  | 4               | 414               |
|                        |                           | 6               | 415               |
|                        |                           | 8               | 417               |
|                        |                           | 10              | 416               |
|                        | 5% + 95%                  | 4               | 332               |
|                        |                           | 6               | 330               |
|                        |                           | 8               | 312               |
|                        |                           | 10              | 298               |
| <i>Control</i>         | 0% + 100%                 | 4               | 112.56            |
|                        | 0% + 100%                 | 6               | 97.56             |
|                        | 0% + 100%                 | 8               | 85.45             |
|                        | 0% + 100%                 | 10              | 83.54             |

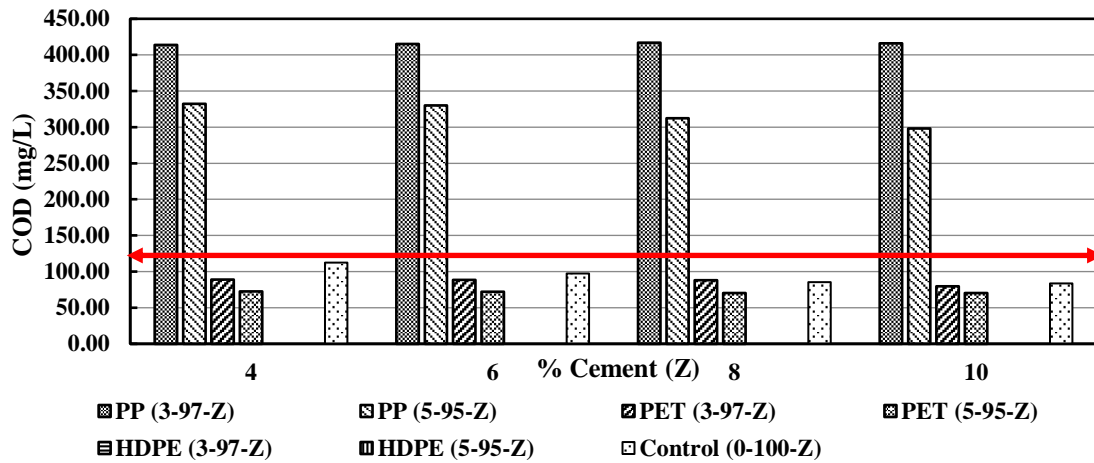


Figure 4-1 COD results with respect to permissible limit (case I)

For case I, every sample tends to be within the USEPA permissible limit for Chemical Oxygen Demand (COD) which is 120 mg/L except those made of PP plastics. COD of samples associating PP plastic particles is explicitly higher than those of other samples.

*Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion*

*Rutting test setup*

Table 4-2 COD test results for Case III

| <i>Plastic Type</i> | <i>% Plastic</i> | <i>Bitumen</i> | <i>COD (mg/L)</i> |
|---------------------|------------------|----------------|-------------------|
| <i>PP</i>           | 4%               | 70-22          | 432.64            |
|                     | 8%               | 70-22          | 421.15            |
|                     | 12%              | 70-22          | 433.21            |
|                     | 16%              | 70-22          | 298.19            |
| <i>HDPE</i>         | 4%               | 70-22          | 78.89             |
|                     | 8%               | 70-22          | 100.76            |
|                     | 12%              | 70-22          | 77.52             |
|                     | 16%              | 70-22          | 52.45             |
| <i>LDPE</i>         | 4%               | 70-22          | 76.32             |
|                     | 8%               | 70-22          | 68.98             |
|                     | 12%              | 70-22          | 61.12             |
|                     | 16%              | 70-22          | 43.12             |
| <i>Control</i>      | 0%               | 70-22          | 98.19             |

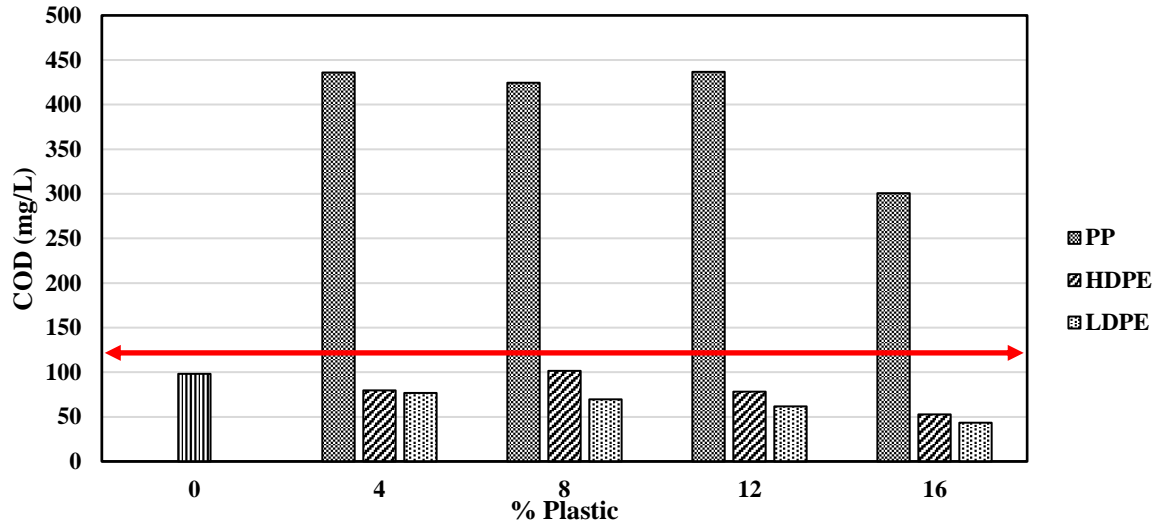


Figure 4-2 COD results with respect to permissible limit (case III)

For case III, samples incorporating shredded PP plastics exhibit higher COD values compared to the other samples with respect to the permissible USEPA limit.

### 4.3 Total Suspended Solids & Total Dissolved Solids

*Case I: Base Course; specimen submerged in stagnant water*

Table 4-3 TSS and TDS results for case I

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>TDS (mg/L)</i> | <i>TSS (mg/L)</i> |
|------------------------|---------------------------|-----------------|-------------------|-------------------|
| <i>PET</i>             | 3% + 97%                  | 4               | 398               | 68                |
|                        |                           | 6               | 445               | 62                |
|                        |                           | 8               | 471               | 59                |
|                        |                           | 10              | 478               | 31                |
|                        | 5% + 95%                  | 4               | 368               | 68                |
|                        |                           | 6               | 415               | 64                |
|                        |                           | 8               | 448               | 64                |
|                        |                           | 10              | 485               | 31                |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 419               | 58                |
|                        |                           | 6               | 424               | 56                |
|                        |                           | 8               | 478               | 49                |
|                        |                           | 10              | 467               | 26                |
|                        | 5% + 95%                  | 4               | 403               | 62                |
|                        |                           | 6               | 445               | 63                |
|                        |                           | 8               | 462               | 50                |
|                        |                           | 10              | 468               | 29                |
| <i>PP</i>              | 3% + 97%                  | 4               | 374               | 185               |
|                        |                           | 6               | 422               | 185               |
|                        |                           | 8               | 498               | 139               |
|                        |                           | 10              | 512               | 101               |
|                        | 5% + 95%                  | 4               | 365               | 194               |
|                        |                           | 6               | 398               | 190               |
|                        |                           | 8               | 478               | 143               |
|                        |                           | 10              | 501               | 100               |
| <i>Control</i>         | 0% + 100%                 | 4               | 489               | 41                |
|                        | 0% + 100%                 | 6               | 495               | 35                |
|                        | 0% + 100%                 | 8               | 496               | 36                |
|                        | 0% + 100%                 | 10              | 503               | 14                |

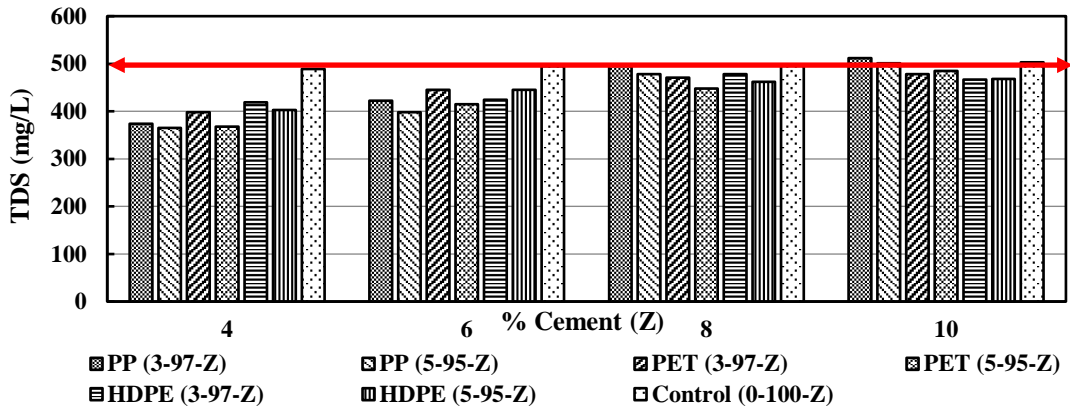


Figure 4-3 TDS results with respect to permissible limit (case I)

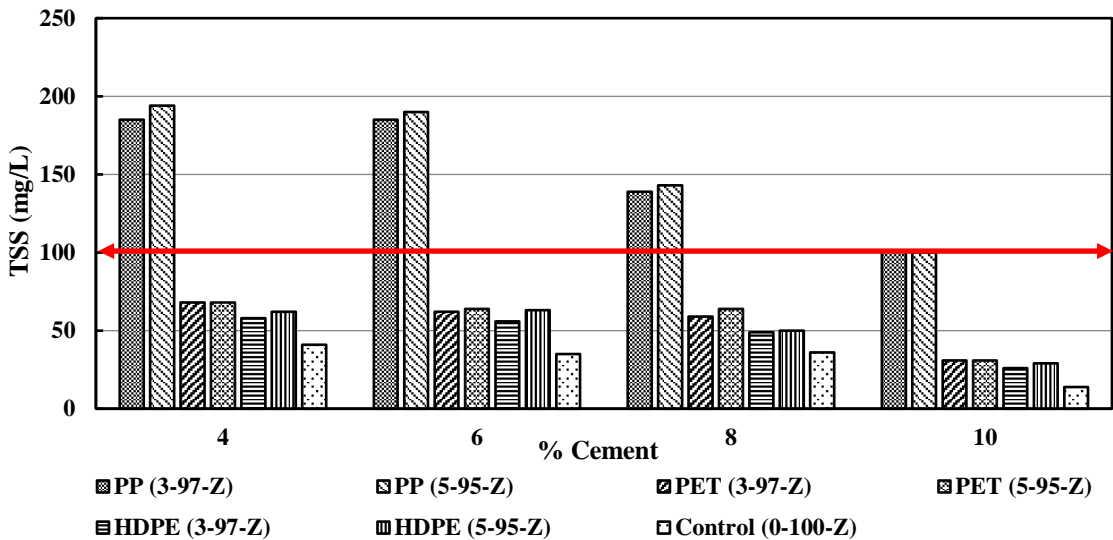


Figure 4-4 TSS results with respect to permissible limit (case I)

For case I where the cylindrical base specimens were kept submerged to collect the leachates, all samples showed reasonable TDS results in terms of the USEPA permissible limit. However, specimens made of PP plastics showed explicitly higher TSS values compared to others in terms of USEPA limit.



*Case II: Base Course; specimen subject to cyclic loading followed by submergence in stagnant water*

Table 4-4 TSS and TDS results for case II

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>TSS (mg/L)</i> | <i>TDS (mg/L)</i> |
|------------------------|---------------------------|-----------------|-------------------|-------------------|
| <i>PET</i>             | 3% + 97%                  | 4               | 125               | 467               |
|                        |                           | 6               | 116               | 518               |
|                        |                           | 8               | 113               | 541               |
|                        |                           | 10              | 78                | 549               |
|                        | 5% + 95%                  | 4               | 125               | 423               |
|                        |                           | 6               | 121               | 480               |
|                        |                           | 8               | 115               | 511               |
|                        |                           | 10              | 90                | 556               |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 115               | 469               |
|                        |                           | 6               | 112               | 491               |
|                        |                           | 8               | 107               | 549               |
|                        |                           | 10              | 58                | 551               |
|                        | 5% + 95%                  | 4               | 120               | 465               |
|                        |                           | 6               | 123               | 517               |
|                        |                           | 8               | 109               | 511               |
|                        |                           | 10              | 110               | 539               |
| <i>PP</i>              | 3% + 97%                  | 4               | 208               | 439               |
|                        |                           | 6               | 182               | 493               |
|                        |                           | 8               | 117               | 574               |
|                        |                           | 10              | 119               | 571               |
|                        | 5% + 95%                  | 4               | 196               | 428               |
|                        |                           | 6               | 133               | 461               |
|                        |                           | 8               | 146               | 555               |
|                        |                           | 10              | 122               | 579               |
| <i>No Plastic</i>      | 0% + 100%                 | 4               | 65                | 554               |
|                        | 0% + 100%                 | 6               | 48                | 556               |
|                        | 0% + 100%                 | 8               | 32                | 549               |
|                        | 0% + 100%                 | 10              | 28                | 562               |

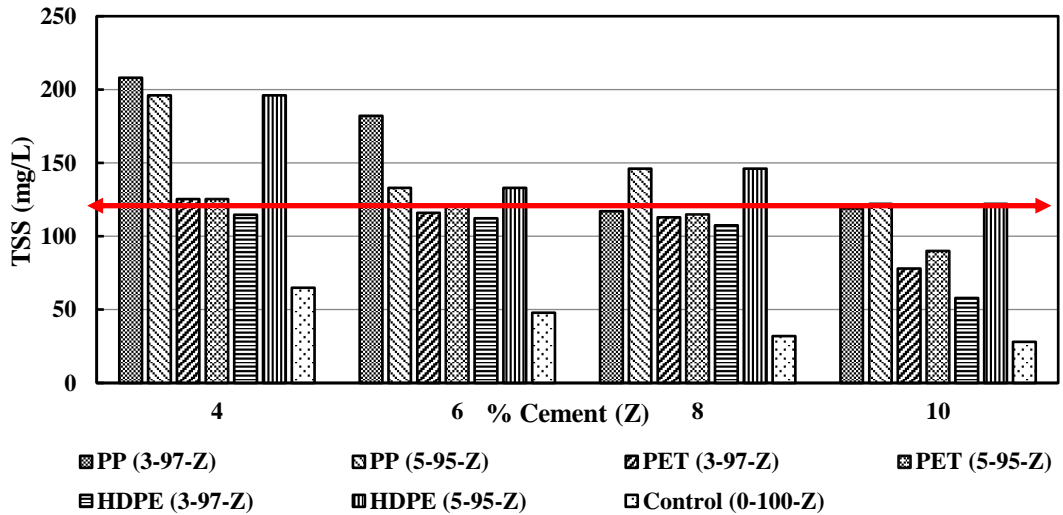


Figure 4-5 TSS results with respect to permissible limit (case II)

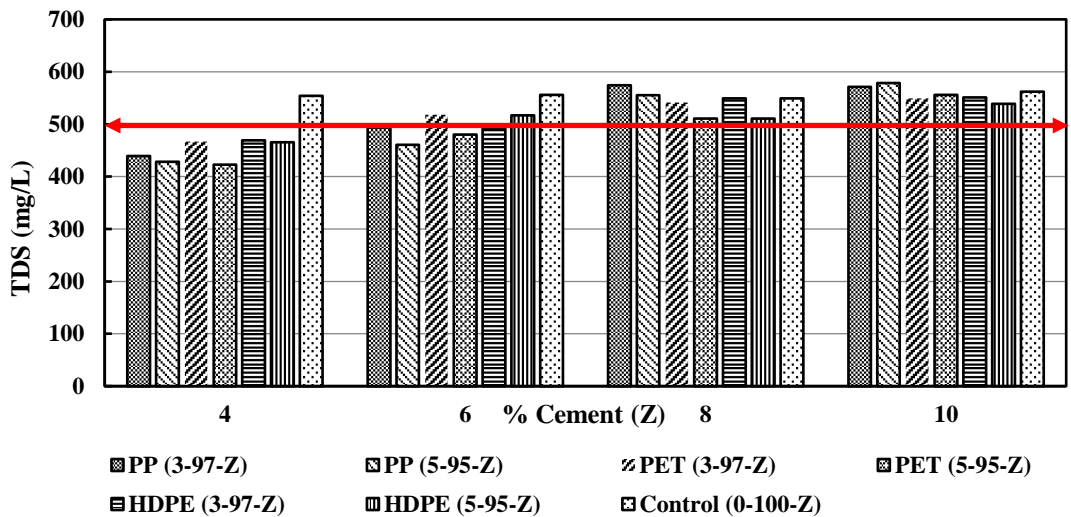


Figure 4-6 TDS results with respect to permissible limit (case II)

For case II TSS results it is quite discerning that, most of the values except those representing control sample with 0% plastic are very much close to and for quite a few occasions have surpassed the acceptable USEPA limit in terms of urban stormwater runoff quality. On the other hand, for TDS results, it can be said that most of the samples represent very high TDS values in response to the acceptable limit, which is 500 mg/L following a given stormwater event.

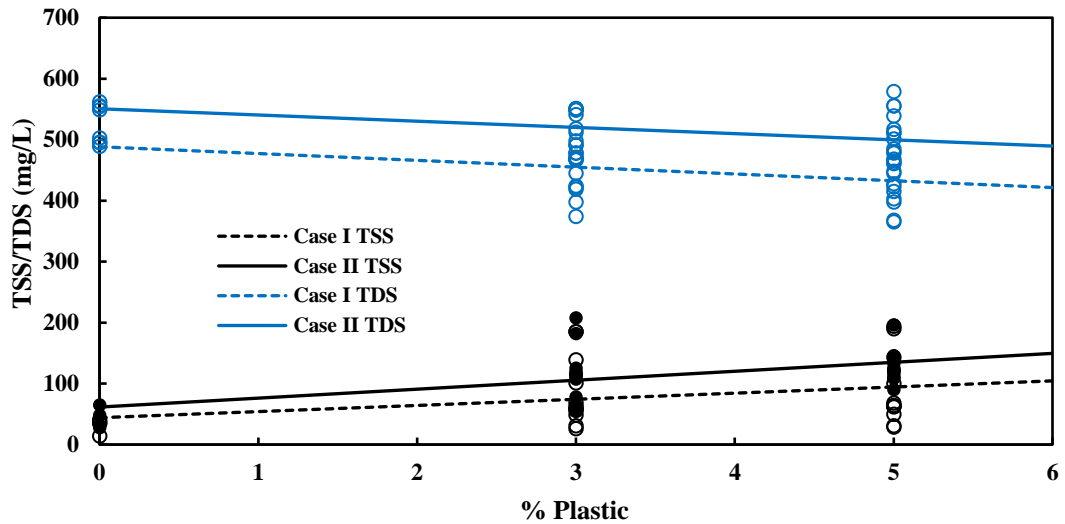


Figure 4-7 Relative change of TSS/TDS with respect to % plastic (case I & case II)

This plot basically shows the relative change/trend of Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) with respect to increasing plastic content in the experimented samples for both case I and case II. What these sets of graphs delineate is that TDS and TSS have got a reciprocal changing trend with respect to increasing plastic content. For both cases it is evident that increasing plastic content in the experimented samples tend to be increasing values for Total Suspended Solids (TSS) and the opposite for Total Dissolved Solids (TDS). This trend analysis could be a vital element in the microplastic tests results as well in upcoming sections, since both TSS, and TDS irrespective of the test cases exhibited a definite yet converse trend with respect to increasing plastic percentage. However, it is also worth mentioning that TSS for case II represents higher average value compared to those of case I and the same trend applies for TDS as well. Albeit there is a discerning trend between TDS/TSS values and plastic percentage, this trend is enough to ensure the presence of microplastics in certain samples. Having said that, this trend could be an important source for the development of statistical model to predict the quantity of microplastics and the risk associated.

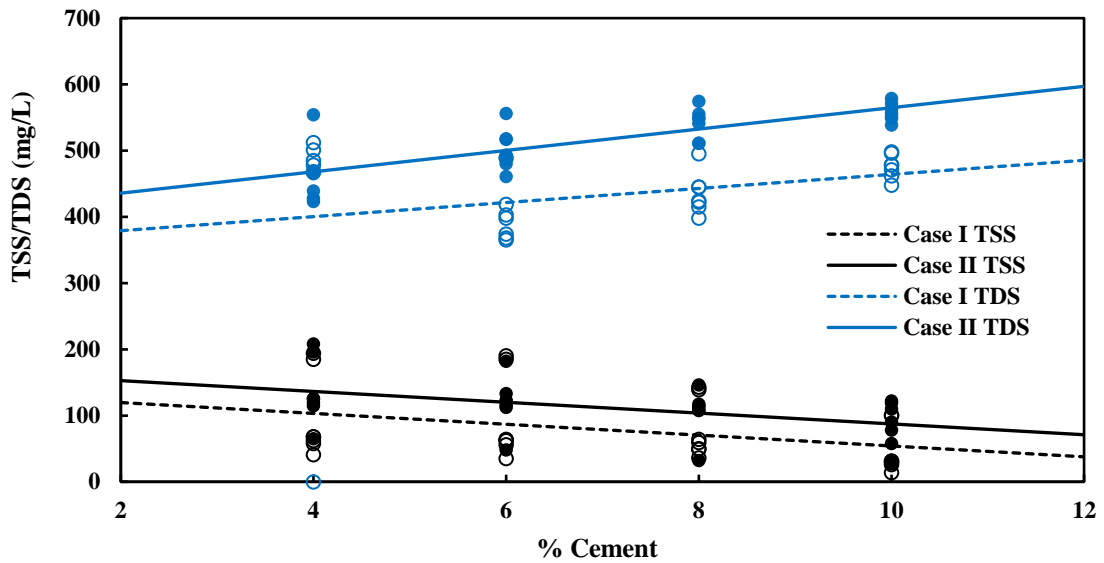


Figure 4-8 Relative change of TSS/TDS with respect to % plastic (case I & case II)

This plot incorporates the relative change/trend of Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) with respect to increasing plastic content in the experimented samples for both case I and case II. These sets of graphs depict that TDS and TSS have got a reciprocal changing trend with respect to increasing cement content. For both cases it is evident that increasing cement content in the experimented samples tend to be decreasing values for Total Suspended Solids (TSS) and the opposite for Total Dissolved Solids (TDS).

Another interesting fact about the sets of graphs shown in figure 4-7 and figure 4-8 that, both TSS values show reciprocal trend with respect to increasing cement and plastic percentage irrespective of the case type and the same statement goes for TDS values as well. For example, disregarding the case type, TSS values increase with increasing plastic percentage and decrease with increasing cement content. On the contrary, TDS values decrease with increasing plastic percentage in the samples but increase the increase of cement percentages in the sample. Hence,

it can be said that not only TDS and TSS values show reciprocal trend, but the relative TDS/TSS trend with respect to both increasing plastic and cement percentage is reciprocal also.

*Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion Rutting test setup*

Table 4-5 TDS and TSS results for case III

| <i>Plastic Type</i> | <i>% Plastic</i> | <i>Bitumen</i> | <i>TDS (mg/L)</i> | <i>TSS (mg/L)</i> |
|---------------------|------------------|----------------|-------------------|-------------------|
| <i>PP</i>           | 4%               | 70-22          | 423               | 182               |
|                     | 8%               | 70-22          | 438               | 154               |
|                     | 12%              | 70-22          | 441               | 129               |
|                     | 16%              | 70-22          | 486               | 113               |
| <i>HDPE</i>         | 4%               | 70-22          | 476               | 75                |
|                     | 8%               | 70-22          | 523               | 82                |
|                     | 12%              | 70-22          | 542               | 67                |
|                     | 16%              | 70-22          | 549               | 43                |
| <i>LDPE</i>         | 4%               | 70-22          | 578               | 47                |
|                     | 8%               | 70-22          | 612               | 56                |
|                     | 12%              | 70-22          | 598               | 38                |
|                     | 16%              | 70-22          | 624               | 29                |
| <i>Control</i>      | 0%               | 70-22          | 561               | 118               |

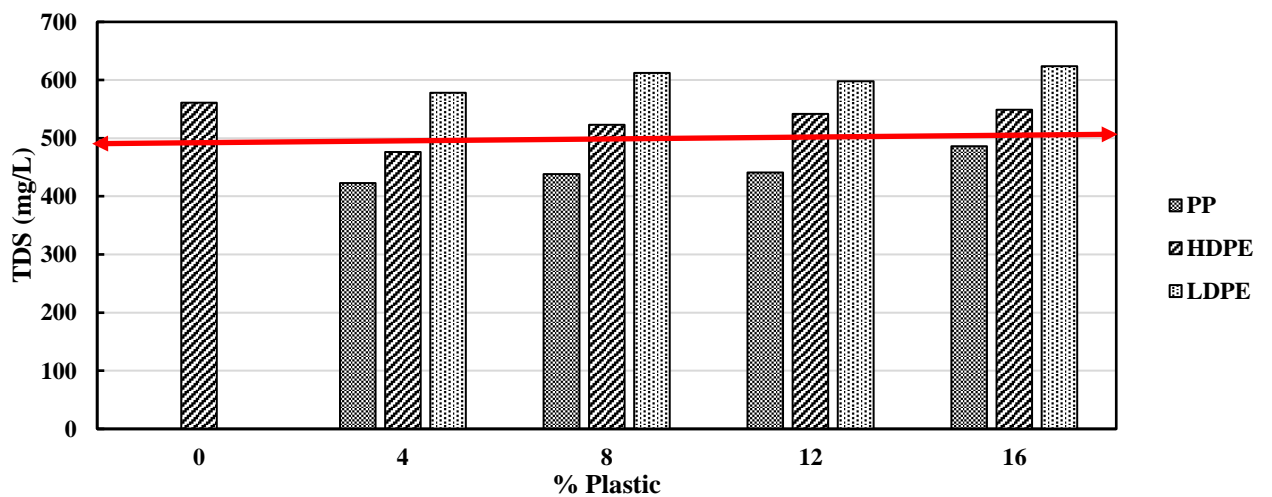


Figure 4-9 TDS results with respect to permissible limit (case III)

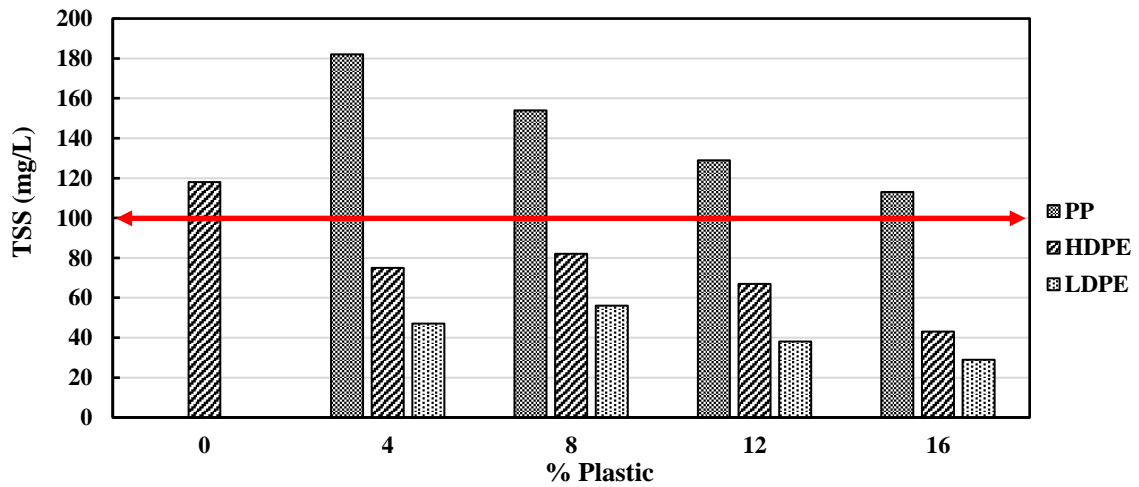


Figure 4-10 TSS results with respect to permissible limit (case III)

From figure 4-9 and 4-10 it is quite imminent that, samples representing PP plastic type showed better result compared to others even better than the control samples as well in terms of the USEPA acceptable threshold TDS value of 500 mg/L. On the other hand, for TSS, all other samples except those incorporating PP plastics type showed reasonable numbers in terms of USEPA permissibility for urban stormwater runoff standard for environmental leaching parameter.

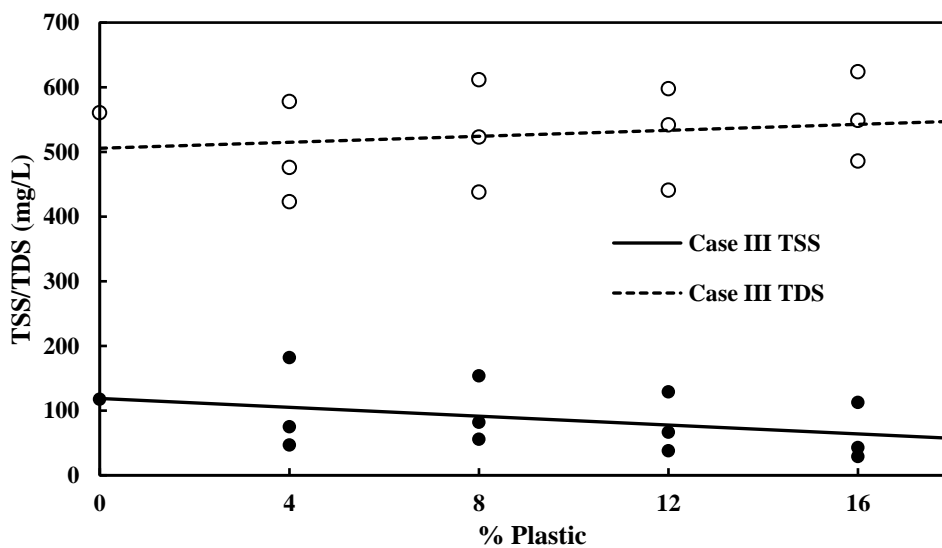


Figure 4-11 Relative change of TSS/TDS with respect to % plastic (Case III)

Figure 4-11 delineates the relative changes in TDS and TSS values with respect to increasing plastic percentage in the experimented samples. It is easily discernible following the trend of the plot that with increasing plastic content Total Suspended Solids (TSS) values tend to decrease whereas Total Dissolved Solids (TDS) values keep on decreasing with additional increase of the plastic percentage in the samples. Although, TDS and TSS values did show a reciprocal relative change with increasing plastic percentage, this change took place in a reverse order compared to the trend observed for case I and case II previously. For case I and II, we have seen that with the increase of plastic percentage in the samples, TSS values tend to increase, and TDS value tend to decrease simultaneously. These two different trends subject to plastic percentage increase could be attributed to the better rutting characteristics of the surface course specimen with increasing amount of plastic percentage in the samples.

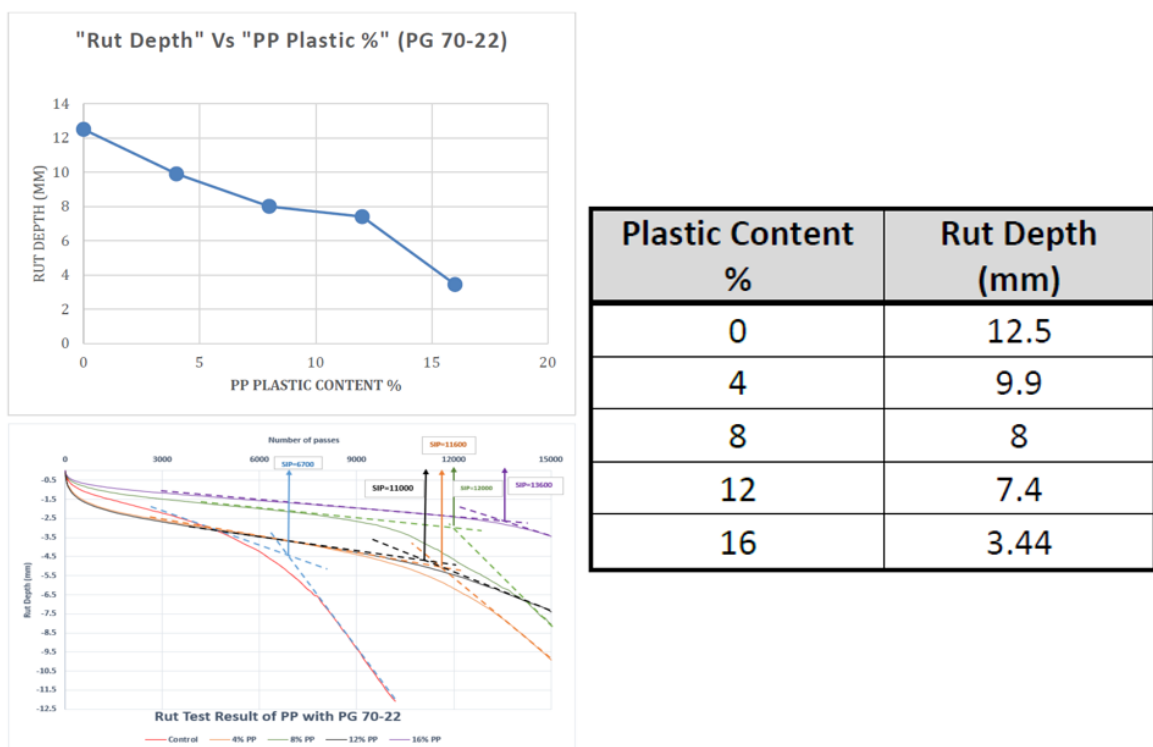
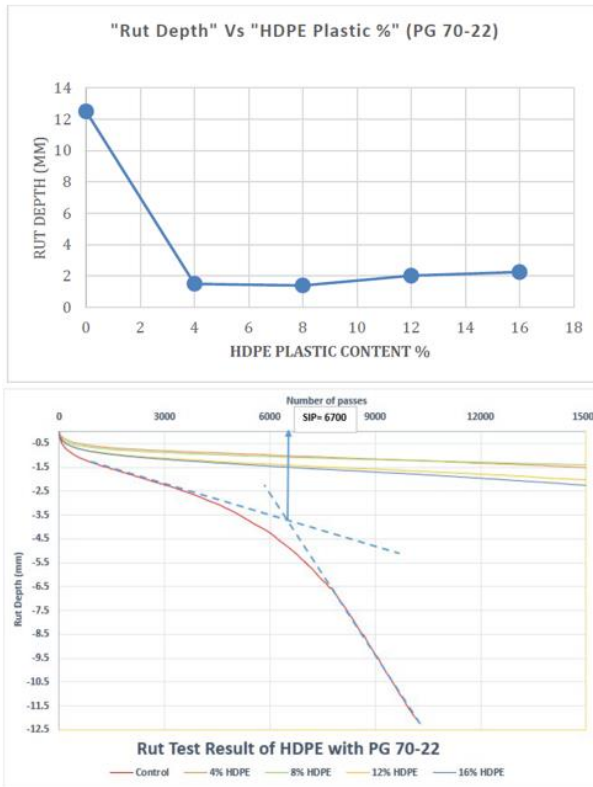
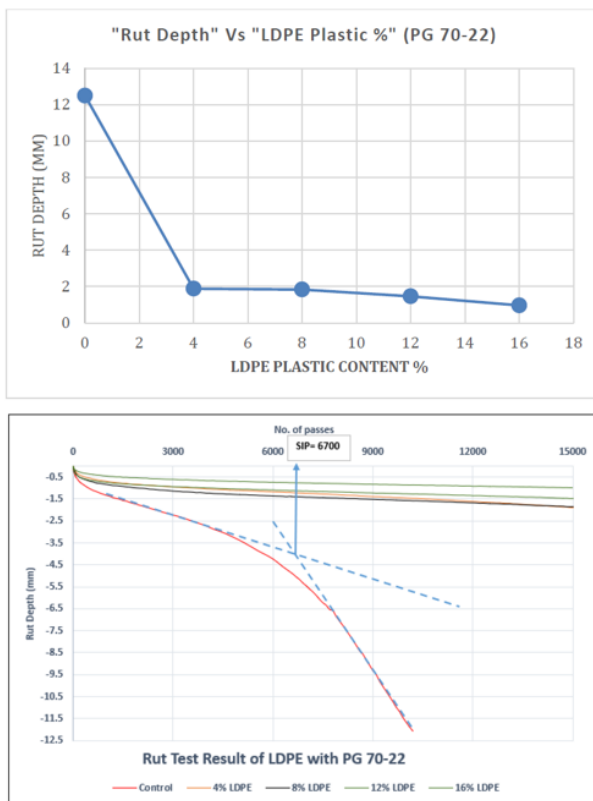


Figure 4-12 Rutting performance of PP plastic with PG 70-22 Bitumen (Singh 2022)



| Plastic Content % | Rut Depth (mm) |
|-------------------|----------------|
| 0                 | 12.5           |
| 4                 | 1.51           |
| 8                 | 1.4            |
| 12                | 2.03           |
| 16                | 2.26           |

Figure 4-13 Rutting performance of HDPE plastic with PG 70-22 Bitumen (Singh 2022)



| Plastic Content % | Rut Depth (mm) |
|-------------------|----------------|
| 0                 | 12.5           |
| 4                 | 1.89           |
| 8                 | 1.84           |
| 12                | 1.47           |
| 16                | 0.97           |

Figure 4-14 Rutting performance of LDPE plastic with PG 70-22 Bitumen (Singh 2022)



Singh (2022) conducted research on use of recycled plastic granules as a mixing constituent for pavement wearing course. What she found through her research works that increased plastic content significantly reduces the rutting depth on the experimented samples in Hamburg rutting test setup. From the figures numbered 5-12, 5-13 and 5-14 it is absolutely imminent that rutting depth decreases significantly with increasing plastic content for the samples made of PP and LDPE plastic types. However, for samples incorporating HDPE plastic type, rutting depth decrease from 0% to 8% increase of plastic content and then increases marginally from 8% to 16% increase of plastic content which is very infinitesimal. These sets of results tend to be a fitted corroboration of the observed results of TSS for case III in this current study.

The following table summarizes the rutting depth values from the study conducted by Singh (2022), and the observed TSS values corresponding to each sample combinations from the current study.

Table 4-6 Rutting depth and TSS values corresponding to case III

| <i>Plastic Type</i> | <i>% Plastic</i> | <i>Bitumen</i> | <i>Rutting Depth (mm)</i> | <i>TSS (mg/L)</i> |
|---------------------|------------------|----------------|---------------------------|-------------------|
| <i>PP</i>           | 4%               | 70-22          | 9.9                       | 182               |
|                     | 8%               | 70-22          | 8                         | 154               |
|                     | 12%              | 70-22          | 7.4                       | 129               |
|                     | 16%              | 70-22          | 3.44                      | 113               |
| <i>HDPE</i>         | 4%               | 70-22          | 1.51                      | 75                |
|                     | 8%               | 70-22          | 1.4                       | 82                |
|                     | 12%              | 70-22          | 2.03                      | 67                |
|                     | 16%              | 70-22          | 2.26                      | 43                |
| <i>LDPE</i>         | 4%               | 70-22          | 1.89                      | 47                |
|                     | 8%               | 70-22          | 1.84                      | 56                |
|                     | 12%              | 70-22          | 1.47                      | 38                |
|                     | 16%              | 70-22          | 0.97                      | 29                |
| <i>Control</i>      | 0%               | 70-22          | 12.5                      | 118               |

The following plot aims at developing a correlation between the observed TSS values from the current study and the rutting depth observed from the study conducted by Singh (2022) for all combinations involving three different types of plastics, i.e., PP, HDPE and LDPE and bitumen grade PG 70-22.

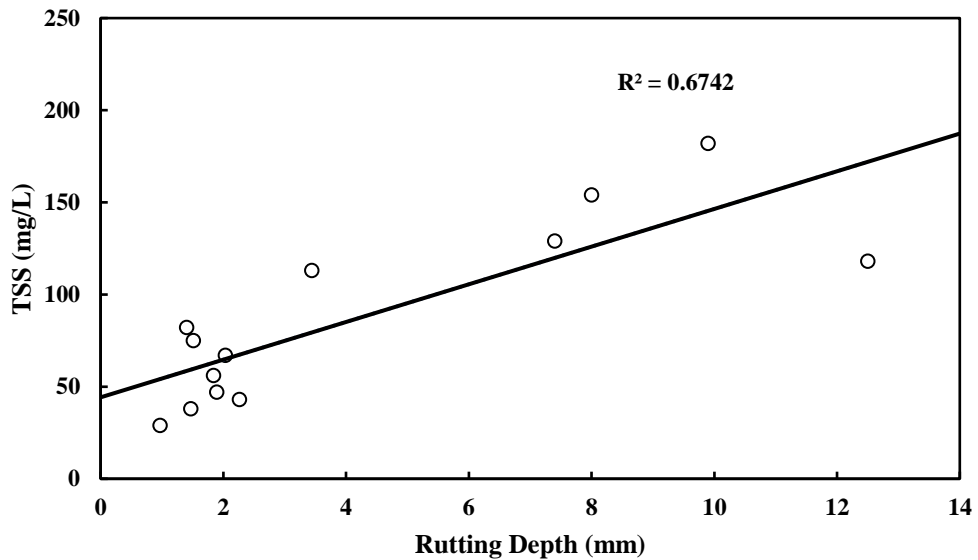


Figure 4-15 TSS Vs Rutting depth

The following graph shows the correlation between rutting depth and plastic percentage in the experimented samples.

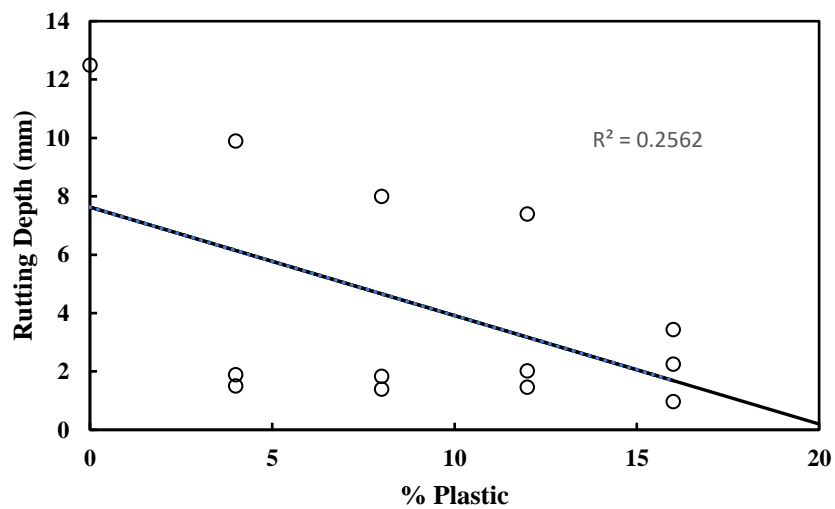


Figure 4-16 Rutting depth Vs % plastic

The graph shown in figure 4-15 exhibits a reasonable correlation between TSS and rutting depths of the cylindrical specimen prepared. It clearly defines that with increase of the rutting depth, TSS values tend to increase. The correlation can strongly be corroborated by a reasonable  $R^2$  value of 0.6742. On the other hand, figure 5-16 shows that rutting depth has got an inverse correlation with increasing plastic percentage. And, in this section previously we have come to know that, for case III, TSS decreases with increase of plastic. So, all these attributes and parameters are interrelated either in a proportionate or in an inversely proportionate way. Hence, it can be proclaimed that rutting depth could be one of the important parameters of statistical model aiming at predicting microplastic risk for case III, which we will figure out in next chapter.

#### 4.4 Specific Conductance

*Case I: Base Course; specimen submerged in stagnant water*

Table 4-7 Specific conductance test results for case I

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>SC (<math>\mu\text{mohs/cm}</math>)</i> |
|------------------------|---------------------------|-----------------|--|
| <i>PET</i>             | 3% + 97%                  | 4               | 492.45                                     |
|                        |                           | 6               | 493.59                                     |
|                        |                           | 8               | 512.13                                     |
|                        |                           | 10              | 552.45                                     |
|                        | 5% + 95%                  | 4               | 431.63                                     |
|                        |                           | 6               | 487.82                                     |
|                        |                           | 8               | 493.01                                     |
|                        |                           | 10              | 571.14                                     |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 489.13                                     |
|                        |                           | 6               | 487.39                                     |
|                        |                           | 8               | 499.48                                     |
|                        |                           | 10              | 573.56                                     |
|                        | 5% + 95%                  | 4               | 487.39                                     |
|                        |                           | 6               | 512.15                                     |
|                        |                           | 8               | 532.18                                     |
|                        |                           | 10              | 543.62                                     |
| <i>PP</i>              | 3% + 97%                  | 4               | 489.54                                     |
|                        |                           | 6               | 497.55                                     |
|                        |                           | 8               | 512.56                                     |
|                        |                           | 10              | 586.31                                     |
|                        | 5% + 95%                  | 4               | 429.74                                     |
|                        |                           | 6               | 421.65                                     |
|                        |                           | 8               | 512.64                                     |
|                        |                           | 10              | 588.12                                     |
| <i>No Plastic</i>      | 0% + 100%                 | 4               | 551.47                                     |
|                        | 0% + 100%                 | 6               | 572.43                                     |
|                        | 0% + 100%                 | 8               | 498.29                                     |
|                        | 0% + 100%                 | 10              | 544.65                                     |

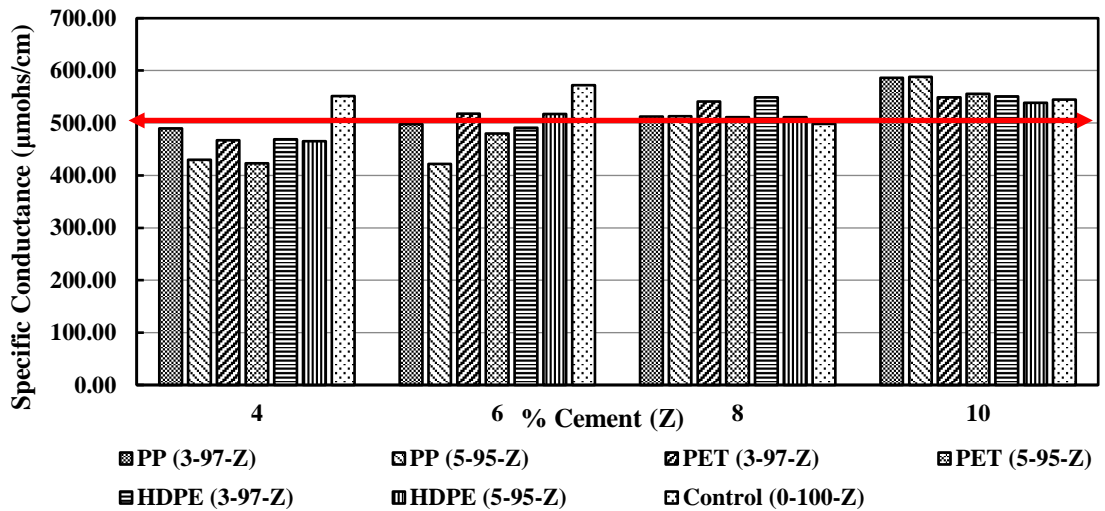


Figure 4-17 Specific conductance test results with respect to permissible limit (case I)

Figure 4-17 suggests that the more cement added to the samples percentage wise, the more the values for specific conductance irrespective of plastic types being using preparing the sample. For lower cement percentage (4% and 6%, specific conductance tends to be lower than permissible USEPA threshold of 500 µmhos/cm except those control samples without plastics. However, for higher dosage of cement percentage in the sample we could see the values for specific conductance have gone past the acceptable USEPA range in terms of urban stormwater runoff quality.

According to the USEPA benchmark, the favorable limit of specific conductance has been given as 200 µmhos/cm. However, the conductivity of rivers in the United States generally ranges from 50 to 1500 µmhos/cm. Studies of inland fresh waters indicate that streams supporting good mixed fisheries have a range between 150 and 500 µmhos/cm. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. That is why the allowable limit of specific conductance has been revised to 500 µmhos/cm.

*Case II: Base Course; specimen subject to cyclic loading followed by submergence in stagnant water*

Table 4-8 Specific conductance test results for case II

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>Specific Conductance (μmhos/cm)</i> |
|------------------------|---------------------------|-----------------|--|
| <i>PET</i>             | 3% + 97%                  | 4               | 571.39                                 |
|                        |                           | 6               | 574.68                                 |
|                        |                           | 8               | 594.47                                 |
|                        |                           | 10              | 633.80                                 |
|                        | 5% + 95%                  | 4               | 502.50                                 |
|                        |                           | 6               | 567.43                                 |
|                        |                           | 8               | 572.55                                 |
|                        |                           | 10              | 632.41                                 |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 534.56                                 |
|                        |                           | 6               | 565.58                                 |
|                        |                           | 8               | 578.82                                 |
|                        |                           | 10              | 651.84                                 |
|                        | 5% + 95%                  | 4               | 522.45                                 |
|                        |                           | 6               | 596.11                                 |
|                        |                           | 8               | 617.02                                 |
|                        |                           | 10              | 630.56                                 |
| <i>PP</i>              | 3% + 97%                  | 4               | 579.42                                 |
|                        |                           | 6               | 586.40                                 |
|                        |                           | 8               | 595.63                                 |
|                        |                           | 10              | 681.90                                 |
|                        | 5% + 95%                  | 4               | 507.51                                 |
|                        |                           | 6               | 491.78                                 |
|                        |                           | 8               | 599.97                                 |
|                        |                           | 10              | 684.55                                 |
| <i>Control</i>         | 0% + 100%                 | 4               | 628.98                                 |
|                        | 0% + 100%                 | 6               | 646.62                                 |
|                        | 0% + 100%                 | 8               | 652.13                                 |
|                        | 0% + 100%                 | 10              | 604.64                                 |

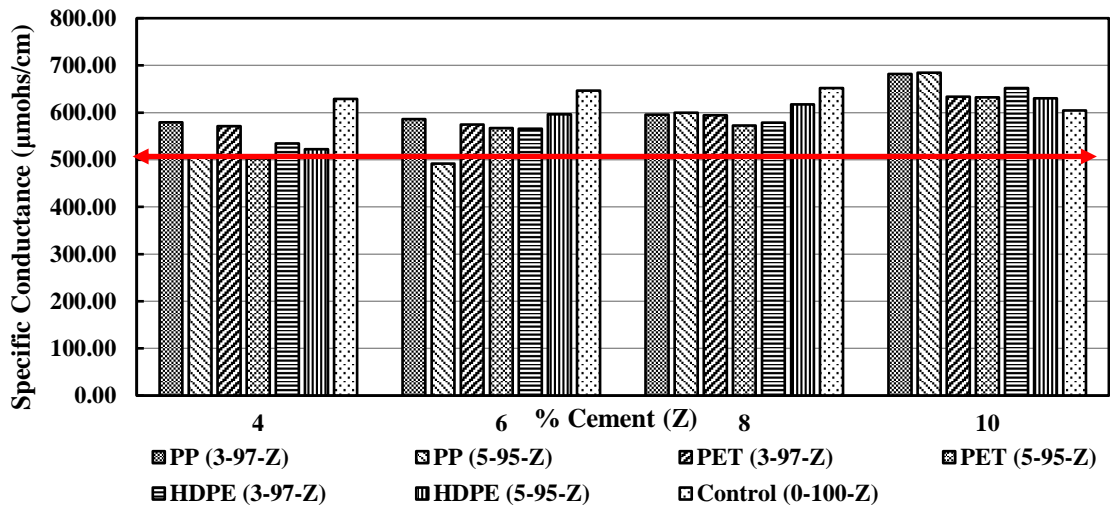


Figure 4-18 Specific conductance test results with respect to permissible limit (case II)

Figure 4-18 suggests that for case II, all the samples exhibit higher than acceptable threshold numbers of specific conductance according to the USEPA benchmark which is 500 µmhos/cm. It signifies the increased amount of dissolvable particles which is in particular conductive in nature due to the cyclic actions on the cylindrical base specimen in a resilient moduli test setup representing long term effects on pavement base due to periodically cyclic loading exerted on the specimens.

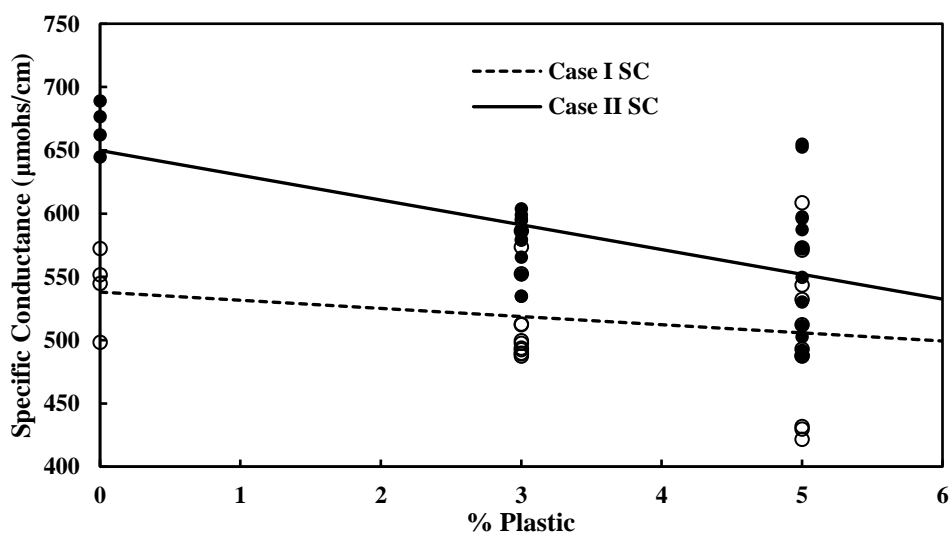


Figure 4-19 Change of specific conductance with respect to % plastic (case I & case II)

From figure 4-19 it can be postulated that for base course specific case I and case II referring to two different weathering conditions of cylindrical representative base specimens, with the increase of plastic percentage (irrespective of plastic types used to prepare the specimen), specific conductance tends to decrease. However, the decreasing trend of specific conductance for case II is sharper and more dramatic with increasing plastic percentage compared to that observed for case I.

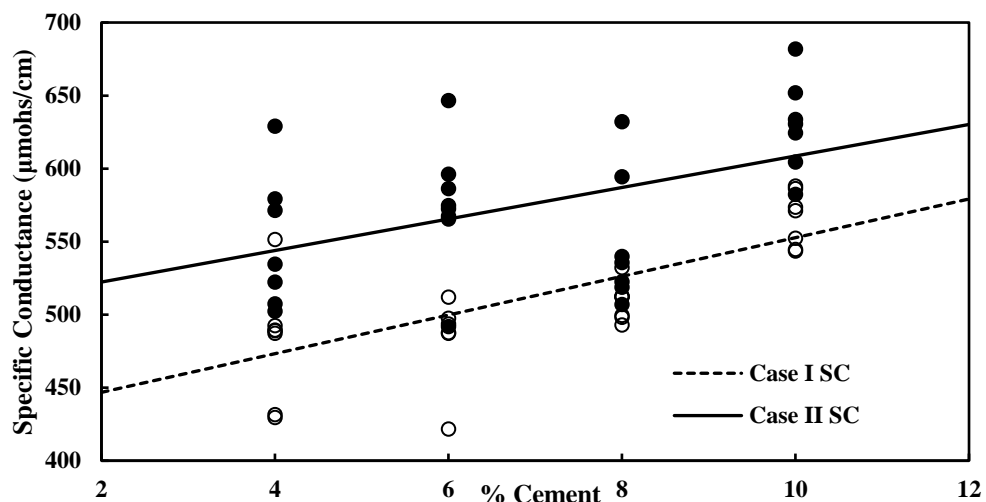


Figure 4-20 Change of specific conductance with respect to % cement (case I & case II)

From figure 4-20 it can be observed that for base course specific case I and case II referring to two different weathering conditions of cylindrical representative base specimens, with the increase of plastic percentage (irrespective of plastic types used to prepare the specimen), specific conductance tends to increase. This increasing trend of specific conductance with respect to increasing cement percentage in the specimens is however reciprocal of the trend shown in figure 5-19 where we could see a decreasing trend of specific conductance with respect to increasing plastic percentage in the samples.



Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion Rutting test setup

Table 4-9 Specific conductance test results (case III)

| <i>Plastic Type</i> | <i>% Plastic</i> | <i>Bitumen</i> | <i>Specific Conductance (μhos/cm)</i> |
|---------------------|------------------|----------------|---------------------------------------|
| <i>PP</i>           | 4%               | 70-22          | 528.75                                |
|                     | 8%               | 70-22          | 547.5                                 |
|                     | 12%              | 70-22          | 551.25                                |
|                     | 16%              | 70-22          | 607.5                                 |
| <i>HDPE</i>         | 4%               | 70-22          | 595                                   |
|                     | 8%               | 70-22          | 653.75                                |
|                     | 12%              | 70-22          | 677.5                                 |
|                     | 16%              | 70-22          | 686.25                                |
| <i>LDPE</i>         | 4%               | 70-22          | 722.5                                 |
|                     | 8%               | 70-22          | 765                                   |
|                     | 12%              | 70-22          | 747.5                                 |
|                     | 16%              | 70-22          | 780                                   |
| <i>Control</i>      | 0%               | 70-22          | 623                                   |

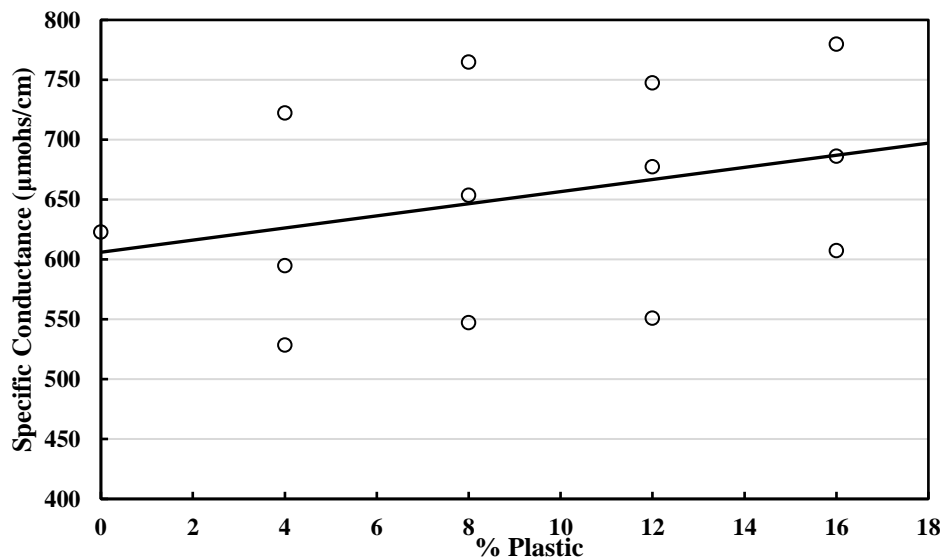


Figure 4-21 Change of specific conductance with respect to % plastic (case III)

Figure 4-21 depicts a proportionately increasing trend of specific conductance with respect to increasing plastic contents in the samples for case III which is a similar trend shown by the TDS results for case III as well.

#### 4.5 Optical Microscopic Detection

As mentioned earlier, this study involves two types of microplastic detection, i.e., Optical microscopic detection (quantitative analysis) and Fourier Transform Infra-Red (FTIR) spectroscopic detection (qualitative analysis). Detailed experimental methodology for optical microscopic inspection and quantification has been already discussed in previous chapter. This section of chapter 4 will focus on the observed results and subsequent risk characterization statistics in terms of microplastic contamination for different sample combinations corresponding three different cases. For the sake of calculation, analysis, and data representation microplastic concentration for each individual sample combination will be presented via Risk Characterization Ratio (RCR). The definition of Risk Characterization Ratio can be referred to as following equation.

$$\text{Risk Characterization Ratio (RCR)} = \frac{\text{Observed Microplastic Concentration, } N}{\text{Predicted No Effect Concentration, } PNEC} \dots (4.1)$$

Equation 4.1 delineates how to calculate the Risk Characterization Ratio (RCR). It is a unitless number which expresses the risk hierarchy in terms of microplastic concentration or contamination depending on the number itself. It is worth mentioning that concept of RCR to characterize risk is not only valid for microplastic contamination, but also for contamination associated with any sort of ecotoxicological substance present in the environment, i.e., heavy metals, carcinogenic substance, Poly Aromatic Hydrocarbons (PAHs) or any other known hazardous materials. It is a universal standard to characterize risk subject to the exposure of a

known toxic material. If  $RCR > 1$ , observed concentration is likely to pose an immediate or long term ecotoxicological risk (Véronique Adam et al., 2019). Although this statement by Véronique Adam et al., 2019 was exclusively made for microplastic risk in surface water environment, it can be applied to any other kind of hazardous materials exposure as well.

In chapter 3, details about microplastic concentration,  $N$  and Predicted No Observed Effect Concentration (PNEC) have been covered. For this study, microplastic concentration is measured in terms of particulate numbers observed or identified through an optical microscope within a sample size of 50 ml. And then the numbers are extrapolated to convert to particles/ $m^3$ . Since the standard practice of reporting  $N$ , and PNEC is in particles/ $m^3$ . The rationale for selecting an appropriate value for PNEC has been analyzed in detail in chapter 3. To recapitulate, PNEC is defined as the maximum possible concentration of microplastic theoretically present in fresh water, surface water or marine environment that would not pose any physiologically adverse effects on the micro vertebrates or invertebrates and will be tolerated by the microorganisms without any negative repercussions. Based on the previous studies and extensive research works it has been finalized that the PNEC value for this study is taken as  $9.5 \times 10^3$  particles/ $m^3$ . In that case, we can rewrite equation 4.2 as following incorporating that value for PNEC.

$$Risk\ Characterization\ Ratio\ (RCR) = \frac{N}{9.5 \times 10^3} \dots\dots\dots (4.2)$$

In this section of chapter 4, results of microscopic quantification will be tabulated and graphically presented. At the same time, the correlations between Risk Characterization Ratio (RCR) and multiple environmental leaching parameters (TDS, TSS, Specific Conductance) and other constituent parameters (% cement, % plastic, rutting depth) will also be established to

facilitate formulating statistical model that would help predict microplastic risk of an integrated plastic road in multiple weathering conditions.

#### 4.5.1 Risk Characterization Ratio (RCR) Results

*Case I: Base Course; specimen submerged in stagnant water*

Table 4-10 Optical microscopic test results for case I

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>MP Concentration, N (Particles/m<sup>3</sup>)</i> | <i>RCR</i> |
|------------------------|---------------------------|-----------------|--|------------|
| <i>PET</i>             | 3% + 97%                  | 4               | 100,000  | 0.105      |
|                        |                           | 6               | 100,000  | 0.105      |
|                        |                           | 8               | 80,000   | 0.084      |
|                        |                           | 10              | 40,000   | 0.042      |
|                        | 5% + 95%                  | 4               | 160,000  | 0.168      |
|                        |                           | 6               | 120,000  | 0.126      |
|                        |                           | 8               | 100,000  | 0.105      |
|                        |                           | 10              | 20,000   | 0.021      |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 80,000   | 0.084      |
|                        |                           | 6               | 80,000   | 0.084      |
|                        |                           | 8               | 80,000   | 0.084      |
|                        |                           | 10              | 20,000   | 0.021      |
|                        | 5% + 95%                  | 4               | 100,000  | 0.105      |
|                        |                           | 6               | 100,000  | 0.105      |
|                        |                           | 8               | 40,000   | 0.042      |
|                        |                           | 10              | 40,000   | 0.042      |
| <i>PP</i>              | 3% + 97%                  | 4               | 200,000  | 0.211      |
|                        |                           | 6               | 200,000  | 0.211      |
|                        |                           | 8               | 140,000  | 0.147      |
|                        |                           | 10              | 60,000   | 0.063      |
|                        | 5% + 95%                  | 4               | 240,000  | 0.253      |
|                        |                           | 6               | 200,000  | 0.211      |
|                        |                           | 8               | 160,000  | 0.168      |
|                        |                           | 10              | 60,000   | 0.063      |
| <i>Control</i>         | 0% + 100%                 | 4               | 40,000   | 0.042      |
|                        | 0% + 100%                 | 6               | 20,000   | 0.021      |
|                        | 0% + 100%                 | 8               | 60,000   | 0.063      |
|                        | 0% + 100%                 | 10              | 40,000   | 0.042      |

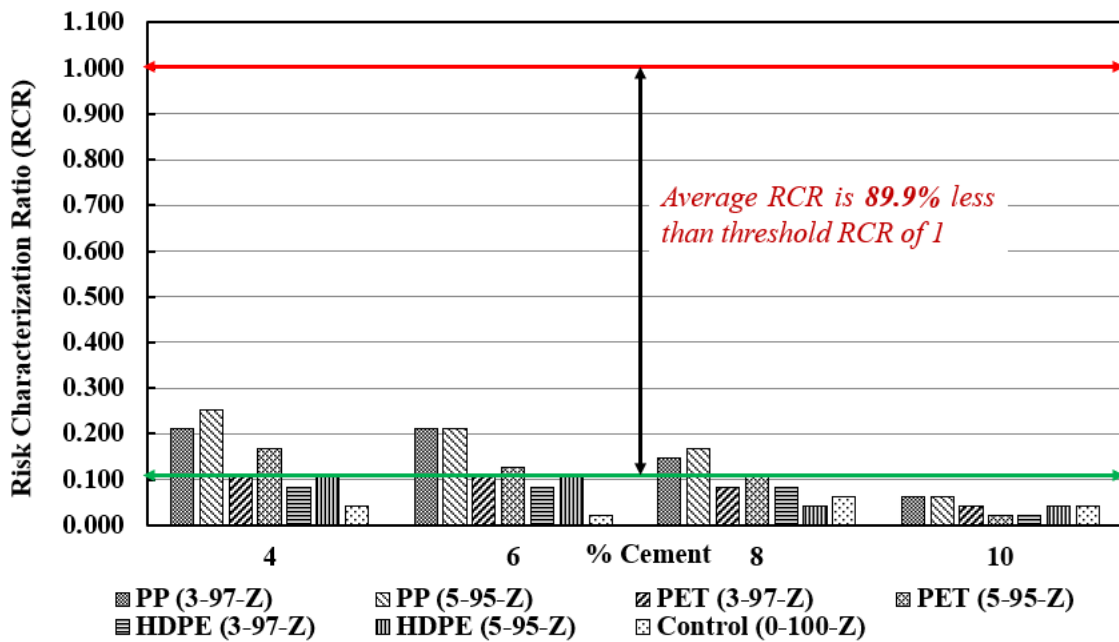


Figure 4-22 RCR values (case I)

From table 4-9 and figure 4-22 it is easily decipherable that the observed RCR for case I representing leaching sample of base specimens being submerged in stagnant water for 28 days, observed RCR is way below the threshold risk characterization quotient of 1. If we would take the average RCR for all corresponding RCR values for case I, it would be 0.101 which is almost 90% less than the threshold RCR of 1 as depicted in figure 5-22. As long as the different types of plastics used for preparing the samples are concerned, it could be observed that samples fabricated using PP plastic type resulted in more RCR values than other samples made of PET and HDPE type of plastics. And the statement remains valid for all sample combinations using different cement dosages. However, it is also evident that increasing cement stabilization results in lower RCR values for all sample combinations irrespective of different percentages of plastic and plastic type i.e., PP, PET, and HDPE. And, on an average samples made of HDPE plastics showed the lowest average RCR values among all the sample combinations.

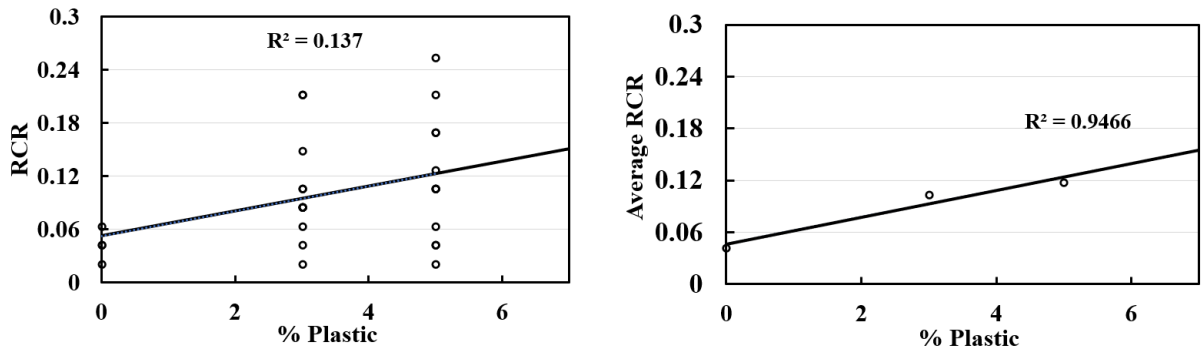


Figure 4-23 Change of RCR with respect to % plastic (case I)

From figure 4-23 it is evident that for case I, RCR values tend to increase proportionately with the increase of plastic percentage in samples. And if the arithmetic values of RCR for all pertinent sample combinations is plotted against % plastic, the resulting graph yielded in a substantially significant correlation having a  $R^2$  of 0.9466.

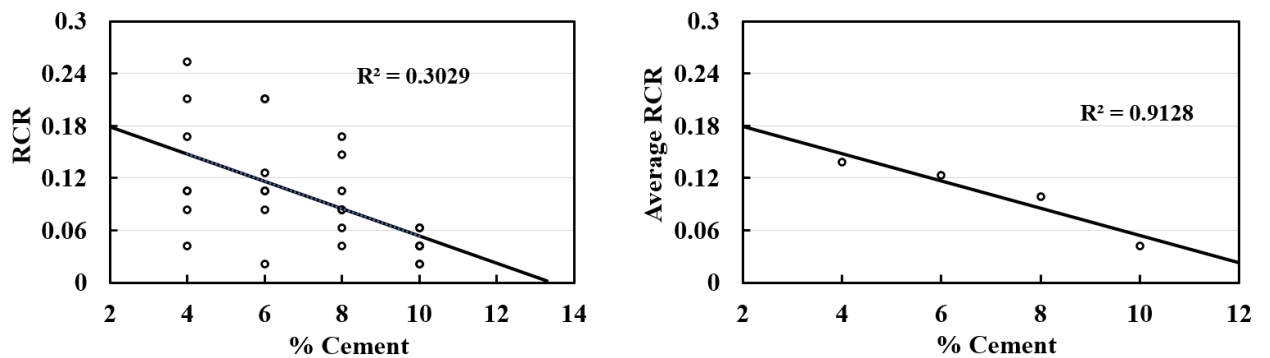


Figure 4-24 Change of RCR with respect to % cement (case I)

From figure 4-24 it is conspicuous that for case I, there is an inverse correlation between RCR and % cement used to fabricate the base specimens. RCR values tend to decrease proportionately with the increase of cement percentage in samples. And if the arithmetic values of RCR for all pertinent sample combinations is plotted against % cement, the resulting graph yielded in a substantially significant correlation having a  $R^2$  of 0.9128.

*Case II: Base Course; specimen subject to cyclic loading followed by submergence in stagnant water*

Table 4-11 Optical microscopic test results for case II

| <i>Type of Plastic</i> | <i>% Plastic + % RCCA</i> | <i>% Cement</i> | <i>MP Concentration, N (Particles/m<sup>3</sup>)</i> | <i>RCR</i> |
|------------------------|---------------------------|-----------------|--|------------|
| <i>PET</i>             | 3% + 97%                  | 4               | 900,000  | 0.947      |
|                        |                           | 6               | 650,000  | 0.684      |
|                        |                           | 8               | 600,000  | 0.632      |
|                        |                           | 10              | 400,000  | 0.421      |
|                        | 5% + 95%                  | 4               | 900,000  | 0.947      |
|                        |                           | 6               | 800,000  | 0.842      |
|                        |                           | 8               | 650,000  | 0.684      |
|                        |                           | 10              | 600,000  | 0.632      |
| <i>HDPE</i>            | 3% + 97%                  | 4               | 800,000  | 0.842      |
|                        |                           | 6               | 800,000  | 0.842      |
|                        |                           | 8               | 800,000  | 0.842      |
|                        |                           | 10              | 420,000  | 0.442      |
|                        | 5% + 95%                  | 4               | 900,000  | 0.947      |
|                        |                           | 6               | 800,000  | 0.842      |
|                        |                           | 8               | 900,000  | 0.947      |
|                        |                           | 10              | 600,000  | 0.632      |
| <i>PP</i>              | 3% + 97%                  | 4               | 1200,000   | 1.263      |
|                        |                           | 6               | 800,000  | 0.842      |
|                        |                           | 8               | 600,000  | 0.632      |
|                        |                           | 10              | 600,000  | 0.632      |
|                        | 5% + 95%                  | 4               | 1200,000   | 1.263      |
|                        |                           | 6               | 120,000  | 1.263      |
|                        |                           | 8               | 900,000  | 0.947      |
|                        |                           | 10              | 600,000  | 0.632      |
| <i>Control</i>         | 0% + 100%                 | 4               | 300,000  | 0.316      |
|                        | 0% + 100%                 | 6               | 240,000  | 0.253      |
|                        | 0% + 100%                 | 8               | 200,000  | 0.211      |
|                        | 0% + 100%                 | 10              | 200,000  | 0.211      |

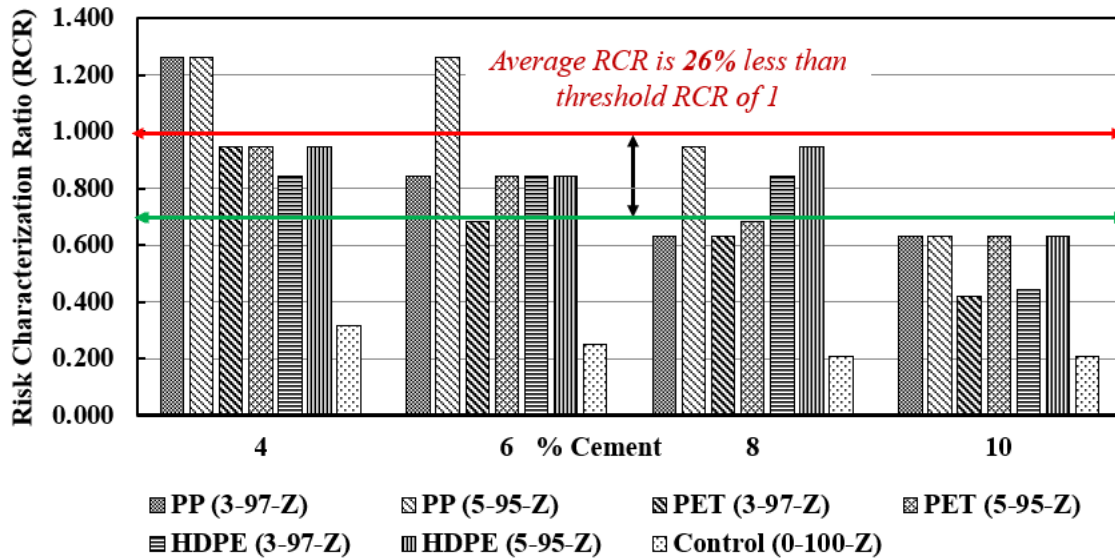


Figure 4-25 RCR values (case II)

From table 4-10 and figure 4-25 it can be said that the observed RCR for case II representing leaching sample of base specimens subject to cyclic loading in a resilient modulus testing setup until they implode and then eventually being submerged in stagnant water for 28 days, observed RCR is marginally below the threshold risk characterization quotient of 1 for majority of the samples at lower cement dosages (4% and 6%). However, samples fabricated from PP plastic types at lowest cement dosages (4%, 6%) exceed the RCR threshold of 1. However, for control samples with 0% plastic RCR values are significantly lower than 1 for all available cement dosages and hardly go past 0.3. Although the value 0.3 suggests that there is still microplastic trace being present in the samples, even though no recycled plastic was used to prepare those specimens and samples. As the cement dosage increases (8%, 10%) RCR values tend to decrease substantially for all sample combinations irrespective of plastic type used to fabricate the cylindrical specimens and subsequently prepare the leaching samples after having a cyclic duress in resilient moduli setup and 28 days of continual submergence in a container of stagnant water. Case II is aiming at recreating the worst possible condition for a standard cylindrical base specimen endured in an adverse condition as the periodic weathering



due to repetitive live loads from the traffic on pavement and simultaneous interference of stormwater stagnancy for a hypothetical extended period. Even considering that adverse condition in a conservative approach, RCR values observed for base course samples deem to be lower than threshold value of 1 for most of the cases.

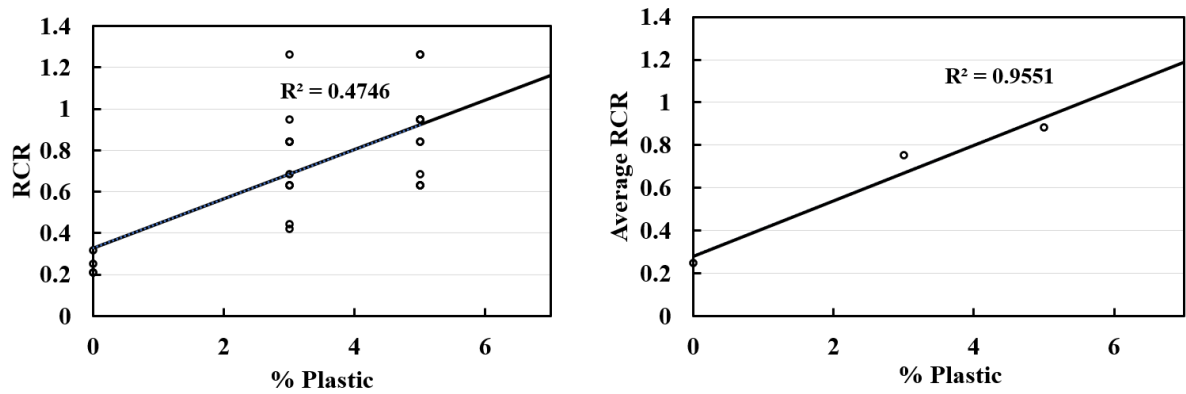


Figure 4-26 Change of RCR with respect to % plastic (case II)

From figure 4-23 it is evident that for case I, RCR values tend to increase proportionately with the increase of plastic percentage in samples. And if the arithmetic values of RCR for all pertinent sample combinations is plotted against % plastic, the resulting graph yielded in a substantially significant correlation having a  $R^2$  of 0.9551.

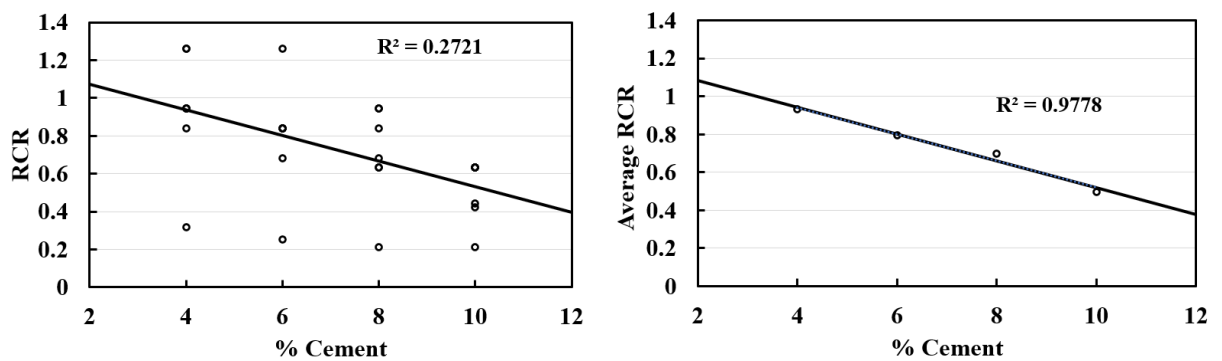


Figure 4-27 Change of RCR with respect to % plastic (case II)

RCR values tend to decrease proportionately with the increase of cement percentage in samples like the ones exhibited case I samples.

Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion Rutting test setup

Table 4-12 Optical microscopic test results for case III

| <i>Plastic Type</i> | <i>% Plastic</i> | <i>Bitumen</i> | <i>MP Concentration, N (particles/ m<sup>3</sup>)</i> | <i>RCR</i> |
|---------------------|------------------|----------------|---|------------|
| <i>PP</i>           | 4%               | 70-22          | 300,000   | 0.316      |
|                     | 8%               | 70-22          | 240,000   | 0.253      |
|                     | 12%              | 70-22          | 300,000   | 0.316      |
|                     | 16%              | 70-22          | 200,000   | 0.211      |
| <i>HDPE</i>         | 4%               | 70-22          | 200,000   | 0.211      |
|                     | 8%               | 70-22          | 160,000   | 0.168      |
|                     | 12%              | 70-22          | 180,000   | 0.189      |
|                     | 16%              | 70-22          | 120,000   | 0.126      |
| <i>LDPE</i>         | 4%               | 70-22          | 100,000   | 0.105      |
|                     | 8%               | 70-22          | 80,000  | 0.084      |
|                     | 12%              | 70-22          | 60,000  | 0.063      |
|                     | 16%              | 70-22          | 60,000  | 0.063      |
| <i>Control</i>      | 0%               | 70-22          | 300,000   | 0.316      |

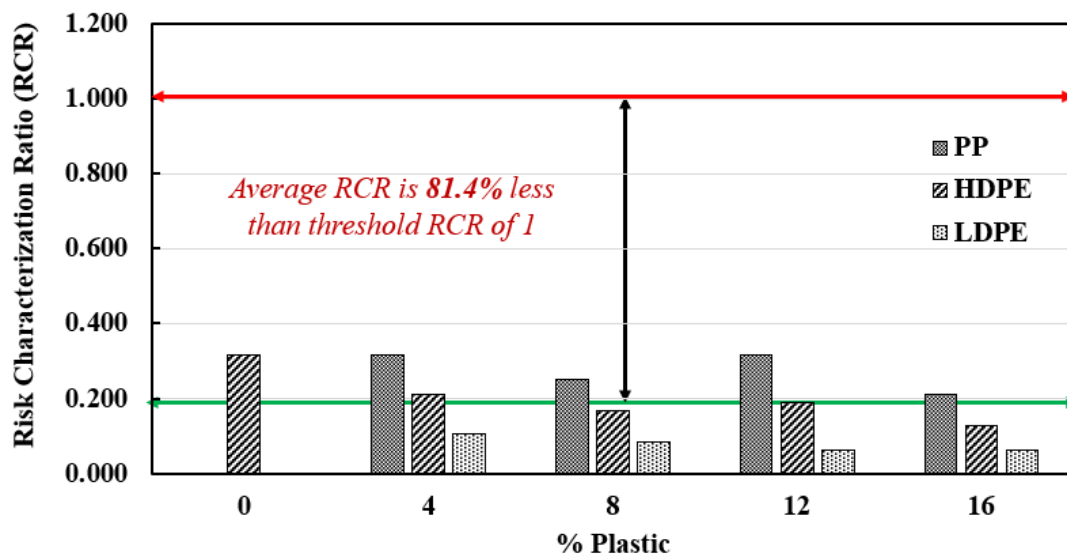


Figure 4-28 RCR values (case III)

From table 4-11 and figure 4-28 it is easily perceivable that the observed RCR for case III representing leaching sample of surface course specimens subject to Hamburg rutting setup,

observed RCR values are significantly lower than the threshold risk characterization quotient of 1.

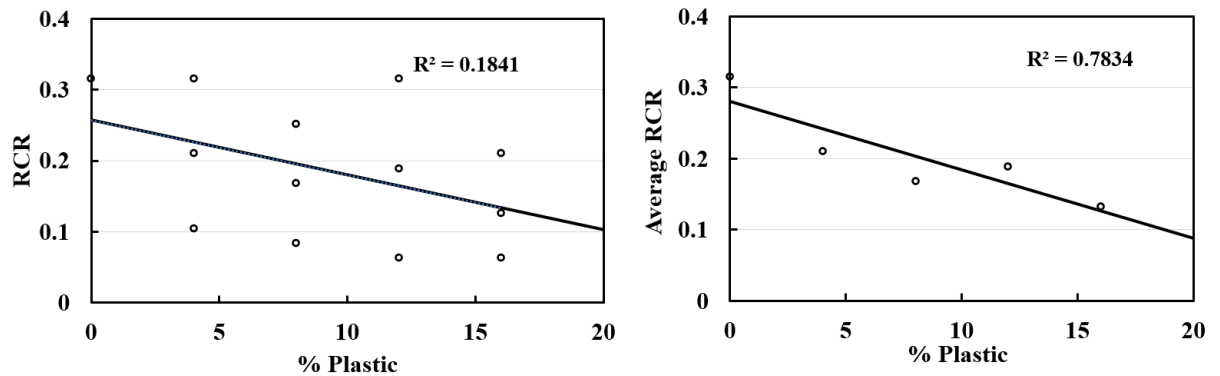


Figure 4-29 Change of RCR with respect to % plastic (case III)

Unlike case I and II, case III represents an inverse correlation between RCR and % Plastic. This aberration could be attributed to the better rutting characteristics of the surface course specimen with increasing amount of plastic percentage in the samples which has been discussed and analyzed in detail in the previous section 4.3 of this chapter. Where, we have analyzed the results obtained from the study conducted by Singh (2022) and have figure out that with the increase of plastic content in the cylindrical representative specimens, rutting depth decreases significantly irrespective of different types of plastic used. As the rutting depth decreases significantly, the specimen builds up a resistive characteristic against the passing wheel in the Hamburg rutting machine resulting in less suspended materials due to the repetitive abrasive forces exerted on the specimens. Since, we know that microplastic is one of the principal constituents of suspended solids, there is a possibility of having a reasonable reverse correlation between RCR and rutting depth of the specimens as well. We will attempt to find out the correlation which would facilitate establishing the statistical model to predict RCR value for any given combination of surface course leaching sample incorporating the primary physical and secondarily obtained known parameters.

#### **4.5.2 Correlation Between RCR and Leaching Parameters**

In previous subsection of this chapter, we have come to address about the correlation between Risk Characterization Ratio (RCR) and different constituent primary parameters for all sample combinations regardless of case scenario. Constituent parameters did include percentage of plastic, percentage of cement dosage for two different cases pertinent to base sample whereas constituent parameters for surface course sample mostly incorporate plastic content. In this chapter, we will however attempt to establish correlation between RCR, and various resultant leaching parameters that we have observed through conducted environmental leaching tests, i.e., Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Specific Conductance. These different sets of correlations will further facilitate envisage an establishing respective statistical model to predict the Risk Characterization Ratio (RCR) associated with the use of recycled shredded plastics as alternative materials for pavement construction.

For each case as defined in the current study, multiple correlations will be formed along with an existing trend and comparative analysis of these trend will be discussed. These correlations will also help us identify the change of RCR and based on that a detailed statistical modeling could be established. Statistical model will focus on predicting the Risk Characterization Ratio (RCR), which is the primary contamination indicator of microplastic resulted from an integrated plastic road. In this subsection, all pertinent secondary resultant parameters will be plotted against the observed Risk Characterization Ratio (RCR) numbers and subsequently corresponding correlations will be established. From these correlations, we will have a preliminary idea about the possible predictability which would be further corroborated by statistical analysis in the next chapter incorporating all primary constituent, and secondary environmental leaching parameters.

Case I: Base Course; specimen submerged in stagnant water

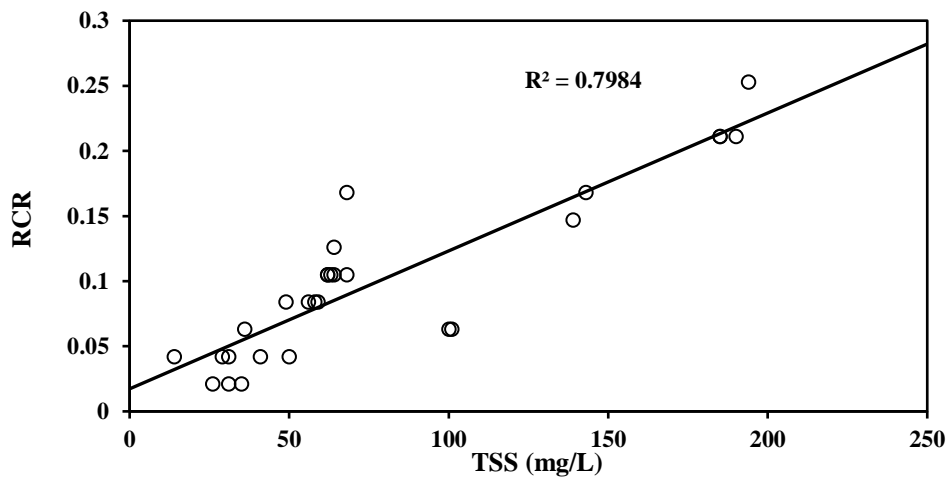


Figure 4-30 RCR Vs TSS (case I)

Figure 4-30 establishes the correlation between RCR and Total Suspended Solids (TSS) for case I. It is conspicuous that RCR increases with the increase of TSS of the corresponding sample. A reasonably strong coefficient of determination ( $R^2$ ) of 0.7984 does suggest that there is a constructive correlation between RCR and TSS for this case I at least. However, a single case or scenario would not justify this correlation to be a universal one. We must take account for the other cases as well.

As it stands, TSS counts for some portion of the total solids pertinent to a specific leaching sample deducting the total dissolved and total settleable solids. In a presumably ideal condition total solids consists of only the suspended and dissolved portions. As a strong polymeric substance, plastics and/or any of its sizeable, measurable, identifiable weighable fragment are not dissolved in water, and hence they understandably make up a significant proportion of the TSS. Based on this definition, this correlation stands with a solid rationale.

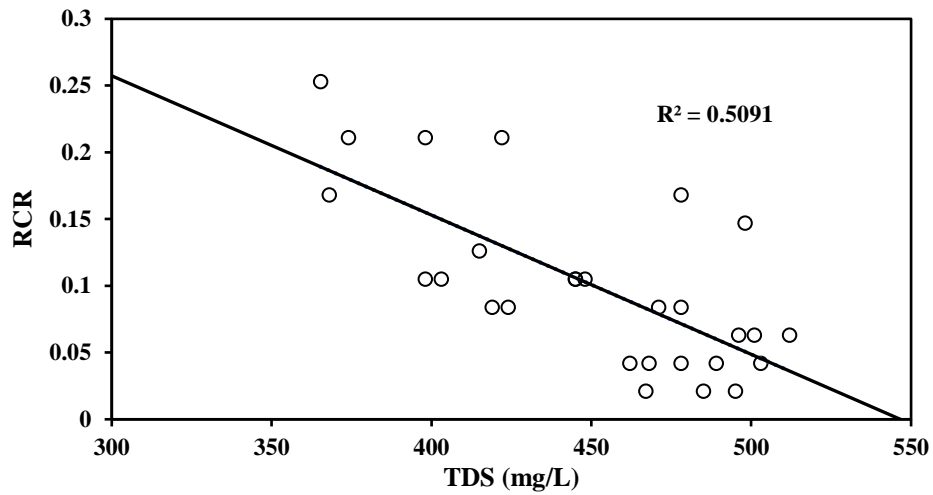


Figure 4-31 RCR Vs TDS (case I)

Figure 4-31 shows the seemingly inverse correlation between RCR and Total Dissolved Solids (TDS) with a moderate coefficient of determination ( $R^2$ ) of 0.5091 which implies that this correlation would not singularly be used as predictor model and warrants incorporation of other variables to establish a more credible prediction model.

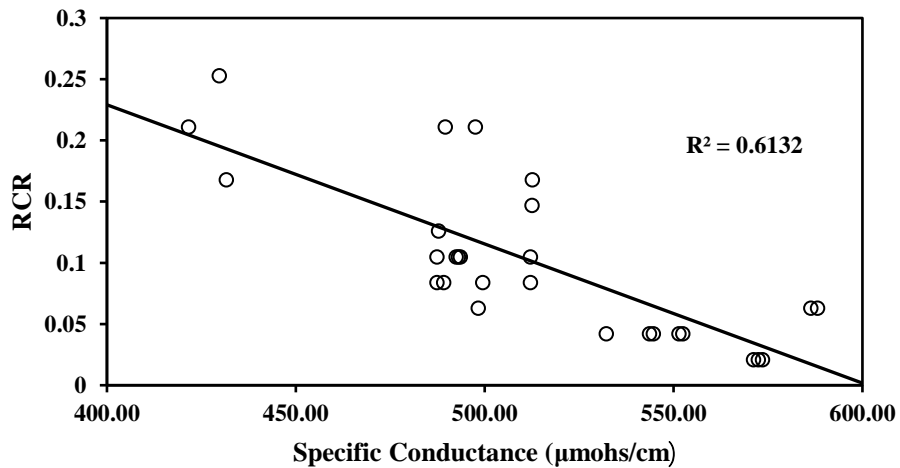


Figure 4-32 RCR Vs Specific conductance (case I)

Figure 4-32 depicts a similar trend like RCR Vs TDS for case I which implies an inverse correlation between RCR and specific conductance with an above average  $R^2$  of 0.6132.



Figure 4-34 shows the seemingly inverse correlation between RCR and Total Dissolved Solids (TDS) with a moderate coefficient of determination ( $R^2$ ) of 0.583 and the trend is similar to that of Case I.

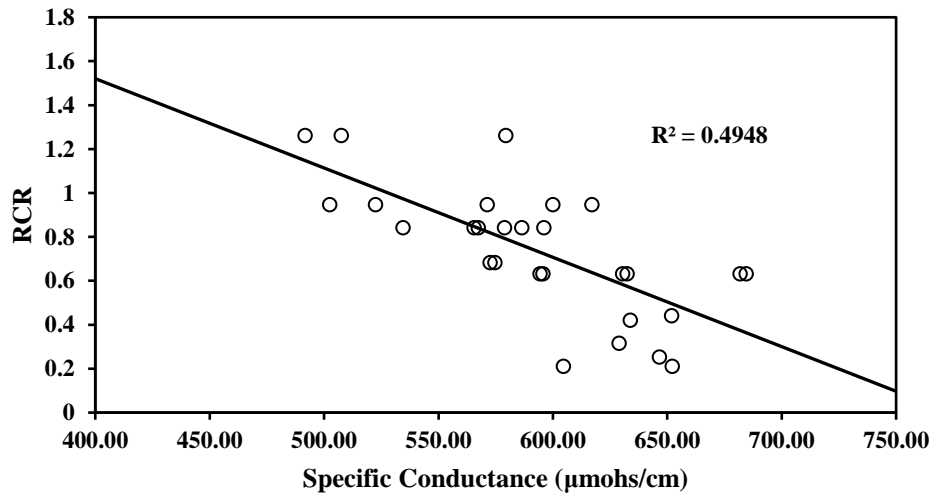


Figure 4-35 RCR Vs Specific conductance (case II)

Figure 4-35 depicts a similar trend like RCR Vs TDS for case II which implies an inverse correlation between RCR and specific conductance with a moderate  $R^2$  of 0.4984. In other words, specific conductance is one indicator of the dissolved solids since specific conductance refers to the dissolvable solids devoid of electric conductivity. That could be one of the reasons for similar trend of RCR Vs TDS and RCR Vs specific conductance for both case I and case II.

Albeit for case I and case II, all correlations depicted above have exhibited similar trend it is worth observing that RCR has got the most promising correlation with respect to Total Suspended Solids having coefficient of determination ( $R^2$ ) values of 0.7984 and 0.7605 respectively for case I and case II. Other correlations as well are moderate, average, and above average in terms of respective coefficient of determination which is a good indicator for statistical modeling.



Case III: Surface Course; specimen subject to wheel passes in Hamburg Immersion Rutting test setup

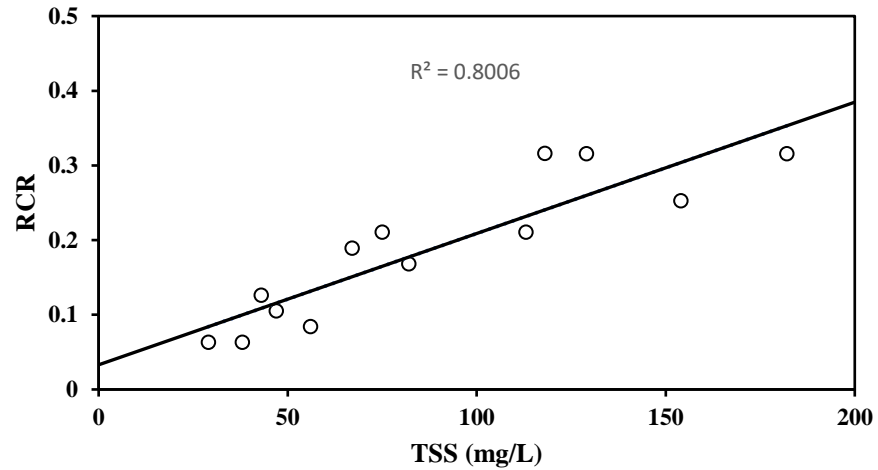


Figure 4-36 RCR Vs TSS (case III)

Figure 4-36 portrays the correlation between RCR and Total Suspended Solids (TSS) for case III. It is discernible that RCR increases with the increase of TSS of the corresponding sample like Case I. A reasonably strong coefficient of determination ( $R^2$ ) of 0.7326 does suggest that there is a strong correlation between RCR and TSS for this case III.

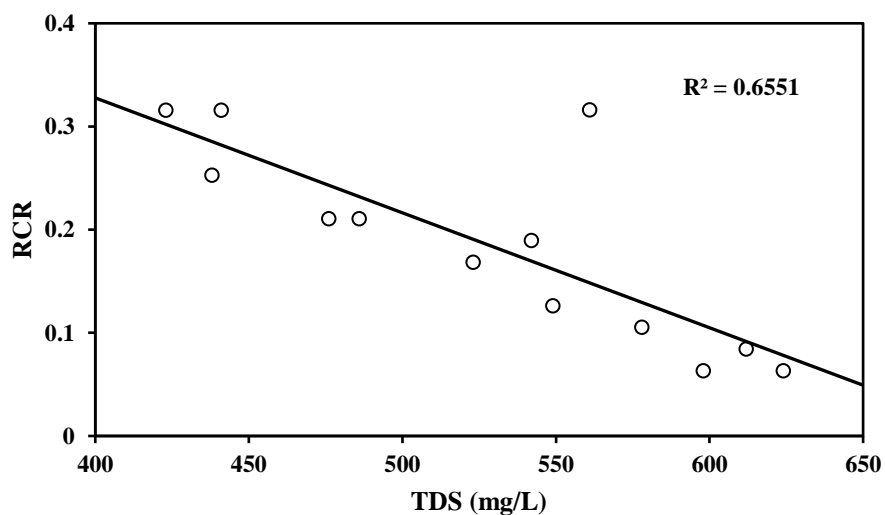


Figure 4-37 RCR Vs TDS (case III)

Figure 4-37 shows the seemingly inverse correlation between RCR and Total Dissolved Solids (TDS) with a above average coefficient of determination ( $R^2$ ) of 0.6551 and the trend is like that of Case I and case II albeit stronger correlation than both case I and case II.

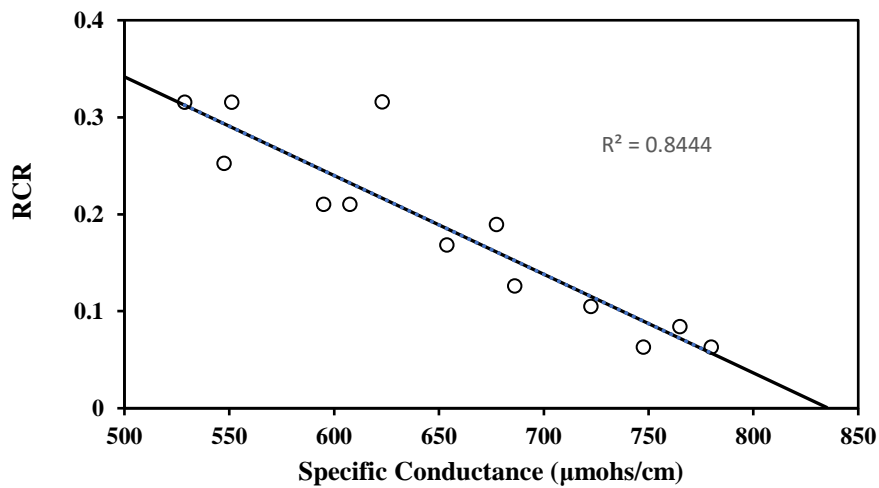


Figure 4-38 RCR Vs Specific conductance (case III)

Figure 8-38 correlates RCR and specific conductance for case III which is similar to the trend of RCR vs TDS, albeit with a stronger correlation coefficient of 0.7144 which means that while constructing the prediction statistical model for case III, specific conductance of the respective samples will play a significant role in defining the final model to predict the theoretical RCR.

## 4.6 FTIR Spectroscopy

Along with the optical microscopic detection of microplastics this study also includes a spectroscopic analysis to qualify the presence of the microplastic type present in each sample combination for either of three cases. There are multiple spectroscopic analyses method available. Fourier Transform Infra-Red (FTIR) microscopy is one of the most common and widely used techniques to identify the microplastic type based on the wavelength responses plotted against absorbance or transmittance. This study incorporates FTIR spectroscopy as a mean to identify microplastic type which would also be a helpful too to identify the presence of any type of different microplastic particle other than the target one based on the type of plastic used to prepare the sample for each case. It is worth mentioning that, the principal objective of this FTIR spectroscopy is to qualitatively identify the presence of microplastics and it does not aim at numerical identification like optical microscopic analysis.

As we have come to know from the previous chapter of this dissertation that, each particle, substance, trace material, measurable entity has a specific response in terms of wavelength against the absorbance/transmittance in a spectroscopic detection apparatus. It is not only valid for FTIR, but also applicable for other spectroscopic analysis as well, i.e., Ultraviolet-Visible (UV/Vis) Spectroscopy, Nuclear Magnetic Resonance (NMR) Spectroscopy, Raman Spectroscopy, X-Ray Spectroscopy. These spectroscopic analyses including FTIR mostly rely on the chemical properties of the constituents of the samples to be experimented. Jun-Li Xu et al., conducted extensive research on microplastic response in a FTIR spectroscopy aiming at identifying microplastic presence as well as differentiating them in terms of their spectroscopic responses. The following table summarizes the wavelength responses of different types of microplastics based on the study conducted by Jun-Li Xu et al., in 2019.

Table 4-13 Microplastic responses in terms of wavenumbers (Jun-Li Xu et al., 2019)

| <i>Microplastic Type</i>         | <i>Wavenumber (cm<sup>-1</sup>)</i> |
|----------------------------------|-------------------------------------|
| PC (polycarbonate)               | ~3000                               |
| HDPE (high density polyethylene) | ~3200                               |
| LDPE (low density polyethylene)  | ~3000                               |
| PS (polystyrene)                 | 1000-1200                           |
| PVC (polyvinylchloride)          | 600-1500                            |
| PP (polypropylene)               | ~2900                               |
| PSu (poly sulphone)              | ~800                                |
| PTFE (polytetrafluoroethylene)   | ~1200                               |
| PET (polyethylene terephthalate) | 800-1500                            |

Red highlights denote the types of plastics being used to prepare the samples for this study.

It is noticeable from the table that, on few occasions corresponding wavenumbers representing different plastic types get overlapped. In those cases, it is not accurately possible to exact the plastic/microplastic type encountered. For example, PC (polycarbonate) and LDPE (low density polyethylene) both exhibit a characteristic wavenumber of 3000 cm<sup>-1</sup> in a FTIR spectroscopy apparatus. Hence, if the response wavenumber is 3000 cm<sup>-1</sup> it is not exactly possible to conclude that the identified polymer is either HDPE or LDPE. And for few other plastic/microplastic types, the corresponding characteristic wavenumber is not a definite number, rather it is a range of numbers. For example, PET has got a very wide range of characteristic wave response which is 800-1500 cm<sup>-1</sup>. Any number within that range could be entitled to PET type of plastic. These are few limitations of not only FTR spectroscopy but of other spectroscopic technique as well. And the entire analysis is based on the assumption that the sample to be examined is completely devoid of organic matter which is not achievable to the highest efficiency. That means if the sample to be examined is not fully devoid of organic

substance or any other non-polymeric material, those substances will exhibit their own wavenumber responses as well leading to a misjudgment of target microplastic type happened to be present in experimented sample.

In this study, FTIR analysis has been conducted for each sample combinations from three cases described in detail in previous chapter. FTIR spectroscopic image for individual sample combination would help us identify the target microplastic particle present and at the same time, it would also facilitate to identify if there is any other outsider microplastic also being present there other than the target type. In this chapter, selected FTIR spectroscopic image results will be portrayed and discussed.

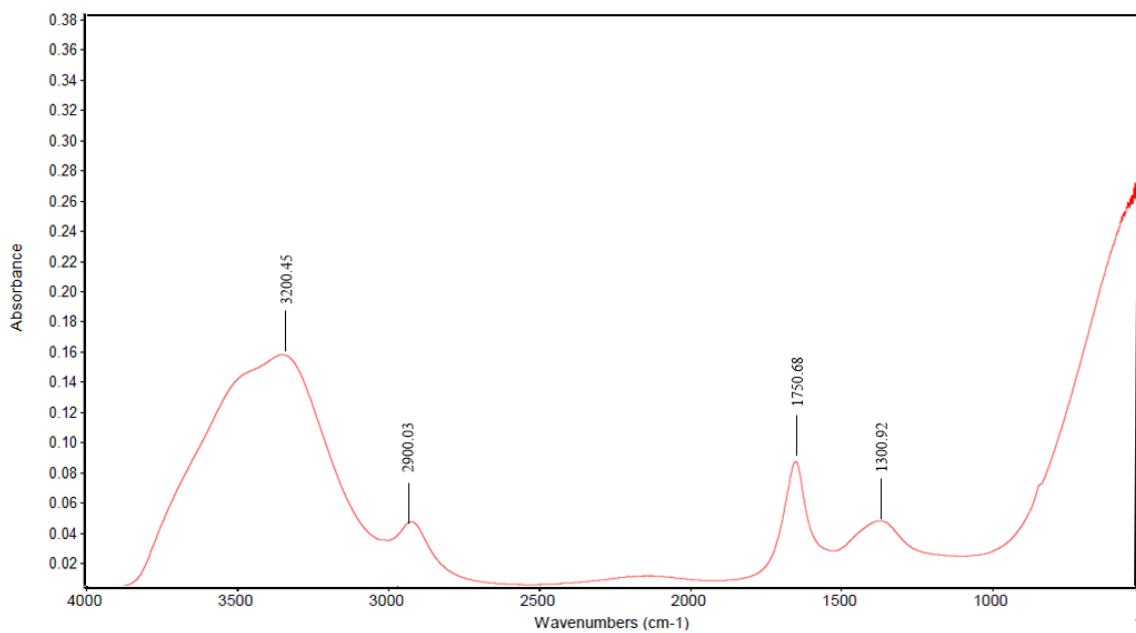


Figure 4-39 FTIR response for sample PP\_3-97-4 (case I)

Figure 4-39 shows the FTIR spectroscopy resulting image for the sample combination PP (3-97-4) representing case I. This sample is collected from a cylindrical specimen made of 3% PP shredded plastics and 97% Recycled Crushed Concrete Aggregates (RCCA) stabilized by 4% ordinary Portland cement. If we refer to the table 4-14, it is understandable from the wave

response of this FTIR image that this sample represent PP microplastics (corresponding wavenumber  $2900.03\text{ cm}^{-1}$ ), however this image also identifies the presence of some other types of microplastics as well. Other three dominant wave peaks numbered  $3200.45\text{ cm}^{-1}$ ,  $1750.68\text{ cm}^{-1}$  and  $1300.92\text{ cm}^{-1}$  represent the presence of HDPE, PET, PS/PTFE types of microplastic as well. That means the presence of a certain microplastic type identified in a FTIR analysis does not necessarily need to have its source from the original type of plastics used to fabricate the specimen and subsequent leaching sample.

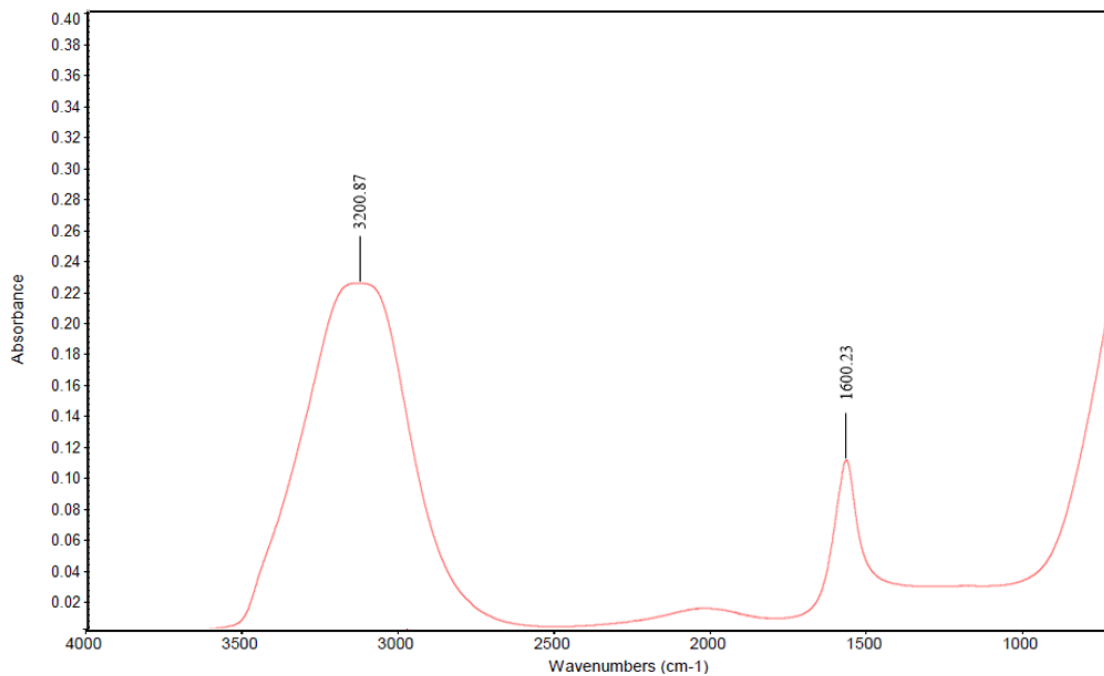


Figure 4-40 FTIR response for sample HDPE\_5-95-10 (case I)

Figure 4-40 shows the FTIR spectroscopy resulting image for the sample combination HDPE (5-95-10) representing case I. This sample is representative of a cylindrical base specimen made of 5% HDPE shredded plastics and 95% Recycled Crushed Concrete Aggregates (RCCA) stabilized by 10% ordinary Portland cement. FTIR wavenumber response of  $3200.87\text{ cm}^{-1}$  rightfully justifies the presence of HDPE microplastic referring to the table 4-14. However, another conspicuous peak can be seen from the image having a wavenumber of

1600.23  $\text{cm}^{-1}$  which might be the existential evidence for other type of microplastic, most likely PET or PVC microplastic type taking account of the reference table 4-14. Compared to the figure 4-39 it is also evident that the wave response has a smaller number of peaks as seen in figure 4-40 indicating a lesser presence of microplastics in the sample combination HDPE (5-95-10) compared to PP (3-97-4). If you recall RCR value for HDPE (5-95-10) used to be 0.042 and that for PP (3-97-4) used to be 0.211 which corroborate the resulting FTIR mage for these two combinations.

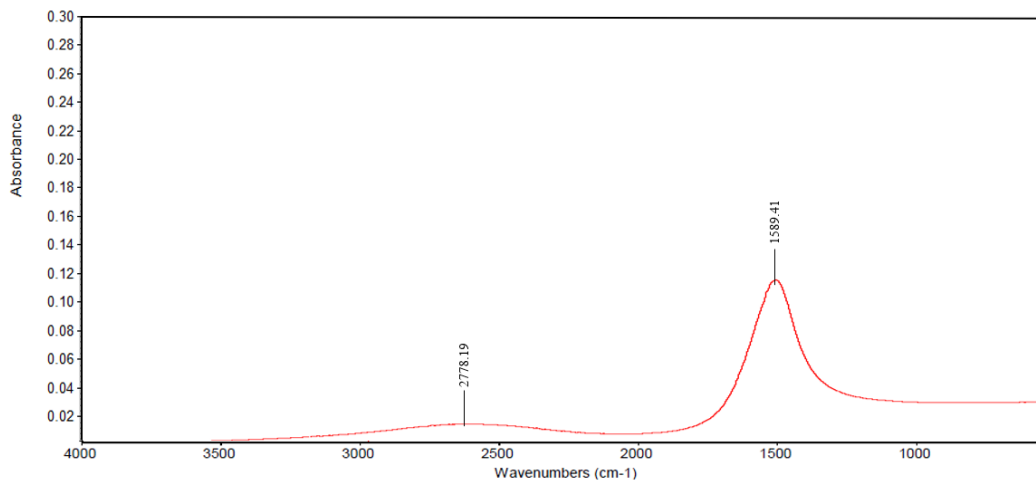


Figure 4-41 FTIR response for sample PET\_5-95-6 (case I)

Figure 4-41 shows the FTIR spectroscopy resulting image for the sample combination PET (5-95-6) representing case I. This sample is representative of a cylindrical base specimen made of 5% PET shredded plastics and 95% Recycled Crushed Concrete Aggregates (RCCA) stabilized by 6% ordinary Portland cement. FTIR wavenumber response of 1589.41  $\text{cm}^{-1}$  could be identified as the presence of PET type of microplastic referring to the table 4-14. However, another noticeable peak can be seen from the image having a wavenumber of 2778.19  $\text{cm}^{-1}$  which might be the existential evidence for other type of microplastic, most likely PP microplastic in line with the reference from table 4-14.

From these three figures, it can be inferred that higher cement stabilization not only resulted in smaller microplastic counts and Risk Characterization Ratio (RCR) but also led to a FTIR spectroscopic image with lesser wave peaks compared to the sample combinations incorporating less percentage of stabilizing cement. Hence, there could be a resulting mutual correspondence between microplastic concentration/Risk Characterization Ratio (RCR) and the FTIR wave peaks.

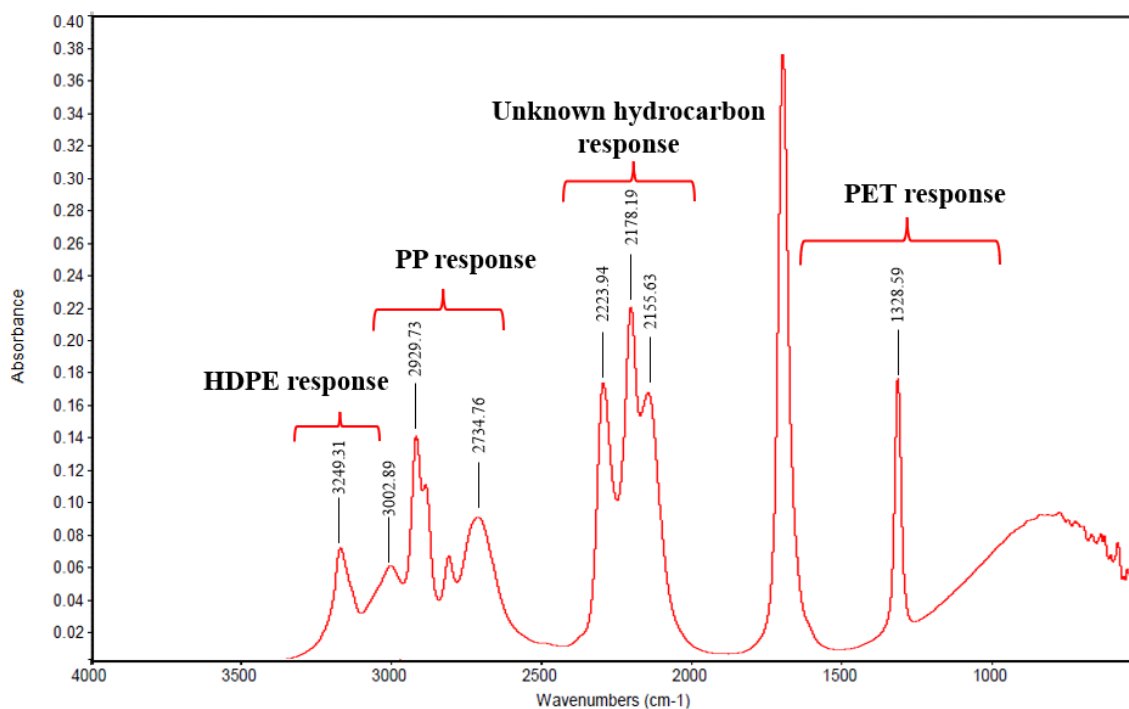


Figure 4-42 FTIR response for sample PP\_3-97-4 (case II)

Figure 4-42 shows the FTIR spectroscopy resulting image for the sample combination PP (3-97-4) representing case II. This sample is representative of cylindrical base specimen subject to cyclic loading in a resilient modulus setup. This spectroscopic image clearly shows more consecutive peaks both in numbers and variations compared to the one we observed for case I considering the similar sample combination. Along with the reasonable PP response (2929.73



$\text{cm}^{-1}$  and  $2734.76 \text{ cm}^{-1}$ , we could also identify responses by the presence of microplastics originated from HDPE and PET type of plastics. Even we could observe some unknown hydrocarbon response. These hydrocarbon responses could be from other types of plastics or even from organic polymers since we already came to know about the limitations of chemical digestion which aims at removing all the organic material from the leaching sample before getting it ready for either optical microscopy or FTIR spectroscopy leading to this unknown organic polymer response. FTIR spectroscopy in this case signifies that the microplastic concentration measured quantitative analysis through an optical microscopy for this sample combination does not include the target microplastic originated from the recycled plastic used to prepare the sample but also from other sources.

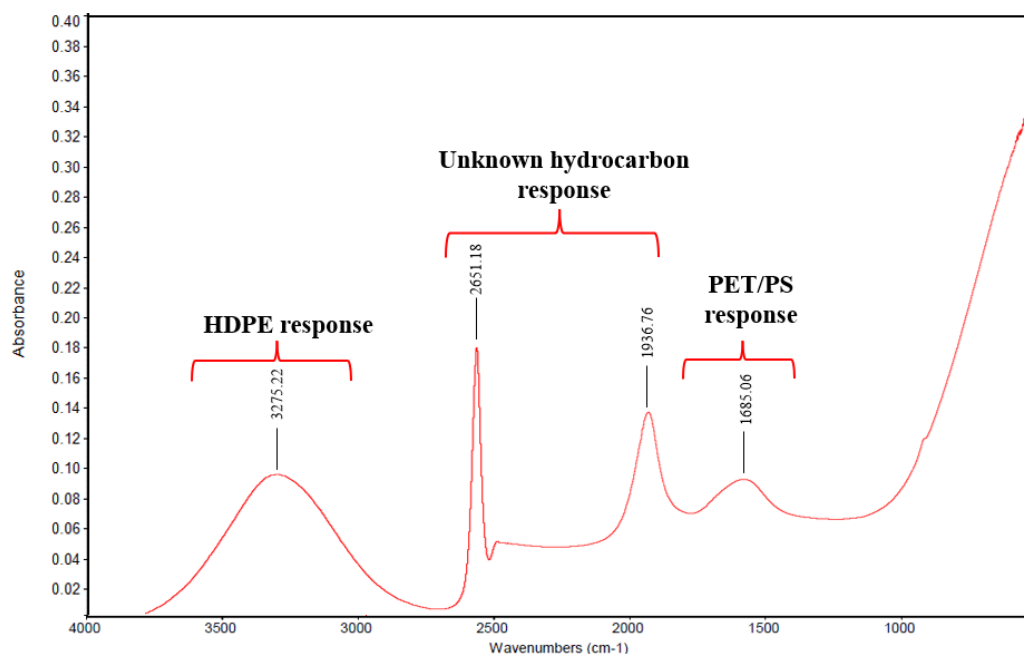


Figure 4-43 FTIR response for sample HDPE\_5-95-10 (case II)

Figure 4-43 shows the FTIR spectroscopy image for the sample combination HDPE (5-95-10) representing case II. Compared to the image associated with same ample combination

for case I, this image clearly shows more frequent responses and higher number of wave peaks. And we could also identify non-HDPE responses including few unknown hydrocarbon responses as well same as figure 4-42. These responses verify the presence of microplastics from sources not associated with the recycled and shredded HDPE plastics used to fabricate the cylindrical specimen and then the pertinent leaching sample for this case.

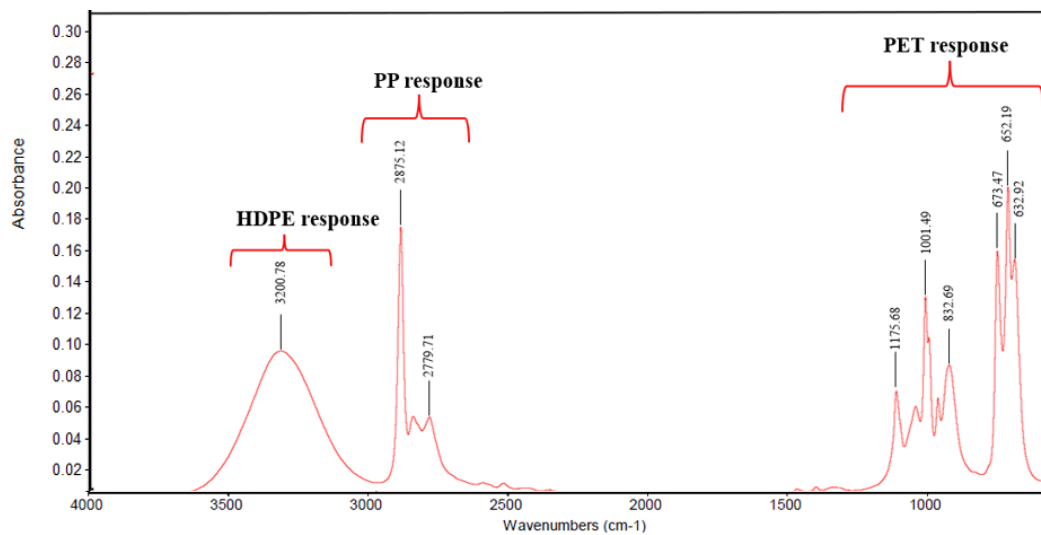


Figure 4-44 FTIR response for sample PET\_5-95-6 (case II)

Figure 4-44 shows the FTIR spectroscopy resulting image for the sample combination PET (5-95-6) representing case II and as we could see more frequent and non-native microplastic responses as well like the other two images for case II.

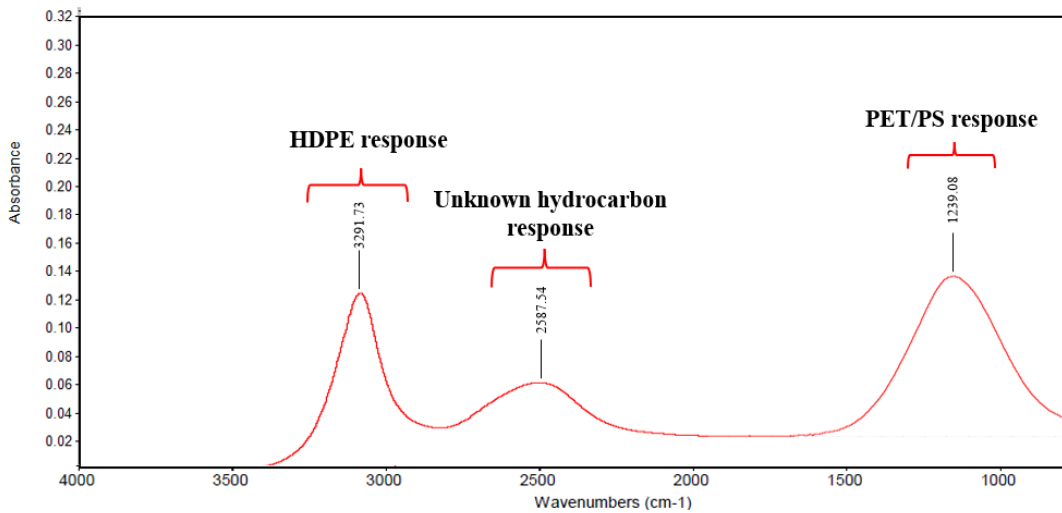


Figure 4-45 FTIR response for sample Control\_0-100-8 (case II)

Figure 4-45 signifies an important phenomenon. Even this FTIR image is representative of control sample consisting of 0% plastic, spectroscopic image portrays the presence of microplastics as we could identify HDPE, PET/PS, and unknown hydrocarbon responses in terms of transmitted wavelength. This FTIR manifests that the microplastic presence/concentration in the tracing samples do not entitle to the plastics used in preparation of the sample only. Microplastics could also be originated from other constituent ingredients of the cylindrical specimen and subsequent leaching sample.

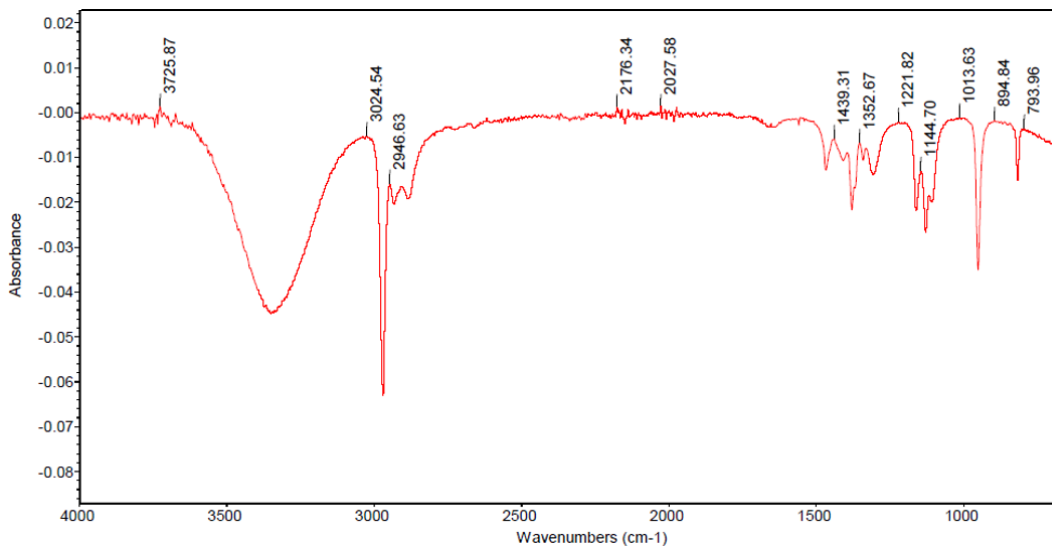


Figure 4-46 FTIR response for sample PP\_4/70-22 (case III)

Figure 4-46 is the corresponding FTIR image for a surface course leaching sample collected from submerged cylindrical specimen in water within a Hamburg rutting test setup. As the figure suggests, this sample is prepared of 4% PP plastic and Bitumen grade PG 70-22. Wave response of this sample delineates that apart from target microplastic PP responses ( $2946.63\text{ cm}^{-1}$ ) we get substantial amount of other microplastic responses too, most noticeably PET/PS responses (in the range of  $800\sim 1500\text{ cm}^{-1}$ ) and a HDPE response ( $3024.54\text{ cm}^{-1}$ ). We could also see some unknown hydrocarbon responses in the spectroscopic image. These all additional responses do suggest that plastics used for fabricating the sample are not the only sources of microplastics being identified.

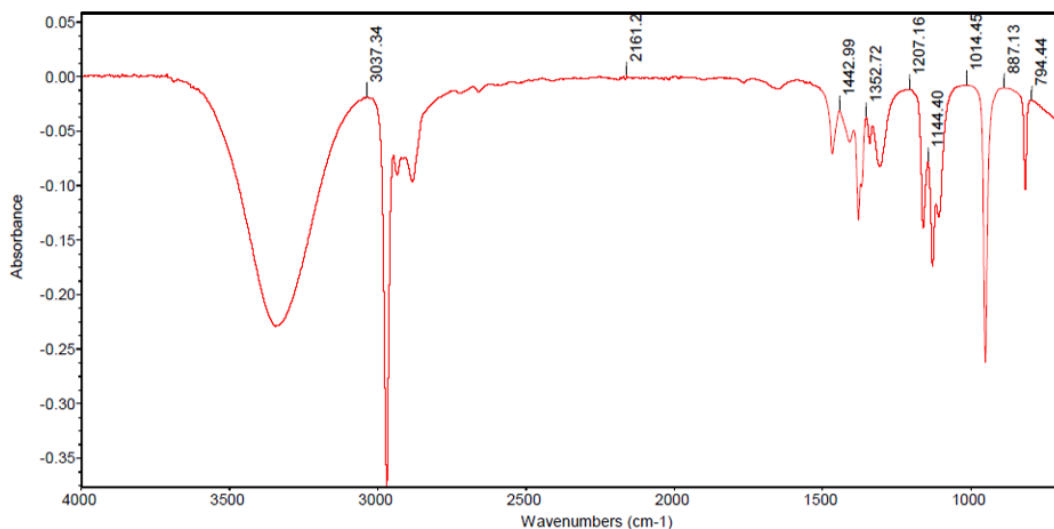


Figure 4-47 FTIR response for sample HDPE\_12/70-22 (case III)

Figure 4-47 is the corresponding FTIR spectroscopic image for surface course sample HDPE (12/70-22). Apart from probable LDPE response ( $3037.34\text{ cm}^{-1}$ ), we could observe some additional microplastic responses. Based on their spectroscopic wavelength ranges, they

could be identified as PET/PS. (800-1500  $\text{cm}^{-1}$ ). Hydrocarbon response can also be found from this image.

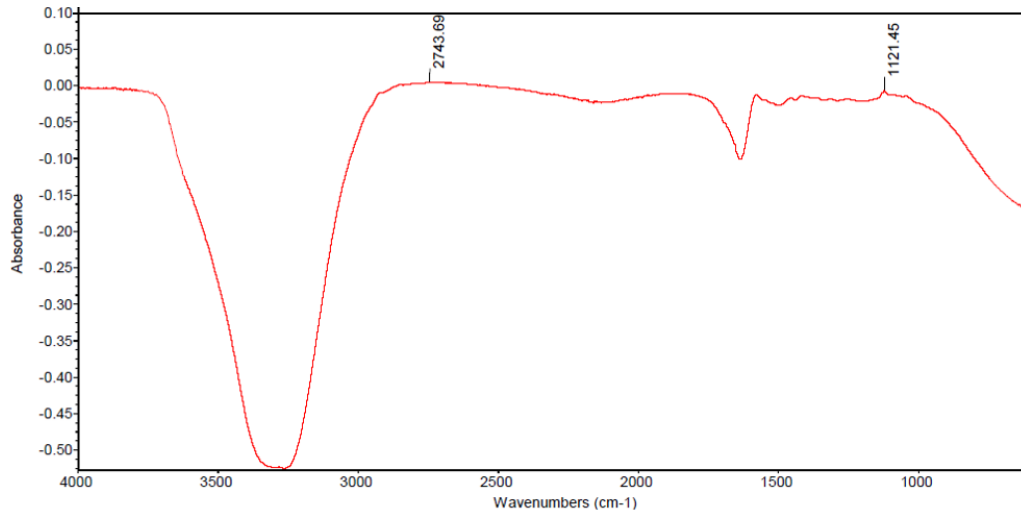


Figure 4-48 FTIR response for sample LDPE\_16/70-22 (case III)

Figure 4-48 represents the FTIR image for the surface course sample LDPE (16/70-22) incorporating 16% LDPE plastic and bitumen PG 70-22. LDPE response could be traced by the wavelength of  $2743.69 \text{ cm}^{-1}$  and additional wavelength response of  $1121.45 \text{ cm}^{-1}$  could be attributed as PET/PS.

However, from images 4-46 through 4-48 it is quite discernible that with the increase of plastic content in the sample, the incidence of wave responses has reduced dramatically. This pattern could be well attributed to the increasing rutting characteristics of the sample with the increase of plastic content subject to less fragmentation, less microparticles and less occurrence of spectroscopic incidents.

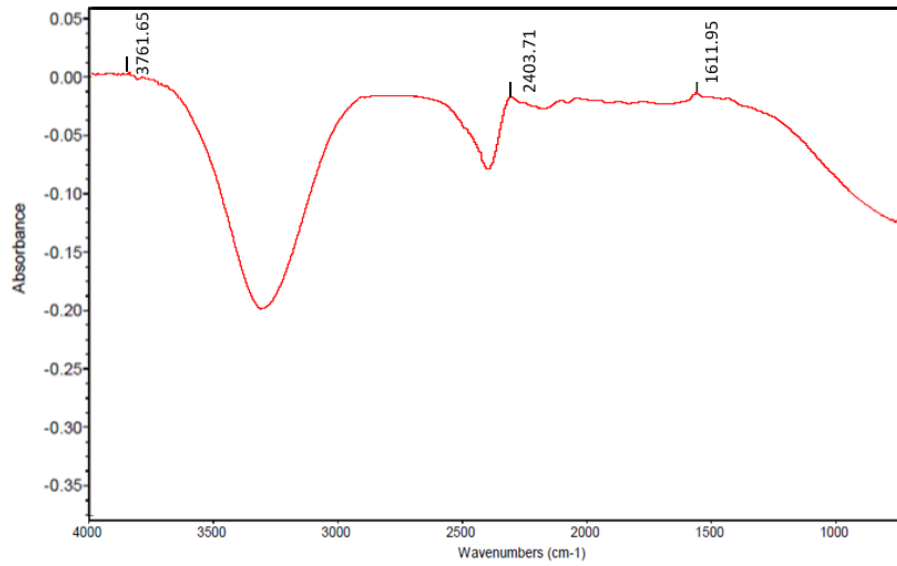


Figure 4-49 FTIR response for sample Control\_0/70-22 (case III)

Figure 4-49 represents control sample without incorporating plastics while preparing the corresponding cylindrical specimen. Even without any constituent shredded plastic involved, this FTIR shows the presence of microplastics and other hydrocarbon particles.

## STATISTICAL ANALYSIS

### 5.1 Introduction

The main goal of this study is to figure out what kind of microplastic risk a plastic road poses. To figure out how dangerous a toxic or potentially dangerous substance is, we need to know what its Risk Characterization Ratio is (RCR). For this study, the only way to describe the risk is by the microplastic RCR. It's important to note that a simple RCR value for microplastic contamination could be the deciding factor in designing an integrated plastic road. This is because RCR would tell us how much plastic we can use in road construction without hurting the environment in the long run. But figuring out how much microplastic there is, what it is, and what kind of risk it poses is a difficult task. Lack of standardized identification methods, clear rules, and expensive state-of-the-art technology make it very hard to measure the amount of microplastics and figure out what kind of risk they pose from a possible plastic road. In this case, it would be very helpful to have a statistical model to predict the RCR based on the primary and secondary parameters that make up the RCR. This model could be used with a high level of confidence to describe the microplastic risk of a plastic road. This chapter aims to do the same thing. In this chapter, MLR (Multiple Linear Regression) models will be made for each of three cases that represent three different situations of a flexible plastic road's base and surface course. For this regression analysis and to get the prediction model we wanted, we used RStudio, a well-known statistical computing and graphics program. No matter what software is used, the following is the main idea behind making an MLR model.

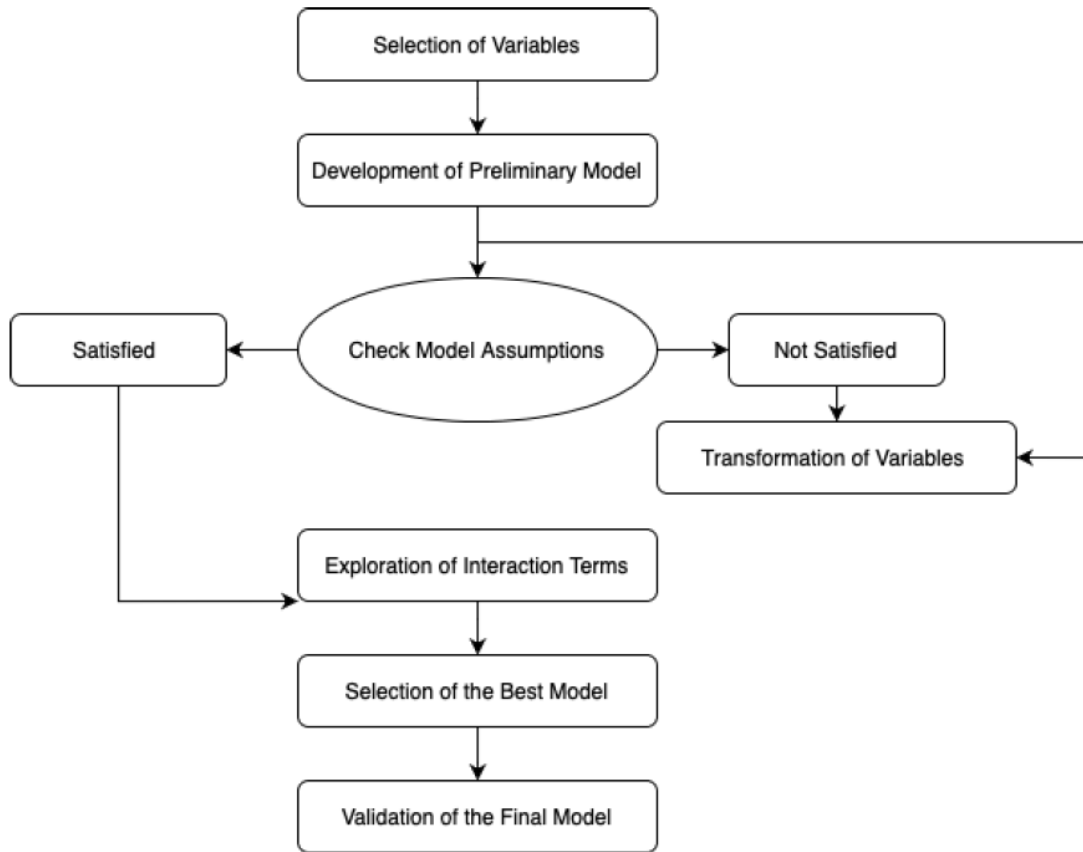


Figure 5-1 Statistical Analysis Flow for the Model Development

## 5.2 Parameters Selection

Predictor variables or parameters are essential elements of every regression model. The model's predictors were chosen as if they were not substantially connected with one another (correlation coefficient less than 0.75). If the predictors do possess significantly large degree of collinearity, the created model may be unreliable, resulting in a reduced coefficient of regression, a greater variance, and an unreliable model (Pituch et al., 2015). High correlation coefficients across predictor variables/parameters are referred to as multicollinearity, which has three potential drawbacks: 1) a decrease in the regression coefficient; 2) an increase in the standard error; and 3) an increase in the variance. 2) Difficulty in establishing the significance of each variable, and 3) Increase in Variance (Stevens 2012).



Taking into account the possibility of extreme multicollinearity, we have discovered five predictor variables for cases I and II (base course of plastic road) and four predictor variables for case III (surface course of plastic road). The predictor variables for these three examples, together with their corresponding abbreviations, will be utilized extensively in model construction and regression analysis.

Variables for case I (base course)

1. Plastic Percentage (PP)
2. Cement Percentage (CP)
3. Total Suspended Solids (TSS)
4. Total Dissolved Solids (TDS)
5. Specific Conductance (SC)

For case III, cement percentage is not used as a predictor variable since there is no cement incorporated for surface course. Instead, rutting depth (RD) has been used as a variable. Following subsections will discuss about the establishment of MLR model for three cases separately.

### **5.2.1 MLR Model for Base Course**

As mentioned earlier, five predictor variables have been selected to establish the Multi Linear Regression (MLR) model for case I. Out of these five predictor variables two are primary constituent variables (plastic percentage and cement percentage) and the rest three are secondary resultant parameters depicting the chemical characteristics of the samples. Detailed step by step progress of developing a MLR model is discussed in the following paragraphs.

### 5.2.1.1 Correlation Analysis

Each pair of predictor variables was subjected to a correlation analysis in order to test multicollinearity. As previously established, increased multicollinearity between variables results in an unreliable prediction model. If there is a strong connection between predictor variables, the MLR model will be hampered. However, the correlation between two variables is deemed strong if  $r$  is more than 0.75 in absolute value (Zach 2020). The table below highlights the association between factors for case I.

Table 5-1 Correlation between predictor variables (case I)

| <i>Variables</i> | <i>RCR</i> | <i>PP</i> | <i>CP</i> | <i>TSS</i> | <i>TDS</i> | <i>SC</i> |
|------------------|------------|-----------|-----------|------------|------------|-----------|
| <i>RCR</i>       | 1          | 0.37      | -0.55     | 0.79       | -0.51      | -0.61     |
| <i>PP</i>        | 0.37       | 1         | 0         | 0.31       | -0.43      | -0.31     |
| <i>CP</i>        | -0.55      | 0         | 1         | -0.34      | 0.66       | 0.68      |
| <i>TSS</i>       | 0.79       | 0.31      | -0.34     | 1          | -0.47      | -0.49     |
| <i>TDS</i>       | -0.51      | -0.43     | 0.66      | -0.47      | 1          | 0.71      |
| <i>SC</i>        | -0.61      | -0.31     | 0.68      | -0.49      | 0.71       | 1         |

From the table, it can be observed that greatest correlation coefficient stands between RCR and TSS (0.79) which is fractionally higher than 0.75. Other than this pair, all coefficients of determination are lower than 0.75. Hence, the multicollinearity between each pair of predictor variables is almost nonexistent which will be further corroborated by conducting multicollinearity test by finding out whether Variance Inflation Factor (VIF) is less than 5 or not. If VIF for mutually corresponding predictor variables is less than 5, it could be inferred that the variables used for prediction model is free of multicollinearity. The following table summarizes the correlation between model objective RCR and predictor variables.

Table 5-2 Correlation between RCR and predictor variables (case I)

| <i>RCR</i> | <i>PP</i> | <i>CP</i> | <i>TSS</i> | <i>TDS</i> | <i>SC</i> |
|------------|-----------|-----------|------------|------------|-----------|
| 1          | 0.37      | -0.55     | 0.79       | -0.51      | -0.61     |

5.2.1.2 Development of preliminary model

After the correlation analysis between pairs of predictor variables is completed, a preliminary MLR was established to predict RCR using RStudio having a format as follows:

$$RCR = \beta_0 + \beta_1 C + \beta_2 F + \beta_3 S + \beta_4 S_P + \beta_5 E + \beta_6 H + \varepsilon_i$$

Where,  $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$  are the correlation coefficients that are discovered through the process of regression analysis by reducing the model data's total squared errors, where  $\varepsilon_i$  stands for random error that is present in the model. The correlation coefficients provide an explanation for the change in the mean response that occurs for each unit change in a predictor variable, provided that all other predictor variables remain unchanged. This is an evolved version of a model based on linear equations with one variable. As an alternative to using a binary linear model, a multilinear regression analysis has been carried out. Tables 5-3 and 5-4, respectively, show estimates of the parameters and a summary of the analysis of variance (ANOVA). The correlation coefficients have the indications that were forecasted for them, and they are consistent with the findings of the laboratory investigation.

Table 5-3 Preliminary model parameters estimate (case I)

|                    | <i>Coefficient Estimate</i> | <i>Std. Error</i> | <i>t value</i> | <i>Pr(&gt; t )</i>     |
|--------------------|-----------------------------|-------------------|----------------|------------------------|
| <i>(Intercept)</i> | 0.3906                      | 0.05765           | 6.775          | 8.28*10 <sup>-7</sup>  |
| <i>PP</i>          | -0.000011                   | 0.00211           | -0.005         | 0.996                  |
| <i>CP</i>          | 0.000379                    | 0.002309          | 0.164          | 0.871                  |
| <i>TSS</i>         | 0.000786                    | 0.000059          | 13.154         | 6.68*10 <sup>-12</sup> |
| <i>TDS</i>         | -0.000141                   | 0.000152          | -0.924         | 0.366                  |
| <i>SC</i>          | -0.000567                   | 0.000111          | -5.098         | 4.16*10 <sup>-5</sup>  |

MLR equation corresponding preliminary model can thus be presented as follows

$$\text{RCR} = 0.3906 - 0.000011\text{PP} + 0.000378\text{CP} + 0.000786\text{TSS} - 0.000141\text{TDS} - 0.000567\text{SC}$$

Table 5-4 ANOVA summary

| <i>Residual Standard Error</i> | <i>R<sup>2</sup></i> | <i>Adjusted R<sup>2</sup></i> | <i>F-Statistic</i> | <i>p-value</i>       |
|--------------------------------|----------------------|-------------------------------|--------------------|----------------------|
| 0.01446                        | 0.9594               | 0.9502                        | 104                | 1.5*10 <sup>-4</sup> |

### 5.2.1.3 Verification of preliminary model

The next stage is to determine whether the MLR model's presumptions have been proven. The model must pass the criteria for outliers, multicollinearity among the predictor variables, and constant error variance in residuals (Kutner et al., 2005).

### Constant Error Variance Test

With the plot Residuals Vs Fitted values could be a good indicator of constant error variance. If the values or points are randomly scattered in the plot, it can be inferred that there is constant error variance or homoscedasticity present for the values.

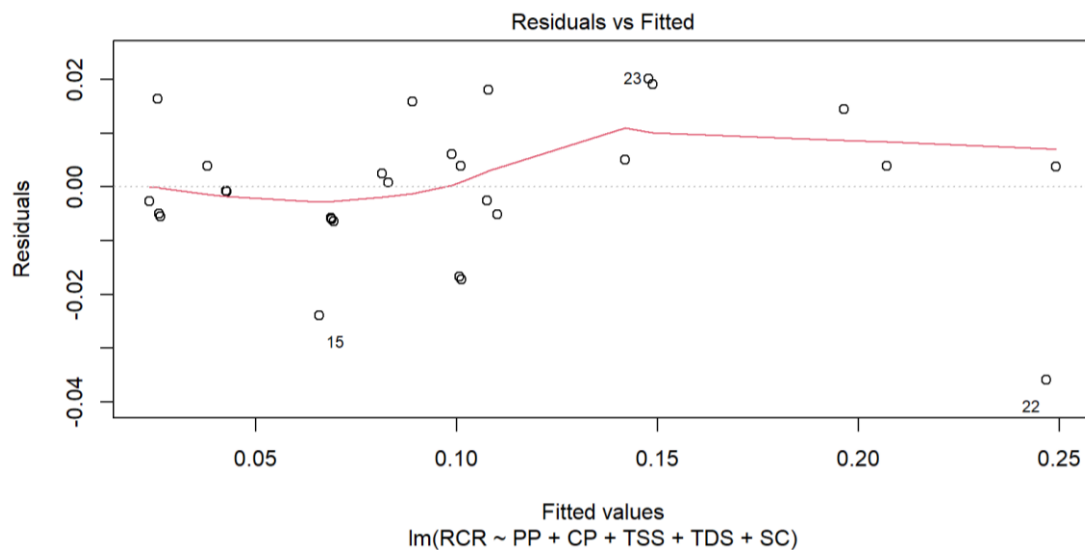


Figure 5-2 Residuals vs. Fitted values plot for preliminary model (case I)

This figure representing residuals vs fitted values show that the points are randomly scattered with no certain trend. That might indicate the presence of constant error variance. By running the studentized Breusch-Pagan test in RStudio, additional analysis was carried out and obtained p-value 0.1508 which is larger than  $\alpha = 0.01$  indicating that the null hypothesis is established, and the residuals are homoscedastic at  $\alpha = 0.01$ .

### Normality Test

The MLR error or residuals ought to follow a normal distribution. A normal probability plot can be used to determine the residuals' normality. The residuals are regularly distributed if there

is a somewhat linear plot. Pattern of a normal probability plot for the preliminary MLR model could be a good indicator of the normality of the residuals.

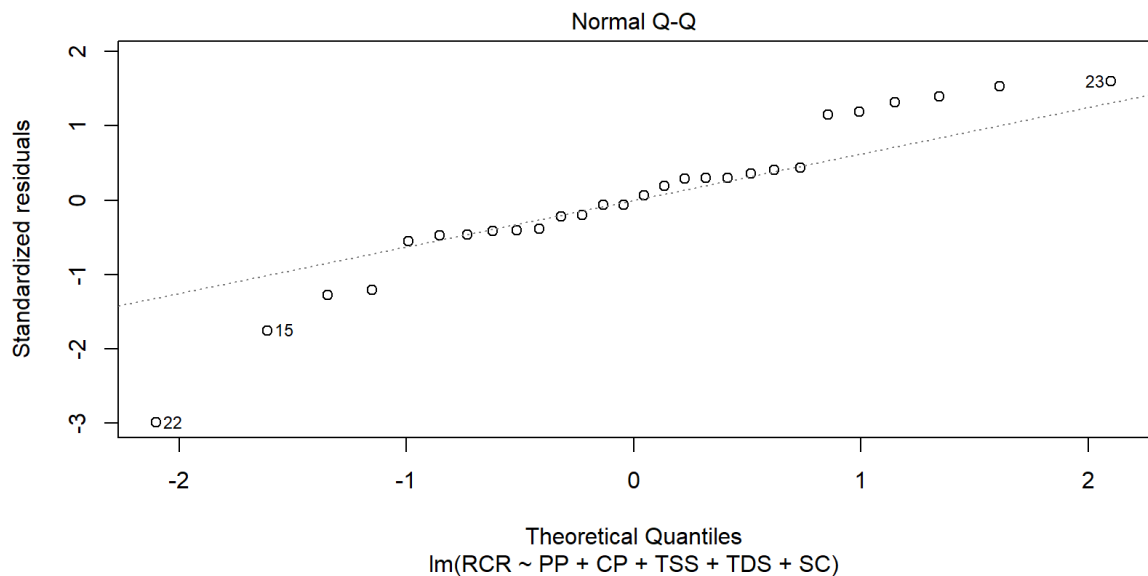


Figure 5-3 Normal probability plot for preliminary model (case I)

From the normal probability plot, we could observe a moderately linear trend except a few aberrations which indicates that the data are normally distributed. To verify the statement, Shapiro-Wilk normality test was conducted in RStudio. Estimated p-value from the test obtained is 0.1046 which is greater than  $\alpha = 0.01$ . So, the null hypothesis was failed to be rejected indicating that the residuals were normally distributed at  $\alpha = 0.01$ .

### Outlier Test

Several common tests in RStudio were used to check the outliers. Outliers were identified using the Bonferroni outlier test. From the Bonferroni outlier test, obtained p-value is 0.029257 which is greater than  $\alpha = 0.01$  implying that the influence of outliers within the data set is

insignificant. DFFITS, and Cook's Distance were used to identify the influence of the outliers in the preliminary model.

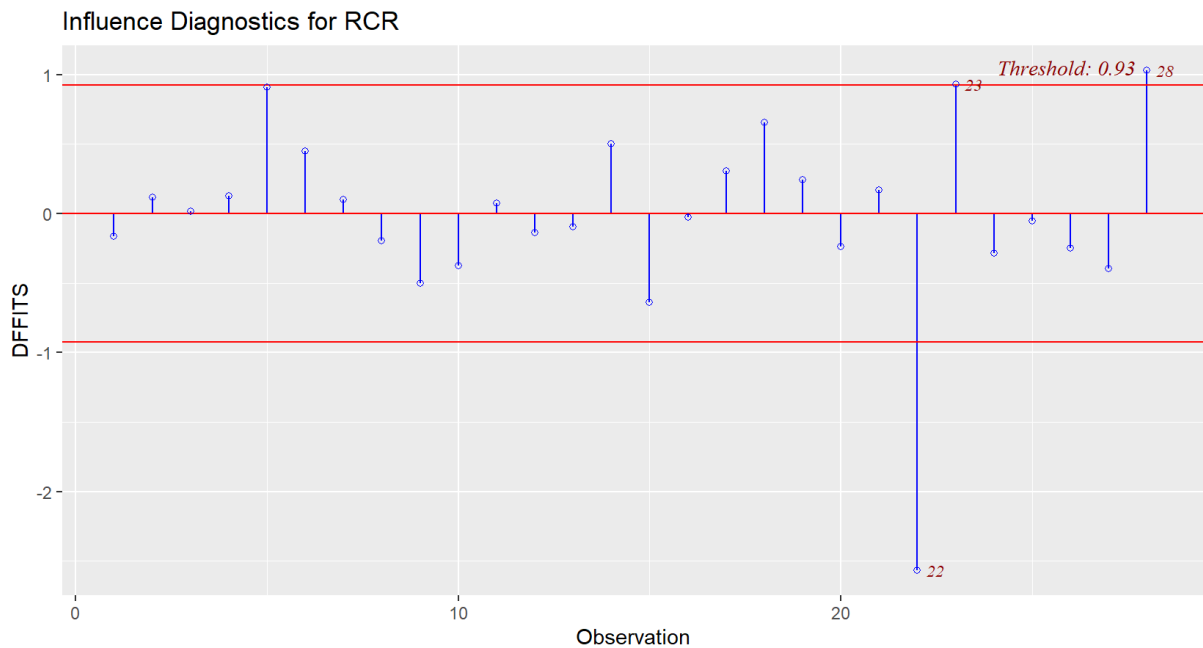


Figure 5-4 DFFITS outlier plot (case I)

There were only two outliers on the DFFITS outlier test plot that had a margin of 0.93, and those were the only two that we were able to notice. The data that featured the numbers 22 and 28 jumped out as being very significant. If a data set contains two outliers, the outliers are considered to have a minor degree of influence, and it is reasonable to dismiss them without severely impairing the prediction model as a result of the decision. In conclusion, when trying to estimate the RCR value by using this model, it will not make any difference at all whether the two outliers are removed from the data or kept in the data. Either way, the prediction will be completely inaccurate. In any case, the model will continue to arrive at the same conclusion.

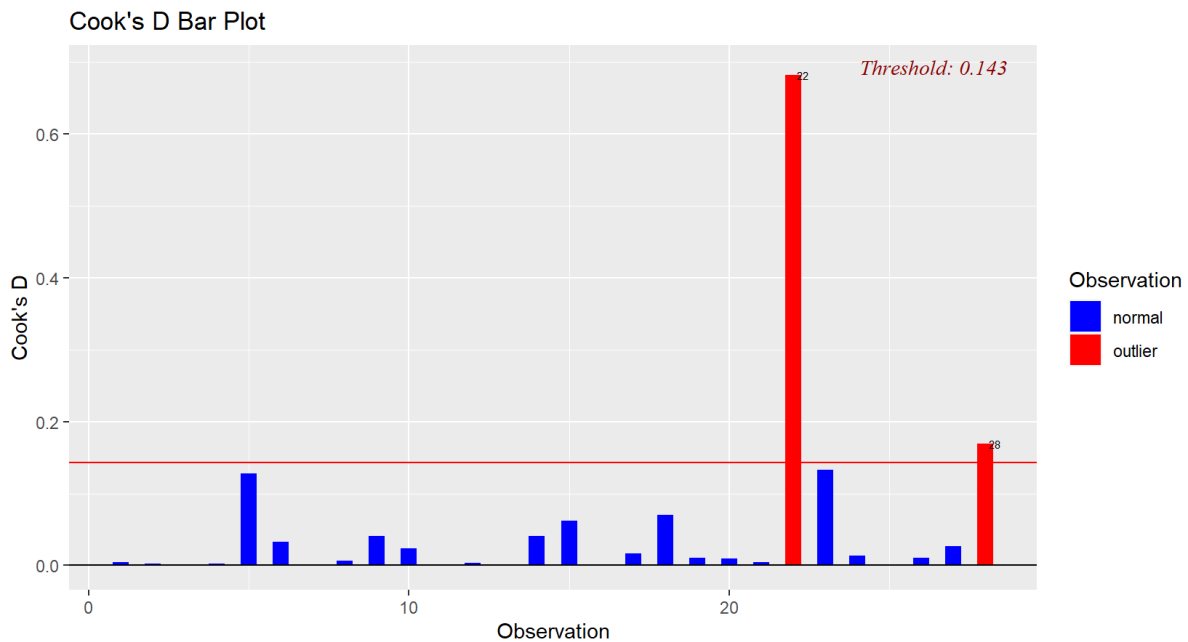


Figure 5-5 Cook's D bar plot (case I)

To crosscheck what we have observed in DFFITS outlier plot, Cook's D bar has also been plotted using RStudio. Corroborating the result obtained from DFFITS outlier plot, Cook's D bar plot also shows two outlier data (data numbered 22 and 28) same as before even with a different threshold margin (0.143). Along with the result obtained from Bonferroni outlier test, these two plots clearly imply that this data set is credible in terms of the presence of outliers.

### Multicollinearity Test

Earlier in this chapter, we have already gotten the mutual correlation among the predictor variables and tabulated the findings. In addition, we observed that the multicollinearity that was expected among the variables was virtually completely absent. The multicollinearity test and the determination of the variation inflation factor were both carried out in RStudio as part of the process of cross-verifying this statement (VIF). In the event that VIF is more than 1, multicollinearity will take place among the predictors. Having said that, only predictors with a



VIF greater than 5 could be troublesome. If the VIF is greater than 10, this implies that there is high multicollinearity and a poor estimation of the response. Therefore, the value of the VIF ought to be lower than 5.

Table 5-5 Variation Inflation Factor data (case I)

| <i>Predictor Variables</i> | <i>VIF</i> |
|----------------------------|------------|
| <i>PP</i>                  | 1.843194   |
| <i>CP</i>                  | 3.571242   |
| <i>TSS</i>                 | 1.376143   |
| <i>TDS</i>                 | 4.873229   |
| <i>SC</i>                  | 3.184415   |

Table 5-5 summarizes the VIF values for all predictor variables involved in this MLR model. all the VIFs are within the suggested range. Thus, no concerning multicollinearity takes place among the predictor variables.

Since the preliminary MLR model met all of the conditions for constant error variance, normality, the influence of outliers, and multicollinearity, there is no need to change the variables to identify a more suitable model. Last but not least, we can select the preliminary MLR model as the final one based on a very conventional best subset selection. Relevant characteristics for the optimal subset selection technique are R2, modified R2, Mallow's Cp, and the Bayesian Information Criteria (BIC). The technique selects the model with the highest R2 and adj. R2, the lowest Mallow's Cp, and the smallest BIC. In this particular instance. Since no variable transformation was necessary, it is more likely that the subsets utilized for the preliminary prediction MLR model would also be the optimal subset. To cross-verify this, RStudio's best subset selection tool has been deployed, and the resulting results are given in the table below.

Table 5-6 Summary of best subset selection (case I)

| <i>Predictor Variables</i> |      |       |       |      | $R^2$         | $Adj. R^2$    | $C_P$      | $BIC$         |
|----------------------------|------|-------|-------|------|---------------|---------------|------------|---------------|
| $PP$                       | $CP$ | $TSS$ | $TDS$ | $SC$ |               |               |            |               |
|                            | -    | ✓     | -     | -    | 0.4887        | 0.4805        | 534.9      | -23.8         |
|                            | -    | ✓     | ✓     | -    | 0.6341        | 0.6298        | 398.6      | -77.2         |
|                            | ✓    | ✓     | ✓     | -    | 0.7543        | 0.7511        | 223.5      | -98.6         |
| ✓                          | ✓    | ✓     | ✓     |      | 0.8967        | 0.8841        | 134.6      | -136.8        |
|                            | ✓    | ✓     | ✓     | ✓    | 0.9101        | 0.9063        | 59.3       | -200.8        |
| ✓                          | ✓    | ✓     | ✓     | ✓    | <b>0.9594</b> | <b>0.9502</b> | <b>8.7</b> | <b>-228.3</b> |

This table clearly shows that while we take all the predictor variables as selected for the preliminary model, we get the best subset selection in terms of highest  $R^2$ ,  $Adj. R^2$  and lowest  $C_P$  and  $BIC$  values.

#### 5.2.1.4 Validation of Final Prediction Model

Hence, the MLR model obtained through the regression analysis satisfying all statistical fairness criteria, and best subset selection is as following:

$$RCR = 0.3906 - 0.000011PP + 0.000378CP + 0.000786TSS - 0.000141TDS - 0.000567SC$$

Now the final step is the validation of the prediction model. To validate the prediction model, a different set of data has been used. Prediction model has been developed using the data corresponding to 3% and 5% HDPE, PET, PP plastics. New set of data corresponds 1% and 2% HDPE plastics. Result of RCR for this new data set will be plotted against the predicted result using the MLR equation obtained through this detailed regression analysis and the resulting plot is as follows:

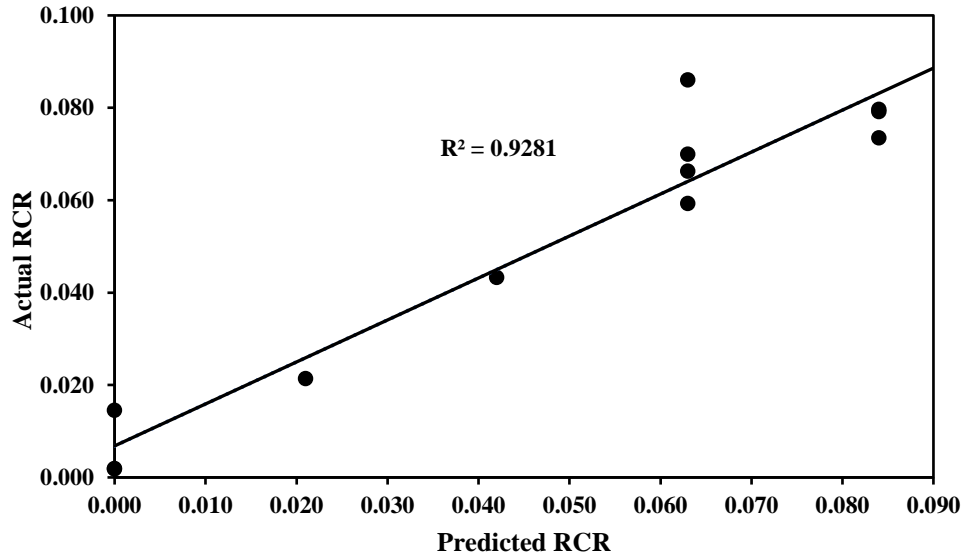


Figure 5-6 Validation of prediction model (case I)

Figure 5-6 delineates the correlation between the actual RCR of a data set and the predicted RCR using the MLR model. As we can see, the coefficient of determination/correlation is 0.9281 indicating not only a strong correlation between the data but also implying a credible, reliable regression model to predict the microplastic Risk Characterization Ratio (RCR) of a recycled plastic induced base course of a plastic road.

## 5.2.2 MLR Model for Surface Course

As mentioned earlier, five predictor variables have been selected to establish the Multi Linear Regression (MLR) model for surface course. Plastic percentage is primary constituent variable, rest are secondary resultant parameters depicting the chemical characteristics of the samples. Detailed step by step progress of developing a MLR model is discussed in the following paragraphs.

### 5.2.2.1 Correlation Analysis

Table 5-7 Correlation between predictor variables (case I)

| <i>Variables</i> | <i>RCR</i> | <i>PP</i> | <i>TSS</i> | <i>TDS</i> | <i>SC</i> | <i>RD</i> |
|------------------|------------|-----------|------------|------------|-----------|-----------|
| <i>RCR</i>       | 1          | -0.43     | 0.73       | -0.65      | -0.71     | 0.65      |
| <i>PP</i>        | -0.43      | 1         | -0.37      | 0.18       | 0.31      | -0.51     |
| <i>TSS</i>       | 0.73       | -0.37     | 1          | -0.75      | -0.72     | 0.67      |
| <i>TDS</i>       | -0.65      | 0.18      | -0.75      | 1          | 0.79      | -0.52     |
| <i>SC</i>        | -0.71      | 0.31      | -0.72      | 0.79       | 1         | -0.68     |
| <i>RD</i>        | 0.65       | -0.51     | 0.67       | -0.52      | -0.68     | 1         |

From the table, it can be observed that greatest correlation coefficient stands between TDS and SC (0.79) which is fractionally higher than 0.75. Other than this pair, all coefficients of determination are lower than 0.75. Hence, the multicollinearity between each pair of predictor variables is almost nonexistent which will be further corroborated by conducting multicollinearity test by finding out whether Variance Inflation Factor (VIF) is less than 5 or not. If VIF for mutually corresponding predictor variables is less than 5, it could be inferred

that the variables used for prediction model is free of multicollinearity. The following table summarizes the correlation between model objective RCR and predictor variables.

Table 5-8 Correlation between RCR and predictor variables (case I)

| <b><i>RCR</i></b> | <b><i>PP</i></b> | <b><i>TSS</i></b> | <b><i>TDS</i></b> | <b><i>SC</i></b> | <b><i>RD</i></b> |
|-------------------|------------------|-------------------|-------------------|------------------|------------------|
| 1                 | -0.43            | 0.73              | -0.65             | -0.71            | 0.65             |

#### 5.2.2.2 Development of preliminary model

After the correlation analysis between pairs of predictor variables is completed, a preliminary MLR was established to predict RCR using RStudio having a format as follows:

$$RCR = \beta_0 + \beta_1 C + \beta_2 F + \beta_3 S + \beta_4 S_P + \beta_5 E + \beta_6 H + \varepsilon_i$$

Where,  $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$  are correlation coefficients which are determined through regression analysis by minimizing the sum of squared errors for the model data and  $\varepsilon_i$  is the random error in the model. The physical significance of correlation coefficients is that they modify the expression of a basic linear equation model by explaining the variance in mean response per unit change of a predictor variable when all other predictor variables are held constant. An analysis of multilinear regression has been performed rather than a binary linear model. The following table lists the parameter estimations and an analysis of variance (ANOVA) summary. The correlation coefficients' sign conventions are as anticipated and correspond to the findings of the laboratory experiments.

MLR equation corresponding preliminary model can thus be presented as follows

$$RCR = 0.6982 + 0.000051PP + 0.0000089TSS + 0.00131TDS - 0.00189SC + 0.00376RD$$

Table 5-9 ANOVA summary (case III)

| <i>Residual Standard Error</i> | <i>R<sup>2</sup></i> | <i>Adjusted R<sup>2</sup></i> | <i>F-Statistic</i> | <i>p-value</i>        |
|--------------------------------|----------------------|-------------------------------|--------------------|-----------------------|
| 0.01446                        | 0.953                | 0.9194                        | 28.36              | 1.66*10 <sup>-4</sup> |

5.2.2.3 Verification of preliminary model

Constant Error Variance Test

With the plot Residuals Vs Fitted values could be a good indicator of constant error variance.

If the values or points are randomly scattered in the plot, it can be inferred that there is constant error variance or homoscedasticity present for the values.

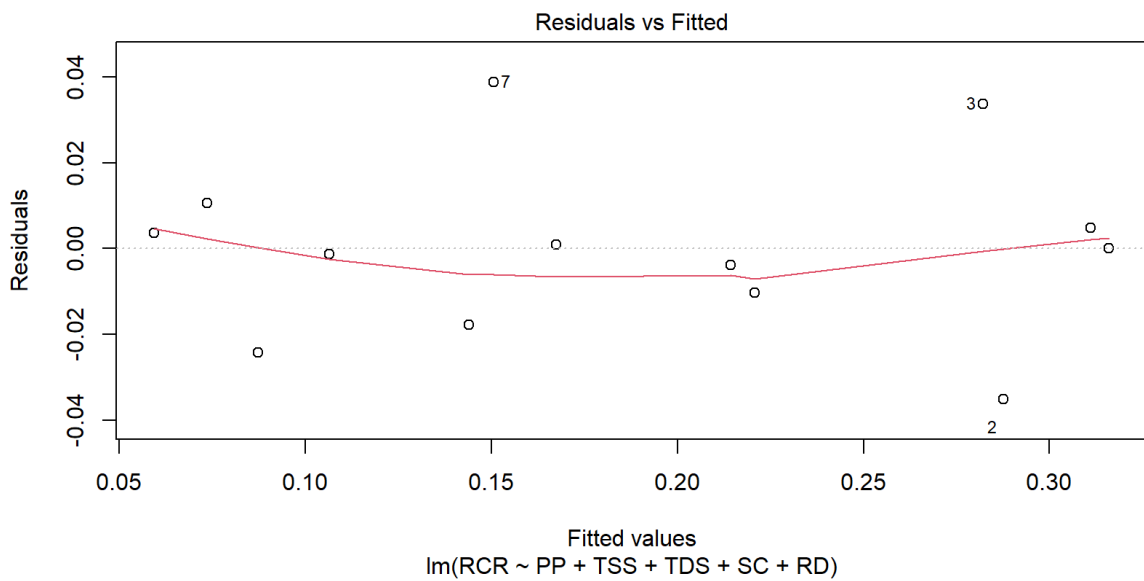


Figure 5-7 Residuals vs. Fitted values plot for preliminary model (case III)

This figure representing residuals vs fitted values show that the points are randomly scattered with no certain trend. That might indicate the presence of constant error variance. Further scrutiny was carried out by studentized Breusch-Pagan test in RStudio and obtained p-value

0.5942 which is larger than  $\alpha = 0.01$  indicating that the null hypothesis is not rejected, and the residuals are homoscedastic at  $\alpha = 0.01$ .

Normality Test

Residuals of MLR should be acted like they are normally distributed. Residuals normality can be determined from a normal probability plot. If there is a moderately linear plot then it signifies normal distribution of residuals. Pattern of a normal probability plot for the preliminary MLR model could be a good indicator of the normality of the residuals.

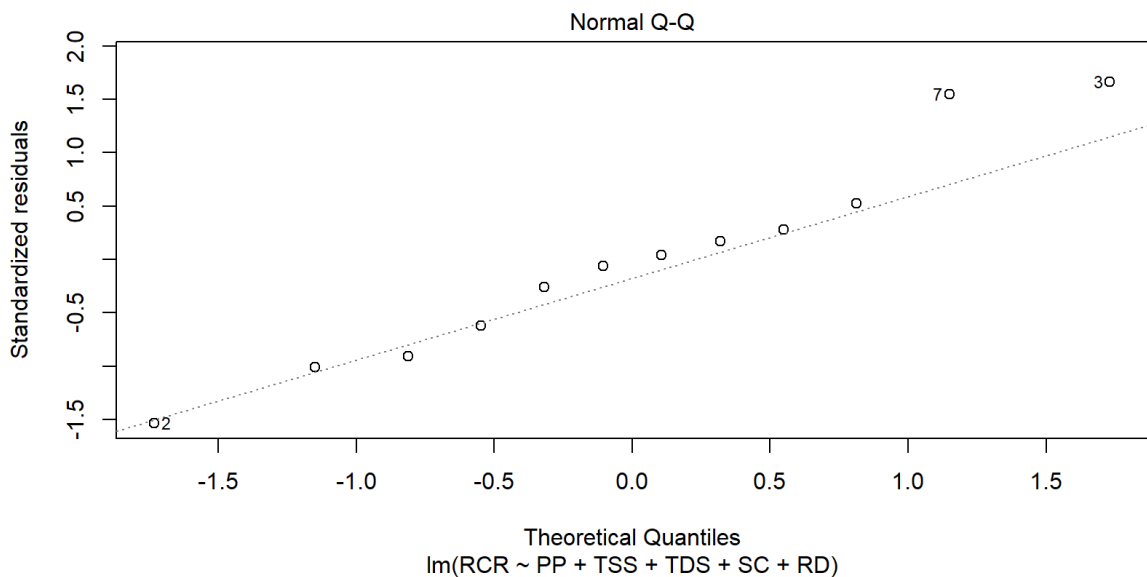


Figure 5-8 Normal probability plot for preliminary model (case III)

From the normal probability plot, we could observe a moderately linear trend which indicates that the data are normally distributed. To verify the statement, Shapiro-Wilk normality test was conducted in RStudio. Estimated p-value from the test obtained is 0.5866 which is greater than  $\alpha = 0.01$ . So, the null hypothesis was failed to be rejected indicating that the residuals were normally distributed at  $\alpha = 0.01$ .

## Outlier Test

The outliers were checked using several standard tests in RStudio. Bonferroni outlier test was used to detect outliers. From the Bonferroni outlier test, obtained p-value is 0.095309 which is greater than  $\alpha = 0.01$  implying that the influence of outliers within the data set is insignificant. DFFITS, and Cook's Distance were used to identify the influence of the outliers in the preliminary model.

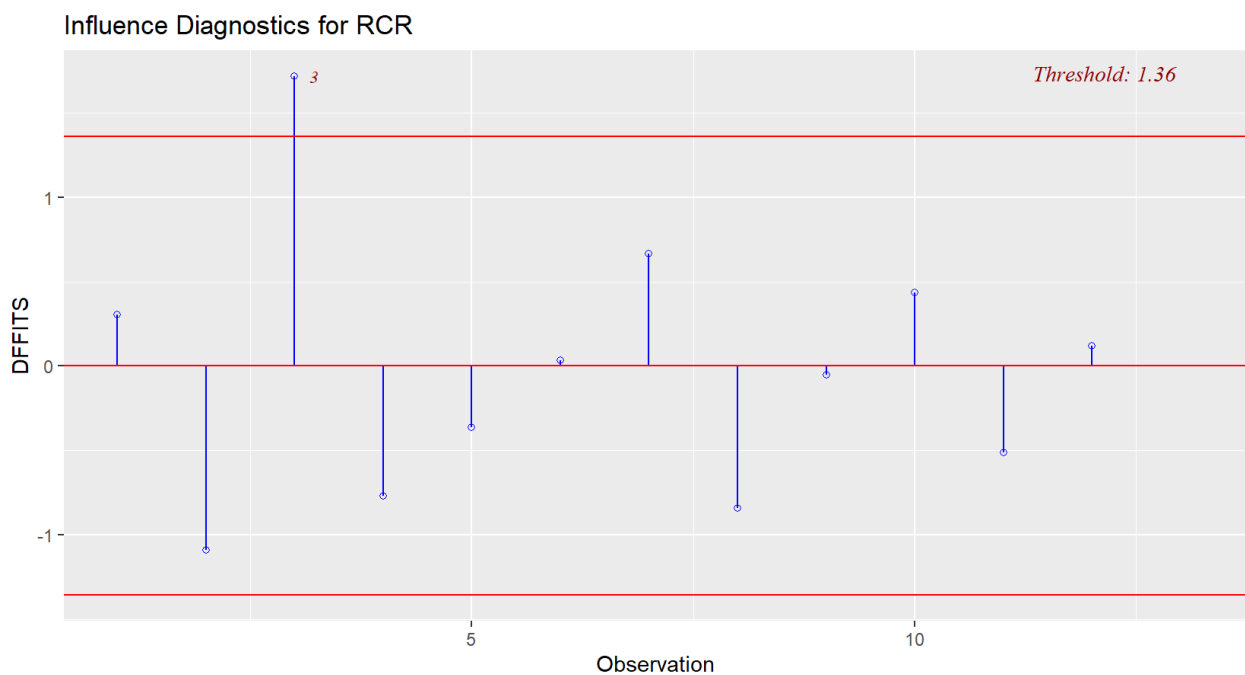


Figure 5-9 DFFITS outlier plot (case III)

From the DFFITS outlier test plot, we could observe only one outlier (data numbered 3) having the threshold margin of 1.36. One outlier for any given data set deems to be insignificantly influential and could be discarded without having a substantial impact on the prediction model. In summary, discarding or keeping that one outlier will not make any difference while predicting the RCR value using this model.



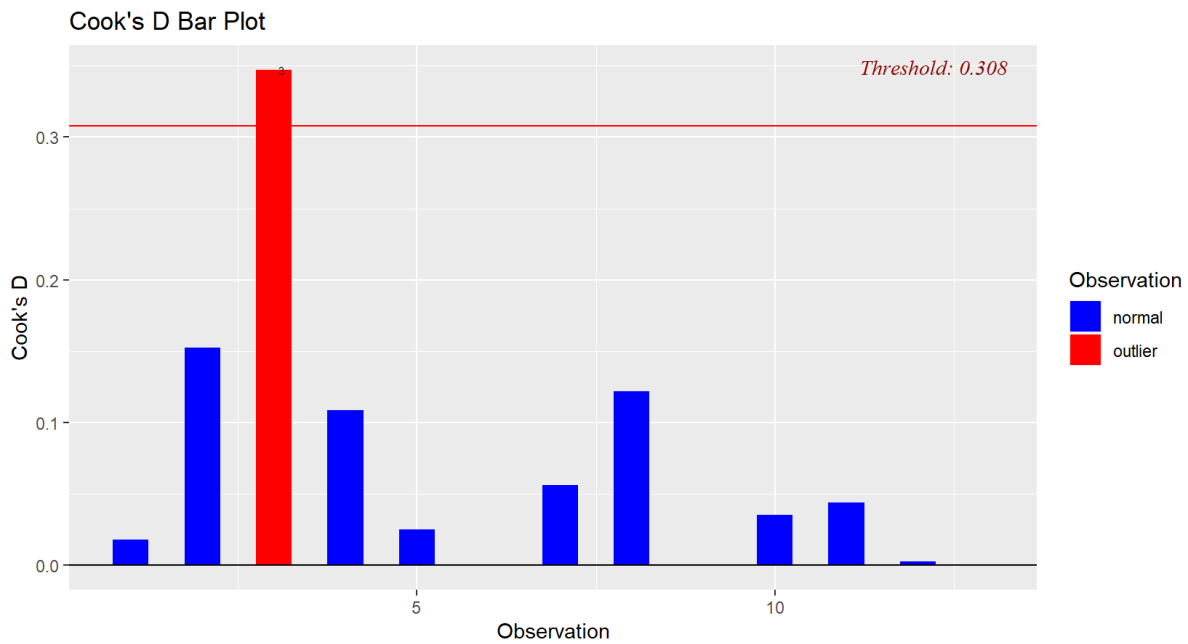


Figure 5-10 Cook's D bar plot (case III)

To crosscheck what we have observed in DFFITS outlier plot, Cook's D bar has also been plotted using RStudio. Corroborating the result obtained from DFFITS outlier plot, Cook's D bar plot also shows one outlier data (data numbered 3) same as before even with a different threshold margin (0.308). Along with the result obtained from Bonferroni outlier test, these two plots clearly imply that this data set is credible in terms of the presence of outliers.

### Multicollinearity Test

We have already obtained the mutual correlation among the predictor variables and tabulated the results earlier. And we have found that multicollinearity among the variables is almost nonexistent. To cross verify this statement multicollinearity test has also been conducted using RStudio to determine the Variation Inflation Factor (VIF). If  $VIF > 1$ , multicollinearity transpires among the predictors. However, only predictors with a  $VIF > 5$  maybe problematic.

A VIF > 10 suggests high multicollinearity and indicates a poor estimate of the response. Thus, the VIF should be less than 5.

Table 5-10 Variation Inflation Factor data (case III)

| <i>Predictor Variables</i> | <i>VIF</i> |
|----------------------------|------------|
| <i>PP</i>                  | 1.583418   |
| <i>TSS</i>                 | 3.804240   |
| <i>TDS</i>                 | 4.312485   |
| <i>SC</i>                  | 4.590685   |
| <i>RD</i>                  | 4.631866   |

Table 5-9 summarizes the VIF values for all predictor variables involved in this MLR model. all the VIFs are within the suggested range. Thus, no concerning multicollinearity takes place among the predictor variables.

Since, the preliminary MLR model did satisfy all the requirements in terms of constant error variance, normality, outliers' influence, and multicollinearity there is no need for transformation of variables to find out a more suited model. Finally, we can select the preliminary MLR model as the final one based on a rather customary best subset selection. The pertinent attributes for the best subset selection method are  $R^2$ , adjusted  $R^2$ , Mallows' Cp, and Bayesian Information Criteria (BIC). The method selects the best model with the highest  $R^2$  and adj.  $R^2$ , and the lowest Mallows' Cp and BIC. In this case. Since no transformation of variables has been required, it is more likely that the subsets used for the preliminary prediction MLR model would dem to be the best subset as well. To cross verify that, best subset selection tool has been deployed in RStudio and the obtained results have been listed in the following table.

Table 5-11 Summary of best subset selection (case III)

| <i>Predictor Variables</i> |       |       |      |      | $R^2$        | $Adj. R^2$    | $C_P$      | $BIC$          |
|----------------------------|-------|-------|------|------|--------------|---------------|------------|----------------|
| $PP$                       | $TSS$ | $TDS$ | $SC$ | $RD$ |              |               |            |                |
|                            | -     | ✓     | -    | -    | 0.3721       | 0.2987        | 675.67     | -5.87          |
|                            | -     | ✓     | ✓    | -    | 0.4341       | 0.3398        | 558.63     | -13.21         |
|                            | ✓     | ✓     | ✓    | -    | 0.6543       | 0.6219        | 303.51     | -48.69         |
| ✓                          | ✓     | ✓     | ✓    |      | 0.7531       | 0.7441        | 233.93     | -136.84        |
|                            | ✓     | ✓     | ✓    | ✓    | 0.8914       | 0.8756        | 259.1      | -236.74        |
| ✓                          | ✓     | ✓     | ✓    | ✓    | <b>0.953</b> | <b>0.9194</b> | <b>3.2</b> | <b>-342.65</b> |

This table clearly shows that while we take all the predictor variables as selected for the preliminary model, we get the best subset selection in terms of highest  $R^2$ ,  $Adj. R^2$  and lowest  $C_P$  and  $BIC$  values.

#### 5.2.1.4 Validation of Final Prediction Model

Hence, the MLR model obtained through the regression analysis satisfying all statistical fairness criteria, and best subset selection is as following:

$$RCR = 0.6982 + 0.000051PP + 0.0000089TSS + 0.00131TDS - 0.00189SC + 0.00376RD$$

Now the final step is the validation of the prediction model. To validate the prediction model, a different set of data has been used. Prediction model has been developed using the data corresponding bitumen grade PG 64-22 instead of PG 70-22. Results of RCR for this new data set will be plotted against the predicted results using the MLR equation obtained through this detailed regression analysis and the resulting plot is as follows:

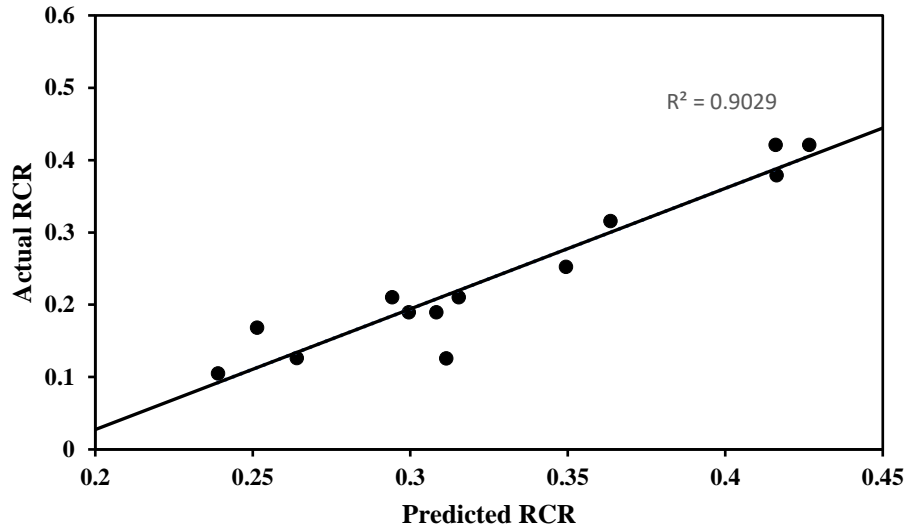


Figure 5-11 Validation of prediction model (case III)

Figure 5-11 delineates the correlation between the actual RCR of a data set and the predicted RCR using the MLR model. As we can see, the coefficient of determination/correlation is 0.9029 indicating not only a strong correlation between the data but also implying a credible, reliable regression model to predict the microplastic Risk Characterization Ratio (RCR) of a recycled plastic induced surface course of a plastic road.

## SUMMARY AND CONCLUSION

### 6.1 Introduction

The creation, and subsequent consumption of seemingly nondecaying plastics coupled with a growing population, has resulted in an ever-increasing plastic waste crisis all over the world. One solution to this crisis can be attributed to reusing or more ideally repurposing plastic in useful operation. Concept of an integrated plastic road is one dimension of solution to global plastic waste crisis incorporating shredded plastics in multiple layers. Instead of using plastic only as a constituent of binder course, a macroscale use of waste plastics in base/subbase course of a pavement must be considered. However, proper investigation should be carried out not only to suffice the mechanical property requirements of a plastic road, but also to scrutinize the environmental repercussions as well. Whenever, the concept of plastic road is publicized, the automatic reverberating term transpires is “Microplastics” which indeed a rising global concern on top of already minacious waste plastic crisis. Since, both the concept of integrated plastic road and the research on microplastics are on their very nascent juncture, unfortunately there has hardly been any effort to investigate on the microplastic aspect of a plastic road. This study aims at filling that gap to carry out an extensive analysis on microplastic risk associated with a plastic road. The primary objective of this study was to characterize the microplastic risk in terms of Risk Characterization Ratio (RCR) and to develop a statistical multilinear regression model to predict the extent of that risk. The study and the subsequent dissertation portrayed a way to answer those questions transpired from microplastic viewpoint of a plastic

road. The major findings from the laboratory test results, analysis, statistical regression of the data is summarized in this chapter. Recommendations for future investigation on this topic are also listed afterwards.

## **6.2 Summary and Conclusion**

1. Four different types of plastics have been used for this study. HDPE, PET, PP plastics are used for base course, and for surface course LDPE plastic is used in place of PET.
2. For base course samples, plastic percentage ranges from 0% (control) to 5%, and for surface course samples, that range stands as 0% (control) to 16%.
3. Considering base course samples incorporating HDPE plastics showed better results in terms of microplastic risk and samples subsuming PP plastics showed comparatively worse results. However, overall RCR values for base course remained almost 90% below threshold RCR of 1.
4. Base course samples were also subject to an adverse condition involving a repetitive cyclic loading. For this condition as well, samples with PP plastics performed worst. Even, the overall RCR for this condition was significantly higher, it remained 26% below the RCR threshold of 1.
5. Out of all surface course sample combinations, HDPE and LDPE samples fared better compared to PP samples. In terms of overall RCR, it was observed that the value remained in between the two cases mentioned above and it is 84% below the RCR threshold value of 1.
6. Regardless of combinations, weathering conditions, percentage of plastics and other constituent materials used (recycled aggregates, bitumen, cement, moisture) Risk

Characterization Ratio (RCR) remained below 1 implying nonexistent ecotoxicological microplastic risk associated with Plastic Road.

7. RCR analysis was also carried out for control samples (0% plastic) for both base and surface course. Even, no plastic was used to prepare the sample, presence of microplastics was identified.
8. This study also incorporated Fourier Transform Infra-Red (FTIR) spectroscopy on top of regular optical microscopy. FTIR results did show that source of microplastic detected through an optical microscope is not necessarily the type of plastic used to fabricate a certain sample. For example, a sample representing HDPE type of plastic exhibited trace of PET microplastics. And this phenomenon has been observed for both base and surface course samples.
9. FTIR spectroscopy was also carried out for control samples with no plastics. And like RCR analysis, presence of microplastics was confirmed.
10. Microplastics presence in control samples corroborated by both RCR and FTIR analysis is a significant finding of this study. It means microplastics are not only resulting from plastics used to prepare the samples, but other constituent materials are also contributing to overall microplastic concentration.
11. Statistical model to predict the RCR values for base course of a plastic road has been developed. Prediction model for base course sample is as follows:  
$$\text{RCR} = 0.3906 - 0.000011\text{PP} + 0.000378\text{CP} + 0.000786\text{TSS} - 0.000141\text{TDS} - 0.000567\text{SC}$$

This model possesses an impressive coefficient of determination or correlation coefficient of 95%.

12. Statistical model to predict the RCR values for base course of a plastic road has been developed. Prediction model for base course sample is as follows:

$$\text{RCR} = 0.6982 + 0.000051\text{PP} + 0.0000089\text{TSS} + 0.00131\text{TDS} - 0.00189\text{SC} + 0.00376\text{RD}$$

This model attributes a correlation coefficient of almost 92%.

13. Thus, for base course 95% of the variation in RCR is explained by the model in relation to plastic percentage, cement percentage, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and Specific Conductance (SC) .

14. For surface course almost 92% of the variation in RCR is explained by the model in relation to plastic percentage, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Specific Conductance (SC) and Rutting Depth (RD).

### **6.3 Recommendation for Future Studies**

1. In this study, only four types of plastics were used: HDPE, LDPE, PET, and PP. Other plastic types might be used for future investigations to characterize and compare microplastic risk.
2. For different sample combinations, different types of plastics have been incorporated separately. A further investigation should be carried out subsuming mixture of multiple plastics type.
3. For base course, only cement has been used for stabilization. Other stabilization techniques such as lime, lime kiln dust, fly ash, grout should also be considered to prepare the samples.



4. For surface course, bitumen type PG 70-22 and PG 64-22 have been considered. However, future investigations might consider using other bitumen type, i.e., PG 76-22.
5. RCR analysis has been carried out in a very conservative approach assuming microplastic carrying leachate entirely emanating to the natural waterbodies without considering the interlayer microplastic accumulation. Future study should incorporate the runoff flow within the layers and long-term accumulation.
6. Prediction model is entirely based on and validated through laboratory experiments. A more realistic approach should be analyzing the RCR data from an actual plastic road and then revalidate the statistical modelling.
7. A wide range of weathering conditions for the samples could be introduced to compare the results. For example, samples can be subject to simulated rainwater.
8. An investigation can be carried aiming at Life Cycle Analysis of plastic road to find out the cumulative RCR at the end of pavement design life.

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