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Effect of Impurities in Plastic Waste on the Performance of Plastic road

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EFFECT OF IMPURITIES IN PLASTIC WASTE ON THE PERFORMANCE OF PLASTIC ROAD

By

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ABSTRACT

EFFECT OF IMPURITIES IN PLASTIC WASTE ON THE PERFORMANCE OF PLASTIC ROAD

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Plastic waste generation has become a global concern, with a large portion of plastics ending up in landfills. China's recent decision to stop importing waste from various countries, including the USA, has exacerbated the issue of plastic pollution. These plastics, as coming from the household and commercial trash, contain impurity and contamination. This makes the recycling process of plastics more hectic and causes issues in reusing them for other purposes. Impurity and contamination, in fact, is a major issue in material science.

Researchers have been studying ways to improve the performance of bituminous pavement, as highways are experiencing increased demand and various distresses such as rutting, fatigue cracking, and moisture-induced stripping. One potential solution being explored is the use of recycled plastic waste as an asphalt modifier. Studies in different countries have shown that waste plastic can effectively enhance pavement performance. However, most studies have used clean plastics, while plastics directly collected from landfills may contain impurities that can affect the performance of the aggregate-bitumen-plastic mix. This is particularly relevant in developing countries where plastics may not undergo thorough cleaning procedures. Therefore, the objective of this study is to find out the effect of impurity present in waste plastics in evaluating the performance of plastic road asphalt mix design.

The experimental program for this study was divided into two parts. Preliminary, plastic wastes have been collected and the amount of impurity that the waste plastics can contain was determined. It was found that Low Density Polyethylene (LDPE) contains a higher amount of impurity than the other grades. Concurrently, the effect of impurity was determined on the performance and volumetric tests of the asphalt mix design. Since the effect was certain, further experiments have been carried out introducing specific percentage (10%, 20% and 30%) of impurity that replaces the plastic. 4% and 8% plastics have been mixed in the asphalt as a replacement of bitumen. High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), and Polypropylene (PP) type plastics were utilized in this study to mix with Superpave SP-C mix with virgin and recycled aggregates such as Type C rock, Type D rock, man sand and Recycled Asphalt Pavement (RAP).

According to this study, impurities in plastic waste can make the asphalt mix perform reciprocally in rutting depending on the type of plastic and the impurity contained by it. LDPE at 4% with impurity decreased the rut depth by 20%, however, PP at 4% with 30% impurity can increase the rut depth more than 30% compared to clean plastic use. Nevertheless, in all combinations of plastic and impurity, the rut depth is less than 4mm. In tensile strength, 4% HDPE with the increasing impurity showed a decline in the strength, however, using 8% HDPE with impurity resulted in the increased tensile strength. Allowing impurity in the asphalt mix with plastic made the mix more moisture susceptible compared to the clean plastic mix, however, PP with impurity up to 20% proved to be moisture resilient. Overall, the volumetric tests and the performance tests proved that plastics with up to 20% impurity can be allowed in the asphalt mix.

Lastly, a Multiple Linear Regression (MLR) model was developed to determine the value of indirect tensile strength (IDT) for different combinations of plastic type, plastic content, and the impurity content present in the plastic. IDT was taken as the response variable because IDT values altered mostly due to the intrusion of impurity in the asphalt mix with waste plastic.

This research work aimed to study the potential impurities present in the waste plastic that can affect the enhancing performance of plastic road. This study can help in the method of collecting and reusing waste plastics and reduce the cost of different variables in the process of managing the waste plastic before using them in the asphalt mix.

Keywords: Rutting, Cracking, Moisture Susceptibility, Skid Resistance, Asphalt, Bitumen, Impurity, Contaminant, Waste Plastic, Plastic Road.

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CHAPTER 1

INTRODUCTION

1.1 Background

The performance of bituminous pavement has been a research interest for a very long time and recently, scientists and researchers have incorporated different methods and processes to enhance the performance of pavements. The demand for constructing highways has increased due to the increasing amount of traffic and these highways are subjected to different kinds of distresses among which rutting, fatigue cracking and stripping due to the intrusion of moisture (Ragnoli 2019) are significant. The distresses happen when the pavement does not have sufficient stability, proper compaction, and desired strength. Rutting occurs due to high temperature, and it causes permanent deformation due to repetitive loading. Fatigue cracking, another means of distress, causes over time, mostly due to decrease in temperature and repeated load coming to the surface of the pavement. These have led to an ever-increasing rise in construction and rehabilitation costs. In fact, estimates show that the state of Texas spends almost 9 billion USD to 15 billion USD annually (Jones and Jefferson 2012). The amount includes all the construction process, maintenance, and repair of the roads. As per the records from "Texas Department of Transportation" it should require almost less than $5 billion if the excessive pavement distresses could be in control (Chukka and Carr, 2016).

At the same time, plastic waste generation has been a concern all over the world. Most of the plastics have been landfilled and 8.5 percent of total plastic generated has been recycled only according to Environmental Protection Agency (EPA) in 2017. China has recently ostracized importing waste from different countries in the world which includes USA as well. This resulted more in the increase of plastic pollution.

Since scientists and engineers are constantly searching for different methods to improve the performance of asphalt pavements, a new idea has come up to use recycled plastic waste as asphalt modifier (Tiwari et al., 2018). There are so many researches going on in different countries like India (Vasudevan et al., 2011; Beena and Bindu, 2010), China (Hadidy and Yi,qui, 2009), Nigeria (Akinpelu et al., 2013), Turkey (Kofteci, 2016), Spain (Movilla-Quesada et al., 2019), UK (White & Reid, 2018) and some of them have come to conclusion that waste plastic can be used in the construction of roads to improve the pavement performance (Sangita et al., 2011; Venkat 2017). From the late 90's, polymer modified bitumen has become popular as research has shown that modified bitumen performs significantly better, and it can reduce the use of bitumen and the cost incorporated with it. Plastic has become a well-approved additive in aggregate-bitumen mix. Plastic can be used as a coating on the aggregates and this process can reduce absorption of moisture in the aggregates and can enhance the performance of the pavement (Bajpai 2017). However, most studies incorporated clean plastics as an additive. Plastics may contain other waste components such as soil particles, food wastes, fibers and so on if they are collected directly from landfills. In many countries, significantly in developing countries, the plastics may not go through thorough cleaning process and that will result in the impure plastics mixed as an additive and it can deteriorate or enhance the performance of the aggregate-bitumen-plastic (ABP) mix.

1.2 Problem Statement

Plastic waste in asphalt pavement:

Only 9% of all plastic waste has been recycled, 12% incinerated, while the rest 79% has been accumulating in landfills, dumpsites or has leached into the environment (UNEP, 2018). Hence, modification of bitumen with recycled plastic provides a new approach to overcome new technical demands as well as eliminates plastic as waste.

There are two approaches of incorporating recycled plastics in asphalt pavements: the wet process and the dry process (NCAT, 2019). In the wet process, recycled plastics are added to the asphalt binder as polymer modifiers, where mechanical mixing is required to achieve a homogenous modified binder blend. In the dry process, recycled plastics are added directly to the mixture as aggregate replacement or mixture modifiers. The main obstacle to the implementation of the dry process is a concern of lack of consistency of the final produced mix. However, the wet process also has limitations due to the poor storage stability of the plastic modified binders, where the recycled polymers tend to separate from the asphalt binder due to the difference in density and viscosity as well as the incompatibility between the two components.

India reportedly has over 15 years of experience recycling waste plastics in asphalt pavements using the dry process. The Indian Roads Congress (IRC) specification (2013) allows the incorporation of up to 10 percent of LDPE, HDPE, polyurethane, and PET by weight of asphalt binder. During mix production, waste plastic materials are added to the aggregates at an elevated temperature of 160 to 180°C, where the plastics are melted and coat the surface of the aggregates.

Impurities in the plastic waste:

The plastic waste that was retained by Material Recovery Facility (MRF) was used as additives in the bituminous mix for enhancing the performance of pavements (Islam, 2021). Laboratory scale specimens were prepared and resistance against rutting, cracking and moisture could be escalated in this research. Yet, another scope of research stays unexplored which is the amount of impurities that the plastic waste can contain when they are recovered directly from the landfills and can be used as an additive in the pavement materials. Plastics can contain two different types of impurities. Firstly, there are elemental impurities which can only be detected by various scanning methods such as Computed Tomography (CT) scanning or Fourier Transform Infrared (FTIR) Spectroscopy. Secondly, plastics can physically contain unwanted materials such as organic and inorganic waste and these materials can result in changes in physical behavior if they are used with the plastics as additive (Zhou, 2014). It also affects the thermal behavior of the mixture (Babafemi et al., 2018). Among these wastes, there can be clays, sands, metals, food waste, fibers and so on. These wastes can be identified by bare eyes (Figure 1). If the plastics are used as additives and these wastes cannot be got rid of, the physical properties of the materials used as paving materials should change significantly.

As the plastic wastes collected from landfill may not go through physical cleaning, the chances of mixing the impurities along with the plastic as additives gets higher. It was found out in China, that the percentage of impurity can go more than 70% and normal manual cleaning techniques have a difficulty in thoroughly getting rid of all the impurities (Zhou 2014). As a result, impurities in the plastics from the landfill can be a point of research to a great extent and the results can be compared to the clean plastic used as an additive. In many countries in the world, mostly in the developing countries, the mixing plants may not have the facility to clean the plastics before mixing them with the aggregates. Hence, plastics containing impurities should be mixed as additive and determine the performance in the laboratory.

Figure 1.1 Impurities in the waste plastics visible to naked eyes

1.3 Objectives

The overall objective of this study is to understand the ‘Effect of Impurities in Plastic Waste on the Performance of Plastic Road.’

Plastic with impurities (impurities denote soil particles, food wastes, fibers, grease etc.) will replace a specific percentage of bitumen in aggregate-bitumen mix. As a part of the study, optimum bitumen content (OBC) and optimum impure-plastic content (OPC) will be determined. The results will be compared with clean plastic induced asphalt mix.

The specific tasks to complete the objective of the study is as follows:

a) Collection of aggregate and bitumen (Task 1)
b) Collection of waste, sorting of plastics from the waste and determine impurity in the plastics (Task 2)
c) Shredding of sorted plastic (Task 3)
d) Development of an experimental program for optimum mix design (task 4)
e) Determination of volumetric characteristics for the mix design (task 5)
f) Evaluation of performance of the mix design (Task 6)
g) Propose optimum plastic content (Task 7)

1.4 Dissertation Organization

The dissertation is organized into six chapters. The summary of each chapter is presented as follows:

Chapter 1 presents the background, problem statement, and research objectives of the current study. The contents of each chapter are also summarized.

Chapter 2 presents a literature review on previous studies conducted on understanding the sources, types, detection methods and control strategies of impurities in different industries. A brief overview of recycled plastic situation in the world and introducing plastic in the asphalt mix is discussed. It also provides a glimpse of the performance of plastic modified bitumen mix with impurity analyzing different studies and test results of rutting, cracking, skidding and moisture susceptibility.

Chapter 3 describes the experimental program on determining the impurity in plastic wastes and preparation of recycled plastic after getting rid of the impurity along with the process for several sample preparation with impurity infused plastic waste in asphalt mix and test procedures, such as Bulk density test, Rice gravity test, Hamburg wheel tracker test, Indirect tensile strength test, Overlay test and Moisture susceptibility test.

Chapter 4 presents test results, analysis and discussions of the results.

Chapter 5 provides a description of the multiple linear regression analysis procedure and development of a statistical model to determine the value of rutting depth, using indirect tensile strength, RAP content, Plastic type and plastic content for using impure plastic in asphalt mix

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

Plastic road design has been an engaging topic of research in the current world. This topic has become interesting not only from the viewpoint of civil engineering but also from the perspective of an environmentalist. Throughout the years, numerous studies have been conducted to improve asphalt mixture design for better performing pavements (Cao, 2007; Onyango, 2015; Jain et al, 2011). This can be achieved by providing good structural pavement design as well as good asphalt mixture design (Naghawi et al, 2018). Plastic road has manifested a good asphalt mix for the pavement. The idea of plastic road mainly comprises of reusing the recycled plastics in the asphalt mix. In this case, plastics can be obtained from the roadside (in the developing or underdeveloped countries where waste management or plastic recycling do not take place) or from the landfill in the developed countries like the United States or China (World bank, 2021). These collected plastics are exposed to different types of impurities or contamination (Eriksen et al, 2018), and this is going to affect the design of plastic road if the plastics contain impurities and contamination.

2.2 Global Plastic Waste Scenario

Plastic waste has emerged as a global environmental challenge, with significant implications for ecosystems, human health, and sustainability. The issue of plastic waste has become a significant global concern due to its far-reaching environmental, economic, and social implications. This section highlights the significance of the problem and provides an overview of the global scale of plastic waste generation and its impacts.

2.2.1 Environmental Impact

Plastic waste poses severe threats to ecosystems and the environment:

a) Marine Pollution: Plastic debris pollutes oceans, rivers, and coastlines, harming marine life through ingestion, entanglement, and habitat destruction (Schmaltz et al, 2020).

b) Terrestrial Pollution: Plastic waste contaminates soil, affecting plant growth, and can leach harmful chemicals into the environment (Malizia et al, 2019).

c) Air Pollution: Incineration of plastic waste releases toxic pollutants and greenhouse gases, contributing to air pollution and climate change.

2.2.2 Economic Impact

The economic consequences of plastic waste are substantial:

a) Cleanup Costs: Governments and municipalities incur significant expenses for cleaning up plastic waste from public spaces, water bodies, and landfills.
b) Tourism and Fisheries: Plastic pollution diminishes the appeal of tourist destinations and affects coastal economies, particularly those dependent on fisheries and marine resources (Beaumont, 2019).
c) Damage to Infrastructure: Plastic waste clogs drainage systems, leading to flooding and damage to infrastructure, further burdening public finances.

2.2.3 Human Health Impact

Plastic waste also poses risks to human health:

a) Chemical Exposure: Certain plastics contain hazardous chemicals that can leach into food, water, and beverages, potentially causing adverse health effects upon ingestion or inhalation.
b) Microplastics: Microplastic particles, both in the environment and in food chains, raise concerns about potential health impacts, although the extent is still being studied (Prata et al, 2019).

2.2.4 Scale of Plastic Waste Generation

The global scale of plastic waste generation is staggering:

a) Production: Over 359 million metric tons of plastic were produced in 2018, and production is projected to increase further in the coming years (Leal Filho et al, 2021).
b) Single-Use Plastics: Single-use plastics, such as bottles, bags, and packaging, account for a significant portion of plastic waste due to their short lifespan and limited recycling rates (Ncube et al, 2021).
c) Global Plastic Waste Generation: It is estimated that around 8-12 million metric tons of plastic waste enters the oceans each year, contributing to the estimated 150 million metric tons of plastic waste in marine environments (Francis et al, 2020).

2.2.5 Plastic Waste Scenario in the USA

During the last several years, plastic waste has been generated and discarded at an exponential rate. By 2015, production has increased from 2.3 million tons in 1950 to 448 million tons, a nearly two-hundred-fold increase. It is estimated that production will double by 2050. Over 8.3 billion tons of plastic have been produced since 1950, according to researchers. Also, it has been reported that during COVID-19 pandemic the plastic waste generation increased by 17%. According to USEPA 2017, plastic waste generation was 13%, and it increased to 30%, after COVID, according to a study conducted by (Aurpa, 2021). There is a significant environmental burden associated with the massive ingestion of post-consumer and post-industrial plastic waste.

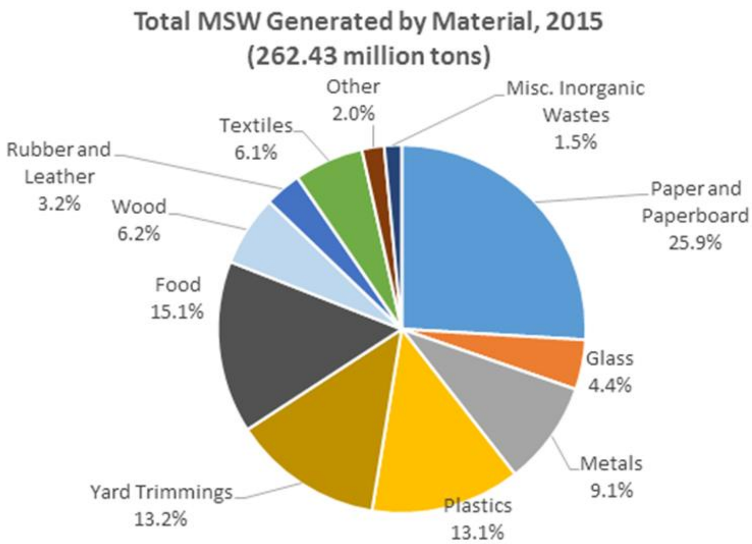


Figure 2.1 Total MSW generation in USA, 2018 (Environmental Protection Agency)

Plastics are in widespread use; due to its many good properties such as inexpensiveness, light weightiness, durability, easy availability, easy processibility etc. However, in spite of the increased production of plastics, recycling efforts have lagged (Figure 2.2). Only 9% of all plastic waste ever produced has been recycled. About 12% has been incinerated, while the rest 79% has been accumulated in landfills, dumps or the natural environment (UNEP, 2018). The reason behind this huge production and discard of plastic is that single-use and disposable plastics have become our addiction. Every minute, one million plastic drinking bottles are sold around the world, and five trillion single-use plastic bags are used each year. Approximately half of all plastic produced is made for single use and then discarded. Plastics are synthetic materials that mostly consist of hydrogen, carbon, and oxygen and are derived from petroleum or natural gas.

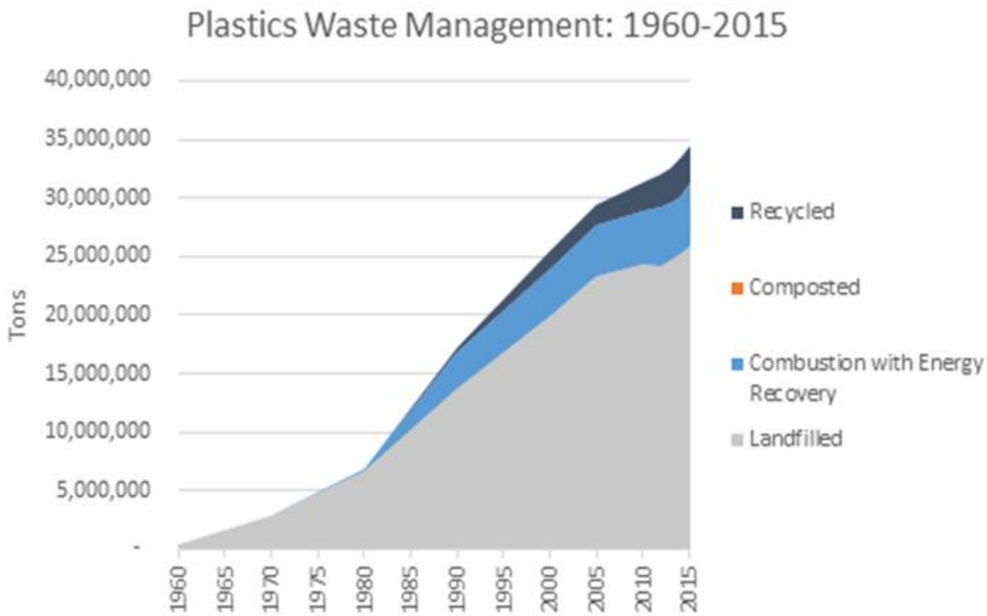


Figure 2.2 Plastic Waste Management (American Chemistry Council, 2016)

In addition to their high decomposition temperature, high resistance to UV radiation, and inability to biodegrade, they are typically non-biodegradable. As a result, they can remain on both land and sea for years and cause environmental pollution. These disposables are used for just a few moments before they are left in the environment to persist for hundreds of years, wreaking havoc through its interactions with the natural ecosystem. Plastic waste is now omnipresent and highlights that all plastic ever produced still exists in some shape or form either as macro, micro or nano plastics, making it one of the greatest challenges facing our planet today. These small plastic fragments (macro, micro or nano plastics) have specific and significant effects on ecosystems and can have negative health effects on people and animals due to their chemical structure (Guru et al, 2014).

Total U.S. plastic waste generation grows 3.8% per year (2015 vs 2014 growth rate from USEPA) resulting this waste generation from 34.5 million tons in 2015 to 38.5 million tons in 2018. Jan Dell, 2018, a chemical engineer, used U.S. Environmental Protection Agency (EPA) data and industry data to estimate the U.S. plastic recycling rate and found that it would sink from 9.1 percent in 2015 to 4.4 percent in 2018. Dell, 2018 estimated the recycling rate could drop as low as 2.9 percent in 2019 if plastic waste import bans are adopted by more countries in Asia. Table 2-1 shows the summary of US plastic waste generation and recycling rates.

Plastic pollution is also having a negative impact on our oceans and wildlife health. There have been many instances of marine impacts. By 2050, the oceans will contain more plastic than fish by weight (Jambeck et al, 2015). The United States ranks 20th on the list of countries contributing to plastic pollution in the ocean, with an estimated 88 to 242 million pounds per year of plastic marine debris. The annual International Coastal Cleanup confirmed the evidence of plastic pollution on U.S. coasts in 2017, when more than 3.7 million pounds of trash, most of it plastic, was collected by 209,643 people on a single day.

Table 2-1 Summary of US Plastic Waste Generation and Recycling Rates (Dell, 2018)

Plastic Waste	**2015 (million tons) USEPA**	**2015 Actual % USEPA**	**2018 Projected (million tons)**	**2018 Projected %**	**2019 Projected (Million tons) (Basel Convention enacted)**	**2019 Projected % (Basel Convention enacted)**
Total Generated	34.5		38.5		40	
Recycled	3.14	9.1	1.68	4.4	1.14	2.9
Composted	0	0	0	0	0	0
Combusted - Energy Recovery	5.35	15.5	5.35	13.9	5.35	13.4
Landfilled	26.0	75.4	31.5	81.7	33.5	83.7

Considering all the adverse effects of plastic it can be concluded that plastics must be disposed or else it will be hazardous to nature and environment. So, one of the best ways of disposal of these plastics is to use in bituminous road construction by melting them. Many researchers are doing various studies on environmental suitability and performance of recycled products in high construction. Use of these waste plastics in bituminous road construction will help in disposal of vast quantities of plastic.

2.3 Plastic Recycling in USA

Plastic usage is increasing gradually and controlling its disposal is very difficult because of the development of urbanization, population growth, and rapid transformations in people's daily lifestyles (Venkat, 2017). They are landfilled or incinerated, neither of which is environmentally friendly, and they pollute our air, land, and water (Prasad et al. 2012). Covid-19 has also affected the increase in plastic waste in the landfills (Aurpa 2022). Reusing and recycling plastic would not only reduce the amount of waste in landfills, but also make significant contributions to crude petrochemical savings and energy conservation (EPA, 1991; Solid waste and office water rates, 1990). Rabies and Craft (1995) identified the following technical and financial barriers that might constrain a comprehensive and effective recycling approach to turning plastic waste into new beneficial products: (i) Plastic waste can be contaminated by dirt, dust, and metals that can damage the equipment used in waste recycling; (ii) Plastics are heterogeneous materials, unlike paper and aluminum, and the wide range of types have different melting behaviors, rheology, and thermal stability; (iii) Plastics are generally not soluble in any mixes and form independent phases within a continuous phase; (iv) The raw materials in plastics are not usually identical over time; and (v) Waste plastic has a comparatively low density for which compaction, shredding or grinding are required prior to transportation to decrease shipping and handling expenses. Figure 2.3 presents the most recently reported data for key polymers in the USA, illustrating that PET is the most widely recycled type of polymer.

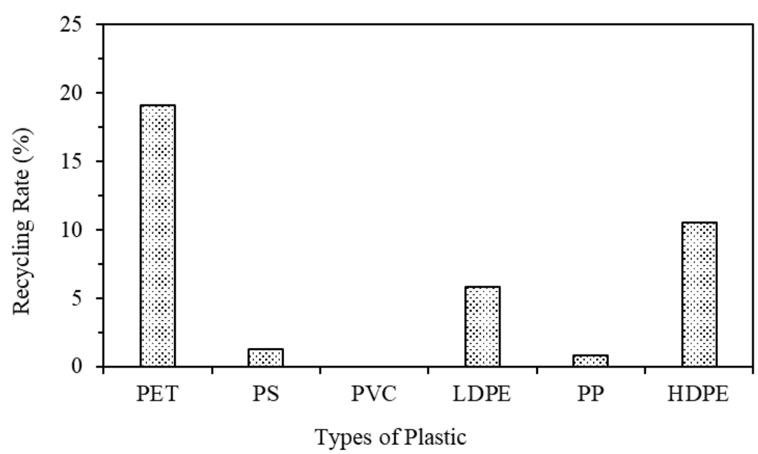


Figure 2.3 Recycling rate of plastics in the USA (Redrawn from Tsakona and Rucevska, 2020)

2.4 Plastic Type

In accordance with the Society of the Plastics Industry (SPI), there are seven types of plastic. A classification system was created by SPI in 1988 so that consumers and recyclers could distinguish between different types of plastic. Each plastic product is equipped with an SPI code, which is usually molded into the bottom. The following is a brief overview of the types of plastics associated with each of the code numbers described in this guide.

Grade 1. Polyethylene terephthalate (PET or PETE)

PET is tough, transparent, and has good barrier properties against gases and moisture. It is usually used in soft drink bottles. Foods and beverages stored inside these containers tend to absorb odors and flavors. This plastic is used for a variety of household appliances and everyday essentials.

Figure 2.4 Polyethylene terephthalate (PET or PETE)

Grade 2. High Density Polyethylene (HDPE)

HDPE products are typically recycled. These plastics are used to make milk containers, motor oil containers, shampoo bottles, detergent bottles, and bleach bottles. A HDPE bottle should not be used as a food or drink container if it did not originally contain any edible material. This is because of the risk of contamination.

Figure 2.5 High Density Polyethylene (HDPE)

Grade 3. Polyvinyl Chloride (PVC)

Many everyday objects are made of PVC, though it is primarily used in the plumbing and construction industries. There are major rigid markets for bottles and packaging sheets, as well as in the construction market where it is widely used in pipes and fittings. As a dangerous, toxic chemical, this plastic should not be used for food.

Figure 2.6 Polyvinyl Chloride (PVC)

Grade 4. Low Density Polyethylene (LDPE)

Polyethylene is the most common polymer in plastics, since it is made from ethylene monomers. Plastics made from polyethylene are flexible and durable. Food can be stored safely with it because it does not release hazardous chemicals. Many common items made of LDPE include plastic grocery bags, sandwich bags, squeezable bottles, and cling-film.

Figure 2.7 Low Density Polyethylene (LDPE)

Grade 5. Polypropylene (PP)

Polypropylene has a high melting point, is chemically resistant, and is strong, making it suitable for liquid hot filling, as well as packaging for catchups and margarine. There are many uses for it, such as lunch boxes, yogurt pots, syrup bottles, prescription bottles. PP is typically used for plastic bottle caps. PP is a strong plastic that can typically withstand higher temperatures.

Figure 2.8 Polypropylene (PP)

Grade 6. Polystyrene (PS)

Polystyrene can be rigid or foamed depending on its structure. Polystyrene is a hard, clear material that is brittle and hard. The melting point is relatively low. Packaging, containers, lids, cups, bottles, trays, and containers can be used as protective packaging.

Figure 2.9 Polystyrene (PS)

Grade 7. Other

Miscellaneous plastic types are described with code 7 instead of the other six codes. These include polycarbonate and polylactic acid. Plastics of this type are very difficult to recycle. Polycarbonate (PC) is used in baby bottles, compact discs, and medical storage containers.

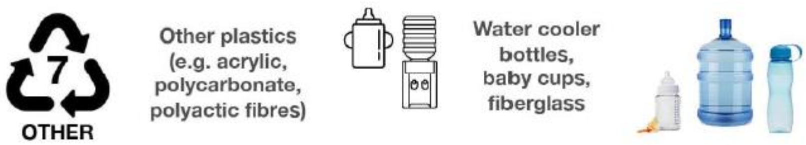


Figure 2.10 Other type of plastics (Grade 7)

2.5 Impurity and Contamination

Impurities are unwanted substances that can be found in various industries, ranging from pharmaceuticals to food, water, and chemicals (Szekely et al., 2015). Understanding the sources, types, detection methods, and control strategies for impurities is crucial for ensuring product quality, safety, and compliance with regulatory standards.

2.5.1 Impurity in Industrial Sector

Impurities are unwanted substances or contaminants that can be found in various industries, including pharmaceuticals, food and beverages, water, chemicals, and cosmetics. These impurities may arise during the manufacturing, processing, or storage of products, and they can have significant consequences on product quality, safety, and efficacy (Eon-Duval et al., 2012). The significance of impurities lies in their potential to compromise the intended functionality and performance of products, posing risks to human health, environmental sustainability, and regulatory compliance. Identifying, monitoring, and controlling impurities is crucial to ensure the integrity and reliability of products in different industries, protect consumer safety, meet regulatory requirements, and maintain the reputation and trust of manufacturers and suppliers. Understanding the nature, sources, and impact of impurities is fundamental to developing effective strategies for their detection, prevention, and mitigation, thereby upholding the standards and quality expectations of various industries.

As the world is moving towards mobility, all the industries are becoming more precise. As a matter of fact, the materials involved in these industrials need to be pure and sophisticated to ensure the best quality in the manufacturing of the products. Among these industries, the pharmaceutical industry has always been in the front to make sure the products are definite and without impurity. The automobile industry is also leaning towards perfection with the raw materials regarding the presence of impurity or any type of contamination in the materials used in the manufacturing and production process (Grilli et al., 2021).

Figure 2.11 Impurity in the gold during smelting process

This century has churned up the hype of construction of rockets to explore beyond the earth. Impurity in metal and metallurgical industry has become a matter of interest to scientists. In addition, the automobile industry is leaning towards battery derived electric vehicles and impurities can influence the industry by affecting the cathode performance (Nasser and Petranikova, 2021).

Figure 2.12 Impurity in the uncut diamond

The United States Food and Drug Administration (FDA) and other regulatory bodies around the world require that impurities in drug substance and drug product levels recommended by the International Conference on Harmonization (ICH) be isolated and characterized (Ahuja and Alsante, 2003).

Identifying process-related impurities and degradation products also helps us to understand the production of impurities and assists in defining degradation mechanisms. When this process is performed at an early stage, there is ample time to address various aspects of drug development to prevent or control the production of impurities and degradation products well before the regulatory filing and thus assure production of a high-quality drug product.

While the use of pharmaceuticals is always a balance of risks and benefits, the same is not true for impurities in pharmaceuticals; impurities convey only risk (Jacobson-Kram and McGovern, 2007). A number of international guidelines and regional guidance instruct drug developers and regulatory agencies on how to evaluate and control impurities in drug substances and drug products. While impurities should always be reduced to the lowest levels that are reasonably practical, it is acknowledged that impurities cannot be reduced to zero and specifications for impurities need to be established.

2.5.2 Impurity in Plastic Waste

Plastic can be made from different polymers and contains a variety of substances, added intentionally to enhance the plastic's properties (metals added as fillers, colorants, etc.). Moreover, plastic can be contaminated during use and subsequent waste management (Eriksen et al., 2018). Impurity and contamination become a part of the plastic waste when obtained from the recycling facility and landfills.

The four routes of PSW treatment are detailed and discussed covering primary (re-extrusion), secondary (mechanical), tertiary (chemical) and quaternary (energy recovery) schemes and technologies (Al-Salem et al., 2009). Primary recycling, which involves the re-introduction of clean scrap of single polymer to the extrusion cycle in order to produce products of the similar material, is commonly applied in the processing line itself but rarely applied among recyclers, as recycling materials rarely possess the required quality. The various waste products, consisting of either end-of-life or production (scrap) waste, are the feedstock of secondary techniques, thereby generally reduced in size to a more desirable shape and form, such as pellets, flakes or powders, depending on the source, shape and usability. Tertiary treatment schemes have contributed greatly to the recycling status of Plastic Solid Waste (PSW) in recent years. Advanced thermo-chemical treatment methods cover a wide range of technologies and produce either fuels or petrochemical feedstock. Nowadays, non-catalytic thermal cracking (thermolysis) is receiving renewed attention, due to the fact of added value on a crude oil barrel and its very valuable yielded products.

Plastic waste is a complex and heterogeneous material stream, due to several factors. First, plastic as material refers to numerous different polymers with different chemical properties that need to be separated from each other prior to recycling. The main polymers found in plastic from HHW are polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP) and polystyrene (PS) (Edjabou et al., 2015), collectively representing 63.2% of the plastic demand in Europe (Plastics Europe and EPRO, 2017). Second, many different additives can be introduced during the production phase to control the properties of the plastic and make it fulfil the requirements for use in specific applications. These include additives such as colorants, fillers, plasticizers, lubricants, antioxidants (Hahladakis et al., 2018), commonly used in packaging (Lahimer et al., 2013), as well as additives such as flame retardants, commonly used in plastic for electronics (Hansen,2013). While plastic packaging represents a significant share of plastic in HHW (Edjabou et al., 2015), waste electronics end up in HHW primarily due to miss-sorting (Edjabou et al., 2015). The type and content of these additives is regulated to varying degrees when it comes to use in specific applications. As an example, plastic used in food packaging needs to comply with the most strict and comprehensive legislation with respect to chemical composition and migration of potentially problematic substances (EU,2011b). Consequently, plastic applicable for food contact is in this study defined as ‘‘high-quality”. Thereby, this term refers to the potential applicability (and ‘‘circularity” of the plastic) with respect to legal requirements for chemical composition, rather than the physical and mechanical properties of the material (melt flow index, impact strength, etc.). In contrast to high-quality plastic, ‘low-quality” is used to characterize plastic applicable only for applications with less strict requirements in relation to chemical composition or migration (electrical and electronic equipment, non-food packaging, etc.). Hence, plastic in such applications might contain higher concentrations of potentially problematic substances. Consequently, the chemical properties and the quality of the plastic can vary depending on the specific product and its application. Third, substances can be added non-intentionally, either in the production phase (e.g., residues from catalysts, metal impurities in non-metal additives (Lahimer et al., 2013)) or as contamination through potential sorption during use and waste management (Pivnenko and Astrup, 2016). Some contaminants might be chemically embedded in the plastic matrix rather than being present as physical contamination (‘dirt’) that can be removed during recycling, e.g., during washing of the plastic waste. Consequently, there is a risk of recycling not only the desired plastic material, but also potentially problematic substances, ultimately affecting the applicability and quality of the reprocessed plastic material. This phenomenon has been demonstrated quantitatively for other materials (e.g., paper (Pivnenko et al., 2016a)), and several sources have underlined the importance of a ‘‘clean” circular economy in relation to plastic recycling (Ellen MacArthur Foundation,2016; Goldberg, 2017).

Most studies focused on the presence or migration of organic substances as contaminants. While organic substances may degrade or migrate during use and recycling, inorganic substances, such as metals, are in most cases expected to persist in the material after recycling (Hansen, 2013), though small amounts might migrate during use (Whitt et al., 2016; Bach et al., 2012). Several metals are currently intentionally added during plastic production (often as oxides, acids, etc. (Hahladakis et al., 2018; Hansen, 2013). These include additives such as colorants (containing Ti, Cr, Co,Cd, Pb, Zn, Fe, Al, Cu), antioxidants and stabilizers (containing Cd, Pb, Zn) or other additives (containing As, Li, Pb, Cd, Zn, Sb, Al) (Hahladakis et al., 2018; Hansen, 2013). Moreover, metals in plasticcan originate from catalysts used in plastic production (e.g., Sb, Ti, Cr, Hg, Mn), or contamination added or sorbed to the plastic during production, use and waste management (e.g. Fe, Al, Cu, Mn, Zn, Ni) (Hahladakis et al., 2018; Hansen, 2013; Bach et al., 2012; Romãoet al., 2010; EC, 2008). As most of these metals have well-documented toxic effects and/or can be classified as persistent and bio accumulative (Goldberg, 2017; EC, 2008), it is desirable to reduce recycling of metals in plastic, in order to minimize potential health risks and deterioration of material quality. Where the form of the metals, their hazardousness and exposure influence the potential risk to human health and the environment, the total metal content can be used to identify potential deterioration of material quality, which affects the applicability of the recycled plastic and thereby the circularity (Eriksen et al., 2018). Currently very limited knowledge exists about the fate of metals during plastic recycling, and metal contamination in plastic has been assessed previously only by focusing on one single source of plastic, polymer, or metal (Götze et al., 2016; Bach et al., 2012; Romão et al.,2010). Consequently, there is a need to quantify and document the total metal content in conjunction with the plastic material quality, rather than potential health risks, as a first step towards coherently assessing the metal content in plastic collected from various steps in the recycling chain.

In the metal content analysis, iron was detected at levels up to 700 ppm in the recyclable waste plastics fraction, which is of concern due to its potential to catalyze redox reactions during melt processing and thus accelerate the degradation of plastics during recycling. Toxic metals were found only at very low concentrations, with the exception of lead and cadmium which could be detected at 200 ppm and 70 ppm levels, respectively, but these values are below the current threshold limits of 1000 ppm and 100 ppm set by the Restriction of Hazardous Substances directive (Stenvall et al., 2013).

2.6 Detection of Impurity

There are a lot of chemical and microscopic processes to find out the impurity in different materials found in nature as well as manufactured or produced materials. Most of these processes require expensive instruments in a laboratory scale. A few important analytical techniques for impurity analysis are as follows:

i. Optical Microscopy and Scanning Electron Microscopy (SEM)
ii. Energy-Dispersive X-ray Spectroscopy (EDS)
iii. Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
iv. X-ray Diffraction (XRD) and X-ray Fluorescence (XRF)
v. Secondary Ion Mass Spectrometry (SIMS)

2.6.1 Scanning Electron Microscopy (SEM)

For scanning electron microscopy (SEM), an electron beam is generated at the emission cathode by applying a high voltage, which is then focused on the sample through magnetic lenses. This focused beam is then used to scan the sample. The surface excited by the high-energy electron beam delivers various signals which can be used for evaluation. Secondary electrons (SE) are emitted from the uppermost nanometers of the surface and thus map the topography of the surface with a resolution in the nanometer range. More energetic than the secondary electrons are the backscattered electrons (BSE). The intensity of the signals recorded here depends on the emitting material. Heavy elements (metals) provide more intense signals and appear bright, light elements (carbon, oxygen) appear dark.

Figure 2.13 Scanning Electron Microscope (jeol.com)

Since SEM/EDX measurements are performed in (high) vacuum, the sample size is limited by the instrument. The sample to be examined must not exceed an edge length of 70 mm and a height of 10 mm. In the case of large components, the areas to be examined may have to be sawn out in order to obtain a handy sample. Furthermore, no samples should be examined that are not suitable for vacuum (foams, surfaces coated with adhesive, etc.).

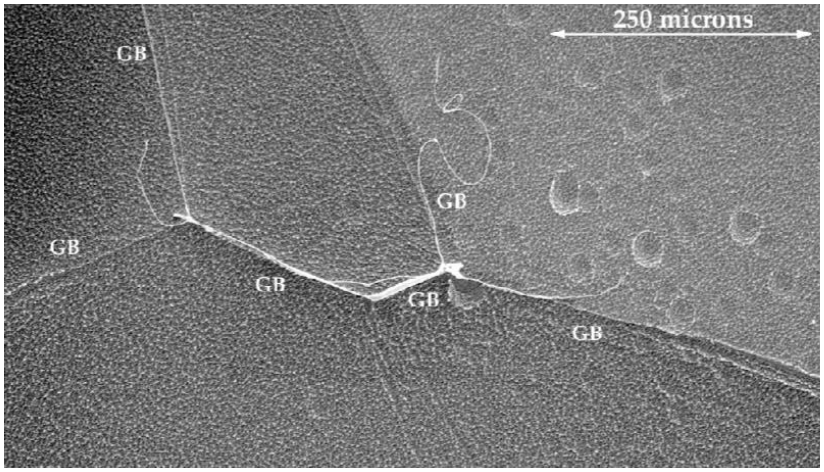


Figure 2.14 Impurity in natural ice as filaments in the grain boundaries (Cullen et al., 2022))

It is very common to find out the microscopic impurities in water and ice/snow by utilizing Scanning Electron Microscope (SEM). Cullen et al., (2002) found out impurity using SEM in the natural ice collected from 4 locations in Antarctica, Greenland and New Hampshire (Figure 2.14). During magnesium extraction from the sea water, impurities were found by microscopic analysis by SEM/EDX (Natasha and Firdiyono, 2017).

Following are the photos of plastics in the SEM.

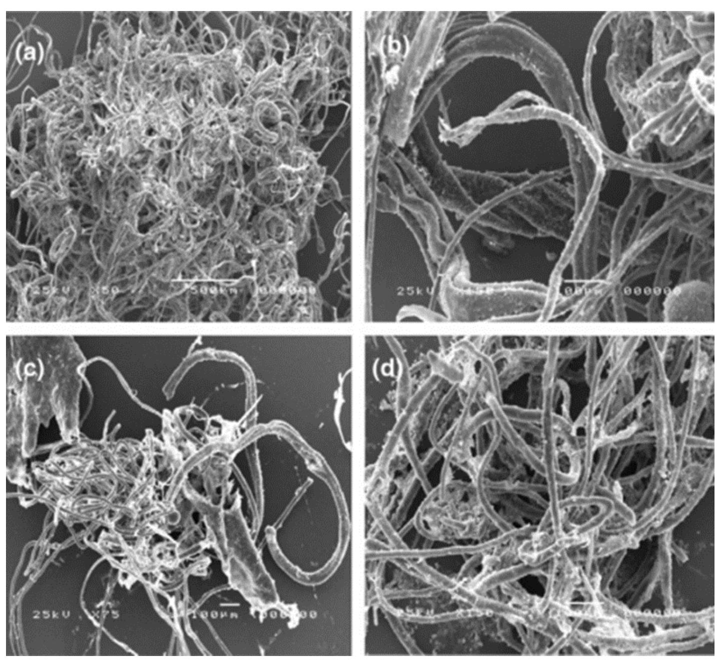


Figure 2.15 Scanning electron microscope (SEM) pictures of plastics found in Nephrops norvegicus (Clyde Bay, Scotland); (Picture taken from Murray et al. 2011)

2.6.2 Energy-Dispersive X-ray Spectroscopy (EDS)

The Energy-Dispersive X-ray Spectroscopy (EDS) detector is the tool we utilize for measuring the energy of the emitted photons in the X-ray electromagnetic spectrum. It is an addition to the SEM machine technically.

The detector is a solid-state chip or crystal that is cooled to superconducting temperature for high quantum efficiency and is off axis from the incident beam.

The detected X-rays are segregated into energy channels based on their interaction with the detector and form a spectrum of detected energies. With the spectrum, we can identify the peak energies and determine what electron transition occurred and thus what element it corresponds to. We can also couple this data to the SEM imaging technique to form X-ray "maps" of data to overlay or present areas of high individual elemental concentrations. Figure 2.16 shows how EDS can identify elemental concentration from an SEM image.

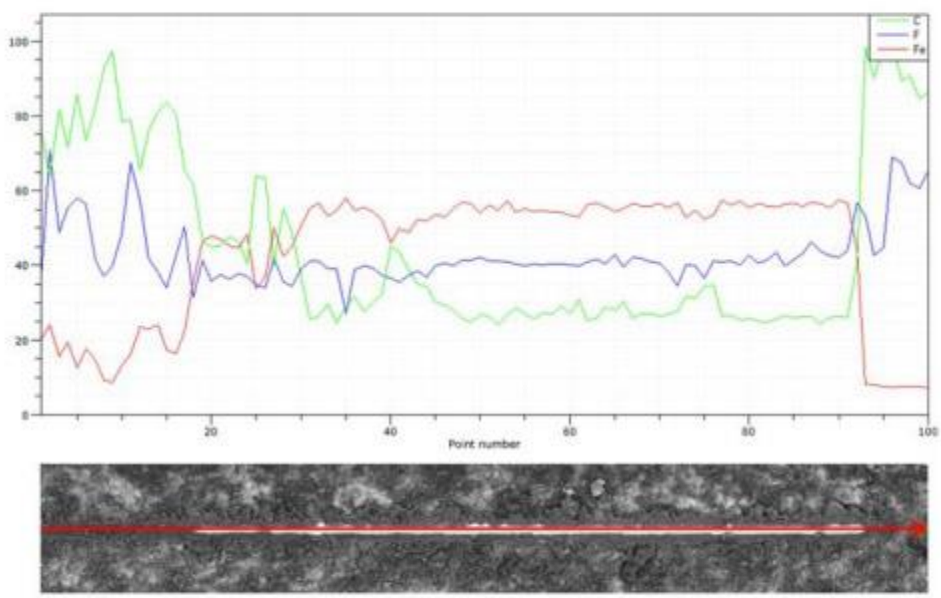


Figure 2.16 EDS elemental concentration profiles along the red scan line (ebatco.com)

2.6.3 Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)

Inductively coupled plasma mass spectrometry (ICP-MS) is a type of mass spectrometry that uses an inductively coupled plasma to ionize the sample. It atomizes the sample and creates atomic and small polyatomic ions, which are then detected. It is known and used for its ability to detect metals and several non-metals in liquid samples at very low concentrations. It can detect different isotopes of the same element, which makes it a versatile tool in isotopic labeling.

Figure 2.17 Analytical instrument ICP-MS from Varian company

Compared to atomic absorption spectroscopy, ICP-MS has greater speed, precision, and sensitivity. However, compared with other types of mass spectrometry, such as thermal ionization mass spectrometry (TIMS) and glow discharge mass spectrometry (GD-MS), ICP-MS introduces many interfering species: argon from the plasma, component gases of air that leak through the cone orifices, and contamination from glassware and the cones.

ICP-MS is an also analytical technique that can be used to measure elements at trace levels in biological fluids (Wilschefski and Matthew, 2019). This method is now widely used because of the potential for both spectroscopic and non-spectroscopic interference. Elemental concentration analysis can be done using spectroscopy.

2.6.4 X-ray Diffraction (XRD) and X-ray Fluorescence (XRF)

XRF and XRDX-ray fluorescence (XRF) is a non-destructive analytical technique used to determine the elemental composition of materials. XRF analyzers determine the chemistry of a sample by measuring the fluorescent (or secondary) X-ray emitted from a sample when it is excited by a primary X-ray source. Each of the elements present in a sample produces a set of characteristic fluorescent X-rays that is unique for that specific element. XRF analyzers are available in handheld models designed to provide instant elemental analysis for immediate feedback in the field, or in lab-based systems designed to provide qualitative and quantitative analysis for process and quality control. Both types of XRF equipment are used in applications as diverse as cement manufacturing, metallurgy, mining, petroleum, polymers, paints and chemicals, forensics investigations, and environmental analysis. XRF analysis determines the elemental composition of a sample but does not provide information about how the various elements are combined together. Such mineralogical information is only available through X-ray diffraction (XRD). XRD is a versatile and nondestructive analytical technique that reveals detailed structural and chemical information about the crystallography of materials. XRD looks at a crystalline material's characteristic X-ray scattering, or diffraction pattern, which reveals the material's atomic structure. Qualitative analysis is possible by comparing the XRD pattern of an unknown material with a library of known patterns. XRD's many applications include:

i. Identification of single or multiple phases in an unknown sample
ii. Quantification of known phases of a mixture
iii. Amorphous content evaluation
iv. Crystallography – solving crystal structure
v. Non ambient analysis – crystal structure changes with temperature, pressure or gas phase
vi. Surface and thin film analysis
vii. Texture analysis

Figure 2.18 Handheld XRF Analyzers (metallurgistequipment.com)

XRD can be considered complementary to XRF Although its principles are different, XRD can be considered complementary to XRF. In a typical crystalline sample, XRF might measure for example the total calcium (Ca) concentration or the total iron (Fe) concentration. XRD permits analysis of the phases or compounds in crystalline materials such as rocks, minerals and oxide materials and products. So in the same sample, XRD takes the analysis a stage further and gives information about CaO, $CaCO_3$, $Ca(OH)_2$ contents and other Ca phases or the levels of Fe phases, such as FeO, Fe_2O_3 , Fe_3O_4 , Fe_3C and other Fe phases. Therefore, combining the results of both XRF and XRD techniques allows for a better and more complete characterization of any given crystalline sample. Undertaking both types of analysis has traditionally called for two separate X-ray instruments, maintained and operated at significant cost to the user. But the integration of innovative X-ray diffraction systems allows both techniques to be included in the same instrument, bringing significant advantages to the use:

i. Only one sample introduction
ii. Single user interface for both techniques
iii. Elemental and phase results merged into one single analysis bulletin
iv. Minimized floor space
v. No water cooler at mid power levels.

2.6.5 Secondary-ion mass spectrometry (SIMS)

Secondary-ion mass spectrometry (SIMS) is a technique used to analyze the composition of solid surfaces and thin films by sputtering the surface of the specimen with a focused primary ion beam and collecting and analyzing ejected secondary ions. The mass/charge ratios of these secondary ions are measured with a mass spectrometer to determine the elemental, isotopic, or molecular composition of the surface to a depth of 1 to 2 nm. Due to the large variation in ionization probabilities among elements sputtered from different materials, comparison against well-calibrated standards is necessary to achieve accurate quantitative results. SIMS is the most sensitive surface analysis technique, with elemental detection limits ranging from parts per million to parts per billion. This technique is, however, a very expensive one. NASA uses this method to identify the impurities in different aspects in their projects.

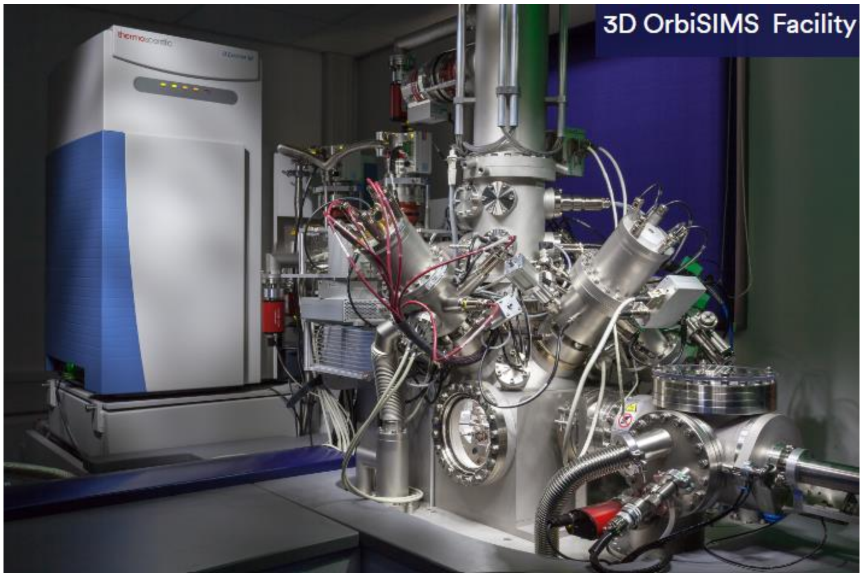


Figure 2.19 3D OrbiSIMS facility in the University of Nottingham

2.7 Pavement Types

Efficient road network is a prerequisite for the social and economic development of a country. The goal of roads is to provide durable and long-lasting pavements to improve riding comfort and safety, as well as to reduce maintenance costs. This can be achieved by providing good structural pavement design as well as good asphalt mixture design (Naghawi et al, 2018). Throughout the years, numerous studies have been conducted to improve asphalt mixture design for better performing pavements (Ca0, 2007; Onyango et al, 2015; Jain et al, 2011).

Pavements can be categorized into two types, flexible pavement, and rigid pavement (Figure 2.31Figure 2.20). Flexible pavements are surfaced with bituminous materials. On the contrary, rigid pavements are constructed using Reinforced Portland Cement Concrete (PCC).

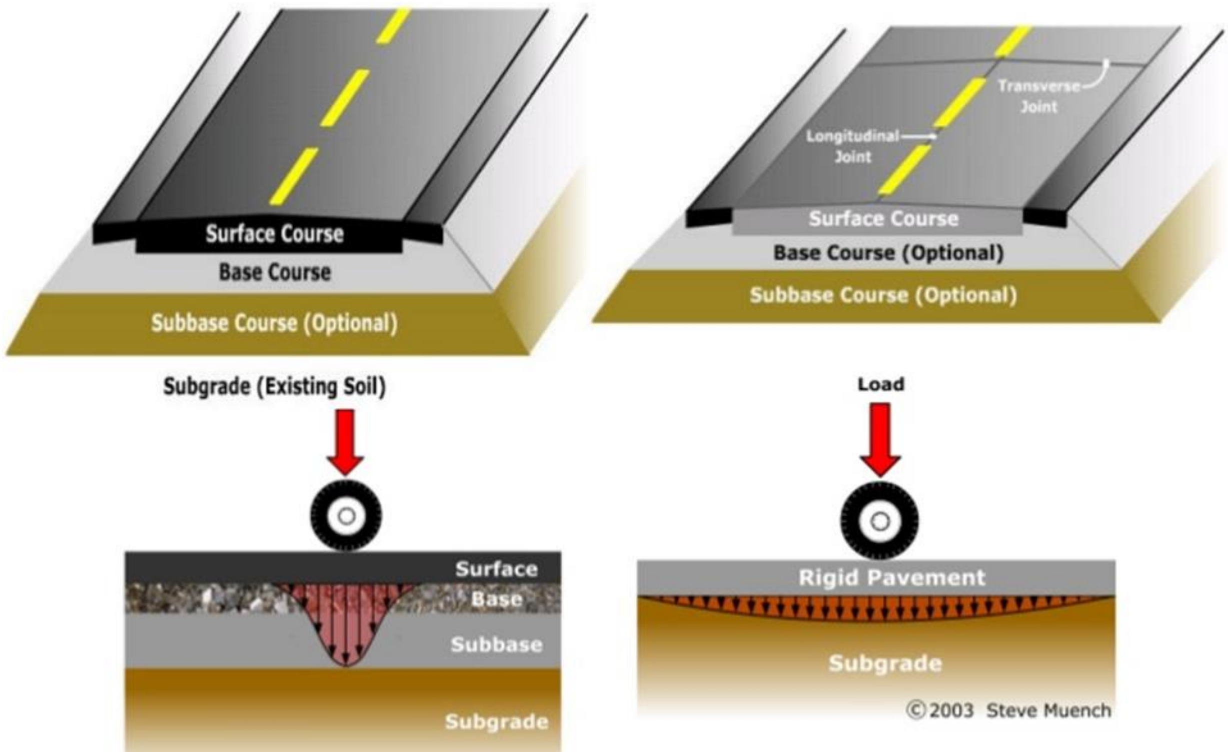


Figure 2.20 Typical cross-section and stress distribution on flexible and rigid pavement (TxDOT Manual)

Between these two types, rigid pavements have higher modulus of elasticity which means rigid pavements have higher strength compared to flexible pavements. But flexible pavements can be constructed in shorter time and lower cost. Additionally, flexible pavements are smoother, so it ensures higher speed and comfort for the vehicles. Therefore, flexible pavements are more desirable than rigid pavements which is why the durability of the bituminous pavement comes in picture. Durability is the resistance of asphalt concrete to the action of traffic, temperature and temperature changes, and the action of air and water. Asphalt pavement performance is affected by several factors, e.g., the properties of the components (binder, aggregate and additive) and the proportion of these components in the mix. The performance of asphalt mixtures can be improved with the utilization of various types of additives, these additives include polymers, latex, fibers, and many chemical additives (Taih, 2011; Awwad & Shabeeb, 2007).

2.8 Structure of Flexible pavements

Flexible pavements are those which are surfaced with bituminous or asphalt materials. This can either be in form of pavement surface treatments (such as bituminous surface treatment (BST) generally found on lower volume roads) or hot mix asphalt (HMA) surface courses (generally used on higher volume roads such as the highways) (TxDOT). These types of pavements are called flexible since the total pavement structure bends or deflects due to traffic loads. A flexible pavement structure is generally composed of several layers of materials which accommodate this "flexing". These materials consist of a mixture of asphalt or bituminous material, aggregates (coarse and fine) placed on a bed of compacted granular material of appropriate quality in layers over the subgrade. The coarse aggregates can be crushed stone and fine aggregates are generally sand. (Both engineered to required specification). The Bitumen is derived from tar which is the final product of fractional distillation of natural oil. These pavements are generally designed for low volume traffic loads as compared to rigid pavements. The stress distribution in these pavements is such that it gradually recedes as the load is transmitted downwards from the surface by virtue of spreading over an increasingly larger area, by carrying it deep enough into the ground through successive layers. Figure 2.21 shows a typical section of flexible pavement.

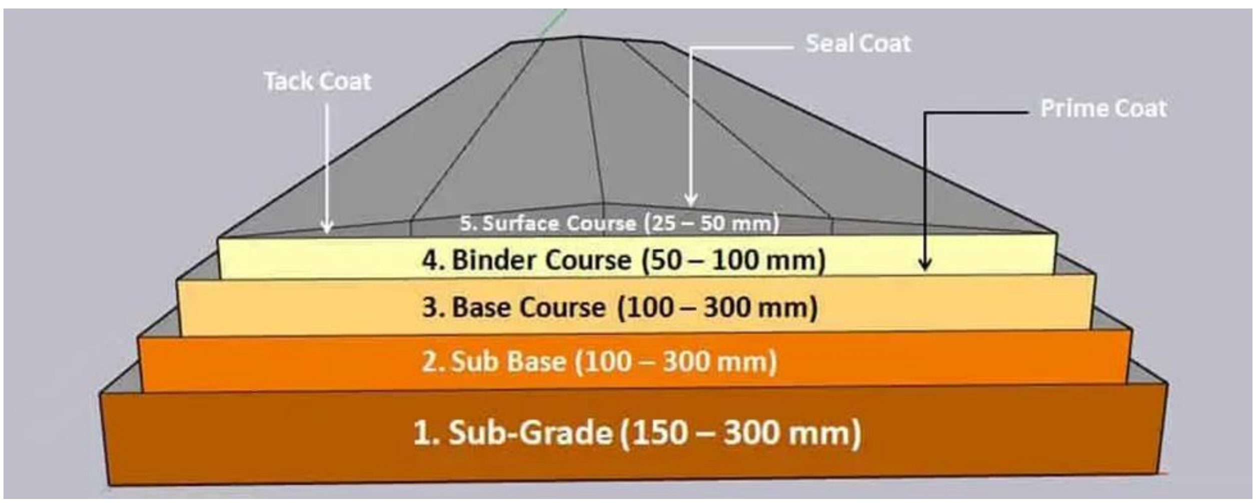


Figure 2.21 Typical section of a flexible pavement (civilengineering.com)

2.9 Types of Asphalt Mix

2.9.1 Dense-Graded Mixes

Bituminous concrete with a dense mix is composed of all constituents in good proportion. It provides durability by offering good compressive strength as well as some tensile strength.

2.9.2 Gap-Graded Mixes

There are some large coarse aggregates missing but they are very strong and have a good fatigue and tensile strength.

2.9.3 Open-Graded Mix

It lacks fine aggregates and fillers, is porous, provides good friction and has low strength.

2.9.4 Hot Mix Asphalt Concrete

The most widely used paving material in the world is hot-mix asphalt (HMA). The material is also known as asphaltic concrete, plant mix, bituminous mix, or bituminous concrete. Aggregates and asphalt binder are its two primary components. Aggregates consist of coarse and fine materials, usually a mix of different sizes of rock and sand. By weight, aggregates account for approximately 95% of a mixture. HMA is produced by mixing them with about 5% asphalt binder (Speight, 2016). Prior to mixing the asphalt binder with the aggregate, the asphalt binder must be heated to reduce its viscosity and the aggregate must be dried to remove moisture. In most cases, virgin asphalt is mixed at 150°C with the aggregate.

2.9.5 Warm Mix Asphalt

Zeolite wax, asphalt emulsions, or sometimes even water are added to the asphalt binder prior to mixing to make it. Thus, mixing and laying temperatures can be lowered significantly, which reduces the consumption of fossil fuels, releasing less carbon dioxide, aerosols, and vapours.

2.9.6 Cold Mix Asphalt

It is manufactured by emulsifying asphalt in water before mixing with aggregates. In addition, the mixture has a lower viscosity and is more easily compacted and convenient to work with. Cold mix asphalt acts like cold HMA after evaporation of water breaks the emulsion.

2.9.7 Cut-Back Asphalt Concrete

The binder is dissolved in kerosene or some other lighter fraction of petroleum, making the asphalt less viscous and easier to work and compact. The lighter fraction evaporates after laying of the mix. Due to concerns about pollution caused by volatile organic compounds in the lighter fraction, cut-back asphalt has been largely replaced by asphalt emulsion.

2.9.8 Mastic Asphalt Concrete

In order to produce mastic asphalt, hard grade blown bitumen (oxidation) is heated until it has transformed into a viscous liquid in a green cooker (mixer) before it is mixed with aggregates. Following that, the bitumen aggregate mixture is cooked (matured) for approximately 6-8 hours and then the mastic asphalt mixer is transported to the job site where it is generally laid with athickness of between 3⁄4–13⁄16inches (20-30 mm) for footpaths and roads and around 3⁄8 of an inch (10 mm) for flooring or roofs.

2.10 Hot Mix Asphalt (HMA)

Hot-Mix Asphalt (HMA) is the most widely used paving material around the world. It's known by many different names: HMA, asphaltic concrete, plant mix, bituminous mix, bituminous concrete, and many others. It is a combination of two primary ingredients aggregates and asphalt binder. Aggregates include both coarse and fine materials, typically a combination of different size rock and sand. The aggregates total approximately 95% of the total mixture by weight. They are mixed with approximately 5% asphalt binder to produce HMA (Speight, 2016).

2.10.1 Aggregate

Aggregates (or mineral aggregates) are hard, inert materials such as sand, gravel, crushed rock, slag, or rock dust. Properly selected and graded aggregates are mixed with the asphalt binder to form HMA pavements. Aggregates are the principal load supporting components of HMA pavement. Because about 95% of the weight of dense-graded HMA is made up of aggregates, HMA pavement performance is greatly influenced by the characteristics of the aggregates. Aggregates in HMA can be divided into three types according to their size: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36-mm sieve. Fine aggregates are those that pass through the 2.36-mm sieve and are retained on the 0.075-mm sieve. Mineral filler is defined as that portion of the aggregate passing the 0.075-mm sieve. Mineral filler material also referred to as mineral dust or rock dust - consists of very fine, inert mineral with the consistency of flour, which is added to the hot mix asphalt to improve the density and strength of the mixture. It shall be incorporated as part of the combined aggregate gradation (Chen, 2009; Transportation research board committee, 2011). The aggregate is chosen based on its strength, porosity and moisture absorption capacity (Vasudevan et al., 2011).

2.10.2 Asphalt Binder (Bitumen)

Asphalt binder (bitumen) is a viscous material that is derived from crude petroleum and is used in paving roads to hold aggregate together. Asphalt binder consists mostly of hydrocarbon molecule (hydrogen and carbon), with small amounts of oxygen, sulfur, and nitrogen (Hadidy and Yu, 2008). The physical properties of asphalt binder vary considerably with temperature. At high temperatures, asphalt binder is a fluid with a low consistency similar to that of oil. At room temperature most asphalt binders will have the consistency of soft rubber. At subzero temperatures, asphalt binder can become very brittle. Many asphalt binders contain small percentages of polymer to improve their physical properties; these materials are called polymer modified binders. Most of asphalt binder specification was designed to control changes in consistency with temperature (Transportation research board committee, 2011).

In some applications, however, the performance of conventional bitumen may not be considered satisfactory because of the following reasons:

i. In summer season, due to high temperature, the bitumen becomes soft resulting in bleeding, rutting and segregation finally leading to failure of pavement.
ii. In the winter season, due to low temperature, the bitumen becomes brittle resulting in cracking, raveling and unevenness which makes the pavement unsuitable for use.
iii. In the rainy season, water enters the pavement resulting into potholes and sometimes total removal of bituminous layer.

2.10.3 Reclaimed Asphalt Material

In today's asphalt industry, reusing reclaimed asphalt materials like reclaimed asphalt pavements (RAP) and reclaimed asphalt shingles (RAS) to create new pavements is essential RAP and RAS are used in hot-mix asphalt (HMA) because they provide economic and environmental benefits. As asphalt binder costs have increased (because of the global rise of oil price) and high quality virgin aggregates are in short supply, demand for RAP and RAS has steadily increased in recent years. More than 99 percent of RAP is being reused in new pavements (NAPA, 2011). By using RAP and RAS in 2010, approximately 20.5 million barrels of asphalt binder were conserved (NAPA, 2011). Use of RAP and RAS in 2010 conserved approximately 20.5 million barrels of asphalt binder (NAPA, 2011). RAP, which contains an average of 5 percent asphalt binder, is an excellent source of asphalt binder and high quality aggregates for new HMA.

Recycled Asphalt Pavement (RAP)

As RAP has become more commonly used by the asphalt industry, DOTs have realized they need to update their specifications and testing protocols since more laboratory and field data are needed on asphalt mixes containing RAP. Jones (2008) states that more than twenty DOTs, including Texas, Louisiana and Arkansas, allow RAP of 30 percent or more in base courses and 10 percent or more in surface courses. In many other DOTs, the RAP is limited to 25 percent in the base course and none in the surface course (FHWA, 2009; ODOT, 2009 Jones (2008) found through a survey that stockpile management issues, binder issues, and mix issues are the leading barriers to increasing RAP percentages in asphalt mixes. Managing stockpiles is a challenging task due to unknown original quality, gradation control challenges, and processing requirements. Issues with binding substances consist of bumping binder grades, unknown properties of final blends, and compaction problems. There are unknown performance and durability characteristics of mix materials, additional testing requirements, variability of RAP mixes, and concerns about early failure of mixes. Therefore, the performance of asphalt mixes containing RAP needs to be extensively investigated in the laboratory and in the field.

Recycled Asphalt Shingles (RAS)

The use of RAS in HMA is both economically and environmentally beneficial. By incorporating RAS in HMA, the need for virgin materials, such as asphalt and aggregates, will be reduced (FVD, 2006; Sengoz and Topal, 2005; Foo et al., 1999). In RAS, a source of fine aggregate is found in an amount from 19 to 36 percent, whereas asphalt binder is found in an amount from 20 to 38 percent (CIWMB, 2007; NAHB, 1998). As far as the environment is concerned, RAS will reduce landfill usage and virgin material consumption (Sengoz and Topal, 2005 As per the results of a survey conducted by NAPA (2011), between 2009 and 2010, manufacturers' waste and tear-offs went from 702,000 to 1.1 million tons, an increase of 57 percent. This would represent 234,000 tons of asphalt binder conservation (1.5 million barrels) if 20 percent of the binder was contributed by the shingles (NAPA, 2011).

In several studies, RAS has been shown to be technically feasible in HMA (Sengoz and Topal, 2005; Rajib et al., 2000; Foo et al., 1999; NAHB, 1998; Ali et al., 1995; Button et al., 1995; Grzybowski, 1993). The use of RAS in HMA has also been shown to improve the mechanical properties of pavements, in addition to its economic and environmental benefits. Studies have shown that mixes containing RAS are more rutting resistant, fatigue-resistant, and perform better overall than conventional asphalt mixes, even when moisture is accounted for (Baaj, 2007; Ali et al., 1995; Grzybowksi, 1993). Due to its potential benefits, RAS is expected to become a significant part of recycling in the asphalt industry.

Although reclaimed asphalt and reclaimed aggregate content are reported to improve rutting performance of pavements, contradictory findings have been reported regarding fatigue life and thermal cracking of mixes with reclaimed asphalt and reclaimed aggregate (Huang et al., 2004; McDaniel and Shah, 2003; McDaniel et al., 2000). In this respect, there is a need to investigate the effects of using RAS on dynamic modulus, fatigue life, and thermal cracking of mixes containing local aggregates.

2.11 Desirable Properties of Asphalt Mixes

Mix design seeks to achieve a set of properties in the final HMA product. These properties are related to some or all variables which include asphalt binder content, asphalt binder characteristics, degree of compaction and aggregate characteristics such as gradation, texture, shape, and chemical composition. While the individual properties of HMA components are important, asphalt mixture behavior is best explained by considering asphalt cement and mineral aggregate acting together. The HMA must be internally strong and resilient to resist the compressive stresses and prevent permanent deformation within the mixture. In the same manner, the material must also have enough tensile strength to withstand the tensile stresses at the base of the asphalt layer, and also be resilient to withstand many load applications without fatigue cracking. The asphalt mixture must also resist the stresses imparted by rapidly decreasing temperatures and extremely cold temperatures.

Some of the desirable properties of asphalt mixes are listed below with brief description of each (Wayne et al., 2006):

i. Resistance to permanent deformation: The mix should not distort or be displaced when subjected to traffic loads especially at high temperatures and long times of loading.
ii. Durability: The mix must be capable to resist weathering effects (both air and water) and abrasive action of traffic. Asphalt mix should contain sufficient asphalt cement to ensure an adequate film thickness around the aggregate particles.

iii. Fatigue resistance: The mix should not crack when subjected to repeated loads over a period.
iv. Skid resistance: The mix must have sufficient resistance to skidding, particularly under wet weather conditions. Aggregate properties such as texture, shape, size, are all factors related to skid resistance.
v. Workability: The mix must be capable of being placed and compacted to specific density with reasonable effort.
vi. Moisture damage resistance: HMA should not degrade substantially by losing adhesion between aggregate and asphalt due to moisture penetration into the mix.
vii. Low noise and good drainage properties: This property is important for the wearing layer of the pavement structure.
viii. Resistance to low temperature cracking. This mix property is important in cold regions.

2.12 Limitations in Flexible Pavement Industry

The high summer temperatures soften the asphalt binder, thereby reducing the stiffness of the paving mixture. Due to the low temperatures in winter, the asphalt binder becomes stiff and the paving mixture becomes less flexible. As a result, in summer pavement rutting and in winter thermal cracking of the pavement surface may develop and adversely affect the performance of the paving mixture, resulting in frequent and costly repairs. As a result, there can be rutting in summer and thermal cracking in winter, resulting in more frequent and expensive repair work.

2.13 Flexible Pavement Mix Design

HMA mix design involves determining how much aggregate, asphalt binder, and what blend of the two should be used. A laboratory simulation is used during mix design. To the extent possible, it attempts to simulate actual HMA manufacturing, construction, and performance. Using this simulation, the type of mix design that would be best for the particular application can be determined (with reasonable certainty).

2.13.1 Hveem Mix Design

Francis Hveem developed the basic concept of the Hveem mix design method during his time as a Resident Engineer for the California Division of Highways in the late 1920s and 1930s. At present, several western states are using the Hveem method. The following three points represent the basic philosophy behind the Hveem method (Vallerga and Lovering, 1985):

i. An adequate asphalt binder is needed to coat each aggregate particle to an optimum film thickness (allowing for the asphalt to penetrate the aggregate).
ii. It must be stable enough to resist traffic loads. The stability of the aggregate is achieved through friction between individual particles and cohesion (or tensile strength) provided by the binder.
iii. The durability of HMA increases with a thicker asphalt binder film.

This philosophy dictates that the design asphalt content be selected based on the most durable asphalt content which does not fall below a minimum level of stability. Therefore, the minimum stability requirements should be met while using the maximum amount of asphalt binder.

Hveem mix design is mainly conducted according to AASHTO T 246 and AASHTO T 247. The Hveem mix design method consists of 6 basic steps: Aggregate selection, Asphalt binder selection, Sample preparation and compaction with California Kneading compactor (Figure 2.22), Stability determination using the Hveem Stabilometer (Figure 2.22), Density and voids calculations, Optimum asphalt binder content selection.

Figure 2.22 California Kneading Compactor (left) and Hveem Stabilometer (right)

2.13.2 Marshall Mix Design

Marshall mix design methods were created by Bruce Marshall of the Mississippi Highway Department in 1939 and then refined by the U.S. Army. Approximately 38 states use the Marshall method in some capacity. By using the Marshall method, a suitable asphalt binder content is selected at a density that meets a minimum amount of stability and a range of flow values (White, 1985). Even with its shortcomings, the Marshall method is probably the most widely used mix design method in the world today. It has probably become so widely used because

i. Instead of stressing a portion of the sample, the entire sample was stressed.
ii. Minimal effort was required for rapid testing.
iii. It was compact, lightweight and portable.
iv. It produced densities that are similar to those found in the field.

Marshall mix design procedure is conducted according to AASHTO T 245. The Marshall mix design method consists of 6 basic steps: Aggregate selection, Asphalt binder selection, Sample preparation and compaction with Marshall hammer, Stability determination using the Marshall Stability testing apparatus (Figure 2.23), Density and voids calculations, Optimum asphalt binder content selection.

Figure 2.23 Marshall Stability apparatus

Using the Marshall stability and flow test, the Marshall mix design method can predict performance. As part of the stability test, the test specimen is loaded at a rate of 50.8 mm per minute (2 inches per minute), to measure the maximum load it can support. This is accomplished by increasing the load until it reaches a maximum, then stopping the loading just as the load begins to decrease to record the maximum load.

The dial gauge connected to the loading device measures the plastic flow caused by the loading. At the same time that the maximum load is recorded, the flow value is recorded in 0.25 mm increments.

2.13.3 Superpave Mix Design

As part of the Strategic Highway Research Program (SHRP), a new method of mix design that accounts for traffic load and environmental conditions was developed, along with new methods for evaluating asphalt binder quality. As part of SHRP, these three developments were called theSuperior Performing Asphalt Pavement System (Superpave). As a replacement for Hveem and Marshall, the Superpave mix design method has been developed. Volumetric analysis is the basis for the Superpave mix design method, which is similar to both Hveem and Marshall methods. A Superpave mix design takes traffic and climate into account as well as asphalt binder and aggregate selection. Unlike the Hveem and Marshall procedures, the compaction devices from the mix design use a gyratory compactor, whose compaction effort varies with expected traffic.

The Superpave mix design method consists of 6 basic steps: Aggregate selection, Asphalt binder selection, Sample preparation and compaction with Superpave Gyratory compactor, Density and voids calculations, Optimum asphalt binder content selection and Moisture susceptibility evaluation.

Aggregate Selection:

Several key HMA parameters are affected by aggregate gradation, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage (Roberts et al., 1996). Furthermore, the maximum aggregate size is important when determining compaction and lift thickness. During the aggregate gradation design of superpave mixes, control points are specified through which aggregates must pass. The aggregate specification for Superpave hot-mix asphalt (HMA) mixtures includes a restricted zone that lies along the maximum density gradation between the intermediate size (i.e., either 4.75 or 2.36 mm, depending on the nominal maximum size of the aggregate) and the 0.3-mm size (NCHRP Report). It was recommended that gradations not pass through the restricted zone (Figure 2.5). Superpave adopted the restricted zone requirement in an effort to reduce the incidence of tender or rut prone HMA mixes.

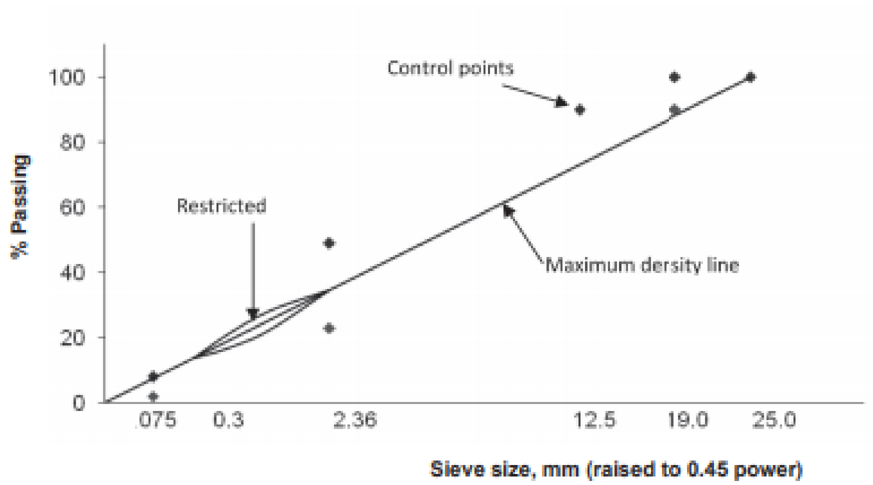


Figure 2.24 Superpave specified gradation for 19.0 mm nominal size (Mampearachchi and Fernando, 2012)

Asphalt Binder Selection:

In contrast to the older system of viscosity-graded binders, which are typically used for surface treatments and aggregate precoating, the Superpave binder specifications are performance-based, hence they are called performance-graded (PG) binders. In the PG binder system, engineering properties believed to be related to the expected performance are measured at temperatures corresponding to the climatic and traffic conditions (maximum 7-day pavement temperature, minimum pavement temperature, loading duration based on truck speed, and traffic volume) of the pavement location. Hence, a binder grade suitable for a particular highway application may be selected. Binder grades are determined by climate parameters.

While selecting a PG binder, a specific binder grade shall meet all the requirements for that grade and all lesser-performing grades. This means a PG 64-22 meets the requirements for PG 58-22, PG 58-16, and PG 64-16. These grades, usually in their manufacture, will not have much of any price difference between them. Therefore, in the multiple layers, a PG 76-22 might be used for the surface and a PG 64-22 for all underlying layers to meet design and economic considerations without requiring too many grades for the contractor to store. For a single-layer project, if the climate showed the necessity of PG 64-16, a PG 64-22 may be specified (theoretically a better performing grade) and expect little to no added binder cost. The properties of the PG binder are tabulated in Table 2-2.

Table 2-2 Properties of PG Binders

	PG 46	PG52	PG 58	PG 64	PG 70	PG 76	PG 82
Grade range	**−34 to −46**	**−10 to −46**	**−16 to −40**	**−10 to −40**	**−10 to −40**	**−10 to −34**	**−10 to −34**
Average 7-day maximum pavement design temperature (°C)	< 46	< 52	< 58	< 64	< 70	< 76	< 82
Minimum pavement design temperature (°C)	>−34 to >−46	>−10 to >−46	>−16 to >−40	>−10 to >−40	>−10 to >−40	>−10 to >−34	>−10 to >−34
		Original binder					
Flash-point temperature, D92; min. (°C)	230						
Viscosity, D 4402: max. 3 Pa × s, test temperature (°C)	135						
Dynamic shear, D7175: G*/sinδ, min. 1.00 kPa; 25 mm plate, 1 mm gap; test temperature at 10 rad/s (°C)	46	52	58	64	70	76	82

Superpave Gyratory Compaction:

The standard gyratory compactor sample preparation procedure is AASHTO TP4. The Superpave gyratory compactor (Figure 2.25) establishes three different gyration numbers:

i. $N_{initial}$: A measure of the compactability of a mixture during construction is the number of gyrations. Mixes that compact too quickly (air voids at $N_{initial}$ are too low) may be tender during construction and unstable when subjected to traffic. An HMA with excess natural sand will often fail the $N_{initial}$ criteria - it is a good indicator of aggregate quality. A mixture designed for greater than or equal to 3 million ESALs with 4 percent air voids at N_{design} should have at least 11 percent air voids at $N_{initial}$.

ii. N_{design}: The design number of gyrations is the number of gyrations required to produce a density that is similar to that of the actual test field after the indicated amount of traffic. When designing the mix, it is desirable to have an air void content of 4 percent at N_{design}.

iii. N_{max}: It should never be exceeded in the field the number of gyrations required to produce a laboratory density. If the air voids at N_{max} are too low, then the field mixture may compact too much under traffic resulting in excessively low air voids and potential rutting. N_{max} should never have a void content below 2 percent.

Typically, samples are compacted to N_{design} in order to determine the optimum asphalt binder content followed by compacting additional samples to N_{max} as a check. Previously, samples were compacted to N_{max} and then $N_{initial}$ and N_{design} were back calculated.

Figure 2.25 Superpave gyratory compactor

Density and Voids Analysis:

All mix design methods use density and voids to determine basic HMA physical characteristics. Two different measures of densities are typically taken:

i. Bulk specific gravity (G_{mb}).
ii. Theoretical maximum specific gravity (TMD, G_{mm}).

These densities are then used to calculate the volumetric parameters of the HMA. Measured void expressions are usually Air voids (V_a), sometimes expressed as voids in the total mix (VTM), Voids in the mineral aggregate (VMA) and Voids filled with asphalt (VFA).

2.14 Distresses of Asphalt Pavements

Properly designed and maintained HMA pavements can provide many years of satisfactory service. However, like all pavements, HMA pavements can be damaged by certain conditions. The primary asphalt distress types that engineer try to avoid are discussed below.

2.14.1 Permanent Deformation/Rutting

Surface depression or permanent deformation is the distress that is characterized by a surface cross-section that is no longer in its design position. Ruts are particularly evident when they are filled with water. It is called permanent deformation because it represents an accumulation of small amounts of deformation that occurs each time a load is applied. Rutting is basically caused by consolidation or lateral movement of the materials due to the traffic loading. Insufficient compaction of HMA layer can cause rutting. If it is not compacted during the construction, HMA pavements may continue to densify under traffic load. Improper mix design or a weak mixture of asphalt will accumulate small but permanent deformations with each truck pass, eventually forming a rut characterized by downward and lateral movement of the mixture (Figure 2.27).

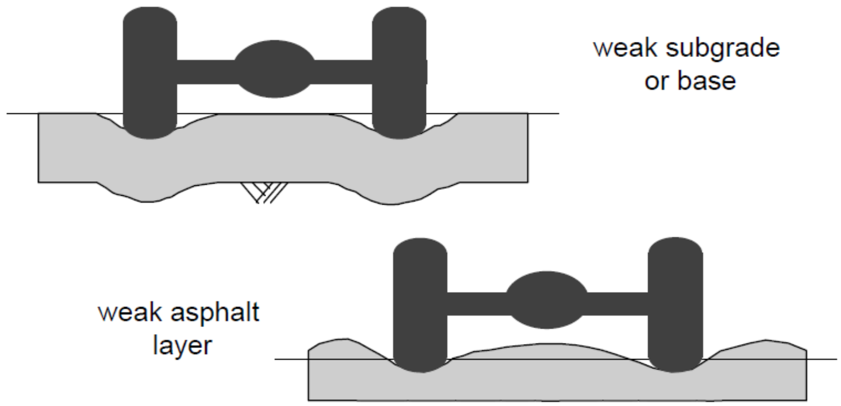


Figure 2.26 Rutting mechanism (FHWA manual)

Figure 2.27 Rutting of pavement (Sarah et al 2017)

2.14.2 Fatigue Cracking

Fatigue cracking occurs when the applied loads overstress the asphalt materials, causing cracks to form. An early sign of fatigue cracking consists of intermittent longitudinal cracks in the traffic wheel path. Fatigue cracking is progressive because at some point the initial cracks will join, causing even more cracks to form. An advanced stage of fatigue cracking is called alligator cracking, characterized by transverse cracks joining the longitudinal cracks (Figure 2.28). In extreme cases, a pothole forms when pavement pieces become dislodged by traffic. Fatigue cracking is usually caused by several factors occurring simultaneously. Obviously, repeated heavy loads must be present. Thin pavements or those with weak underlying layers are prone to high deflections under heavy wheel loads. High deflections increase the horizontal tensile stresses at the bottom of the asphalt layer, leading to fatigue cracking. Poor drainage, poor construction or an under designed pavement can contribute to this problem.

Figure 2.28 Fatigue cracking of asphalt pavement

2.14.3 Low Temperature Cracking

Low temperature cracking is caused by adverse environmental conditions rather than by applied traffic loads. It is characterized by intermittent transverse cracks that occur at a surprisingly consistent spacing (Figure 2.29). Low temperature cracks form when an asphalt pavement layer shrinks in cold weather. As the pavement shrinks, tensile stresses build within the layer. At some point along the pavement, the tensile stress exceeds the tensile strength, and the asphalt layer cracks. Low temperature cracks occur primarily from a single cycle of low temperature but can develop from repeated low temperature cycles. The asphalt binder plays the key role in low temperature cracking. In general, hard asphalt binders are more prone to low temperature cracking than soft asphalt binders. Asphalt binders that are excessively aged, because they are unduly prone to oxidation and/or contained in a mixture constructed with too many air voids, are more prone to low temperature cracking. Thus, to overcome low temperature cracking engineers must use a soft binder that is not overly prone to aging, and control in-place air void content and pavement density so that the binder does not become excessively oxidized.

Figure 2.29 Low Temperature Cracking (Ahmad and Khawaja, 2018)

2.14.4 Moisture Damage

Moisture damage or sensitivity is commonly referred to as stripping. This phenomenon is recognized as asphalt stripping from the aggregate surface. Stripping occurs when the adhesive bond between the aggregate surface and asphalt cement is broken (Fromm, 1974). Due to water, bitumen strips off from the aggregate forming pothole on roads as being water repellent material (Figure 2.30). Moisture damage also weakens the asphalt matrix such that there is lower stability and load carrying capacity. The mechanistic result of moisture damage is a loss in adhesive and cohesive strength. Moisture damage from the loss of adhesive and cohesive properties in HMA will lead to shoving, rutting, and fatigue cracking of asphalt pavement (Ping and Kennedy, 1991).

Figure 2.30 Moisture damage

2.15 Maintenance and Rehabilitation Practices for Asphalt Pavements

Depending on its type, time of application, and quality of maintenance, a pavement's performance can be affected. The deterioration of pavements caused by traffic and environmental factors can be slowed with preventive & timely maintenance. When maintenance is delayed or deferred, the number of defects and the severity of those defects increase, which increases the cost of correcting or repairing them. Deferring maintenance and rehabilitation actions increases the life cycle costs of pavements by shortening the interval between overlays and reconstruction. In order to choose the appropriate maintenance treatments and repair strategies, it is crucial to identify pavement defects and determine their causes. To select the right time for maintenance, it is also important to recognize that different pavements degrade at different rates.

It is important to consider traffic loads, weather, materials, thickness, construction quality, and previous maintenance effectiveness when determining pavement deterioration rates. As materials age and become more used, deterioration rates increase.

Maintenance activities are generally categorized into two types: preventive maintenance and corrective maintenance.

2.15.1 Preventive Maintenance

Preventive maintenance involves activities that protect and improve the quality of the pavement with the aim of decreasing the rate of deterioration. Surface seals and crack sealing are considered under preventive maintenance. Surface seals are those maintenance activities consisting of applications of asphalt alone or asphalt and aggregates which are applied to a pavement surface. These surface seals are most often applied to :

i. ensure that asphalt at the surface is rejuvenated or retarded from oxidizing.
ii. ensure the surface's skid resistance restoration.
iii. ensure that fine cracks at the surface are sealed.
iv. to seal the cracks to prevent water percolation which penetrates through the HMA layer.
v. retard the raveling of aggregates from a weathered, disintegrating surface.

The most common types of seals applied to HMA surfaces are:

i. fog seals,
ii. rejuvenators,
iii. chip seals or surface treatments, and
iv. slurry seals

2.15.2 Corrective Maintenance

The category of activities which is performed in order to correct a specific pavement failure or distress area is called corrective maintenance. Corrective maintenance generally consists of patches, chip seals, and thin HMA overlays.

Some maintenance methods serve both functions of preventive as well as corrective maintenance. The above (Table 2-3) lists some of the most common maintenance methods, distresses which are repaired by each method, and typical life expectancies for each maintenance method.

Table 2-3 Maintenance and Rehabilitation practices for asphalt pavement distresses (Source: Hot Mix Asphalt Materials, Mixture Design, and construction, Third Edition)

Distress	Maintenance/Rehabilitation Methods
Alligator Cracking	Full-Depth Spot Repairs Overlay Recycle
Bleeding	Apply Hot Sand Chip Seal with less binder
Block Cracking	Slurry Seal Chip Seal Overlay Recycle Seal Cracks
Depressions	Level-Up Overlay
Polished Aggregate	Chip Seal Slurry Seal Open-Graded Overlay
Potholes	Full-Depth Repairs Patch Recycle
Ravelling and Weathering	Chip Seal Slurry Seal Fog Seal Sand Seal Stress Absorbing Membrane
Rutting	Overlay Cold Mill Hot Recycle
Swell	Removal and Replace

2.15.3 Rehabilitation

The rate of deterioration of pavements increases with use (traffic loads) and age (weathering). Although preventive and corrective maintenance helps in prolonging their useful life, pavements need to be rehabilitated sooner or later. Quite often, more traffic than estimated warrants the rehabilitation to be conducted sooner than anticipated. (Table 2-4) gives the various rehabilitation techniques used by the highway agencies, depending on the distress types). Hot surface recycling, thin overlays, open-graded friction courses, milling, structural recycling, structural overlays, crack relief layers or treatments, are some rehabilitation alternatives.

Table 2-4 Rehabilitation techniques for asphalt pavement distresses (Source: Hot Mix Asphalt Materials, Mixture Design, and construction, Third Edition)

Distress Type	Possible Cause				Rehabilitation					
	Structural Failure	Mix Composition	Temp. or Moisture Changes	Construction	Surface Recycling	Thin Overlay	Open-Graded Surface	Structural Overlay	Structural Recycling	Reconstruction[1]
1. Alligator or Fatigue Cracking	X							X	X	X
2. Bleeding		X		X	X		X			
3. Block Cracking		X	X		X			X	X	
4. Corrugation	X	X		X	X	X[3]		X	X	X
5. Depression	X			X					X	X
6. Joint Reflection Cracking from PCC Slab			X					X	X	
7. Lane/Shoulder Dropoff or Heave	X		X	X						
8. Lane/Shoulder Separation	X		X	X						
9. Longitudinal and Transverse Cracking					X			X	X	
10. Patch Deterioration	X	X	X	X						
11. Polished Aggregate		X	X		X	X	X			
12. Potholes	X		X	X				X		
13. Pumping and Water Bleeding	X		X	X						X
14. Ravelling and Weathering		X		X	X	X				
15. Rutting	X	X		X	X	X[2]		X	X	X
16. Slippage Cracking				X						
17. Swell			X						X	X

2.16 Modified Asphalt Mix

Recently, many investigations have demonstrated that bitumen properties (e.g., viscoelasticity and temperature susceptibility) can be improved using an additive or a chemical reaction modification. The use of polymer modified bitumen's (PMBs) to achieve better asphalt pavement performance has been observed for a long time. The improved functional properties include permanent deformation, fatigue, and low temperature cracking. The properties of PMBs are dependent on the polymer characteristics and content and bitumen nature, as well as the blending process. Despite the large number of polymeric products, there are relatively few types which are suitable for bitumen modification. The polymers that are used for bitumen modification can be divided onto two broad categories, namely plastomers and elastomers. Elastomers have a characteristically high elastic response and therefore, resist permanent deformation by stretching and recovering their initial shape. Plastomers form a tough, rigid, three-dimensional network to resist deformation. (Louis P. Land, 2009) The thermoplastic rubber, styrene butadiene-styrene (SBS) is an example of an elastomer and the thermoplastic polymer, ethylene vinyl acetate (EVA), is an example of a plastomer. EVA polymers have been used in road construction for more than 20 years in order to improve both the workability of the asphalt during construction and its deformation resistance in service.

It has been also discovered that recycled plastics can be used in the construction of bituminous or asphalt roads. The polymer in plastics and the bitumen mixture can withstand high temperatures and can resist the action of water. The sound proofing properties of plastics causes the roads to reduce noise pollution and no toxic gasses are produced (Swami, 2012). This has been practically implemented in the roads of India and proved to be very efficient (DNA India, 2010). But there are many steps involved from the collection of waste plastics to finally using in the construction. The plastics should be recycled and prepared for usage in the mix designs. However, there is a need for proper regulations and resources to use these wastes into the construction process.

2.17 Background of Asphalt Mix Modified with Waste Products

Better service from paving materials is crucial today because of the increasing vehicle loads, heavier volume of traffic, and the need for longer-lasting roads. Some improvements have been made in asphalt properties by tailoring the refinery processes and/or selecting the best petroleum product, and one manufacturer modified the asphalt to enhance its properties. Studies have suggested that there are ways to make roads more durable. These alternatives mostly use industrial waste, which is difficult and expensive to manage. However, reusing them as a modifier of other structures can be a good measure of avoiding the waste problem (Asutosh and Nawari, 2017). For instance, ash, glass, scrap tire, plastic, etc. are used to make new innovations for road construction and rehabilitation.

2.17.1 Scrap-tire Rubber

The use of scrap tires in the construction of pavements has been established as an effective measure (David et al. 1992; Costa et al, 2013). Scrap tires are typically used in wet and dry processes where they act as a binder or replacement aggregate in asphalt mixtures, respectively (Moreno et al., 2012). The modification of an asphalt cement binder with 5 - 25% by weight of fine tire rubber crumb modifier (CRM) at an elevated temperature refers to the wet process (Cao, 2007). Souza and Weissman (1994) used 15% rubber content as a binder, which showed an improved performance in dynamic stability, flexural strength, and strain value. Studies have also been performed on modifying the properties of asphalt mixtures with recycled tire rubber, using the dry process, to minimize the pollution caused by waste tires and improve the properties of asphalt mixtures. Given the investigative consequences of the Marshall test, rutting test, and indirect tensile test, the inclusion of 3% (by weight of absolute mix) of tire rubber in asphalt blended by the dry process could enhance the protective properties and reduce pavement distortion and low temperature cracking (Cao, 2007).

2.17.2 Ash

Fly ash, bottom ash, pond ash, and magnetherm slag are common industrial wastes that are being used in building and road construction and have gained increased acceptance over a period of many years. Some countries like India have already devised guidelines for using ash in the construction of pavement.

Ali et al. (1996) found that the addition of fly ash enhances the stripping resistance of the mix. Since large quantities of fly ash are produced from the direct combustion of the Jordanian oil shale, which is regarded as a hazardous material to the environment, Asi and Assad, 2005 conducted research to learn how to use it to modify asphalt. They found that because of the pozzolanic cementing properties, asphalt mixed with fly ash has superior properties and is more resistant to water damage. This improvement was proportional to the fly ash content. Moreover, the use of fly ash up to 4% in a dense-graded bitumen mix showed a reduction of 7.5% in the optimum bitumen content compared to the control mix (Mistry and Roy, 2016).

2.17.3 Waste Glass

Studies show that adding fine waste glass to fine aggregates could also produce promising results (Ismail, 2008). It was found that asphalt does not adhere to glass as well as it does to aggregates, which means that glass finer than what can pass through a 3/8 inch sieve can be used up to15% by volume of the total aggregate. A few additives, including hydrated lime, were introduced to reduce the adhesion problem, and the results were promising. To eliminate the adhesion problem for the glass and asphalt, many other anti-stripping agents were also uncovered. This led to the use of waste glass on low volume roads with the help of binders. Glass can be used in both flexible pavements and in rigid pavements, and can be a very efficient substitute in rigid pavements, where concrete is the main element of the roadway. The waste glass shows a lot of promise when used in concrete in numerous forms, including coarse aggregate and fine aggregate (Ahmed, 2011).

According to an experiment at the University of Baghdad, the 28-day compressive strength value of a concrete mix made of 20% waste glass fine aggregate had a value of 45.9 MPa, which represents an increase of 4.23% in the compressive strength, compared to the control mix. After 28 days, the pozzolanic effect of waste glass in concrete became more evident. When 20% of waste glass was used, it gave the maximum values of compressive and flexural strengths. Using finely ground waste glass rather than fine aggregate could produce promising results, assuming that the geometry is less heterogeneous (Ismail, 2008). The specific gravity values were found to be approximately 10% lower than the values of natural aggregate reported by Das (2007).

2.17.4 Waste/Recycled Plastic

The disposal of plastic in landfills is dangerous to the environment but using it in bituminous road construction would provide a way to eliminate that hazard by recycling. Numerous researchers are analyzing the ecological stability and functional capacity of recycled items in different construction scenarios, and there is no doubt that utilizing the plastic waste in flexible pavement construction would accelerate the removal of huge amounts of plastic from the landfills.

Since Professor Vasudevan's achievement, the process has been practically put to test in the streets of India and has been deemed very successful (DNA India, 2010). The Indian government developed 21,000 miles (33,000 kilometers) of streets, utilizing reused plastic in 2017; however, a large majority of them were built in countryside regions (Louise, 2019).

2.18 Plastic Road

The concept of Plastic Road was first devised in early 2000s by an Indian Professor, Dr. Rajagopalan Vasudevan when there were thoughts on banning plastic (Mitra, 2019). He began experimenting with this idea of disposing plastic safely and effectively. During one of his tests he found that plastic can act as a powerful binder, so he decided to do further tests upon this discovery (Jayaraman, 2015). Dr. Vasudevan eventually found that when plastic is combined with stone and bitumen it binds both materials together quickly since both plastic and tar are petroleum products.

This process proved to be very effective, as the plastic infused asphalt is much stronger than traditional pavement. Normally when plastic is exposed to heat and light it will break down and give off toxins, but because it is mixed with the bitumen its properties change and it no longer breaks down. This combination of materials improved the strength of the roads by making it more sustainable and flexible (Hassani et al., 2005).

Dr. Vasudevan’s discovery was finally put into action when he proceeded to build the Jambulingam Street in Chennai in 2002 as one of the world’s first plastic roads (Figure 2.31). The benefits became more apparent once he built this plastic road. After 16 years of use, despite having to withstand a major flood, several monsoons, many heat waves, and non-stop traffic, the street was found to have sustained very little damage, a very impressive feat. The average lifespan of plastic roads is found to be about 10 years, more than double that of a traditional road. This durability helps decrease both time and money spent on road maintenance throughout the years. Some of the additional benefits of building plastic roads are that every kilometer of plastic road uses about one ton of plastic waste, saving that much asphalt, and costs around 8% less than a traditional road.

At least 11 states of India including many cities like Madurai, Chennai, Jamshedpur, Kovilpatti, Kothamangalam, Salem, Wellington, Puducherry, Hindpur (Andhra Pradesh), Kolkata, Goa, Shimla, Thiruvananthapuram, Vadakara, Calicut, and Kochi has been adopted this idea to build more than 33,796 km of roads (World Economic Forum report). Other countries like Indonesia, Australia and UK are trying to adopt this.

Figure 2.31 Jambulingam Street, one of India’s first plastic roads (Mizikar et al, 2019)

2.19 Plastic Types Suitable for Plastic Road

Literature shows that polymer materials that can be used are low-density polyethylene, such as plastic bags, films, foams, high-density polyethylene, polypropylene, and polystyrene. It is impossible to mix PET particles with bitumen because of the high melting point of the PET particles (Modarres and Hamedi, 2014). Vasudevan et al. (2011) stated that polyvinyl chloride should not be used in order to prevent the possibility of chlorine in the system. Examples of different types of plastics usually used in asphalt mixtures and their benefits and drawbacks are given below:

Polyethylene: Previously conducted research on asphalt mixtures with high-density polyethylene (HDPE) and low-density polyethylene (LDPE) has proven that the stiffness modulus decreased, while the Marshall stability (Akinpelu et al., 2013) and indirect tensile strength (ITS) values increased (Ahmadinia et al., 2011; Yin and Wu, 2018; Zoorob and Suparma, 2000). There was also an improved conserved tensile strength ratio (TSR) and an increase in the fatigue resistance (Fazaeli et al., 2016; Lastra-González et al., 2016; Modarres and Hamedi, 2014), offering outstanding impact resistance; lightweight, low moisture absorption; and high tensile strength (Panda and Mazumder, 2002; Awwad and Shbeeb, 2012). Polypropylene (PP): PP has been used in asphalt pavement and offers good chemical and fatigue resistance. However, some disadvantages like oxidative degradation, high shrinkage, and thermal expansion have also been observed for pavements made of PP mixed asphalt. (Sultana and Prasad, 2012; Ali et al., 2017).

Polystyrene (PS): Problems associated with water percolation and drainage in asphalt surfaces can be rectified by using PS, and the resulting asphalt mixture will have more strength and resistance than the control sample (Motlagh et al., 2012). However, the unstable behavior of the polymer during the production of the mixtures proves that the results with PS are not as favorable, and its fatigue resistance and lifespan decrease in the process (Lastra- González et al., 2016).

2.20 Recycled Plastic Mixing Process

The shredded plastics on spraying over the hot aggregate get melted and spread over the aggregate giving a thin coating at the surface. When the aggregate temperature is around 140–160° C the coated plastics remains in the softened state. Over this, hot bitumen (160° C) is added. The added bitumen spreads over the aggregate. At this temperature both the coated plastics and bitumen are in the liquid state, capable of easy diffusion at the inter phase. This process is further helped by the increase in the contact area (increased surface area). These observations may be explained as follows. Waste polymers, namely PE, PP and PS are hydrocarbons with long chains. Bitumen is a complex mixture of asphaltenes and maltenes which are also long chain hydrocarbons. When bitumen was mixed with PCA a portion of bitumen diffuses through the plastic layer and binds with aggregate. The plastic layer has already bonded strongly with aggregate. During this process three-dimensional internal cross linked network structure results between polymer molecules and bitumen constitutes. Therefore, the bonding becomes stronger, and the removal of bonded bitumen becomes difficult. Islam (2021) and Singh (2022) have used the dry methods while figuring out the plastic road asphalt mix.

Hence, the results of the study done by Vasudevan et al (2011) showed that the bonding between stone aggregate and bitumen is improved due to the presence of polymers.

There are two significant processes by which asphalt mixtures can be changed: the wet process and the dry process (Gawande et al., 2012). If the polymer is first blended with bitumen and aggregate is added later, it is known as a wet process. However, if the polymer is covered with aggregate before the bitumen is added, it is known as a dry process (Shiva et al., 2012). The utilization of recycled plastics in asphalt blends is the most recent widely recognized approach to modifying bituminous mixtures to enhance thermal behavior. The wet process can be implemented for reusing any kind, size, and state of waste material, such as plastics, rubber, etc. (Huang et al., 2007). The polymers have good outcomes in all tests since the blends delivered are less vulnerable to temperature variations, fatigue cracking, and permanent deformation, which lead to an extended service life (Atta Elmanan et al., 2011; González et al., 2012; Kök and Çolak, 2011; Oliviero Rossi et al., 2015). This strategy has impediments, however, since the polymer must satisfy certain conditions to guarantee the production of a suitably modified binder while maintaining its engineering properties (Presti et al., 2014). Suitable polymers require specific treatment and blending forms (for example, high temperature and rapid shear blending) to improve the properties of the black-top folio and create stable blends with better mechanical attributes and toughness (Al-Adham and Al-Abdul Wahhab, 2018; Montanelli and srl, 2013).

In the wet process, a maximum of 8% of waste plastic by weight of bitumen can be incorporated (Gawande et al., 2012, Duggal et al., 2019). What's more, the use of such plastic blends is more complicated and difficult, and not all reused plastics have acceptable conduct during the incorporation process (Fernandes et al., 2017; Lastra-González et al., 2016). Hence a new innovative dry process that coated the aggregate with plastic was developed by Vasudevan et al. (2011), and a mixture of the plastic-coated aggregate and bitumen showed better binding properties and fewer voids.

In the dry process, plastics are mixed with the aggregate before they are mixed with the bitumen (Huang et al., 2007; Angelone et al., 2016), which makes a thin layer of plastic coating over the aggregate. As soon as the aggregate is blended with the bitumen, the performance of the asphalt blend is greatly enhanced (Lastra-González et al., 2016; Liang et al., 2017). The level of bonding between the plastics and the remainder of the materials relies upon the softening and melting temperature of the plastic. The time required for mixing and blending is also significant and can fluctuate from 2 to 15 minutes (Ahmadinia et al. 2012; Huang et al. 2007); the size of the polymer should also be considered. If the plastic particles are small, they can be easily dispersed into the asphalt blend, which permits the plastics to bond strongly to the aggregates and bitumen (Fakhri and Azami, 2017; Santagata et al., 2012). One of the most critical favorable circumstances of this procedure is that it does not expect any kind of adjustments to the asphalt blending plants. The utilization of more than 15% of waste plastic is conceivable by this process.

As a matter of fact, pavement base can also be introduced with different types of plastics in dry method, however, it does not require any melting (Shopnil et al., 2023). Tasnim (2022) has also utilized LDPE and HDPE in the above-mentioned process to find the compaction and moisture intrusion in the base layer of pavement.

2.20.1 Marshall Mix Design

Bindu and Beena (2010) used shredded waste plastic to stabilize a stone mastic asphalt (SMA) mixture in flexible pavement. They used waste plastic bottles, bags, wrappers, etc., with bitumen of 60/70 penetration grade. They conducted Marshall stability tests for the plastic-mixed asphalt concrete with 10% plastic content and found that it yielded an increased stability of about 64%.

Sangita et al. (2011) found that a mixture with 8% plastic content performed well. Figure 2.20 depicts that the Marshall quotient or stability of modified blends is higher than other conventional mixes. A 6% to 8% increase in the modifier content increases the stability of modified blends by about 50%, but expanding the modifier content from 6-8% to 12-15% reduces the stability of the modified mixes. That might occur because of the reduced adhesiveness of the mixture.

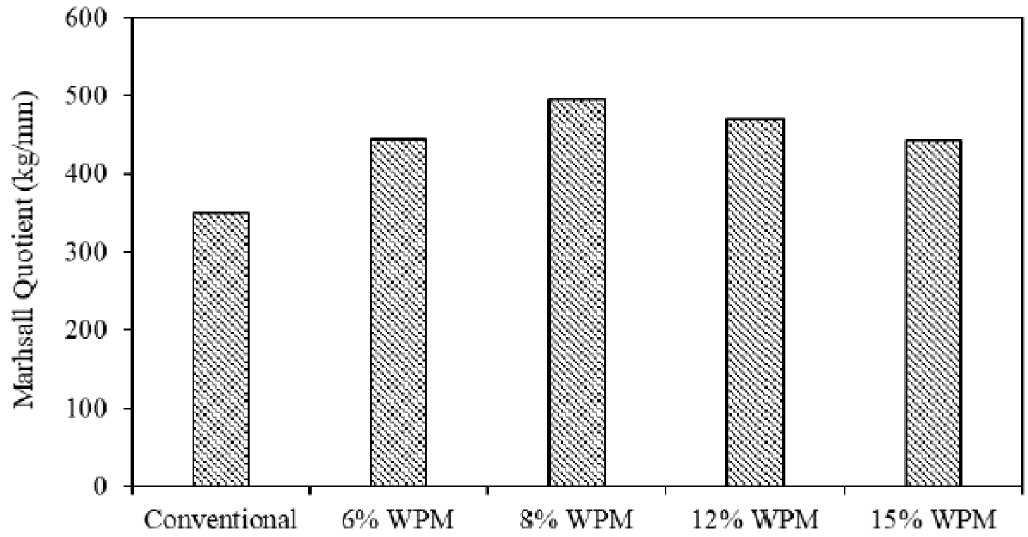


Figure 2.32 Marshall Quotient results (Redrawn from Sangita et al, 2011)

Akinpelu et al, 2013 conducted experiment in Nigeria where six proportions of polyethylene by weight of the optimum binder content were selected to be tested (2.5, 5.0, 7.5, 10, 12.5 and 15%). The obtained optimum proportion of the modifier is 12.5% by the weight of the optimum bitumen content. It is found to increase the stability, reduce the density, and slightly reduce the flow of asphalt concrete specimen. Findings from this study suggest that polythene modifier offers better engineering properties and its usage as bitumen modifier could serve as a means of managing the waste menace. Asare et al, 2019 found that asphaltic materials could compose of more than 10% plastic wastes to still give superior qualities to even exceed standard requirements and bring about economy in both plastic waste management and road construction in Ghana.

Mahabir and Mayajit (2002) used LDPE carry bags as a modifier for asphalt paving materials. The basic properties of modified binder and mixes containing such binders were studied and compared with those of asphalt cement 80/100 penetration grade bitumen. It was observed that the optimum requirement of PE is 2.5%. Hadidy and Yi-qiu (2008) indicated that flexible pavement with high performance, durability and more economic can be obtained with 6% pyrolysis LDPE. Napiah et al. (2014) presents a part of research conducted to investigate the deformation behavior of the well graded bituminous concrete mixture using dynamic creep test for the unmodified control mix and Polyethylene modified bituminous mix. The control mix was prepared with 80/100 Pen bitumen while polyethylene modified mix was prepared using low density polyethylene (LLDPE) as modifier, blended with 80/100 Pen bitumen. The concentration of polymer in the blend was kept at 1%, 2% and 3% by weight of bitumen content. Marshall specimens prepared at optimum bitumen content were used to investigate the creep stiffness of both modified and control mixes. It was found that 3% LLDPE modified bituminous mixes offer better results in comparison to control and 1% & 2% LLDPE modified mixed samples when they were investigated in terms of mixture stiffness obtained at 40°C by dynamic creep test. Results of the rut depth were also calculated, and it was observed in **Error! Reference source not found.**that for the rut depth corresponding to one million axle wheel loads, 3% LLDPE modified bituminous mixture shows lowest rut depth in comparison to unmodified, 1% and 2% LLDPE mix.

Rajput and Yadav (2016) conducted a study using shredded plastic waste (e.g., plastic bags, polyethene, etc.). Plastic-modified mix specimens with different percentages of plastic contents (6%, 8%, 10%, 12%, and 14%) by weight of bitumen content were prepared through a dry process in which plastic was added over the heated aggregates. The Marshall stability value increments drastically as the percentage of waste plastic in the mix was increased (Figure 2.33). The maximum stability was achieved in the mix that contained 12% plastic by weight of the bitumen (the optimum plastic content). The accumulation of plastic waste in the mix decreased the percentage of air voids continuously, and the VFB increased continuously as more plastic filled more voids. Hence, it can be concluded that the percentage of air voids decreases with the increase of plastic.

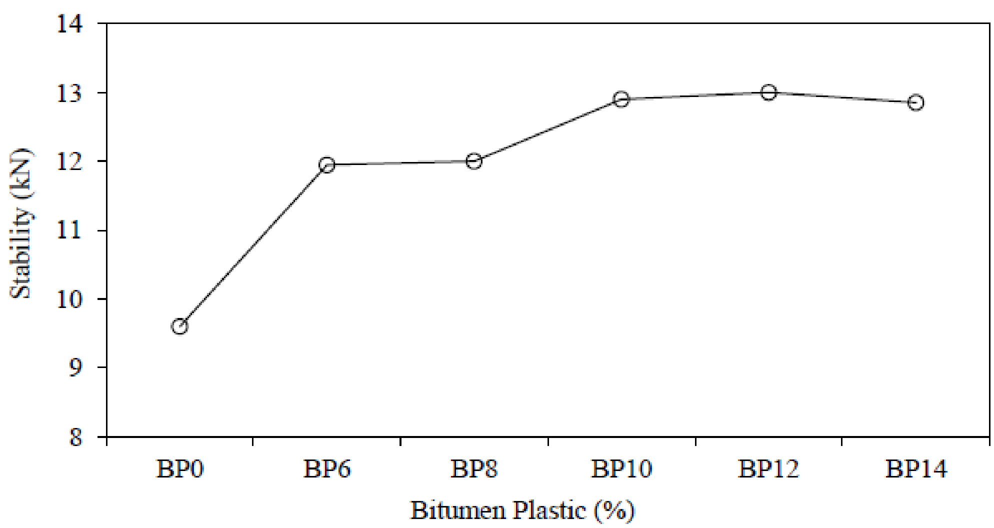


Figure 2.33 Marshall stability results (Redrawn from Rajput and Yadav, 2016)

Hınıslıoğlu and Ağar (2003) concluded that the specimens prepared with the 165 °C mixing temperature and 30 min mixing time for 4% HDPE with AC-20 bitumen have the highest stability and the smallest flow, and so the highest Marshall Quotient (Figure 2.34). A HDPE content of 5% by weight of asphalt is recommended for the improvement of the performance of asphalt concrete mixtures similar to that investigated in this study (Attaelmanan, 2011). Awwad and Shbeeb (2007) experimented by adding two types of polyethylene to modify bitumen in hot asphalt mix. The polymers they used were LDPE and HDPE. They used two different shapes of grinded polymers and non-grinded ones. The results indicated that grinded HDPE polyethylene modifier provides better engineering properties. The recommended proportion of the modifier is 12% by the weight of bitumen content. It is found to increase the stability, reduce the density and slightly increase the air voids and the voids of mineral aggregate.

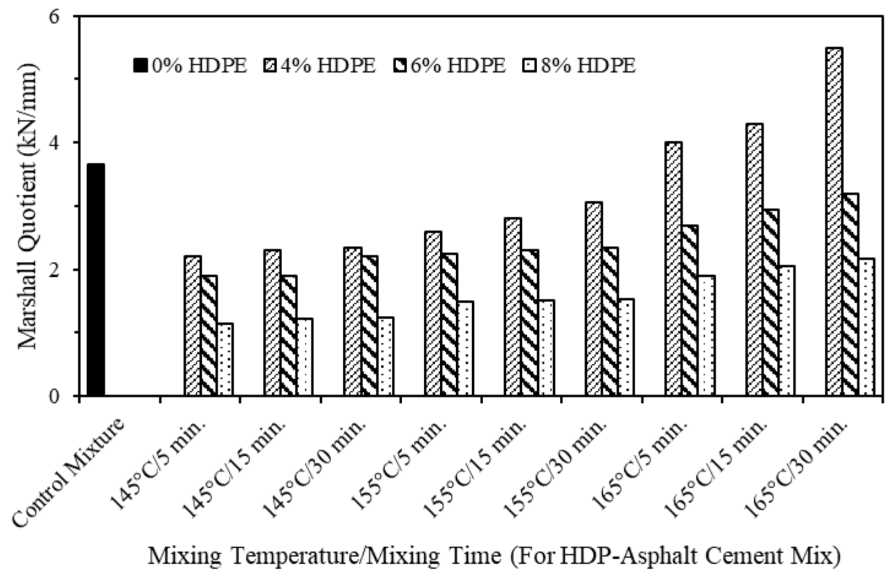


Figure 2.34 Mixing temperature/mixing time vs. Marshall Quotient (Redrawn from Hınıslıoğlu and Ağar, 2003)

Kofteci (2016) used HDPE-based waste materials as a modifier in the amount of 1%, 2%, 3%, and 4% to investigate the performance of an asphalt mixture. The performance of the specimen was first measured by the stability and flow value. The HDPE modifier did not affect the sample at low rates since stability values of 1% and 2% HDPE were very close to the control mix. The best performance was obtained with 4% HDPE content, with an increase of stability value from 960 kg to 1080 kg (Figure 2.35).

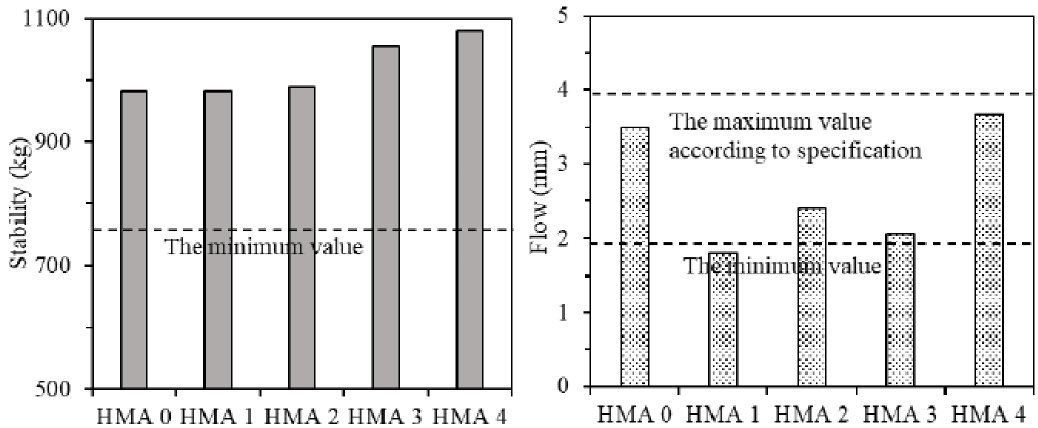


Figure 2.35 Marshall stability and flow results (Redrawn from Kofteci, 2016)

Awwad and Shbeeb (2007) conducted a study to determine the best type and proportion of polyethylene to use. HDPE and LDPE were added through the dry process to coat the agglomeration. The optimum asphalt content was 5.4%, and the polymers were introduced to the mixture in two states (ground and not ground). For the testing process, seven proportions of polyethylene (6, 8, 10, 12, 14, 16, and 18%) by weight of the optimum binder content were selected. The optimum modifier content was found to be 12%. Not all of the individual aggregates could be coated since some of them were not ground. Ground polyethylene was used to strengthen the asphalt mixture's engineering properties, as it provides a better coating for the aggregate and a rougher surface texture. It was concluded that ground HDPE polyethylene modifiers improve the engineering properties, and it was recommended that the modifier proportion be 12% by the weight of bitumen content (Figure 2.36). It was observed that the inclusion of HDPE could reduce the density and increase the stability of the air voids and the voids of the mineral aggregate by a smidgen.

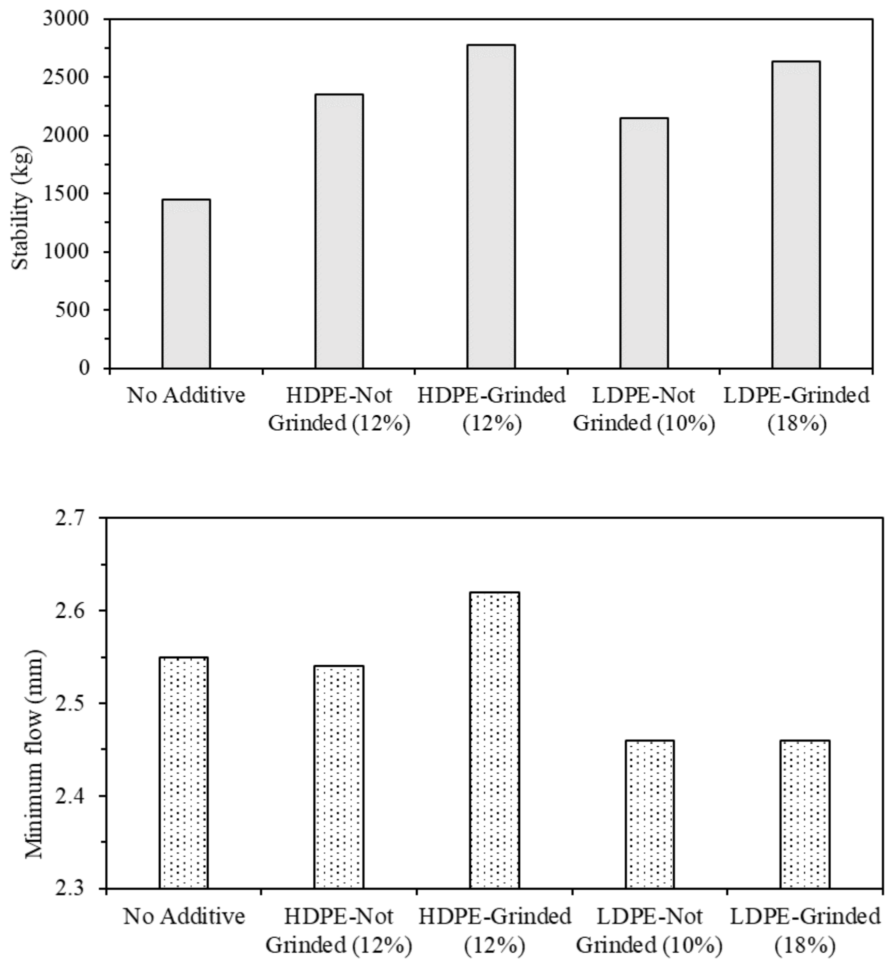


Figure 2.36 Marshall stability and flow results (Redrawn from Awwad and Shbeeb, 2007)

Hadidy and Yi-qui (2009) selected four proportions of pyrolysis polypropylene (PP) to continue their testing. Rheological and homogeneity tests were conducted on unmodified and modified asphalt binders, and the optimum asphalt content obtained from their study was 5.82%. As the stability value was 10.876 KN, 5% PP content by weight of asphalt was recommended to improve the performance of the asphalt concrete mixtures. The addition of PP helped to fill the voids between the particles as well as enhance the interlocking, consequently increasing stability and decreasing flow as the PP content stretched beyond 5% the flow increases and the stability decreases (Figure 2.37).

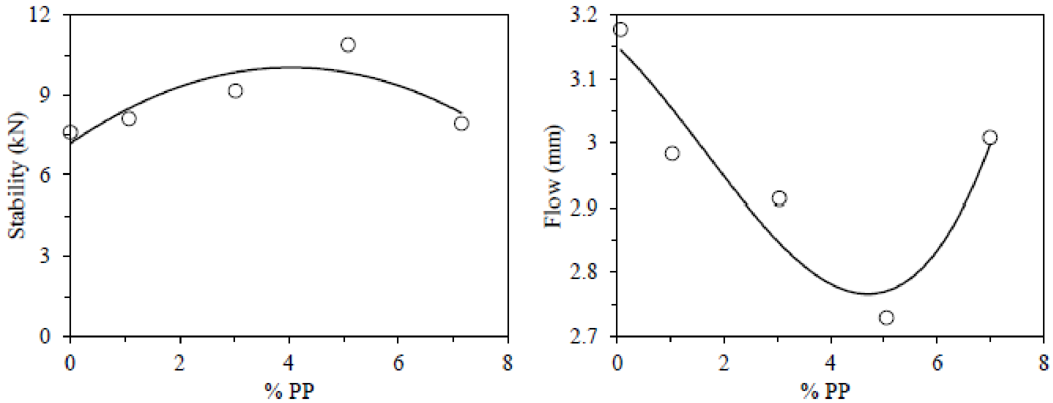


Figure 2.37 Marshall stability and flow Results (Redrawn from Hadidy and Yi-qui, 2009)

2.21 Performance of Waste Plastic Modifier

Vasudevan et al. (2011) stated that the polymer coated aggregate bitumen mix perform better for flexible pavements compared to the conventional bitumen. It improves the properties of bitumen resulting in increase in Softening Point and decrease in Penetration value thus improving the durability. Probably, the inter-molecular bonding between waste polymer coated aggregate and bitumen enhanced the strength and quality of the bituminous concrete mixes (Sabina et al, 2009).

Flynn, 1993 has reported that recycled polythene from grocery bags may be useful in bituminous pavements resulting in reduced permanent deformation in the form of rutting and reduced low-temperature cracking of the pavement surfacing. Similarly, the resistance to deformation of bituminous concrete modified with approximately 5% low density polythene was found significantly better than that of unmodified mixes (Little, 1993). According to A.V Tiwari et. al (2017) the addition of 6% LDPE and HDPE plastic waste improves the stability value of the bituminous mix which results is the increase in the toughness of the mix. The roads can withstand heavy traffic and shows better service life. Addition of plastic waste results in decrease in the air voids which reduces the bleeding of bitumen.

Agrawal H. S. and et.al (2017) studied the addition of 10% of plastic in bitumen improves the stability, strength, life and other desirable properties of bitumen. Utilization of waste plastic in the construction of pavement has shown better resistance to water which reduces the stripping of bitumen from aggregate and also made investigations over the use of waste plastic in road construction as an effective way to reutilize the plastic waste. According to various tests conducted, addition of plastic shows increases in compressive strength, tensile strength and stability value which is useful to sustain large load. Dr. Hamed M. Jassim et.al (2014) studied optimum use of plastic waste to enhance the marshall properties and moisture resistance of hot mix asphalt. According to Chukka and Carr (2016) the indirect tensile strength increases by 3 times to that of normal roads. The compressive strength will be very high. This process will cause less bleeding of road during the summer season.

When bitumen is added to plastic waste coated aggregate, a better adhesion formed between bitumen and plastic waste coated aggregate due to strong inter molecular bonding. These inter-molecular attractions enhanced strength of bitumen concrete mix, which in turn helped in enhancing durability and stability of mixes. Plastic-bitumen composite roads have better wear resistance than standard asphalt concrete roads. They do not absorb water, have better flexibility which results in less rutting and less need for repair. It is unaffected by corrosion and weather. The road structure can handle temperatures of -400F to temps as high as 1760F with no negative effects. As this road can handle excessive seasonal temperature variation, it causes less pavement distress. Thus, plastic waste modified bitumen concrete mixes are expected to be more durable, less susceptible to moisture and temperature in actual field conditions with improved performance (Sabina et al, 2009).

Different advantages of plastic road over conventional one and reasons behind this are briefly discussed in the next section.

2.21.1 Rutting

Use of waste plastic in asphalt mixtures increases the resistance against deformation compared to the regular reference mixture. Also, the plastic mixed asphalt can be used in roads associated with high and heavy volume of traffic as well as severe climatic conditions (Lastra- González et al., 2016). The Hamburg wheel tracking tests were conducted by Sangita et al. (2011), and it was found that the conventional bituminous concrete mixes performed poorly and were more susceptible (up to 6.44 mm) to rut deformation than the modified mix consisting of 8% waste polymer modifier, which performed a lot better and was less susceptible (3.68 mm) to rut deformation (Figure 2.38).

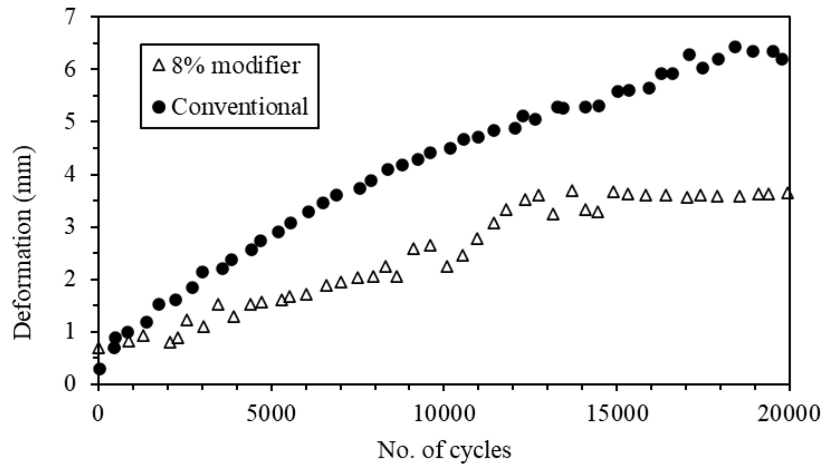


Figure 2.38 Hamburg wheel tracking test results (Sangita et al., 2011)

Napiah et al. (2014) performed research to investigate the deformation behavior of well-graded bitumen and calculate the rut depth. Figure 2.39 shows that the rut depth corresponding to one million axle wheel loads of unmodified, 1%, and 2% LLDPE mix is higher compared to the 3% LLDPE modified bituminous mix which offers the lowest rut depth.

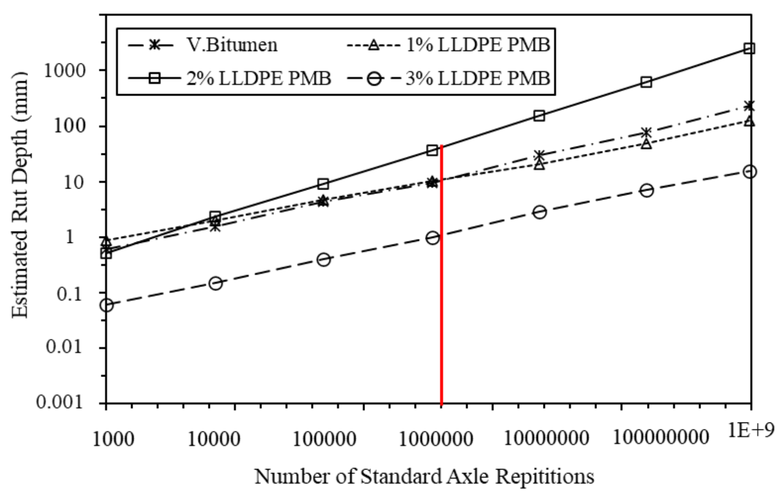


Figure 2.39 Rutting results (Redrawn from Napiah et al., 2014)

Islam (2021) proved by laboratory performance test that using LDPE at 8% can reduce the rut depth by 66%. However, too much reduction may make the plastic road rigid. Hence, 0.5% PP was introduced as a replacement for aggregate because PP is flaky material, and its low stiffness can make the mix more flexible. Using HDPE and PP, it was also possible to reduce the asphalt mixture's deformation significantly (Figure 2.40).

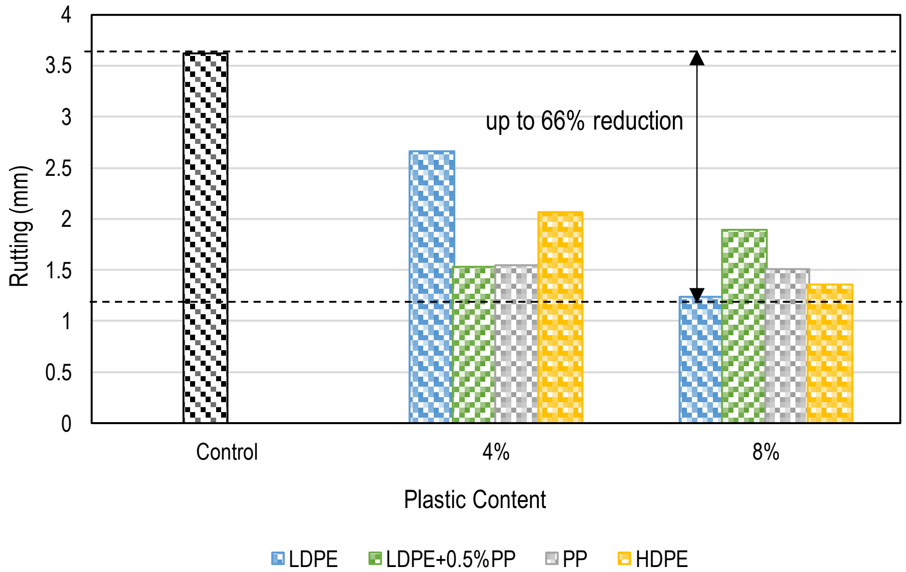


Figure 2.40 Reduction of rut depth for using plastics in the asphalt mix design (Redrawn from Islam (2021)

Figure 2.41 Condition of the samples after the HWTT (the left one is the control sample, and the right sample is a mixed plastic sample)

Figure 2.41 shows the outcome of the rutting test on the control sample (no plastic was mixed) and the Plastic mixed samples. It is evident from this picture that Plastic samples are performing significantly well under wheel passes in submerged conditions.

2.21.2 Tensile Strength

In Punith and Veeraragavan’s (2007) study, various percentages of PE (2.5, 5.0, 7.5, and 10% by weight of bitumen content) were mixed with 80/100 paving grade asphalt. LDPE plastic bags were added to the asphalt by the wet process. PE ratios greater than 10% posed problems, as blending them with the asphalt cement became difficult due to increased viscosity of the binder. They also conducted indirect tensile strength tests and found that the indirect tensile strength was 38 KN, while it was 29 KN with no PE content (Figure 2.42).

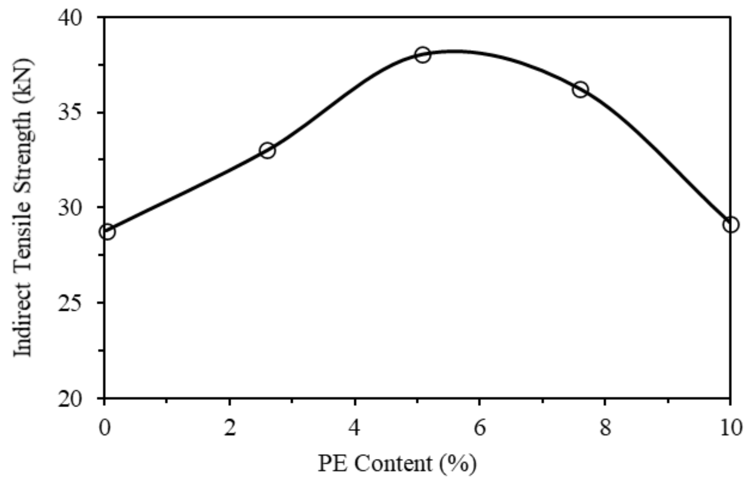


Figure 2.42 IDT results (Redrawn from Punith and Veeraragavan, 2007)

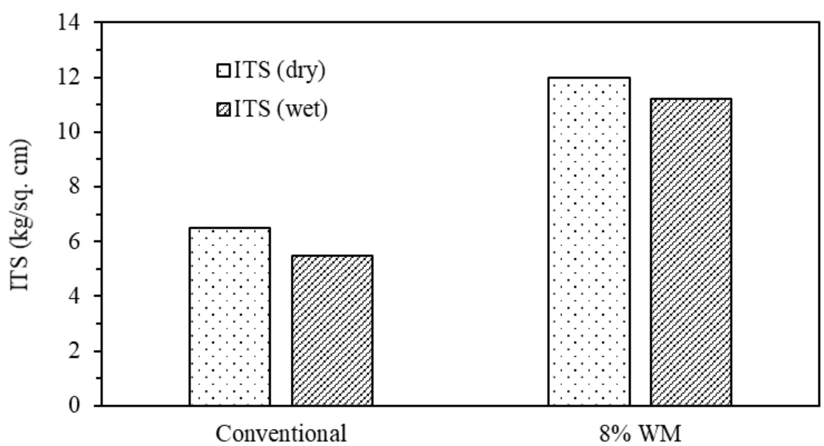


Figure 2.43 Indirect tensile strength result (Redrawn from Sangita et al., 2011)

Sangita et al (2011) showed that when the WPMB mix contained 8% WPM, its indirect tensile strength (ITS) results were higher (12 kg/sq.cm) than the conventional mix (6 kg/sq.cm), as shown in Figure 2.43. This shows that the WPMB mix can withstand high tensile strains before it reaches its cracking state.

Attaelman et al. (2011) used 0-7% HDPE with 80/100 penetration-grade bitumen. The mixtures that contained HDPE had a tensile strength ratio greater than 85%. The tensile strength increased up to a 5% addition of HDPE, then it began to decrease (Figure 2.28). The high stability made way for increased resistance against permanent deformation.

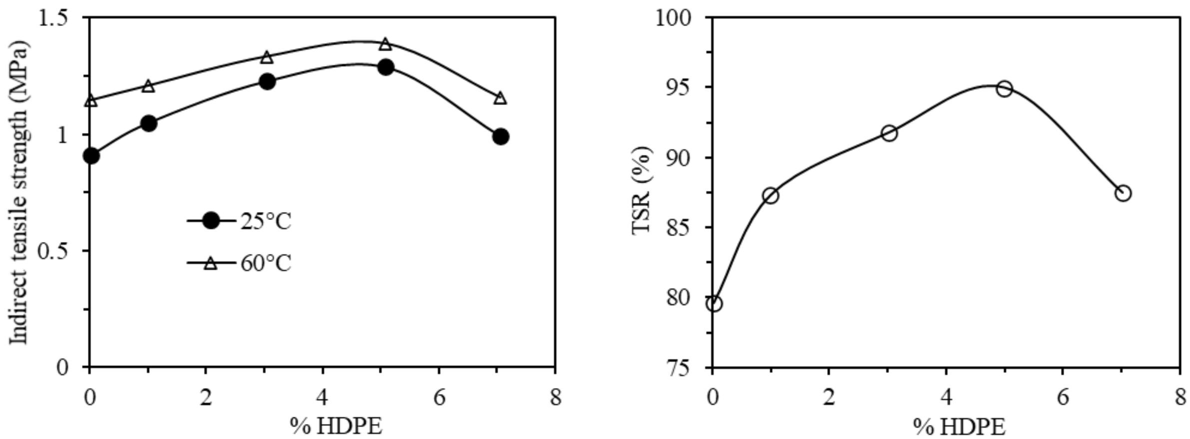


Figure 2.44 IDT and TSR results (Redrawn from Attaelman et al., 2011)

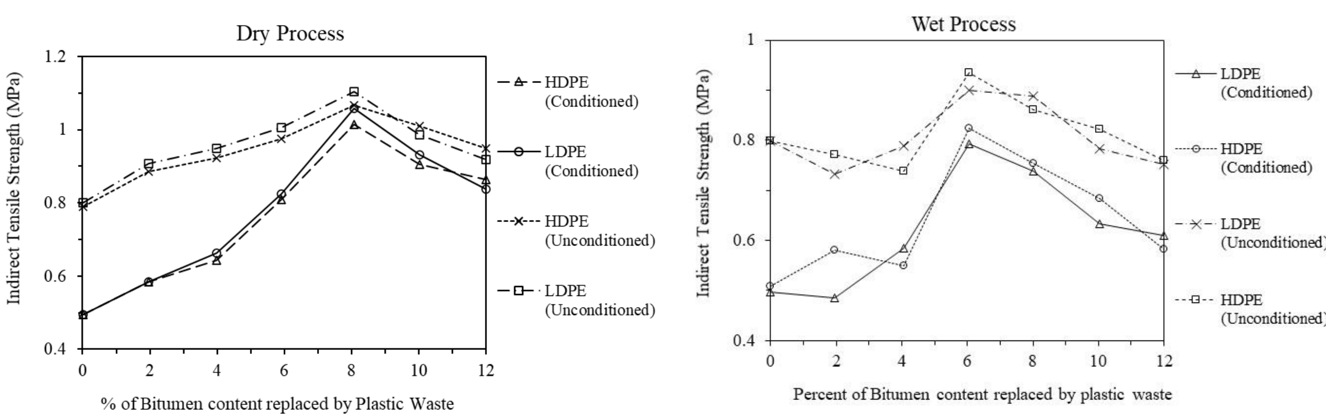


Figure 2.45 IDT test Results (Redrawn from Anurag and Rao, 2018)

Anurag and Rao (2018) used the dry and wet processes for their mixes with waste plastic for their experimentations. They conducted the indirect tensile strength test since a decent tensile strength indicates a better resistance to cracking and found that the indirect tensile strength (ITS)) of the sample increased up to 8% for the dry process and 6% for the wet process when using LDPE and HDPE types of waste plastic (Figure 2.45).

According to Pamungkas et al. (2018), PP has the highest tensile strength (6738 KPA) than other types of plastic mixtures like LDPE (1211 kPa) and PET (4703 kPa). In the ITS test, PP mix objects turned out to be 56.3% stronger than PET and 397% stronger than LDPE. PP mixed samples had higher tensile strength due to the nature of the PP plastic. It can change shape and become softer in heat conditions, the aggregate attachment becomes stronger, and the object becomes denser after compaction, resulting in higher tensile strength.

Islam (2021) showed that all plastic mixes have a tensile strength more significant than the control mix. Specifically, adding up to 8% of LDPE and PP increases the tensile strength of the mixture up to 77% and 58%, respectively. Furthermore, adding HDPE at 4% and 8% increases the strength by more than 25%. The rutting test showed promising results with 0.5% PP as aggregate replacement with LDPE in the mix; this combination was utilized to find the strength. Together by replacing bitumen and aggregate, LDPE and PP can increase the strength by up to 63% (Figure 2.46).

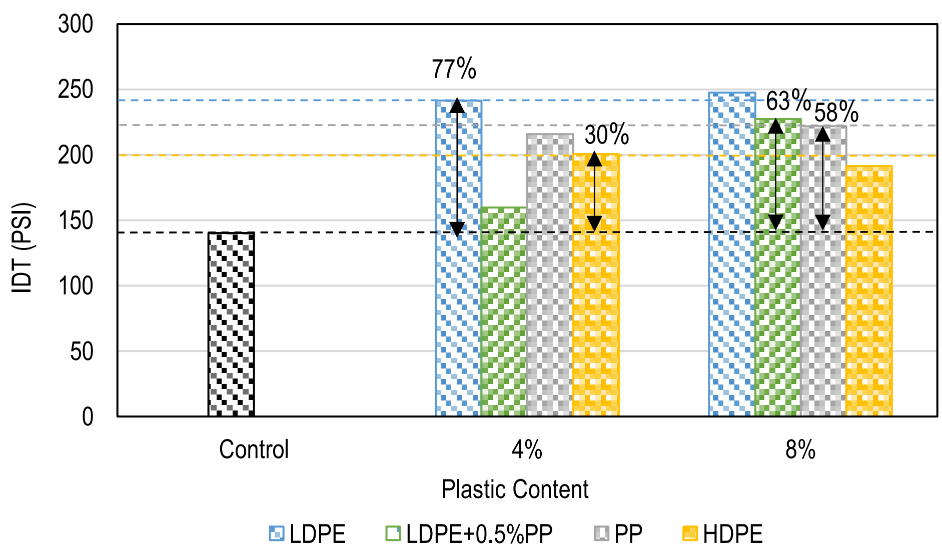


Figure 2.46 Indirect tensile strength test results with different combinations of Plastic (Redrawn from Islam (2021))

2.21.3 Compressive Strength

The relation of the compressive strength with the variations of the ratio of PP content was shown by Hadidy and Yi-qui (2009). It can be observed that at 5% PP content, the compressive strength (6 MPa) was the highest in this mix (Figure 2.47). The study revealed that the addition of 5% PP in asphalt increased the percentage of the compressive strength value, which was found to be 20.9% and 49.2% at 25 °C and 60 °C, respectively.

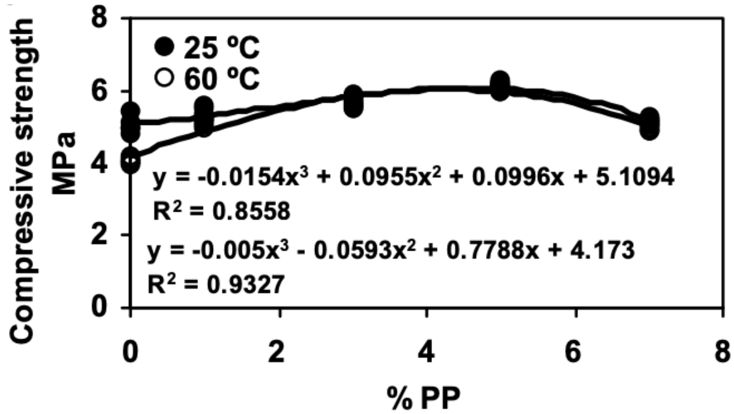


Figure 2.47 Compressive strength result (Hadidy and Yi-qui, 2009)

Pamungkas et al. (2018) investigated the effects of adding different types of plastic on the compressive strength of asphalt concrete. They concluded that the mixtures that contained PP had higher compressive strength (11840 KPa) than the other types of mixtures (Figure 2.48). When the UCS test was conducted, it showed that the PP mix sample was able to hold the vertical pressure of 253% and 399% stronger than PET and LDPE, respectively.

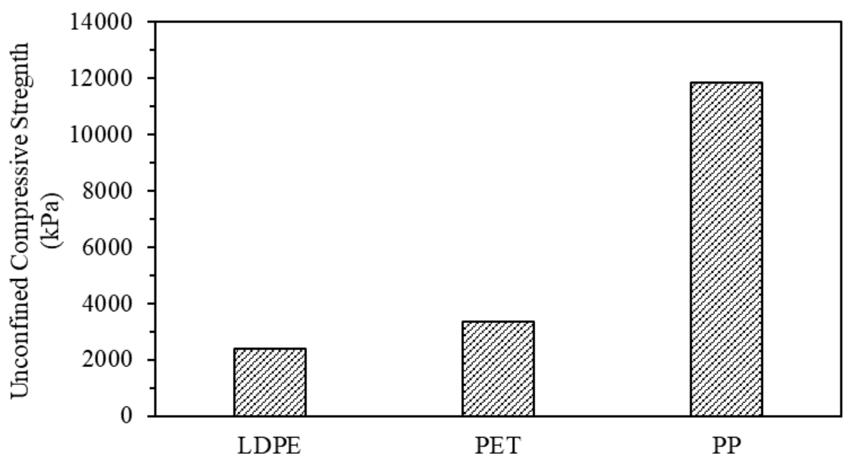


Figure 2.48 Compressive strength result (Pamungkas et al. 2018)

2.21.4 Resilient Modulus

Punith and Veeraragavan's investigation in 2007 showed that 5% of PE content by weight of asphalt improves the performance of asphalt concrete mixtures, as the resilient modulus value increased by 28.9% (from 2040 MPA to 2630 MPa) at 25°C (Figure 2.49).

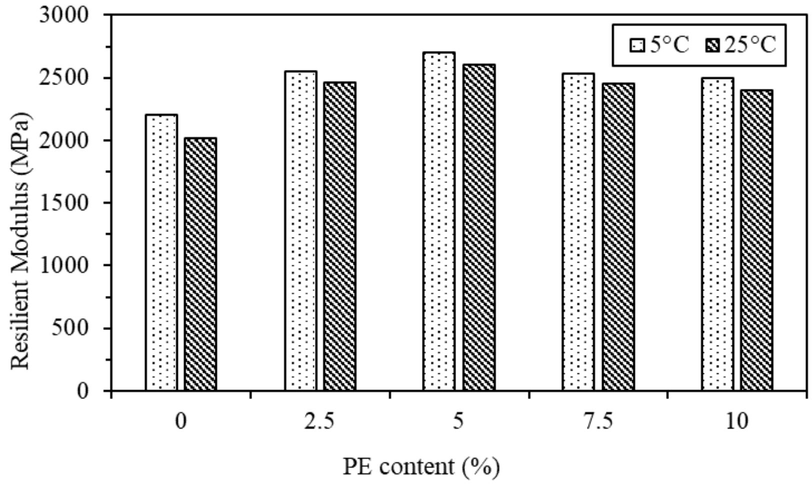


Figure 2.49 Resilient modulus results (Redrawn from Punith and Veeraragavan, 2007)

Attaelman et al. (2011) reported an increase in resilient modulus values at a high (25 °C) temperature when HDPE was used in asphalt concrete mixtures. The modifiers do not weaken the mixture, even when it is exposed to moisture, but just 5% HDPE can result in a flexible, great performing, durable, economical pavement (Figure 2.50).

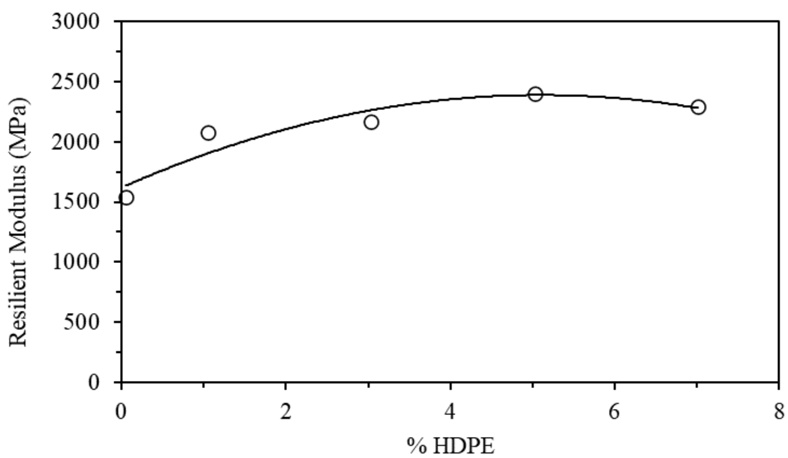


Figure 2.50 Resilient Modulus results (Redrawn from Attaelman et al., 2011)

2.21.5 Moisture Susceptibility

Islam (2021) showed that LDPE alone in the mix did not fulfill the minimum required criteria. Since LDPE is softer and thinner than other types of Plastic, it melts quickly, leaving less coating on the aggregate surface and less bonding between the mix. As a result, a significant amount of voids remained in the mix, allowing water to percolate, and making the sample susceptible to moisture. To improve the moisture susceptibility, 0.5% by weight of aggregate was replaced by PP. This combination of plastics filled the void of the mix and made better bonding between them. Thus, it improved the moisture resistance of the asphalt mixture and showed TSR values between 0.7 to 0.9. Similarly, PP and HDPE mix improved the moisture susceptibility while using up to 8% plastic.

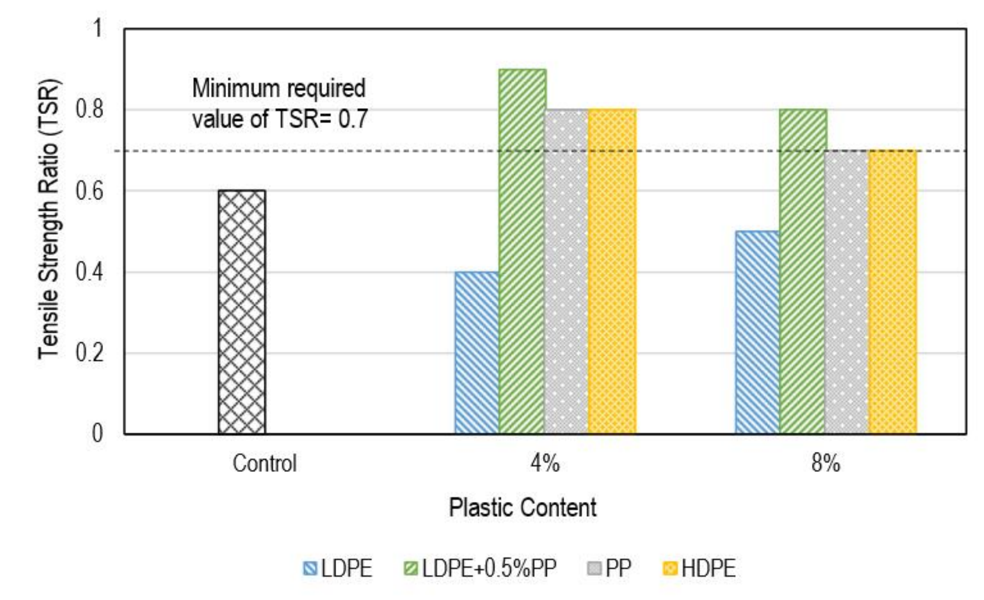


Figure 2.51 Tensile strength ratio (TSR) of asphalt mix with different combinations of Plastic (Redrawn from Islam (2021))

CHAPTER 3

METHODOLOGY

3.1 Introduction

The objective of this study is to find out the amount of impurities contained by the waste plastics when collected from primary and secondary sources and evaluate the effect of impurity contained by the plastic wastes in the design and performance of the of plastic road. The experimental program was developed in two stages. First, the amount of impurity was determined and finally, the effect of those impurities in the plastics was determined by adding them to the asphalt mix as was researched by Islam (2021). As a part of this research study, plastics were collected, clean, the impurity content was measured and later, after introducing the plastic in the asphalt mix with impurities, the volumetric tests i.e., Bulk density test and Rice gravity test and performance tests as in, Hamburg wheel track test, Indirect tensile strength test and moisture susceptibility tests were performed following the AASHTO and TxDOT guidelines. The complete procedure of the test methods, guidelines and equipment is described in the following section.

3.2 Material Collection

Plastic is the most important component for this research study hence 3 types of plastics along with class A aggregates and PG bitumen have been collected from different locations in Texas. The following chapters provide detailed information regarding the collection of the necessary materials for this study.

3.2.1 Collection of Plastic

Plastics have been collected from 2 different sources: one primary source and one secondary source. Firstly, it was collected from the landfill which is a secondary source (Source 1) and later it was collected from the University of Texas at Arlington Premise which is a primary source (Source 2).

As a secondary source of collection, plastics were collected from the Irving Hunter Ferrell Landfill. Irving landfill receives all types of waste materials mostly coming from Irving city and the working face receives all types of waste except that is hazardous or can be recycled. Although plastics are recyclable and can be used more than once, it was found that plastics eventually end up in the landfill. Hence, plastics required for the research purpose have been collected from the working face directly.

Different types of plastics have been collected from the landfill. Later, in the laboratory, the plastics were recognized, and High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE) and Polypropylene (PP) were sorted out.

As a primary source of collection, plastics were collected from the UTA premise. The plastics were collected from the general garbage bins to ensure the highest amount of impurity. Plastics were also collected from the garbage bin, however, the plastics contained less than 5% of impurity if it was collected from the recycling bin in the premise. In this case as well, the plastics were sorted and HDPE, LDPE and PP were sorted as well.

3.2.2 Plastic Processing

Plastics were processed in two stages. These 2 stages are named as preliminary and final study for analyzing the plastics and impurities contained by the plastics. Preliminary study was done to understand the effect of impurities in the asphalt mix, later in the final study, a more comprehensive study was done on the effect of impurities. In this section the 2 stages are described briefly.

Preliminary Study:

One of the main objectives of this study is to determine the impurity content in plastic wastes. Therefore, the plastics were collected from the Irving landfill and the plastics needed to be analyzed to find out the impurity contained by them. The plastics were first sorted based on different grades. Only High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE) and Polypropylene (PP) were sorted out. The plastics were then divided into two groups. One group was subjected to be cleaned and the other group was separated for shredding.

The following steps were followed for the first group to find out the impurity:

- The initial weight of each plastic component with impurity was taken before cleaning,
- It was then cleaned thoroughly until all the stains were removed for the plastic,
- It was then put in the oven at 105° C for 24 hours to dry
- Later, taking out the plastic from the oven, the weight of the plastic was measured again without impurity.

- Hence, the amount of impurity that the plastic component was containing was found out (Figure 3.1).

In this process, a total number of 211 plastics collected from the landfill and 106 plastics were cleaned to find out the impurity content contained by the 3 types of plastics. The remaining 105 plastics were kept for shredding without cleaning. The percentage of impurity found from the first group was considered to be contained by the 2nd group of plastics as these plastics came from the same source.

(a) (b) (c) (d)

Figure 3.1 Cleaning procedure of plastics: (a) initial weight with impurity; (b) cleaning individual plastic; (c) oven drying plastics; (d) final weight without impurity

The overall plastic processing steps are shown in the Figure 3.2.

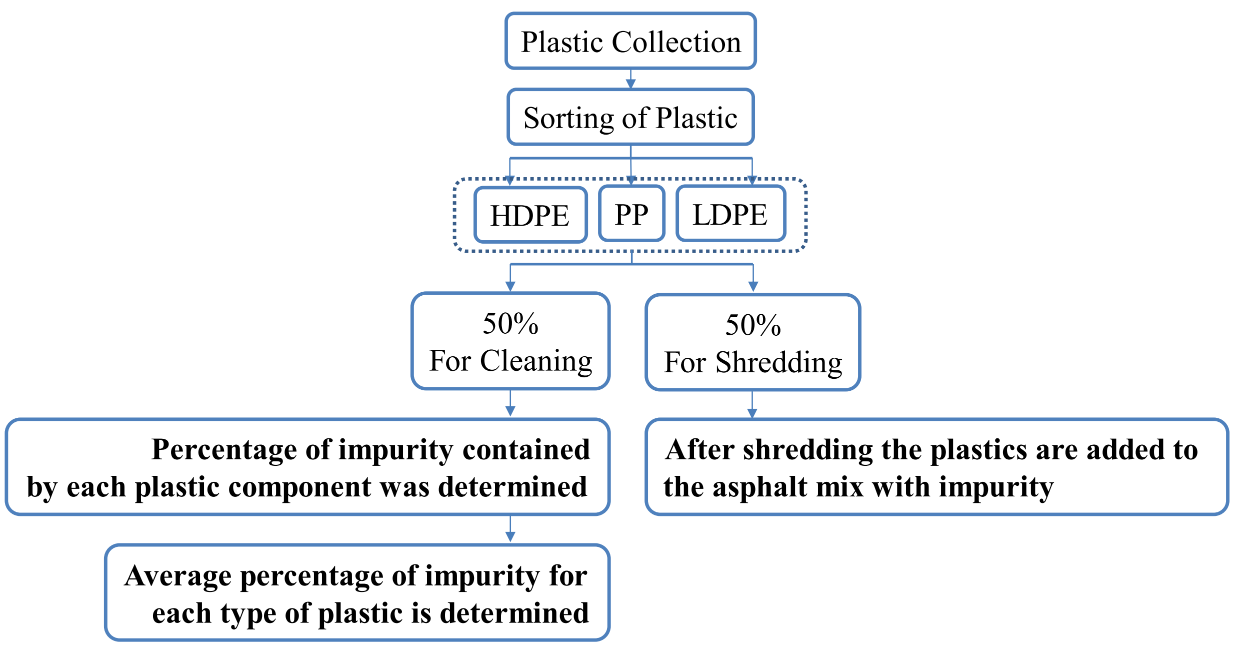
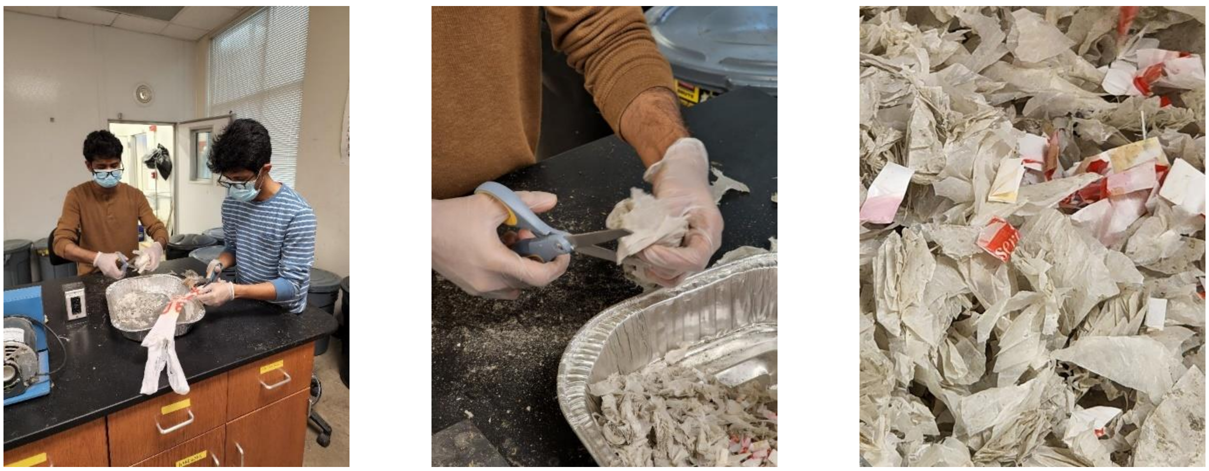


Figure 3.2 Plastic processing steps for the preliminary study

Plastics that were left for shredding was shredded in the laboratory. The HDPE and PP are required to shred into small pieces of 3mm-6mm to use the plastic for further use. Using a small-scale shredder, the shredding was done in the Civil Engineering Laboratory Building. For this research study INTBUYING 220V Heavy Duty Plastic Grinder/Granulator is used to shred the plastics into smaller sizes. LDPE plastic bags could not be shredded in this machine; therefore, LDPE bags were cut manually with the help of scissors.



(a) Manual cutting of LDPE type plastics

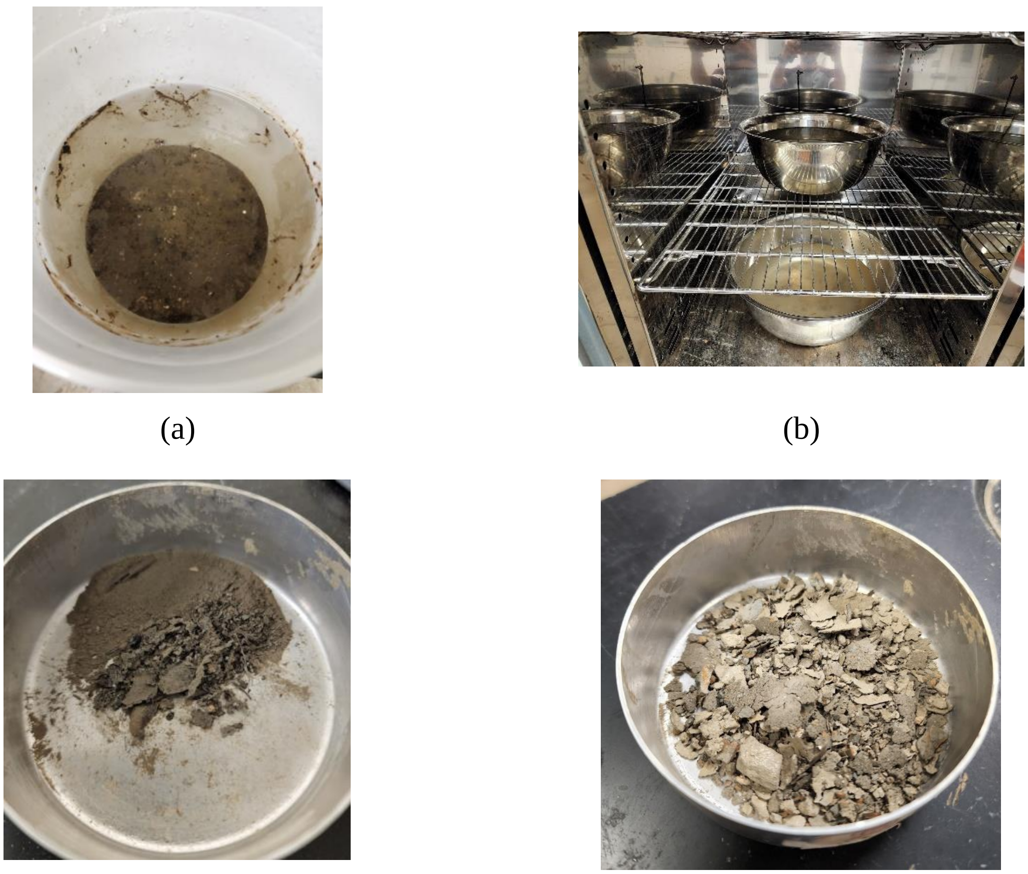
(b) Laboratory shredding machine to shred HDPE and PP

Figure 3.3 Shredding process for impure (a) thin LDPE and (b) HDPE and PP

<u>Final Study:</u>

Afterwards, more plastics collected from the landfill were analyzed. In this stage, 40 more plastics were cleaned that were collected from the landfill as secondary source (source 1). 70 plastics were also collected from the UTA premise and the cleaning process was followed to find out the impurity in the plastics collected from landfill and university premise.

Later, the water initially used for cleaning the plastics was dried in the oven and the impurities are regained for adding them in different percentages with the asphalt mix (Figure 3.4). Plastics have been added as 4% and 8% respectively as a replacement of the bitumen content in this research study. The impurities regained were mixed in the asphalt to replace the plastic content. 3 different percentages (10%, 20% and 30%) of impurity replacing the plastic content were considered in the study. These percentages came up after the preliminary study where impurities were determined from the first group of separated plastics.



(a) (b)

(c)

Figure 3.4 Procedure for regaining the impurity: (a) water used for cleaning; (b) over drying the water to regain impurity; (c) impurity regained after drying

However, later, the cleaning procedure was followed quite a few times more to have the impurity needed for the total experimental program. The plastics in this case were cleaned altogether, not individually. The reason for this procedure was to mitigate the time that is needed for cleaning individually. Cleaning the plastics individually was a very time-consuming procedure and the impurity gained in this process was very little in amount. Hence, plastics were later cleaned altogether.

3.2.3 Collection of Aggregate and Bitumen

For this project, various types of aggregates are gathered from approved locations designated by TxDOT. The research focuses on utilizing Superpave SP-C aggregate gradation and performance-graded (PG) binders for the surface course.

The process of hot mix asphalt (HMA) mix design involves determining the appropriate aggregate and asphalt binder, as well as finding the optimal combination of these ingredients. Mix design is conducted in a laboratory setting to simulate actual HMA manufacturing, construction, and performance as accurately as possible. By simulating these conditions, it becomes possible to predict the most suitable mix design for a specific application and its expected performance with reasonable certainty.

Under the Strategic Highway Research Program (SHRP), an initiative was launched to enhance materials selection and mixture design. This led to the development of a new mix design method called the Superior Performing Asphalt Pavement System (Superpave), which incorporates considerations for traffic loading and environmental conditions. The Superpave system aims to replace the Hveem and Marshall methods by integrating asphalt binder and aggregate selection into the mix design process while accounting for traffic and climate factors. Consequently, all mix designs in this research will be conducted according to the Superpave mix design, and samples will be compacted using the Superpave Gyratory Compactor.

To adhere to the Superpave SP-C aggregate gradation, Type C rock, Type D rock, Manufactured sand, and recycled asphalt pavement (RAP) are collected.

Sieve analysis, following the standard test method outlined in TxDOT guidelines (Tex-110E) for particle size analysis of aggregates, was performed to determine the particle size distribution of all materials used. The gradation of recycled base materials was examined to ensure compliance with TxDOT standards. According to the specifications of the Texas Department of Transportation (TxDOT) Item 276, a hydrometer analysis is not required if the percentage passing through the

No. 200 sieve is below 1%. Since the percentage passing through the No. 200 sieve in this case was less than 1%, a hydrometer analysis was not deemed necessary.

To conduct the analysis, the material retained in each sieve was weighed, and the percentage passing through the sieve was calculated. The weight of the material retained in each sieve was divided by the total sample weight and subtracted from the total percentage of material. This allowed for the determination of the percentage of material passing through each sieve.

As per TxDOT recommendation, a Superpave SP-C aggregate gradation is chosen to conduct this research and the mix design that was followed in this research contained 25% Type C-Rock, 30% Type D-Rock, 30% Man Sand and 15% RAP. The results from sieve analysis are tabulated in Table 3-1.

Table 3-1 Gradation of the aggregates used for the current study

Passing	**Retained**	**Individual Retained, %**	**Cumulative Retained, %**	**% Passing**
-	1"	0.00	0.00	100.00
1"	3/4"	0.00	0.00	100.00
3/4"	1/2"	6.25	6.25	93.75
1/2"	3/8"	9.38	15.63	84.37
3/8"	No. 4	29.77	45.39	54.61
No. 4	No. 8	19.04	64.44	35.56
No. 8	No. 16	10.33	74.77	25.23
No. 16	No. 30	6.35	81.12	18.88
No. 30	No. 50	7.02	88.14	11.86
No. 50	No. 200	8.55	96.69	3.31
No. 200	Pan	3.31	100.00	0.00

A semi-log graph paper was used to plot the percentage of material passing through each sieve against the corresponding sieve size Figure 3.5. Atterberg limits were not assessed due to the same aforementioned reason.

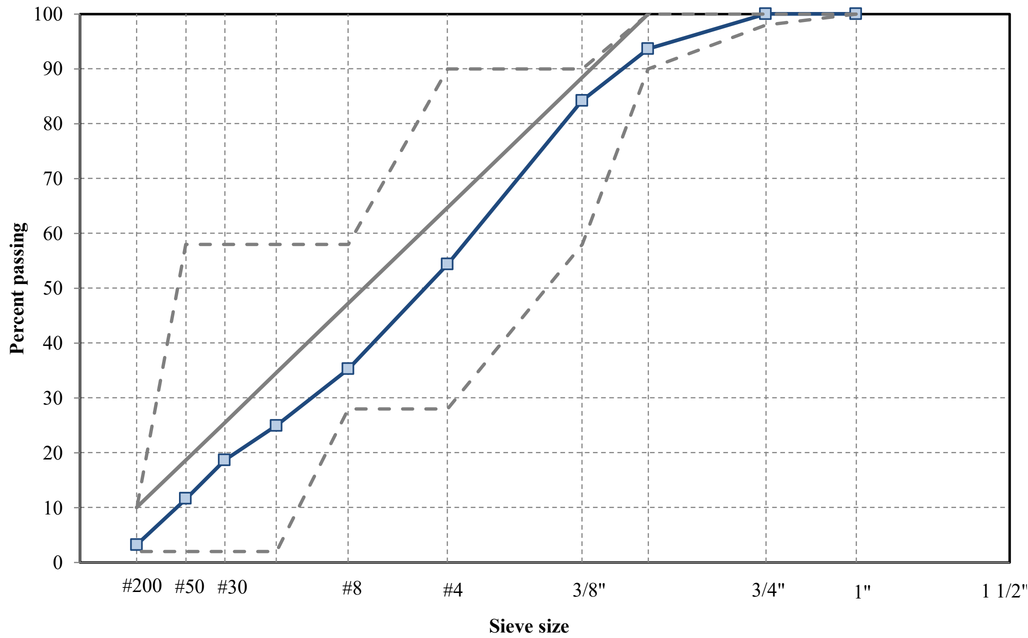


Figure 3.5 Gradation chart of the aggregates used for the current study

(a)

(b)

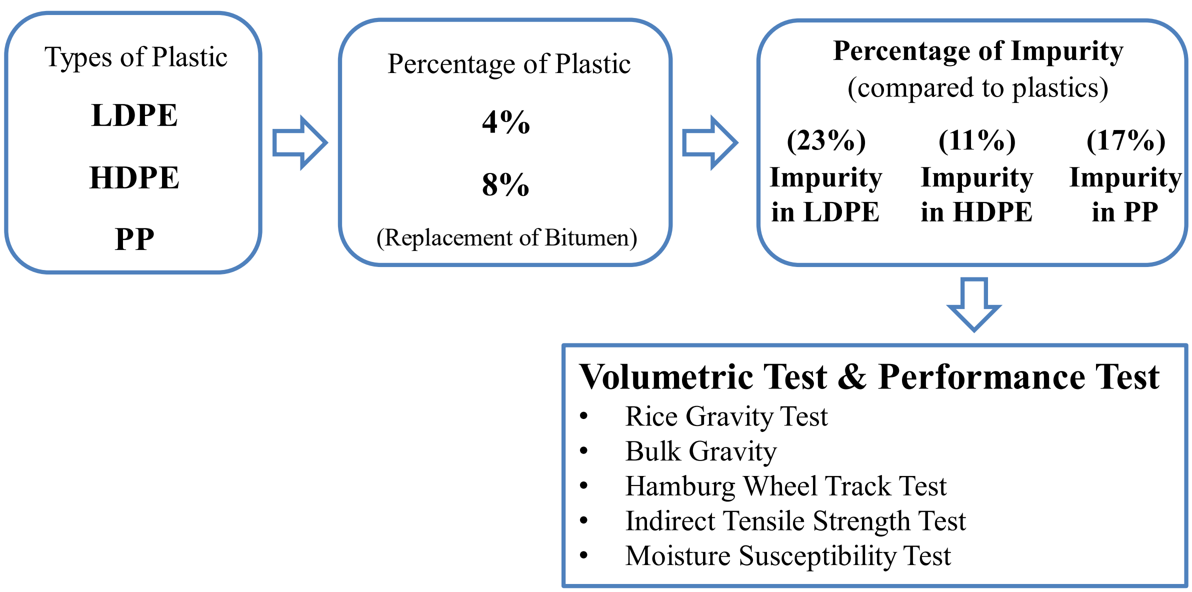
Figure 3.6 (a) Collection of aggregate from Austin Asphalt, Goodnight Lane, Dallas; (b) Collected aggregates and bitumen from Dallas

The Superpave binder specifications are performance-based, thus referred to as performance-graded (PG) binders, unlike the previous system of viscosity-graded (AC) binders commonly used for surface treatments and aggregate precoating. In this research, a PG 64-22 binder with a specific gravity of 1.032 and a flash point of 313°C, obtained from Austin Asphalt in Dallas, is being utilized.

3.3 Experimental Program

As a part of this research, different plastic combinations with different amount of impurity have been used in the asphalt mix. In the preliminary study, plastics with impurities were directly used and finally, 3 percentages of impurities were determined based on the preliminary study to incorporate in the asphalt mix separately. The experimental program is as follows:

Preliminary Study:



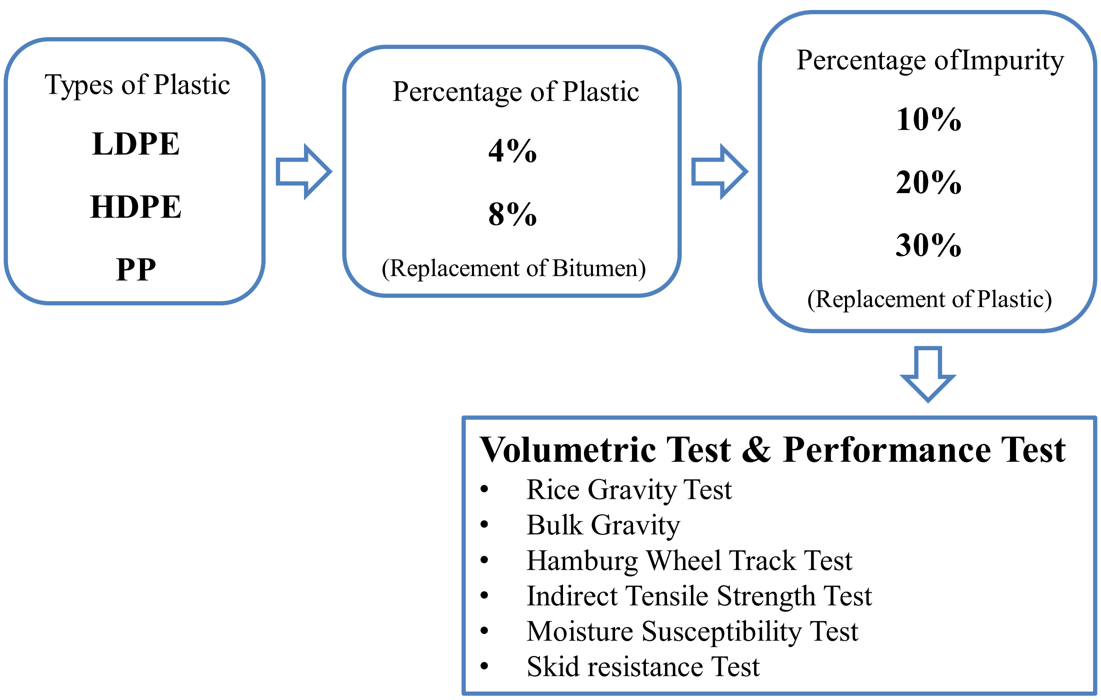
The main objective of the preliminary study was to find out the effect of impurities contained by the plastics. It was found that LDPE, HDPE, and PP containing 23%, 11% and 17% impurity have effect on the volumetric tests, and performance test of the asphalt mix. The results are discussed in the next chapter. From this point the final study started where impurities at 10%, 20% and 30% were introduced with the clean plastics in the asphalt mix. The number of tests in the preliminary study is shown in the Table 3-2.

Table 3-2 Number of tests conducted in the preliminary study

Mix Design	Plastic type	% of Plastic Content	% of Impurity Content	Rice Gravity Test	Bulk Gravity Test	Hamburg Test	ITS Test	Moisture Susceptibility Test
C-Rock = 25% D-Rock = 30% Man Sand = 30% RAP = 15%	PP	4	17%	2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
		8		2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
	HDPE	4	11%	2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
		8		2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
	LDPE	4	23%	2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
		8		2 (2)	2 (2)	2 (2)	3 (3)	3 (3)
Total Number of Tests = 72 (72)				**12 (12)**	**12 (12)**	**12 (12)**	**18 (18)**	**18 (18)**

Final Study:

In the final study, clean plastics were used in the asphalt mix. Along with the clean plastics, impurities at 3 different percentages (10%, 20% and 30%) were also added. The plastics were replacing the bitumen at 4% and 8% respectively.



The number of tests in the final study is shown in the Table 3-3.

Table 3-3 Number of tests conducted in the final study

Mix Design	Plastic type	% of Plastic Content	% of Impurity Content	Rice Gravity Test	Bulk Gravity Test	Hamburg Test	ITS Test	Moisture Susceptibility Test
C-Rock = 25% D-Rock = 30% Man Sand = 30% RAP = 15%	PP	4	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
		8	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
	HDPE	4	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
		8	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
	LDPE	4	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
		8	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
	0.5% PP + LDPE	4	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
		8	10	2	2	2	3	3
			20	2	2	2	3	3
			30	2	2	2	3	3
			10 (Clay)	2	2	2	3	3
			20 (Clay)	2	2	2	3	3
			30 (Clay)	2	2	2	3	3
Total Number of Tests = 324				**54**	**54**	**54**	**81**	**81**

In addition, skid resistance tests were performed with both clean plastics and plastics with impurities. The conditioned and unconditioned samples were taken into consideration for this test. Conditioned samples have been prepared for the Hamburg Wheel Track Test and during this test procedure, the samples were set in a water bath at 50° Celsius for over 8 hours. Unconditioned samples did not have to go through this procedure. The number of skid resistance tests are tabulated here in Table 3-4.

Table 3-4 Number of tests performed for Skid Resistance Test

		Plastic Percentage	Impurity Percentage	Plastic Type & Number of Samples			
Conditioned Samples	Clean	0% (Control)	-	**HDPE**	**LDPE**	**PP**	**0.5%PP +LDPE**
		4%		3	3	3	3
		8%		3	3	3	3
		12%		3	3	3	3
		16%		3	3	3	3
	Impure	4%	10%	3	3	3	3
			20%	3	3	3	3
			30%	3	3	3	3
		8%	10%	3	3	3	3
			20%	3	3	3	3
			30%	3	3	3	3
Unconditioned Samples	**Clean**	8%	-	4	4	4	4
			Total Number of Tests =	**136**			

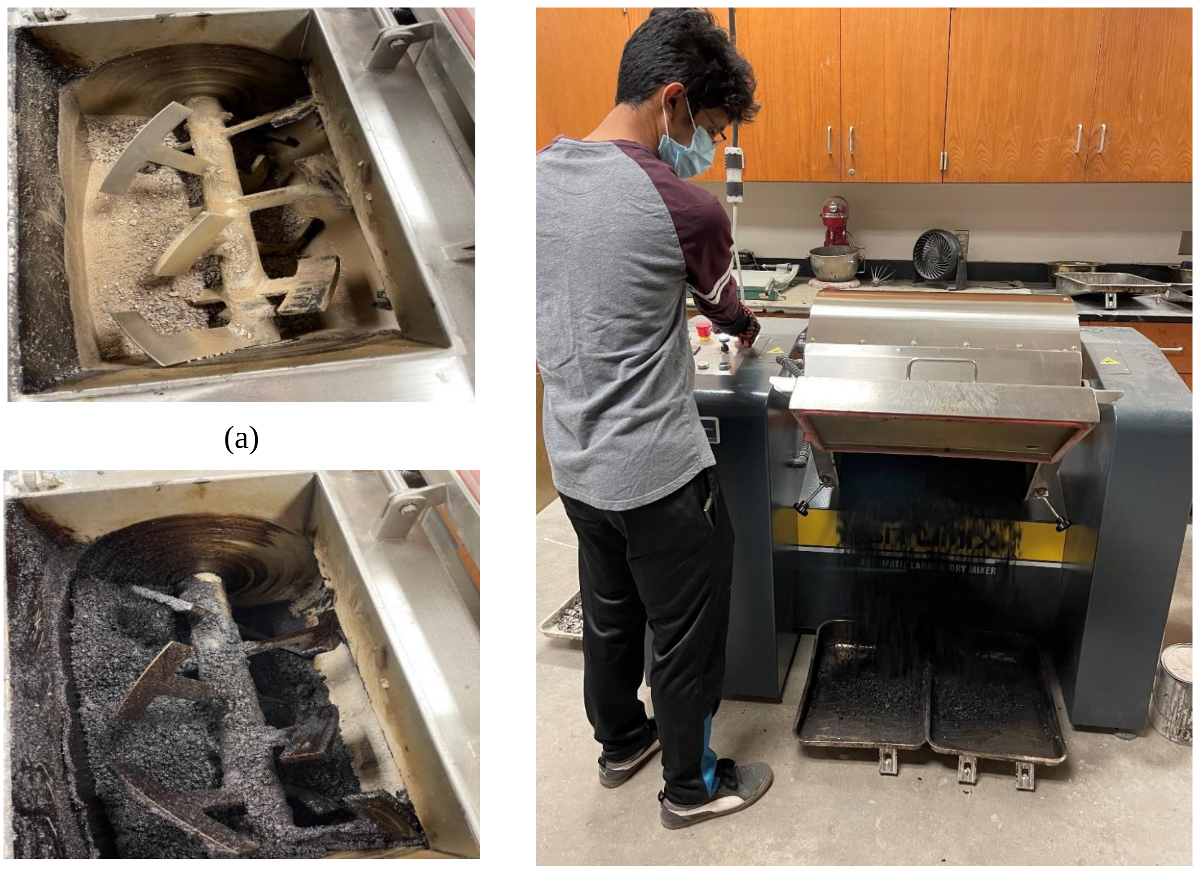
3.4 Asphalt Mixing Procedure

It was mentioned earlier that plastics in the asphalt mix can be introduced in two ways: a) dry process and wet process. When the plastic is added to the bitumen directly, this process is known as wet mixing process. When the plastic is mixed with the aggregate first and later bitumen is added, this process is called dry mixing. In this research, dry mixing has been followed.

A temperature controlled automated mixture was utilized in this study. This mixture can mix the samples in a controlled temperature, time and rpm setting which makes the mixing quite convenient and uniform. According to the Thermogravimetric Analysis (TGA) test, HDPE and PP have melting points ranging from 170° to 190° Celsius and LDPE has melting points from 150° to 180° Celsius.

The mixing procedure is followed as the next paragraph.

- The specified amount of coarse aggregate and fine aggregate were placed in a pan and retained in an oven at a temperature of 170°C for 2 hours. Bitumen was kept in the oven at the same time. As aggregates, plastic and bitumen are to be mixed at a heated temperature, preheating is required. The mixing machine temperature was also set to 150°C.
- The aggregates were taken out from the oven and were mixed homogenously inside the mixing machine with the required amount of plastics. This process was continued at 20 rpm for 5 minutes.
- After the plastics put a coat on the aggregates, the bitumen was added to the mix, and this was also homogenously mixed inside the mixer. This was continued for another 5 minutes to make sure all the aggregates were uniformly mixed with bitumen, so that the quality of the asphalt mix is not compromised.



(a) (b) (c)

Figure 3.7 (a) Dry mixing of plastic and aggregate; (b) Mixing with bitumen; (c) The hot-mix asphalt was prepared using the automated mixer

After preparing the hot mix asphalt, the mix was kept inside the oven for another 2 hours to simulate the ageing due to the transportation of the HMA. After 2 hours, the samples for the tests were prepared. Based on the requirements of the tests, the samples were either compacted or kept loose. For compaction, Superpave Gyratory Compactor (SGC). The compacting parameters for Superpave Gyratory Compactor is shown in Table 3-5.

Table 3-5 Compaction parameters for Superpave Gyratory Compactor

Parameter	Value
Diameter	150 mm
Pressure	600±18 kPa
Angle of gyration	1.16° ± 0.02°
Number of gyrations	Ndesign= 50
Speed of rotation	30±0.5 gyrations per minute

The preparation of the samples was followed according to the requirements of the tests. The sample size and condition for each test is mentioned in Table 3-6.

Table 3-6 Sample size and type for the tests

Test Name	Sample Type and Size
Rice Gravity Test	Loose Sample
Bulk Density Test	Compacted; Height (115±5) mm, Diameter 150 mm
HWTT (Rutting Test)	Compacted; Height (62±0.5) mm, Diameter 150 mm
IDT (Strength Test)	Compacted; Height (62±0.5) mm, Diameter 150 mm
Moisture Susceptibility Test	Compacted; Height (62±0.5) mm, Diameter 150 mm
Skid Resistance Test	Compacted; Height (62±0.5) mm, Diameter 150 mm

Figure 3.8 Loose (left) and compacted (right) samples for the tests

3.5 Volumetric Tests

In this section two tests will be done which are bulk density test and rice test/ theoretical maximum specific gravity test. These tests are needed in order to calculate air void. Percent air voids is calculated by comparing a test specimen's bulk specific gravity (G_{mb}) with its theoretical maximum specific gravity (G_{mm}) and assuming the difference is due to air.

In this research, the Optimum Asphalt Content (OAC) is taken as 4.8% found by Islam, 2021 (Figure 3.9). This OAC was found after laboratory tests with clean plastics in asphalt mix. This OAC would be utilized to find out the volumetric test results after introducing impure plastics in the asphalt mix at different levels as previously mentioned.

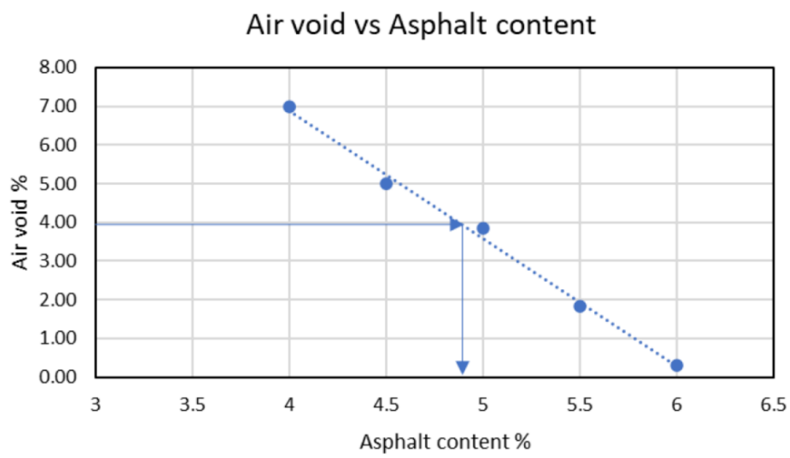


Figure 3.9 Optimum Asphalt Content (OAC) found by Islam, 2021.

3.5.1 Bulk Density Test

The design of SuperPave mixes is a volumetric process; key properties are expressed as volumetric values. Due to the difficulty of direct volume measurements, weight measurements are generally taken and then converted to volume using material-specific gravities. Therefore, Specific gravity is a measure of a material's density (mass per unit volume) as compared to the density of water at 73.4°F (23°C). By definition, water at 73.4°F (23°C) has a specific gravity of 1. In addition to air voids, VMA and indirectly VFA, bulk specific gravity is used in most key mix design calculations. Mix design must be based on the correct and accurate determination of bulk specific gravity. The most common method (AASHTO T 166 or Tex-207 Part 1: Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens), calculates the specimen volume by subtracting the mass of the specimen in water (Figure 3.14) from the mass of a SSD specimen.

SSD refers to a specimen condition in which all the internal air voids are filled with water, while both the surface and the air voids connected to the surface are dry. The samples for this bulk density are prepared with 50 gyrations having 150 mm diameter and 115+/-10 mm height. To get the most accurate result Tex-207 Part 6 should be adopted if the apparatus will be available. The following calculations can be used to determine bulk specific gravity and percent of water absorbed by the specimen:

$$G_{mb} = \frac{A}{B - C}$$

Where, G_{mb} = bulk specific gravity

A = weight of dry specimen in air, g

B = weight of the SSD specimen in air, g

C = weight of the specimen in water, g.

3.5.2 Rice Gravity Test

Rice gravity test will be performed to determine the theoretical maximum specific gravity. HMA mixtures have a maximum specific gravity (G_{mm}) when air voids are excluded. The theoretical maximum specific gravity would be the aggregate and asphalt binder specific gravity added together if all the air voids were eliminated from the HMA sample. To obtain a theoretical maximum density, multiply the theoretical maximum specific gravity (62.4 lbs/ft^3 or 1000 g/L) by the density of water (1000 g/L). Rice density (based on James Rice's procedure) is then the result. As part of the calculation of percent air voids in HMA, the theoretical maximum specific gravity is a critical HMA characteristic. Both Superpave mix design and void detection in-place are determined by this calculation.

The theoretical maximum specific gravity of HMA can be determined by weighing a sample of loose HMA (i.e., not compacted), then calculating the volume it displaces by calculating the weight of water it has (Figure 3.15). The sample weight divided by its volume can then be used to calculate the sample's theoretical maximum specific gravity. The standard theoretical maximum specific gravity test is AASHTO T 209, ASTM D 2041 and Tex-227-F: Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixture. The following equation can be used to calculate the theoretical maximum specific gravity:

$$G_{mm} = \frac{A}{A + D - E}$$

Where, Gmm= Theoretical Maximum Specific Gravity

A = sample mass in air (g)

D = mass of flask filled with water (g)

E = mass of flask and sample filled with water (g)

Figure 3.10 Rice Gravity test apparatus (left) and Bulk Density test apparatus (Right)

3.5.3 Rutting Test

To measure rutting performance of asphalt mixtures different types of laboratory testing can be possible like Asphalt pavement analyzer test, Hamburg wheel track test, Flow number test. Among these three Hamburg wheel track test will be done for rutting test.

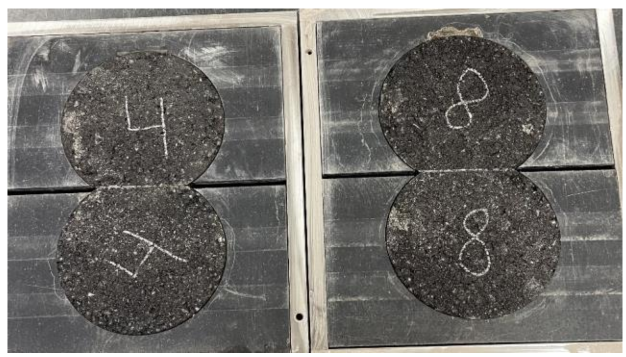
Hamburg Wheel Track Test (HWTT)

HWTT has been widely used by highway agencies, such as California, Colorado, Illinois, Iowa, Louisiana, Montana, Oklahoma, Texas, Utah, Washington, and Wisconsin (Mohammad et al. 2015). The HWTT has been found to have an excellent correlation with field performance (especially in moisture damage evaluation). Figure 3.16 shows a Hamburg Wheel Tracking Device. The HWTT is often conducted following AASHTO T324: Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA) or Tex-242-F. Both slab specimens and cylindrical specimens can be used. A loaded steel wheel is tracked on asphalt pavement samples back and forth with the Hamburg Wheel Tracking Device (HWTD), in order to determine rut resistance. As thousands of these cycles are repeated, it simulates the effects of traffic loads on the pavement over time (Rahman and Hossain, 2014). A continuous measurement of the depth of the ruts is made throughout the test. An HWTD test can also be conducted while a sample is submerged in water. Moisture resistance can also be evaluated using this method. The stability of the mix will, at first, determine how quickly rutting develops after the sample has been consolidated by the initial loading cycles. Following a certain number of load cycles (depending on the moisture susceptibility of the mix), damage from stripping accelerates rut development.

(a)

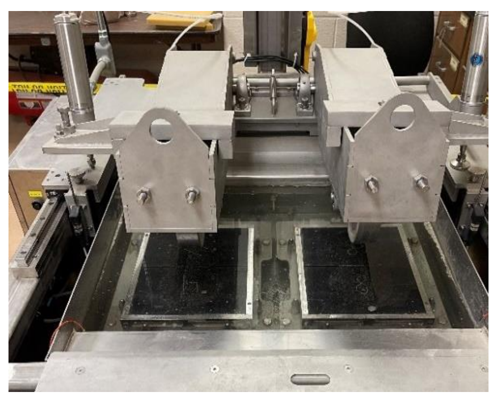
(b)

(c)



(d)

(e)



(f)

Figure 3.11 (a) Samples for HWTT; (b) trimming the sample to required size; (c) trimmed samples; (d) samples placed in the mold; (e) placing the mold with samples; (f) HWTT ready to run

To conduct the test two samples of 62 mm height and 150 mm diameter were compacted for each set of combination. After that the samples were cut 12 mm from their edge to fit them in the Hamburg molds. Then mounting trays with the samples in the molds were placed in an empty water bath. The computer control was activated via a software and

required information entered. Test specifications were as follows:

a) Testing temperature: 122±1.8°F (50±1°C).

b) Load: 158 lb. ± 5 lb. (705±22 N).

c) Number of passes per minute: 50±2.

d) Maximum number of passes setting: 20,000

e) Maximum speed of wheel: 1.1 ft./sec (approximately)

f) Maximum rut depth: 20 mm

g) Rut-depth measurements: every 100 passes.

Upon reaching the desired temperature, water was turned on and the specimen was soaked for an additional 30 minutes. As soon as the specimen was saturated, the arms with wheels were lowered until they rested on it. The device stopped automatically when the maximum rut depth or the maximum number of wheel passes were reached, whichever occurred first. Linear variable differential transducers (LVDTs) connected to the machine on either side measured vertical deformation (rut depth) at 11 different points along the wheel path of the specimen. The HWTD device was connected to a computer-based automated data acquisition system for measuring rut depth. By plotting the number of wheel passes against rut depth, we determined the post-compaction slope, the creep slope, the stripping inflection point, and the stripping slope.

3.5.4 Cracking Test

Two of the most common cracking tests are Texas Overlay Tester (OT) and the Indirect Tension test (IDT). These test methods determine the susceptibility of bituminous mixtures to fatigue or reflective cracking. In this research, to determine the tensile strength of compacted bituminous mixtures IDT tests will be done.

<u>Indirect Tensile Strength Test</u>

The tensile strength of HMA is important since it can be used as an indicator of cracking. The high tensile strength at failure of a particular HMA means that it can tolerate higher strains before failing, implying it is likely to resist cracking better than one with a low tensile strength at failure.

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Zhou et al. (2017) have developed an indirect tension test for asphalt cracking that requires no cutting, no drilling, no gluing, no notching, no instrumentation, minimal temperature conditioning, and minimal testing time. ASTM D6931 – 12 or Tex-226-F can be adopted to conduct this test. The loading head is a strip conforming to that required for a simple indirect tension (IDT) test (Figure 3.12). The only instrumentation required is a load cell capable of applying a compressive load at a controlled deformation rate of 2 in. per minute and loading strips, consisting of 0.5 × 0.5 in. square steel bars for 4 in. diameter specimens, and 0.75 × 0.75 in. square steel bars for 6 in. diameter specimens. The tensile strength can be calculated as follows:

$$\text{Tensile strength, } S_t = \frac{2P}{\pi D t}$$

Where, S_t = tensile strength (psi)

P = maximum load (lbs)

t = sample thickness (inches)

D = sample diameter (inches)

Figure 3.12 Test Set-Up for Indirect Tensile Strength Test

3.5.5 Moisture Susceptibility Test

Water-induced damage of asphalt mixtures has produced serious distress, reduced performance, and increased maintenance for pavements in Texas, as well as in other areas of the United States (FHWA report, 1984). Two laboratory tests have received acceptance in United States to evaluate the moisture sensitivity of HMA: the Lottman procedure (AASHTO T 283) and the HWTT (AASHTO T 324) (Solaimanian et al. 2003). There exists also a TxDOT designation (Tex-531-C) of doing this test. The procedure will subject some molded specimens to moisture conditioning and will compare them by indirect tensile strength to unconditioned specimens (Figure 3.21). This is called the tensile strength ratio (TSR) of a mix. The TSR is, therefore, an indication of loss of strength caused by the moisture conditioning. The TSR value must be greater than 0.7 to be moisture resistant. The TSR value can be calculated as follows:

$$\text{TSR} = \frac{S_1}{S_2}$$

Where, TSR = tensile strength ratio

S1 = average tensile strength of unconditioned samples

S2 = average tensile strength of conditioned samples

Figure 3.13 Conditioning (freezing thawing) the samples to determine TSR for moisture susceptibility test

As stated earlier, the stripping potential can be measured by conducting the rutting test under water. To this end, the concept of stripping inflection point (SIP) is based on rutting vs. wheel pass curves with a sudden rut depth increase when the number of passes increases. At this point, asphalt binders are believed to separate from aggregates.

3.5.6 Skid Resistance Test

Skid resistance is a critical parameter for evaluating the safety and performance of asphalt pavements. Laboratory testing plays a crucial role in assessing the skid resistance characteristics of asphalt materials. ASTM E303-93 'Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester' was adopted in this research to find the skid resistance of the surface of asphalt pavement. The portable skid resistance tester acts like a pendulum swing from side to side during skid resistance test. The term 'Pendulum test' is also used since a pendulum of a known mass rotates about a vertical spindle. This test is conducted to assess the resistance of wet surfaces to slipping and skidding, both in the lab and in the site.

In the laboratory, 6-inch diameter samples with a height of 62 mm were utilized for this test. The test apparatus has a pendulum that passes over the asphalt sample freely. The distance travelled by the pendulum after striking the sample is determined by the friction resistance of the sample surface. From the test, the British Pendulum Number (BPN) is obtained. The following equation is used to find out the skid number from BPN.

$$\text{Skid Number, SN} = 1.32 * \text{BPN} - 34.9$$

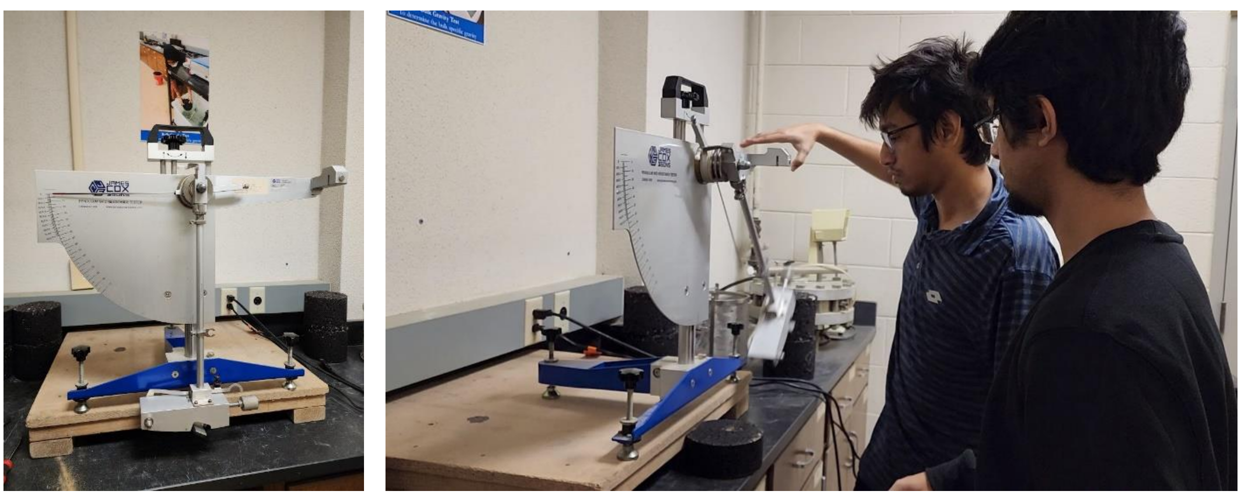


Figure 3.14 Skid resistance test setup and the procedure

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The analysis of the results for the percentage of impurity in different types of plastics obtained from cleaning the plastics is presented in the first part of this chapter, followed by the analysis of the test results of volumetric tests that are Specific Gravity Test, Rice Gravity Test and the performance tests which are Hamburg Wheel Track Test, Indirect Tensile Strength Test, Moisture Susceptibility Test and Skid Resistance Tests. The latter volumetric and performance tests are then compared with respect to the change of plastic type (HDPE, LDPE, PP), plastic content (4%, 8%) and percentage of impurity (10%, 20%, 30%).

4.2 Impurity in the Plastic Waste

The analysis of impurity content was done in two stages. Firstly, the impurity from Preliminary study is presented here and the combined analysis of the percentage of impurity for all the plastics considered from two different sources for this study is shown later.

4.2.1 Preliminary Study

A preliminary study was conducted mainly to find out if there is an effect of impurity in plastic in the plastic mixed asphalt. For the preliminary study, there was only one source for collecting the plastics which was the Irving landfill. Three different types of plastics HDPE, LDPE, PP are considered. Each type of the collected plastics is divided into two equal groups. The first group was separated to find out the impurity content by cleaning thoroughly and the other group was left for shredding and using it in the asphalt mix. The total number of 3 types of plastics are tabulated here (Table 4-1). Preliminary study shows that the number of LDPE type plastics was more than the other two types. HDPE was the least to find among all the plastics.

Table 4-1 Total number of plastics for cleaning, shredding, and mixing for preliminary study

Type of plastic	Number of plastics cleaned for Impurity Content	Number of plastics left for shredding and mixing
HDPE	19	20

LDPE	54	50
PP	33	35

The number of plastics that are mentioned in Table 4-1 is cleaned to find out the amount or the percentage of impurity in different types of plastics. Figure 4.1 shows the percentage of impurity in three different types of plastics.

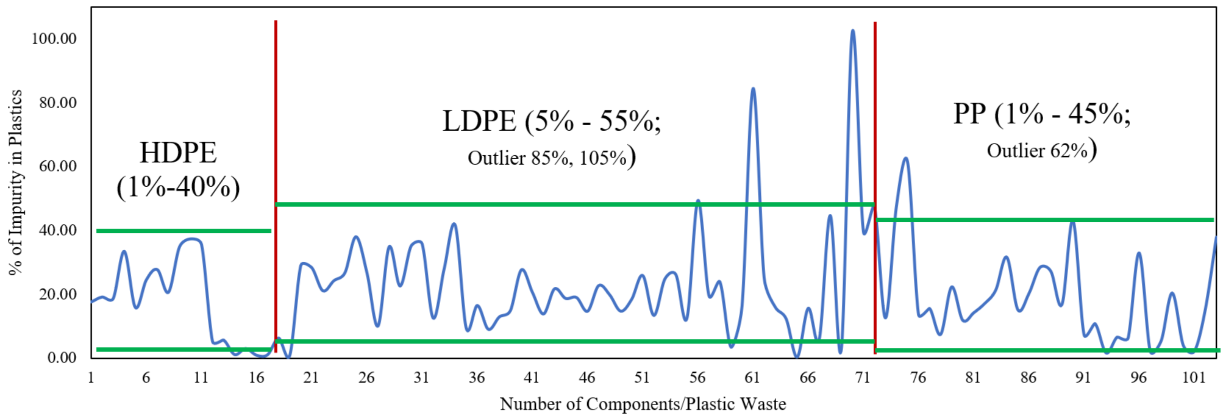


Figure 4.1 Percentage of impurity in three types of plastics

It is clearly evident from this graph that LDPE type plastics contain more impurities than the other two types. HDPE was found to contain up to 40% of impurity of the total weight of plastic and PP to contain up to 45%, however, LDPE was found to contain up to 55% impurity and at least 5% of impurity was present in all the LDPE type plastics. Even, 85% and 105% impurity were found in two LDPE plastic. The average percentage of impurity in HDPE, LDPE and PP are found to be 10%, 23% and 17% respectively. This confirms that the impurity percentage is higher in LDPE type plastics. The summary of calculation for finding out these percentages is shown in Table 4-2. The total weight of 19 HDPE, 54 LDPE and 33 PP type plastics are added respectively before cleaning. After cleaning the dry weight was taken again to find out the percentage of impurity in weight basis.

Table 4-2 Summary of calculation for the percentage of impurity in plastics

Types of Plastics	Total Weight of plastics with IMPURITY (gm) (a)	Total Weight of Clean Plastic (gm) (b)	Total Weight of Impurity (gm) (a)-(b)	Average % of Impurity compared to Clean Plastic (Wt. basis)
HDPE	798.96	726.07	72.89	**10.1**
LDPE	477.02	386.50	90.52	**23.5**
PP	861.15	730.76	130.39	**17.8**

This study with a total number of 106 (used for cleaning) depicts that a significant amount of impurity will be present if plastics are collected from the landfills. The other group of plastics were shredded to mix with the asphalt mix to find out the effect of the impurities in the plastic mixed asphalt. The results which showed that the effect of impurities is significant are presented in the later part of this chapter.

4.2.2 Final Study

In the final study, it was more focused on the level of impurity that can be present in different source of waste plastics. Two of the sources were – Irving landfill and the University of Texas at Arlington Campus that are designated as Source 1 and Source 2 respectively. In the final study the plastics that were clean during preliminary study are also considered. The objective of this final study is to have a bigger sample size. The sample size in the case of preliminary study was small, hence the samples used in the preliminary study was also used in final study. The number of samples are tabulated here (**Error! Reference source not found.**).

Table 4-3 Number of plastics considered for impurity calculation

Plastic Type	Source 1 (Landfill)	Source 2 (University Campus)
HDPE	50	20
LDPE	58	25
PP	38	25

All these plastics were cleaned thoroughly, and the percentage of impurity was found followed by the procedure as mentioned earlier.

Study on Source 1 (Landfill)

The plastics collected from the landfill were found to have more impurities than the university campus. When the plastics were collected from the landfill, these plastics have gone through several processes during its lifetime after disposed including getting blended with different sorts of organic and inorganic waste. However, the waste collected from the university center didn't have chance to get blended with other wastes as much as the ones collected from the landfill. Hence, the less amount of waste from the university campus is assumed valid.

Figure 4.2 shows the percentage of impurity found in all the plastics collected from the landfill. The percentage of impurity seems higher in LDPE followed by PP and HDPE.

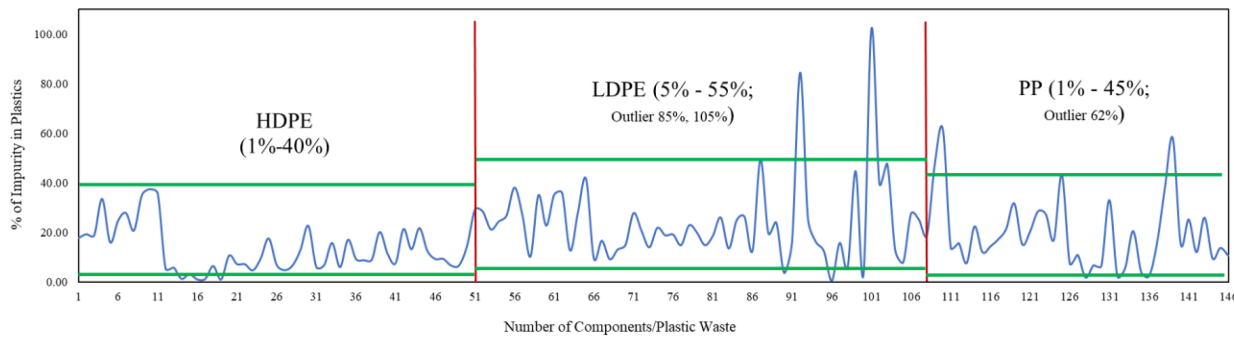


Figure 4.2 Percentage of impurity in the plastic wastes collected from the landfill

This is comprehensible from Figure 4.2 that range that was found from the preliminary study for 3 different types of plastics are still valid for the plastics additionally cleaned and dried for finding out the impurity for the final study. Preliminary study showed that the impurity percentage for HDPE, LDPE and PP were 1%-40%, 5%-55% and 1%-45% respectively with very few outliers in case of LDPE and PP. This range stayed the same for the additional plastics considered later. The summary of calculation for finding out these percentages is shown in Table 4-4.

Table 4-4 Calculation of impurity percentage for all the plastics from landfill

Types of Plastics	Total Weight of plastics with IMPURITY (gm) (a)	Total Weight of Clean Plastic (gm) (b)	Total Weight of Impurity (gm) (a)-(b)	Average % of Impurity compared to Clean Plastic (Wt. basis)
HDPE	2032.65	1798.01	234.64	**13.1**

Types of Plastics	Total Weight of plastics with IMPURITY (gm) (a)	Total Weight of Clean Plastic (gm) (b)	Total Weight of Impurity (gm) (a)-(b)	Average % of Impurity compared to Clean Plastic (Wt. basis)
LDPE	709.41	571.69	137.72	**24.1**
PP	1293.49	1082.60	210.89	**19.5**

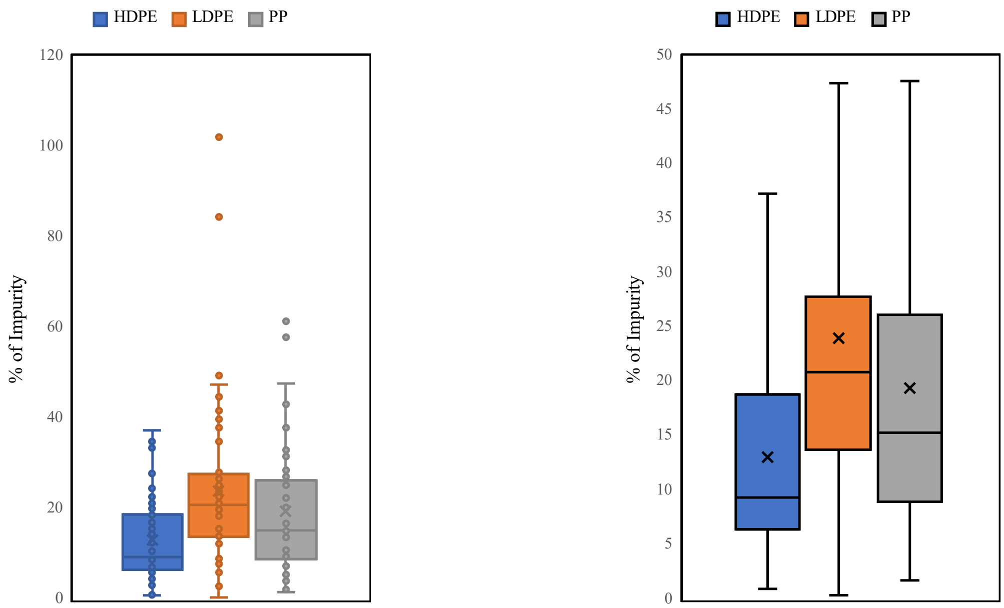
The percentage of impurity after cleaning all the plastics are found 9.7%, 21.4% and 18.8% for HDPE, LDPE and PP respectively. Comparison with the preliminary for the percentage of impurity is shown in Table 4-5.

Table 4-5 Comparison of Impurity Percentage for Plastics from Landfill

Plastic Type	Preliminary Study		Final Study	
	Sample Size	Impurity Percentage	Sample Size	Impurity Percentage
HDPE	19	10.1	50	13.1
LDPE	54	23.4	58	24.1
PP	33	17.8	38	19.5

Table 4-5 shows that the sample size does not change the percentage impurity irrespective of the three different types of plastics. Adding more plastic from the same source will provide equivalent results.

Box and Whisker plot was introduced as a tool to analyze the percentage of impurity from the plastics. Figure 4.3 shows the box and whiskers plot of the percentage of impurity for three types of plastics, with and without outliers.



(a) **(b)**

Figure 4.3 Box and Whisker plot for impurity percentage (a) with outliers and (b) without outliers

In case of HDPE, no plastic had outlying amount of impurity, and the minimum and maximum amount of impurity was as low as 0.9% and as high as 37.4% respectively. However, 50% of the impurity percentage of HDPE ranged from 6.5% to 18.9%. The mean (13.0%) is more than the median (9.3%) meaning that most of the HDPE plastics have impurity less than their mean.

A similar trend was found for LDPE and PP. Both have their median is less than their mean. In the case of LDPE, 50% of the plastics have 13.8% - 27.8% impurity and in case of PP, the impurity ranges between 9.0% - 26.2%. The mean percentage of impurity for LDPE and PP is found 24.1% and 19.5%. Considering all three types, LDPE was found to contain more impurities than others. In two cases, LDPE contained 85% and 105% of impurity and these are considered outliers. These cases may be rare in case of HDPE and PP. A summary of the calculations is shown in Table 4-6.

Table 4-6 Summary of calculations from the Box and Whisker plot for source 1

Impurity Parameters	**HDPE**	**PP**	**LDPE**
Minimum (%)	0.9	0.4	1.7
End of 1st Quartile, Q_1 (%)	6.5	13.8	9.0
End of 3rd Quartile, Q_3 (%)	18.9	27.8	26.2

Median (%)	9.3	20.9	15.3
Mean (%)	13.0	24.1	19.5
Maximum (%)	37.4	105.3	61.6

This plot shows that the boxes are comparatively smaller than the other two quartiles, which means that most of the plastics' impurities tend to cluster in the middle and have a pattern rather than random outlying values.

<u>Source 2 (University Campus)</u>

As mentioned earlier, the university campus plastic waste was not blended in all sorts of wastes, hence, the number of plastics taken into account is considered valid. A total of 70 plastics of three different types were cleaned and their percentage of impurity is shown in the Figure 4.4. The range of percentage of impurity for HDPE, LDPE and PP is found 1%-16%, 5% - 45% and 1% - 28% respectively. This shows a lower range of impurity compared to the landfill and does not have any outlier. This brings back the reason for not getting blended with other types of wastes such as landfill.

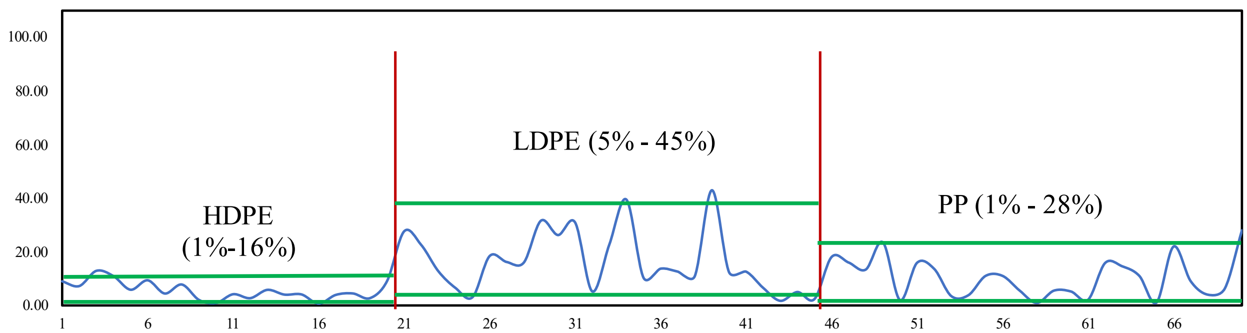


Figure 4.4 Percentage of impurity in the plastic wastes collected from the university campus

Average percentage of impurity was calculated in the same manner as of the waste plastics collected from the landfill. A summary of calculation for the impurity percentage of these plastics are shown in Table 4-7.

Table 4-7 Calculation of impurity percentage for the plastics from university campus

Types of Plastics	Total Weight of plastics with IMPURITY (gm) (a)	Total Weight of Clean Plastic (gm) (b)	Total Weight of Impurity (gm) (a)-(b)	Average % of Impurity compared to Clean Plastic (Wt. basis)
HDPE	1102.7	1046.49	56.21	**5.5**
LDPE	274.09	235.93	38.16	**16.4**
PP	215.47	197.97	17.5	**10.5**

For the plastics from university campus, the average percentage of impurity of HDPE, LDPE and PP is found 5.5%, 16.4% and 10.5% respectively. Average impurity of this source is less than the landfill.

A similar Box and Whisker plot was introduced to analyze the data of impurity percentage gathered by cleaning plastics from the university campus.

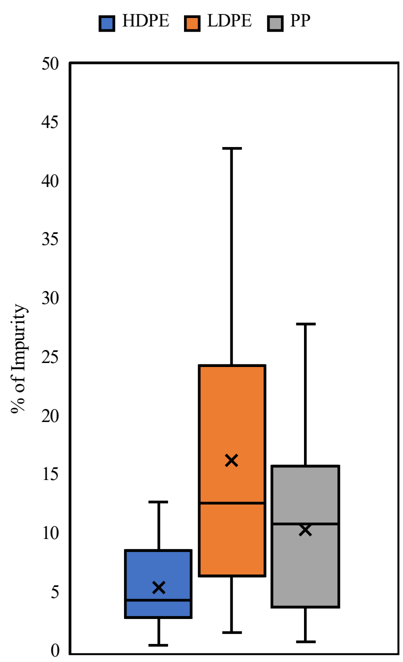


Figure 4.5 Box and Whisker plot for impurity percentage of plastic waste

From Figure 4.5, it is evident that LDPE plastics contain variety range of impurity that's why the 50% box in the middle is bigger than the other two types. It was found that 50% of the total plastics of HDPE have impurity 2.9% - 8.6%, whereas this range for LDPE and PP is 6.5% - 24.4% and 3.8% - 15.8% respectively. In this analysis as well, the median is less than or very close to mean value, which denotes that major plastics have less impurity than the average value. The summary of the box and whisker plot is given here (Table 4-8).

Table 4-8 Summary of calculations from the Box and Whisker plot for source 2

Impurity Parameters	HDPE	LDPE	PP
Minimum (%)	0.6	1.6	0.9
End of 1st Quartile, Q_1 (%)	2.9	6.5	3.8
End of 3rd Quartile, Q_3 (%)	8.6	24.4	15.8
Median (%)	4.4	12.7	10.9
Mean (%)	5.5	16.4	10.4
Maximum (%)	12.8	42.9	27.9

As a part of the statistical analysis, a 95% confidence interval was determined. In such a way, the range of impurity percentage which can be claimed as 95% true can be determined. Figure 4.6 shows the 95% confidence interval for 3 types of plastics from 2 different sources.

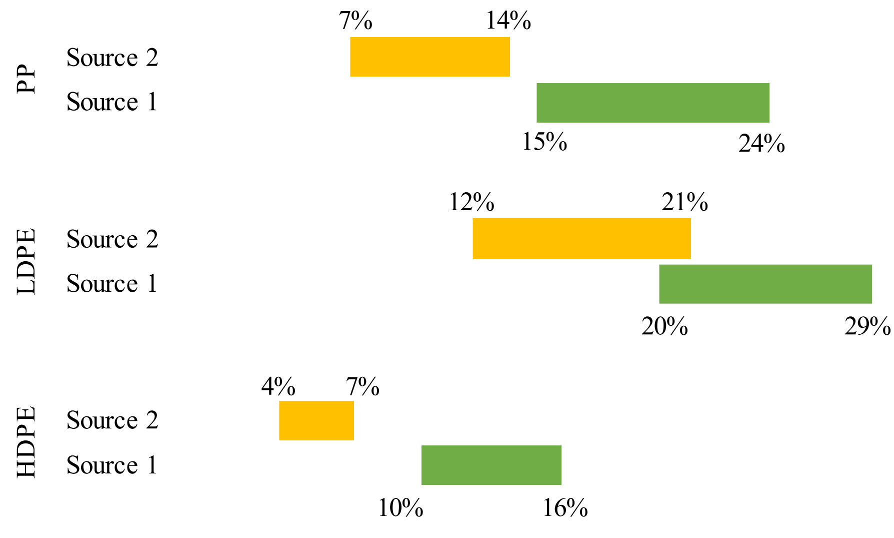


Figure 4.6 A 95% confidence interval for 3 types of plastics from 2 different sources

Figure 4.6 depicts with 95% confidence that in both cases, the HDPE plastics have less than 20% impurity. However, PP may be analyzed depending on the source of collection and LDPE should always be analyzed before claiming that it can contain less than 20% impurity in them. This can be understood from the figure that the range of the percentage of impurity does not vary more than 10% independent of the source or the type of impurity.

<u>Impurities in LDPE</u>

Figure 4.7 Impurities found in the LDPE type plastics

Impurities in HDPE

Food, Paper, Soil

Liquid Food, Paper

Soil Particles

Figure 4.8 Impurities found in the HDPE type plastics

Impurities in PP

Food

Liquid Food

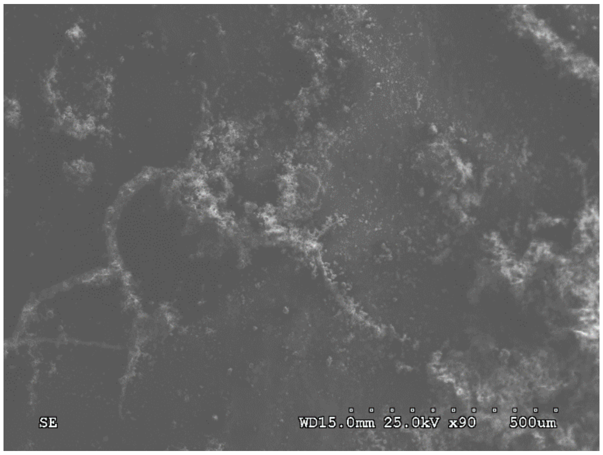
Leftover from Cold Drinks

Paper Labels Food Liquid Food

Rubber Food

Figure 4.9 Impurities found in the PP type plastics

In addition to the visual pictures, Scanning Electron Microscopy (SEM) was carried out to examine plastics with impurity in microscopic level. The scope of SEM was to find any discrepancies in the impurity to visually figure out the type of impurity that was being contained in the plastic sample. In this case 4 pieces of smooth surfaced plastic samples (5mm x 5 mm x 1mm) were used to observed inside the microscope. Followings are the photos observed utilizing SEM.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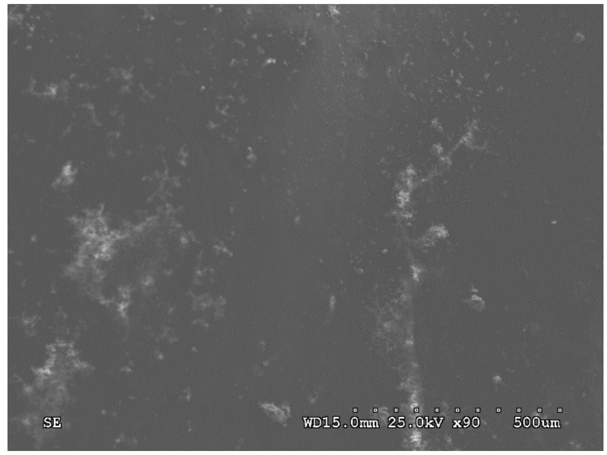
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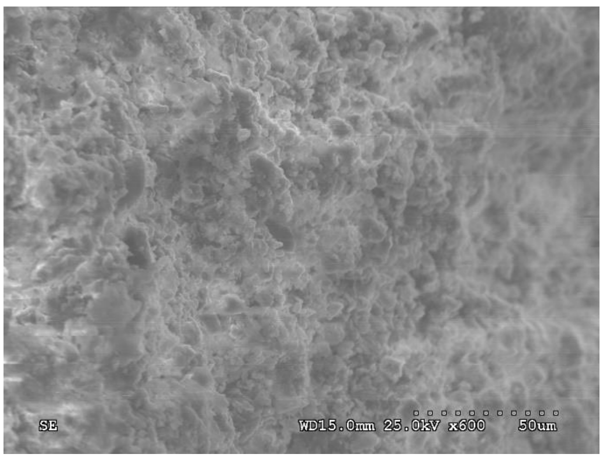
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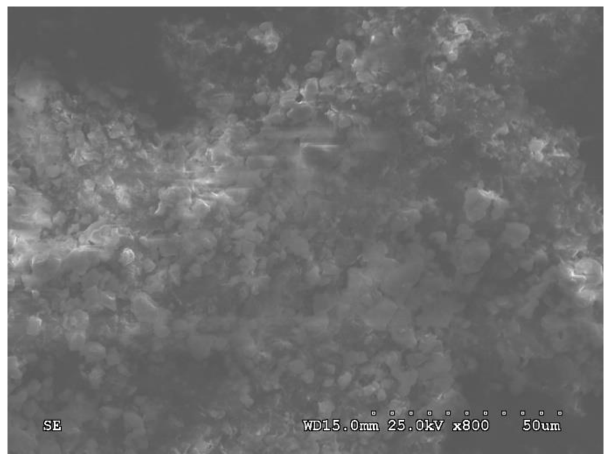
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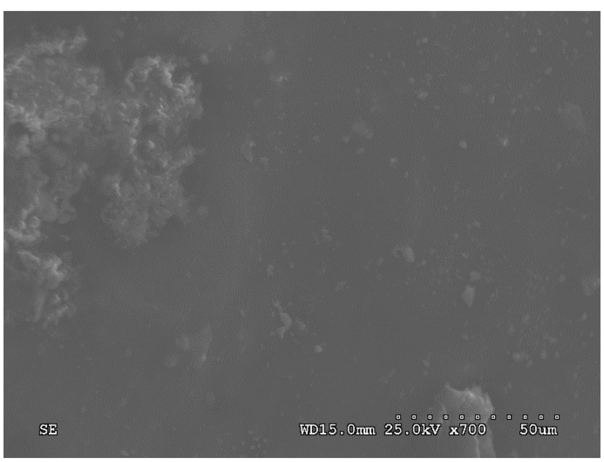
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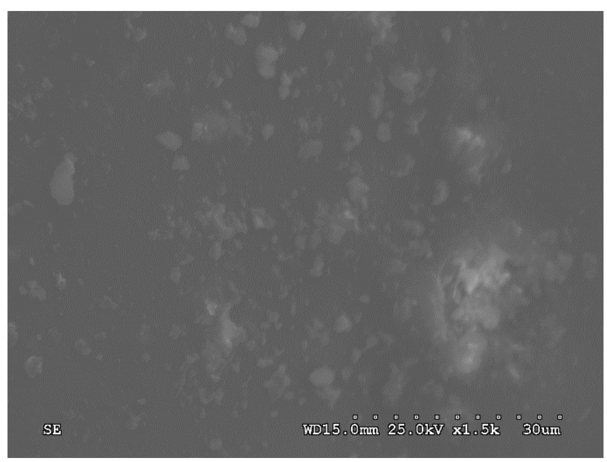
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WD15.0mm 25.0kV x1.5k 30um

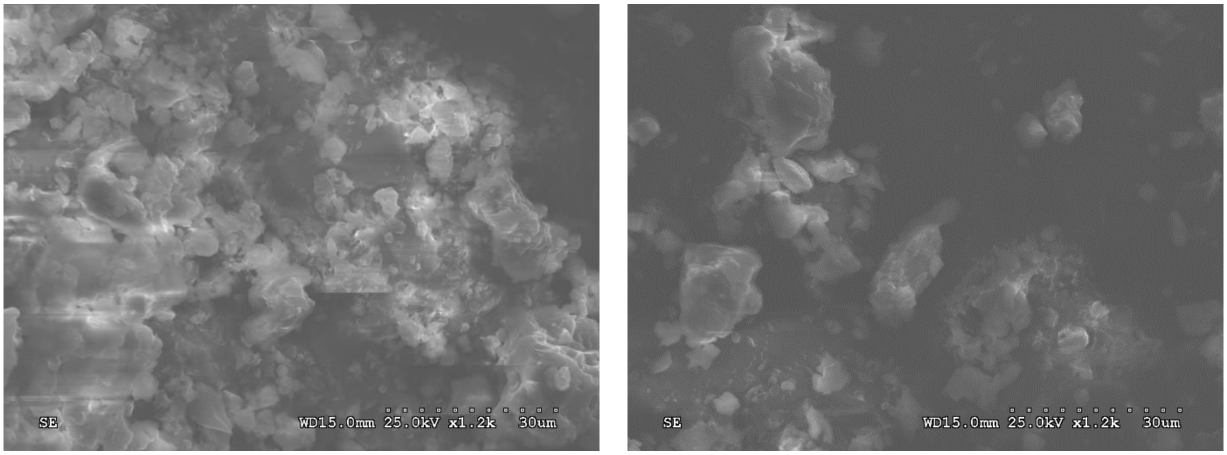


Figure 4.10 Scanning Electron Microscopy (SEM) on plastics with impurity

4.3 Volumetric Analysis

Before performance tests of asphalt mix, volumetric analysis was done. Compaction is an important parameter in superpave mix design. According to TxDOT manual, high traffic i.e., design ESAL ≥ 30 million corresponds to 50 gyrations of superpave gyratory compactor. Volumetric tests are one of the passing criteria for designing asphalt mix because laboratory air voids should be between 3-5%. Hence, the trend of air voids after adding plastics with impurities in the asphalt mix has been considered and checked for the suitability for mix design.

Two volumetric tests were conducted to find out the air voids of asphalt: Bulk density test and Rice gravity test (Theoretical maximum specific gravity test) according to Tex-207 Part I and Tex-227-F respectively. From these two tests, the results were utilized to find out the air void using the following equation.

$$Air\ void\ (\%) = \left(1 - \frac{G_{mb}}{G_{mm}}\right) * 100$$

Where, G_{mb} = Bulk specific gravity (gm/cc)

G_{mm} = Theoretical maximum specific gravity (gm/cc)

At first, the percentage of impurity found from the preliminary study was used for finding out the air void criteria. Table 4-9 shows the preliminary test results of the asphalt mix where the percentage of impurity of HDPE, LDPE and PP were found 11%, 23% and 17%. The data from the air void analysis shows that the air voids for HDPE and LDPE go beyond 5% which is the standard.

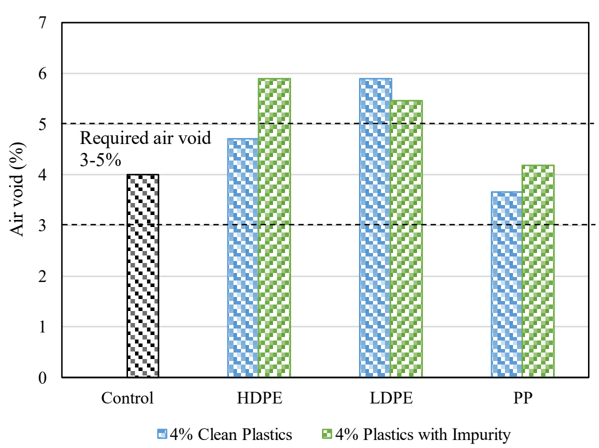
Table 4-9 Volumetric test results for preliminary study

Plastic Type	Percentage of Impurity	Plastic % + Bitumen %	
		4% + 96%	8% + 92%
HDPE	11%	5.89	5.19
LDPE	23%	5.46	5.31
PP	17%	4.18	4.85

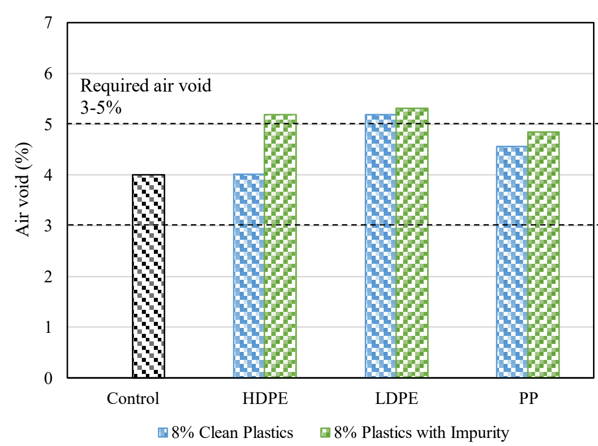
These results were compared with Islam, 2021. It was observed that using 4% and 8% plastics with impurity changes in the air void. The air void for HDPE plastic with impurity went beyond the limiting value in 4% and 8% plastic use, however, it was within limit when the HDPE was used after cleaning.

In the case of PP and LDPE, the trend was similar. LDPE with and without impurity did not yield to the limiting requirement of 5% air void. However, using PP satisfied the limiting requirement of air void in both clean plastic and impure plastics.

Figure 4.11 Preliminary study results of air void analysis. Figure 4.11 shows the analysis of the air void results for 8% and 4% plastic use in asphalt mix with and without impurity. The trend was similar, however, the results in some cases were erratic. Therefore, different levels of impurity were introduced to find out the proper trend of the air void.



(a)



(b)

Figure 4.11 Preliminary study results of air void analysis for (a) 4% plastics and (b) 8% plastics

As per methodology, 3 different percentages of impurity (10%, 20%, 30%) were introduced in the asphalt mix with the plastics of 4% and 8% and the air void was measured performing the laboratory tests. The data and results of 4% and 8% plastic that contain impurity are shown in

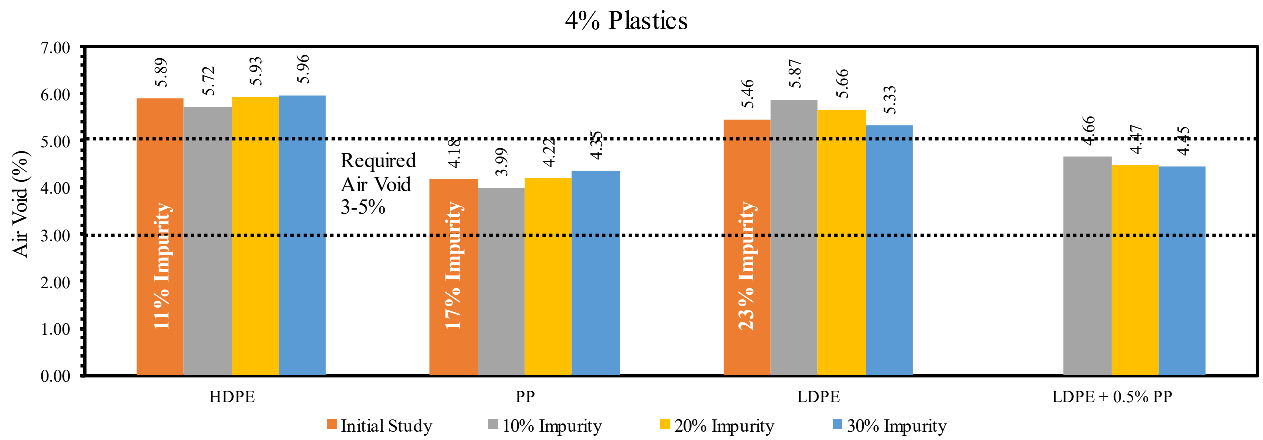
Table 4-10.

Table 4-10 Volumetric test results of asphalt mix with 4% and 8% plastic with impurity

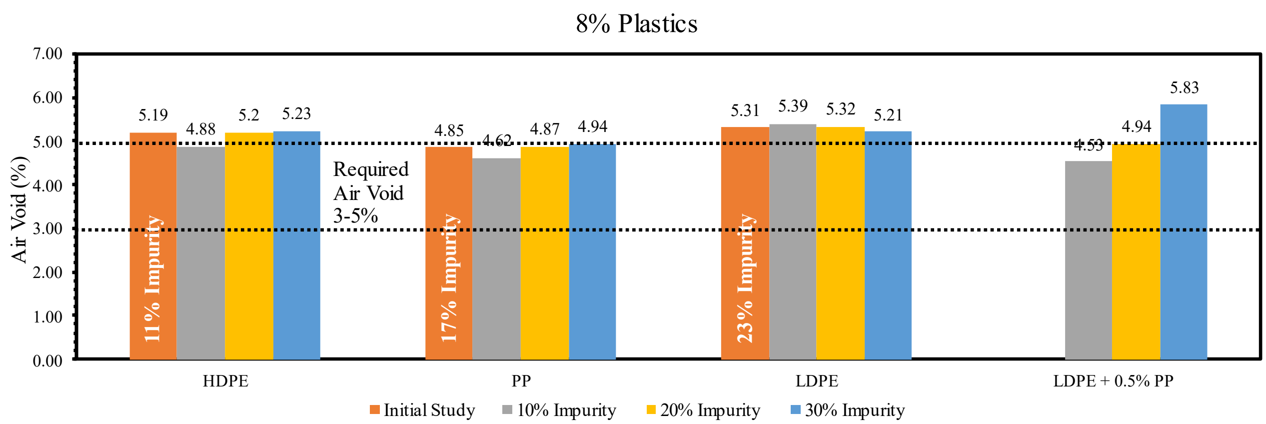
% Plastic + % Bitumen	Plastic Type	% Impurity (of % Plastic)	Specific Gravity, G_{mb} (gm/cc)	Max. Specific Gravity, G_{mb} (gm/cc)	Air Void (%)
4% + 96%	HDPE	10%	2.39	2.53	5.72
		20%	2.45	2.60	5.93
		30%	2.46	2.62	5.96
	LDPE	10%	2.36	2.51	5.87
		20%	2.45	2.59	5.66
		30%	2.41	2.55	5.33
	PP	10%	2.42	2.52	3.99
		20%	2.46	2.57	4.22
		30%	2.38	2.49	4.35
8% + 92%	HDPE	10%	2.48	2.61	4.88
		20%	2.45	2.58	5.20
		30%	2.41	2.54	5.23
	LDPE	10%	2.37	2.51	5.39
		20%	2.41	2.55	5.32
		30%	2.49	2.63	5.21
	PP	10%	2.40	2.52	4.62

	20%	2.46	2.59	4.87
	30%	2.39	2.51	4.94

From this table, it can be observed that only PP mixed asphalt samples irrespective of the percentage of impurity pass the criteria of having air voids in 3-5%. As LDPE has higher than 5% of air voids and PP has less than 5% air voids, a mix has been introduced with 4% and 8% LDPE as replacement of bitumen and 0.5% PP as replacement of aggregate and air void was determined for the asphalt mix in a similar way. Graphical representation of this analysis for 4% and 8% plastic mixed asphalt is shown in Figure 4.12.



(a)



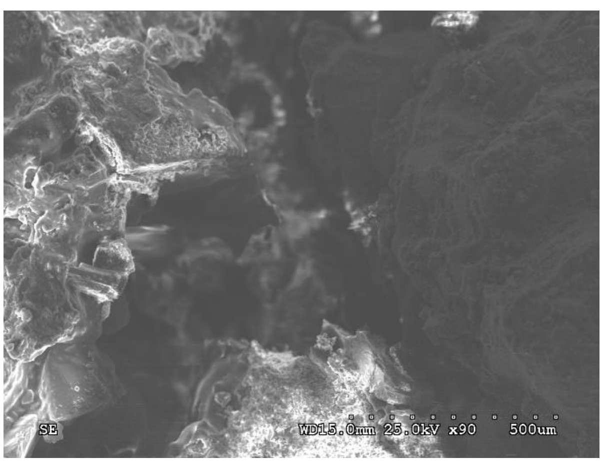
(b)

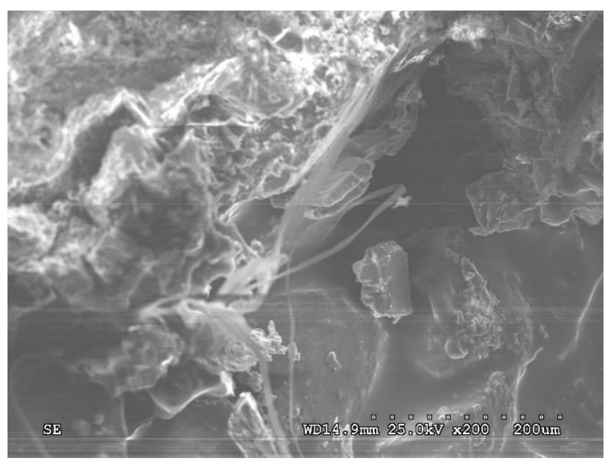
Figure 4.12 Air void analysis of 4% and 8% plastics use in asphalt mix with different level of impurity

In the case of using 4% plastic in the asphalt mix, HDPE and LDPE could not fulfil the air void criteria. The air voids go beyond 5%, whereas using PP with any percentage of impurity keeps the air void in 3-5% range. It can be understood that the change of impurity amount does not affect the air void much rather any percentage of impurity eventually affects the air void. Furthermore, when LDPE and PP are mixed together yet, with different purpose, the air void in the mix could maintain the permissible range.

While using 8% of plastic, eventually the percentage of impurity increases. In the case using HDPE and LDPE, the voids get filled in with the impurities and the bitumen content as well, and the air voids decrease. However, the air voids still stay out of the limit. However, the air voids are very close to 5% in both cases. In the case of using PP the air voids actually increase but it stays within the permissible range. The homogeneity of the impurities present in the asphalt mix results in the different types of behavior in the air voids analysis. The amalgamation of LDPE and PP shows a different trend. As the PP is introduced as aggregate replacement, the air voids start to increase while using 8% LDPE. Therefore, the effect of LDPE seems more than using PP in the asphalt mix. This may also result in because of the increased impurity content due to the increase amount of LDPE in the mix.

The voids in the asphalt mix could be visibly seen under the microscope during examining the plastic mixed asphalt samples. There were 3 samples containing HDPE type plastics in the asphalt mix and the impurity content was 20%. Followings are the photos taken by the microscope.





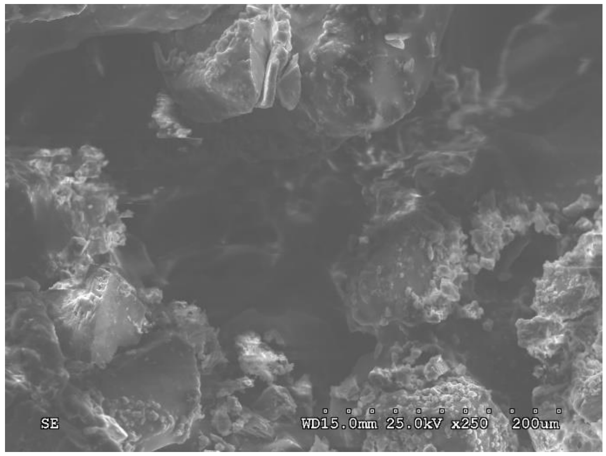


Figure 4.13 Air voids in the asphalt mix found in the SEM

4.4 Rutting Analysis

Hamburg Wheel track Test (HWTT) was conducted to find out the rutting resistance of the plastic-asphalt mix with different levels of impurities in the plastics. The analysis of the rutting test is shown based on different types of plastics and different percentages for each type of plastics. First, analysis for 4% and 8% HDPE is shown followed by LDPE, PP and LDPE + PP combination.

<u>HDPE Plastics</u>

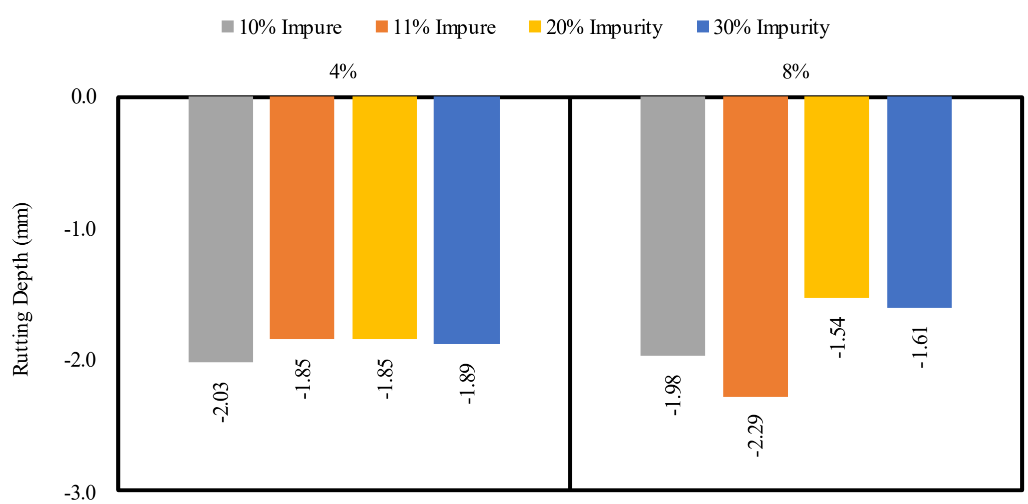
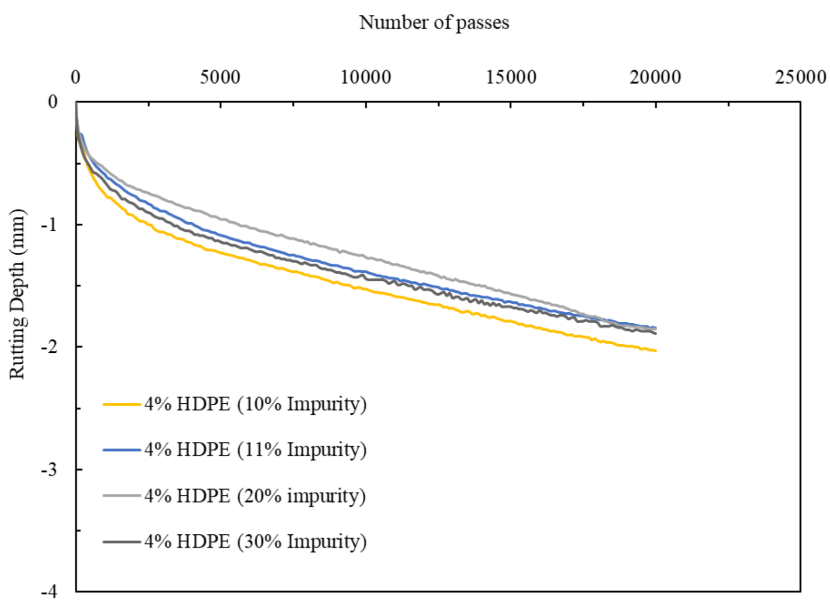
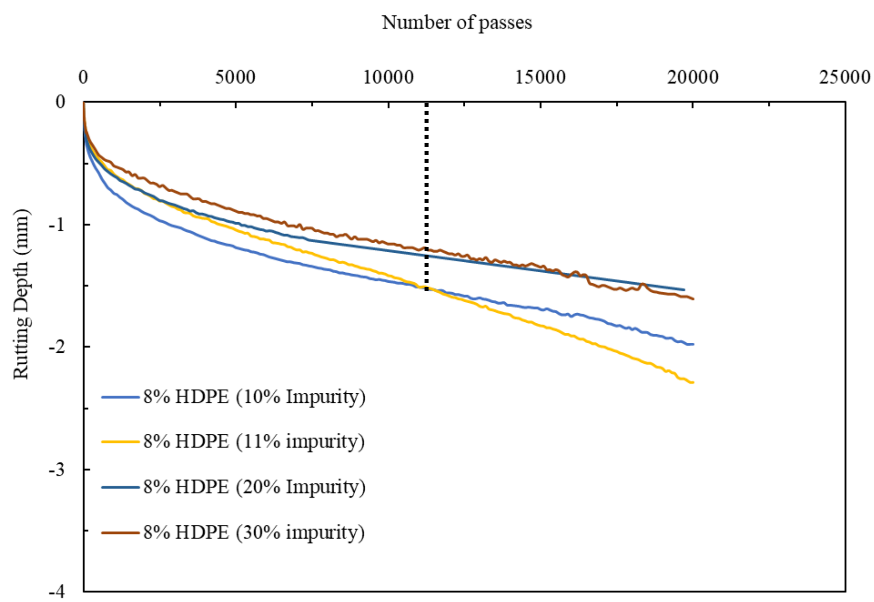


Figure 4.14 Final rut depth for 4% and 8% HDPE in the asphalt mix for different level of impurity

Figure 4.14 shows that impurity is not the biggest factor while adding HDPE in the asphalt mix. For 4% of HDPE, the change in the percentage of impurity did not affect the final rut depth, even adding 30% of impurity in the mix does not change the rut depth much. The effect of mixing HDPE makes the mix stiff enough to prevent it from rutting over the wheel pass and in this case the impurity could not show detrimental effect in it. Figure 4.15 also shows that the rutting profile is more likely the same in all the cases.



(a)



(b)

Figure 4.15 Rutting profile for 4% and 8% HDPE mixed asphalt with impurities

The rutting profile for using HDPE with different levels of impurity is shown in Figure 4.15. For both 4% and 8% HDPE, the change in the profiles due to the presence of impurity is not significant. However, the preliminary study for using 8% HDPE which contained 11% impurity shows that after 11500 passes, the sample becomes susceptible to rutting depression drastically. Yet, it did not show any stripping inflection point (SIP) where the asphalt mix starts to degrade due to moisture damage. Plastics in the preliminary study did not contain as homogenous impurity as the final study which can be a reason of certain depression.

LDPE Plastics

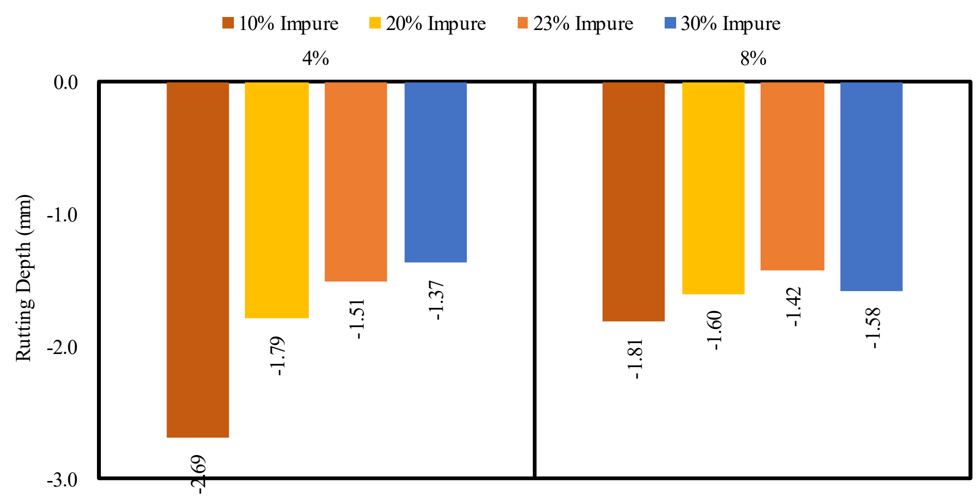
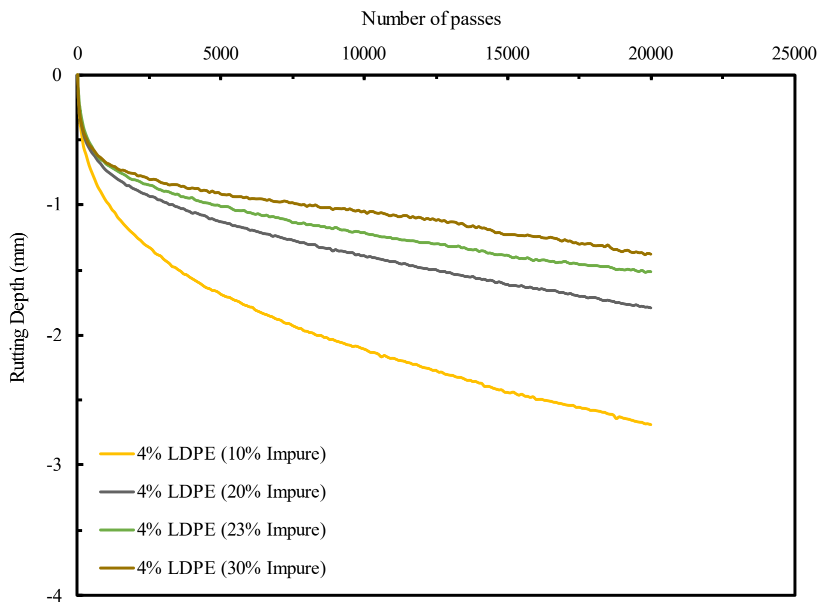


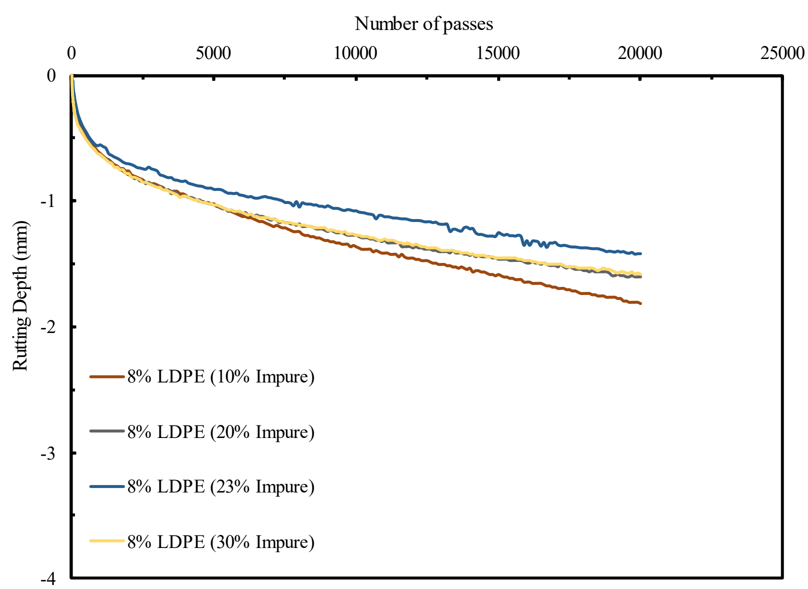
Figure 4.16 Final rut depth for 4% and 8% LDPE in the asphalt mix for different level of impurity

In case of using LDPE with impurity in the asphalt mix, the increase in the amount of impurity decreases the final rut depth of the asphalt mix. For using 4% LDPE in the mix, the increase in the percentage of impurity decreases the rut depth. While 10% impurity in 4% LDPE has the highest rut depth, it decreases as the percentage of impurity increases, meaning that the impurities are imposing positive impact in the mix. This means that the effect of the presence of impurity is more than the effect of 4% LDPE in the asphalt mix. This was the same for 8% LDPE up to 20% of impurity. However, it can be observed that, while containing 8% LDPE in the asphalt mix, presence of impurity does not change the rutting as much as it changed for 4% LDPE. Therefore, it can be concluded that the effect of 8% LDPE surpasses the effect of the impurity.

Figure 4.17 shows the rutting profile for using LDPE with different level of impurities. All the profiles have a similar trend. Although 4% LDPE with 10% impurity had resulted in an increased rut depth, it did not show any stripping inflection point (SIP), hence it can be said that impurity in the LDPE did not affect significantly. As it has already been observed that LDPE contains more amount of impurities than the other, but at this amount, introducing LDPE in the asphalt mix can outstand the impurities.



(a)



(b)

Figure 4.17 Rutting profile for 4% and 8% LDPE mixed asphalt with impurities

PP Plastics

PP, however, while adding in the asphalt mix with impurities shows a different trend. For using 4% and 8% PP, in both cases, as the impurities increase, the asphalt mix shows higher rut depth (Figure 4.18).

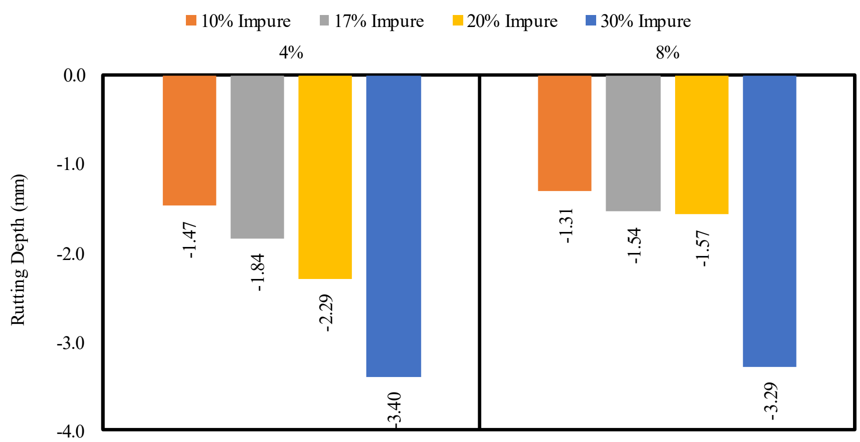
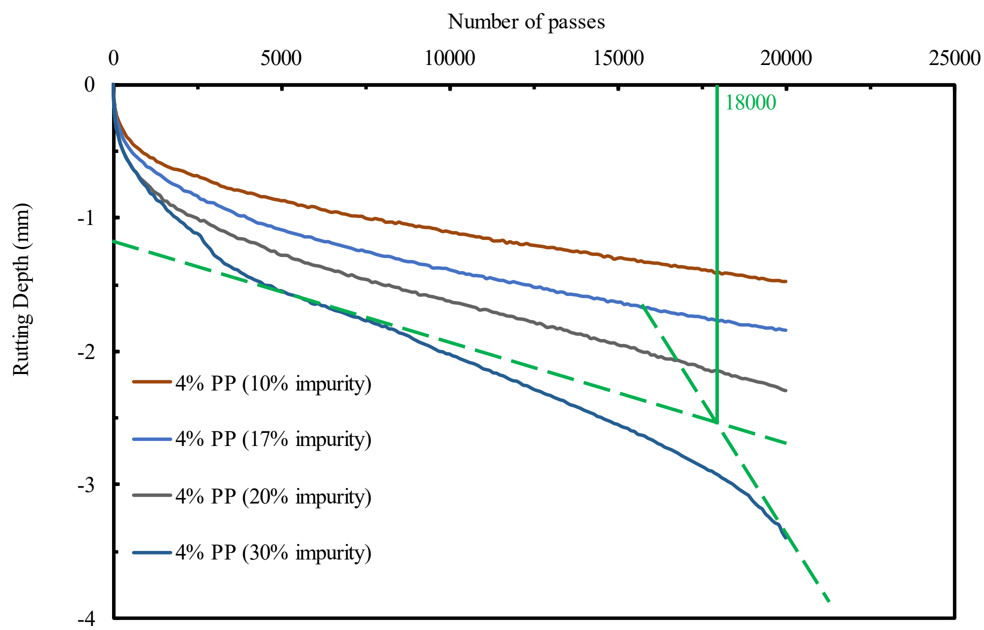


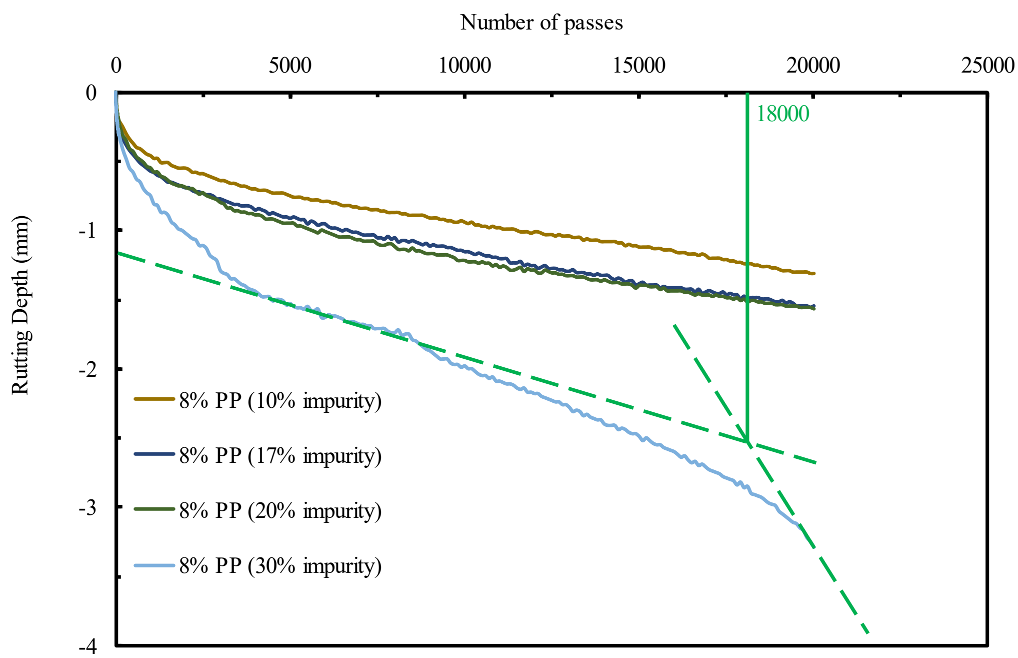
Figure 4.18 Final rut depth for 4% and 8% PP in the asphalt mix for different level of impurity

As shown in the above-mentioned figure, the rut depth keeps on increasing as the percentage of impurity increases. Hence, there is detrimental effect of impurities in the asphalt mix with PP. In case of 4% PP, the effect is mostly increasing at a rate but in case of 8% PP in the asphalt mix, impurity up to 20% was showing almost same trend, however, containing 30% impurity can cause a high rut depth in the pavement.

Not only did adding PP of 4% and 8% with 30% impurity show high rut depth, but it has also initiated the stripping inflection point (SIP).



(a)



(b)

Figure 4.19 Rutting profile for 4% and 8% PP mixed asphalt with impurities

From Figure 4.19, it can be observed that the SIP starts to initiate by the end of 18000-wheel passes in the HWTT and the asphalt becomes susceptible to moisture. This is true for both 4% and 8% PP in the asphalt mix with 30% impurity.

<u>PP+ LDPE Plastic Combination</u>

This generates the idea of mixing PP as aggregate with LDPE as replacement of bitumen. As 8% LDPE with any percentage of impurity was making the asphalt mix stiff, the PP was introduced as a replacement of aggregate. 0.5% PP, as a replacement for aggregate was used in the mix. As PP has a very low density compared to the aggregates, 0.5% contains a lot of PP volume-wise.

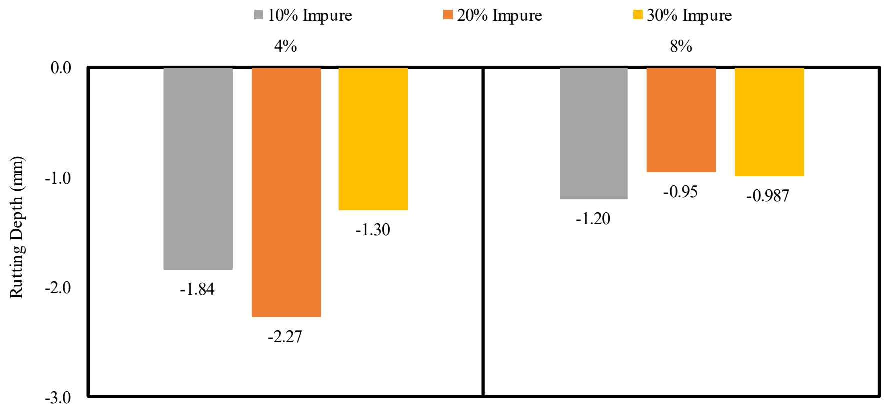


Figure 4.20 Final rut depth for 4% and 8% LDPE with 0.5% PP in the asphalt mix for different level of impurity

Figure 4.20 shows that the combination of 4% and 8% LDPE with 0.5% PP makes the mix stiffer as the final rut depth decreases to a good extent. When the LDPE amount is increased, the rut depth goes below 1 mm with 20% and 30% impurity.

LDPE itself had a lot of fine particles in the impurity. Hence, only fine soil was added as impurity in the LDPE and PP combination. In this case, soil particles that pass through #50 sieve were used. In this soil particle 50% was retained by #200 sieve.

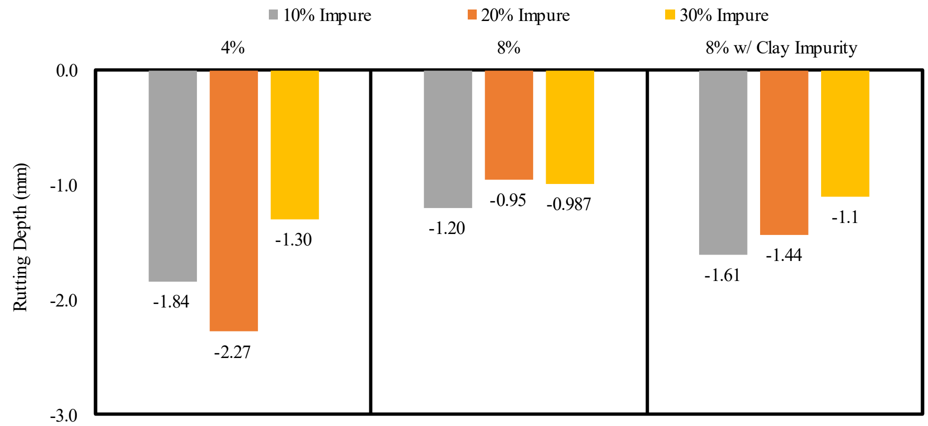
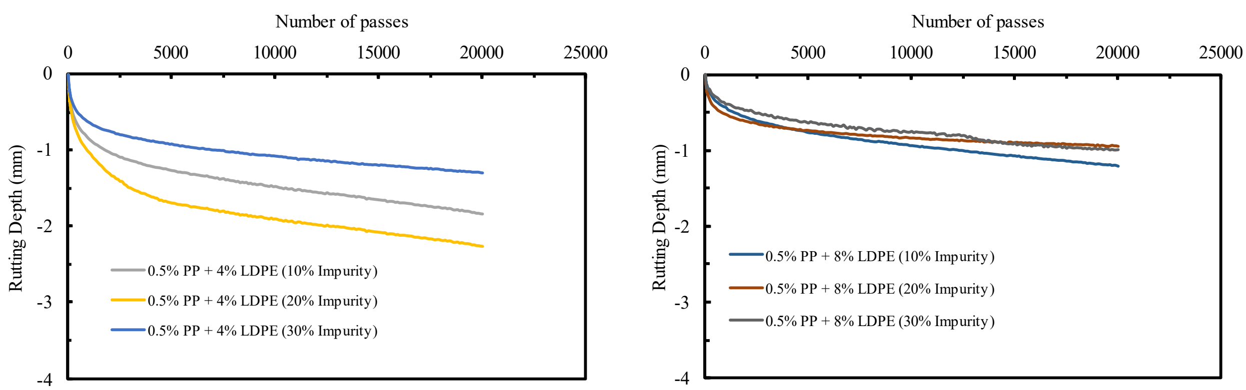
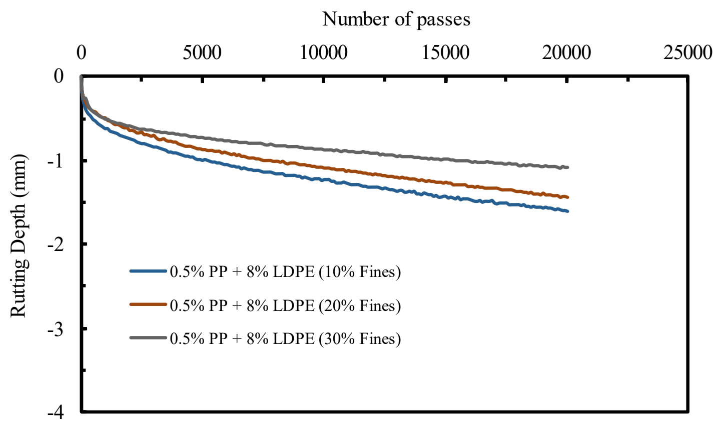


Figure 4.21 Final rut depth for 4% and 8% LDPE with 0.5% PP in the asphalt mix for different level of impurity and fines

Figure 4.21 shows the change while using 8% LDPE with 0.5% PP and different percentage of fine particles in them. The fine particles or soils showed less stiffness than the pervious combination which makes the asphalt mix more flexible. However, in any combination of using LDPE and PP together, the SIP did not initiate that is shown in Figure 4.22.



(a) (b)



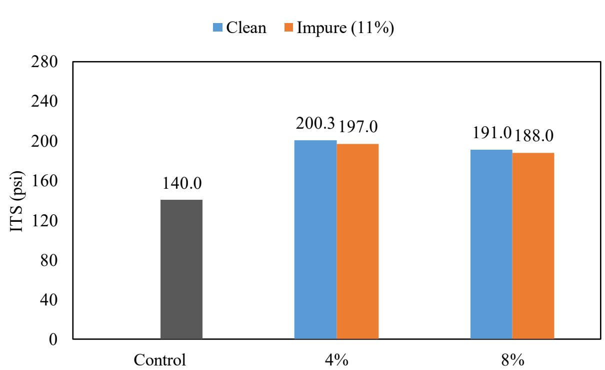
(c)

Figure 4.22 Rutting profile for 4% and 8% LDPE with 0.5% PP in the asphalt mix for different level of impurity and fines

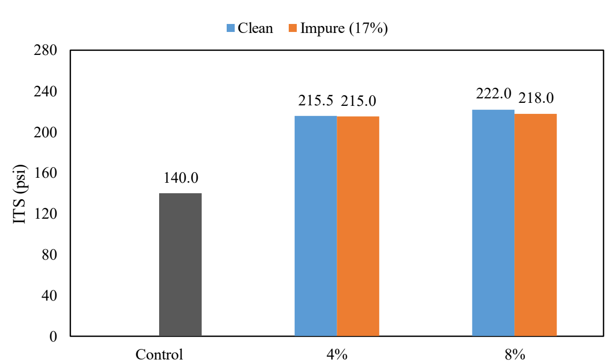
4.5 Indirect Tensile Strength (IDT) Test Analysis

The tensile strength of the asphalt mix modified with plastic with impurity in dry process was investigated by analyzing load-displacement relationships. The load-displacement curve can be analyzed to characterize the crack resistance of the asphalt mix modified with plastic containing impurities. The maximum load was determined from the graph and the value of the loads was compared. Specimens of 150 mm diameter and 62 mm height were prepared by compacting in superpave gyratory compactor and 3 tests were replicated to ensure repeatability of the results.

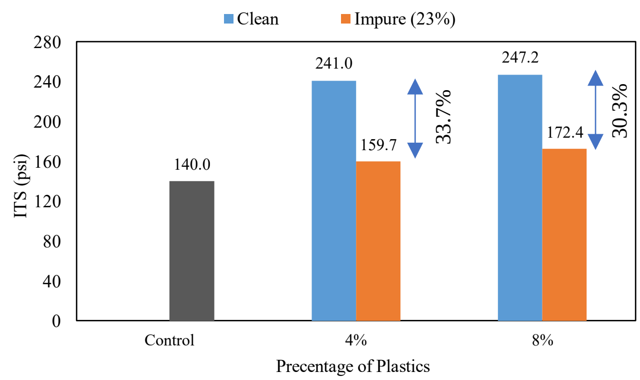
Primarily, indirect tensile strength (ITS) value was found from the preliminary investigated impurity content. For HDPE, LDPE and PP, the impurity content was 11%, 23% and 17% respectively. The ITS results for using plastics with initial impurity percentage is shown in Figure 4.23.



(a) HDPE plastics



(b) PP plastics



(c) LDPE plastics

Figure 4.23 ITS test results for 4% and 8% plastic with impurity (preliminary study) in asphalt mix

Figure 4.23 shows that using HDPE and PP in both 4% and 8% with impurity of 11% and 17% respectively did not change the tensile strength. However, in the case of LDPE which contained 23% of impurity in average showed a significant change in the strength. In both 4% and 8% plastic content, the strength reduction was more than 30%. The strength is, however, more than the control sample. 8% LDPE with impurity showed more strength than 4% LDPE with impurity. This is evident from these test results that more than 20% impurity has deteriorated the performance of the asphalt mix with plastics. Therefore, further investigation into different levels of impurity should be conducted.

Specific amount of impurity (10%, 20% and 30% of the weight of plastic of three types) was introduced to the plastic asphalt mix. The results are discussed in the following part of this section.

<u>HDPE Plastics</u>

HDPE type plastics had the least amount of impurity compared to other types of plastics. Different levels of impurity were introduced in HDPE while mixing HDPE with the aggregate. It was observed that 10% and 20% impurity does not affect the mix if it is compared with the clean sample. However, 30% impurity in 4% HDPE decreased the strength of the samples, on the other hand, 8% HDPE with 30% impurity in fact increased the strength of the samples (Figure 4.24).

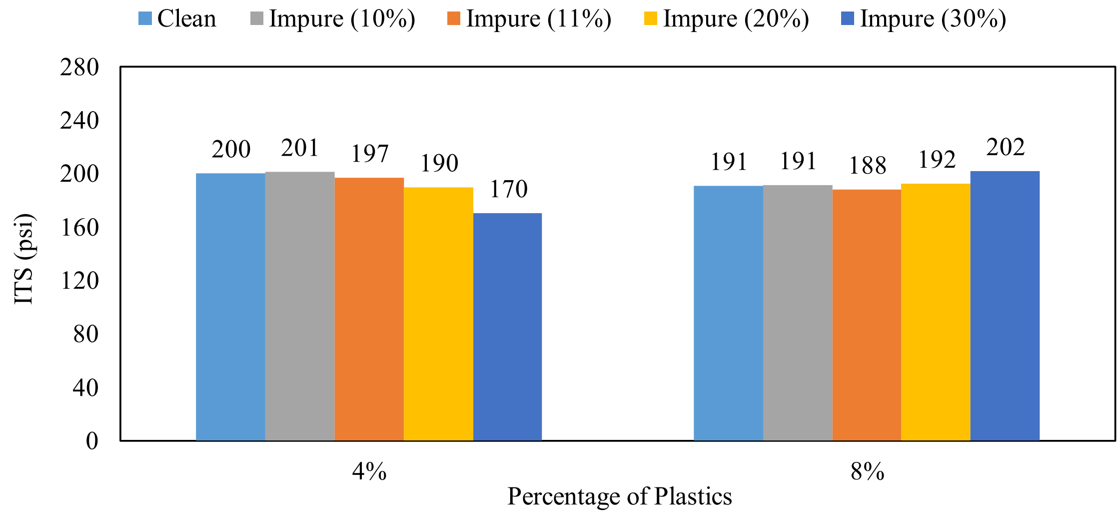


Figure 4.24 ITS of HDPE mixed asphalt samples (clean and different level of impurities)

It can also be observed that, for 4% HDPE, 10% impurities show similar strength compared to clean plastics, however the strength starts to decrease when impurity content increases (Figure 4.25).

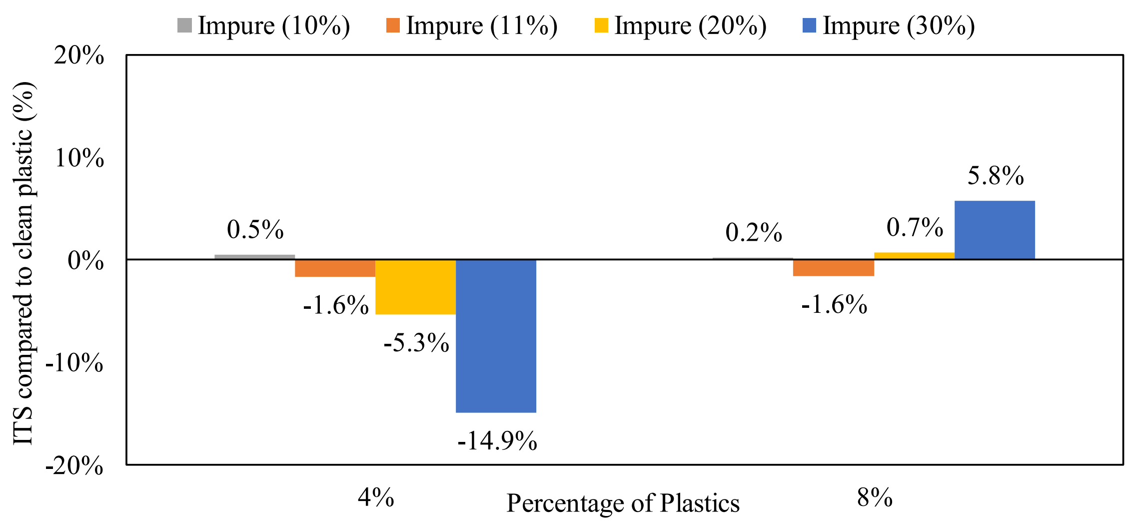


Figure 4.25 Percent change in ITS of impure HDPE mixed samples compared with clean HDPE

At 30% impurity, 4% HDPE shows approximately 15% decrease in strength. Figure 4.25, however shows that 8% HDPE with more than 20% impurity starts to increase the strength though the increase of strength is only 6%. The strength remains similar introducing impurities in case of the strength of the asphalt layer.

PP Plastics

PP, however, shows a different trend in 4% and 8% plastics. 4% plastics with only 10% impurity shows a skewed result. In case of other percentages such as 20% and 30% show uniform results (Figure 4.26). 4% of plastics show gradual increase as the impurity content increase, but 8% plastics show gradual decrease in strength.

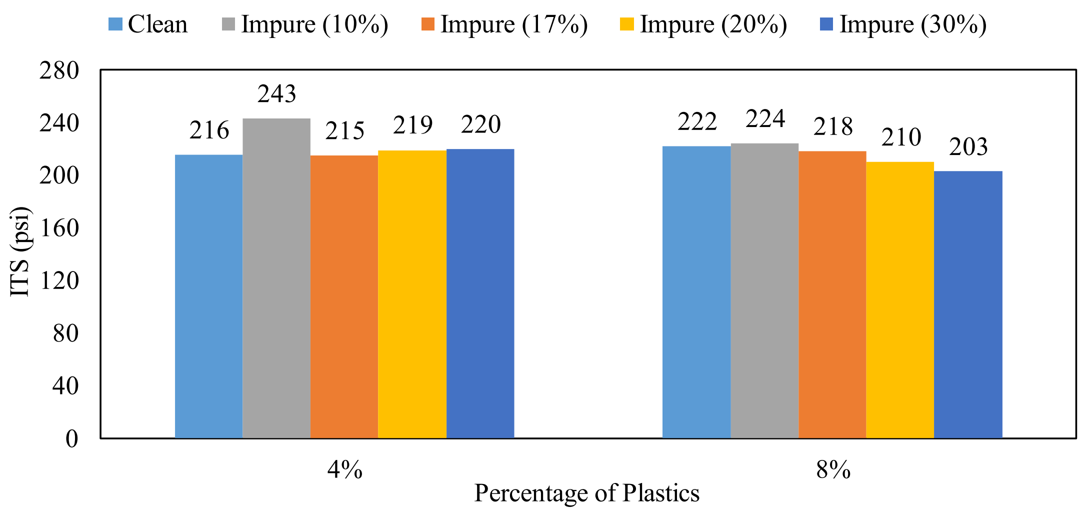


Figure 4.26 ITS of PP mixed asphalt samples (clean and different level of impurities)

The percent change in the strength is not significant if 4% plastics are used. 10% impurity in 4% PP shows more than 12% increase in the strength, nevertheless, up to 30% impurity can contain the similar strength if not increase more.

In the case of 8% PP, the trend shows a decreasing value as the percentage of impurity increases. However, the decrease in strength is not more than 10% and essentially it makes the mix less susceptible to a stiffer one.

Figure 4.27 shows the trend as discussed in the above paragraph. Apart from 4% PP with 10% impurity, the trend is uniform. The increase trend shows that presence of impurity is helping in gaining the strength. However, at 8% plastic, when the impurity is more, the mix starts to show negatively inclined trend in case of strength. Increasing the impurity percentage degrades the strength if the mix.

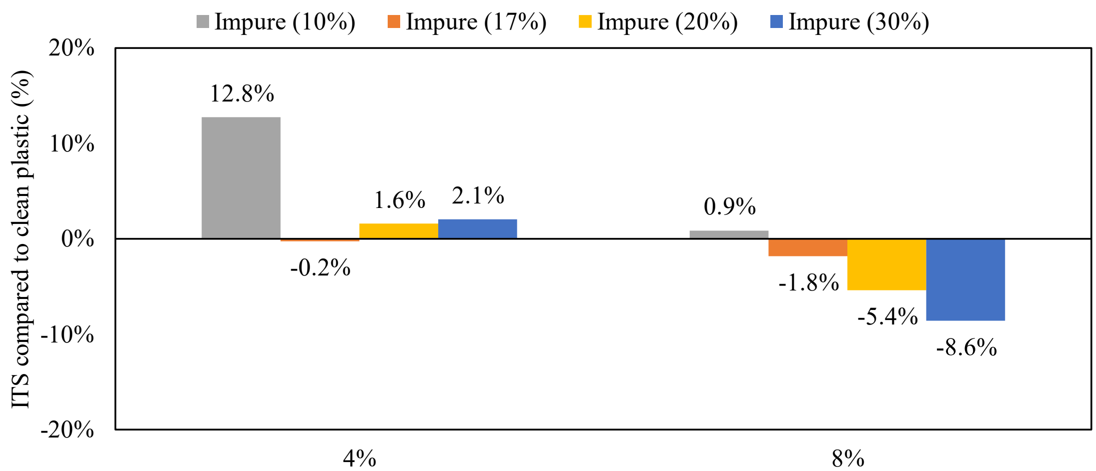


Figure 4.27 Percent change in ITS of impure PP mixed samples compared with clean PP

LDPE Plastics

LDPE type plastics exhibit different trends. As the impurities have been added, the performance starts to deteriorate starting from 10% impurity. This trend is applicable in both 4% and 8% plastics addition. However, at 30% impurity, the ITS increases in 2 different percentages of plastics addition (Figure 4.28). The reason behind this trend is the type of impurity contributing to the strength increase. Moreover, the higher amount impurity works better with the LDPE plastics, and this is a positive impact as LDPE generally contains higher amount of impurity.

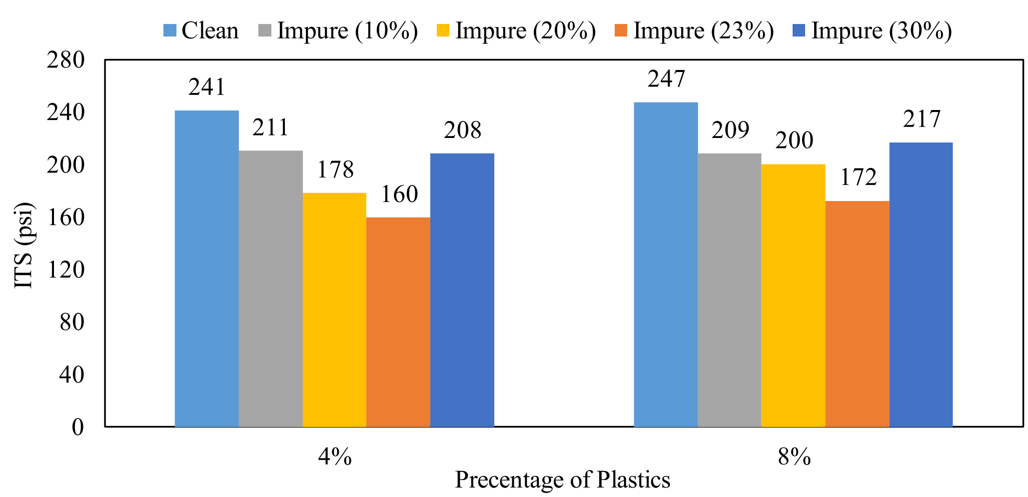


Figure 4.28 ITS of LDPE mixed asphalt samples (clean and different level of impurities)

If the change is compared in percentage, Figure 4.29 shows that 30% impurity in the plastics can increase the strength more than 10% if 4% and 8% plastics are introduced as a replacement of the bitumen. However, up to 25% impurity, the strength actually deteriorates more than 30% which means it can be susceptible to tensile force more than the clean plastics. However, 30% LDPE contained the specific type of impurity which enhances the performance of the asphalt mix to the tensile cracking.

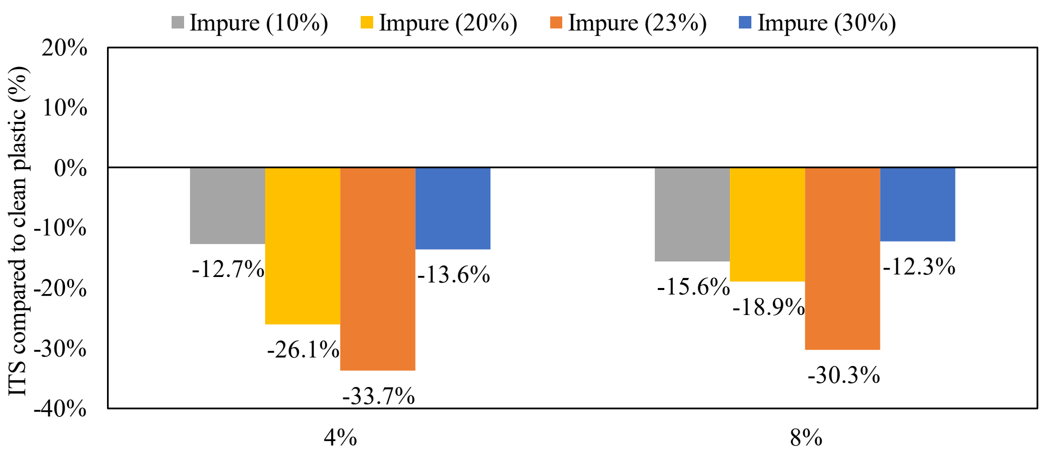


Figure 4.29 Percent change in ITS of impure LDPE mixed samples compared with clean LDPE

<u>**LDPE (replacement of bitumen) + 0.5% PP (replacement of aggregate)**</u>

As recommended by Islam (2021), the samples were prepared using 4% and 8% LDPE as a replacement of bitumen and 0.5% PP as a replacement of aggregate.

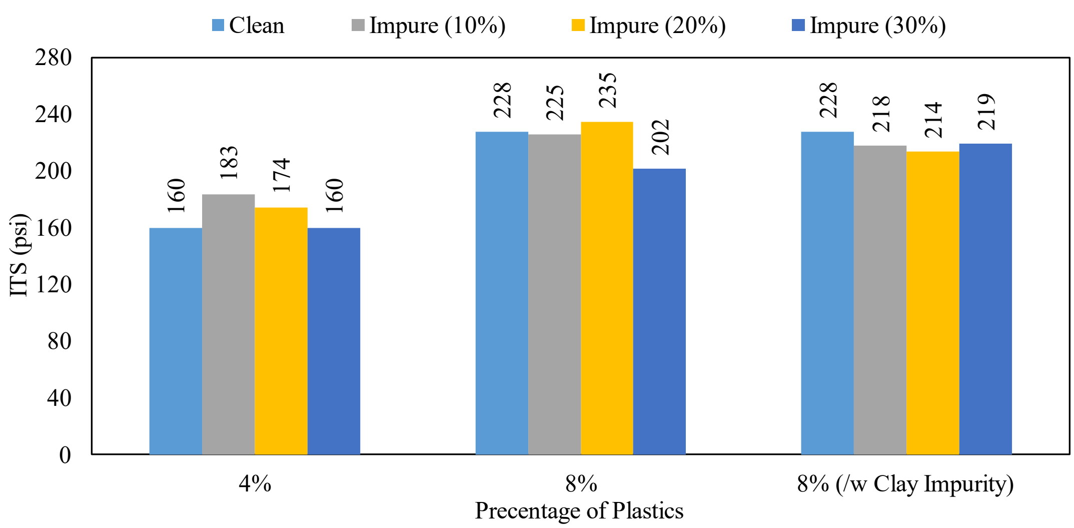


Figure 4.30 ITS of LDPE+PP mixed asphalt samples (clean and different level of impurities)

In both cases, the impurity up to 20% increases the tensile strength. However, when the impurity is 30%, the strength decreases (Figure 4.30). The strength gain or loss can be resulted from the different types of impurities mentioned earlier. The results of adding clay as impurity at different amount in 8% plastics is shown is Figure 4.30. The addition of adding only clay as impurity shows a very uniform strength in different levels of impurity. The increase in impurity from 10% to 30% where only clay is present shows 5% change in the strength although plastics with clay decreases the strength than the clean plastics (Figure 4.31).

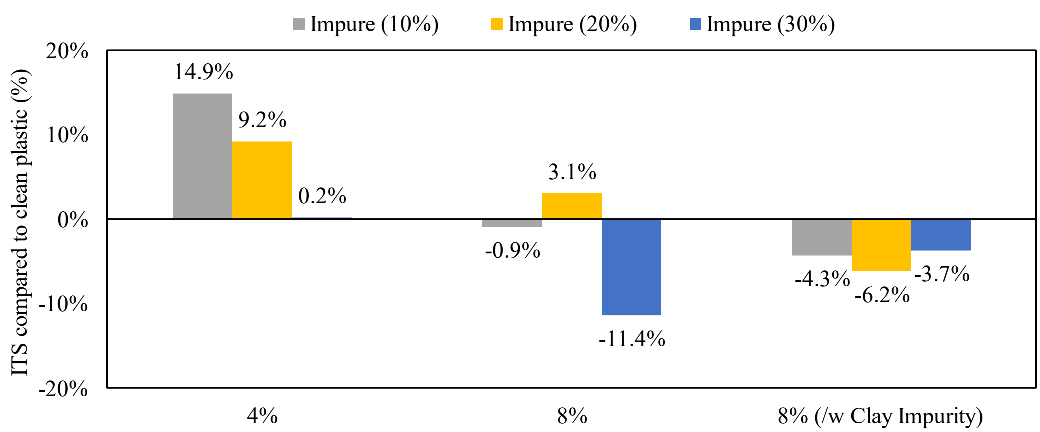


Figure 4.31 Percent change in ITS of impure LDPE+PP mixed samples compared with clean LDPE+PP

Addition of only clay as impurity was an important step to understand the reason of the strength increase or decrease while adding the plastics in different percentages. As clay in different percentages did not alter the strength of the asphalt mix as introduced with plastics, other forms of impurity were the reason for the strength alterations.

4.6 Moisture Susceptibility Test Analysis

Moisture susceptibility of asphalt mix can primarily be determined from the HWTT. However, AASHTO T 283 procedure for moisture susceptibility test exhibits the vulnerability of the asphalt mix after conditioning to moisture intrusions which is a direct measurement. Three samples were prepared for the repeatability of the test for different combinations and different levels of impurity. Similar to Indirect Tensile Strength tests, the average ITS value of the conditioned samples was taken, and the ratio was found out. The allowable value for TSR is reported as a minimum of 0.7. The samples with no plastics (control) comprised of 0.6 TSR which was found out unique tests on conditioned and unconditioned samples.

HDPE Plastics

HDPE plastics, at 4% replacement of bitumen with no impurity showed a significant improvement against moisture susceptibility. However, at 10%, the samples not only showed compromised performance than the clean plastics sample, it also dissatisfied the criteria for moisture susceptibility. The initial study with 11% impurity deteriorated the performance of the mix which complies that the moisture susceptibility depends on the types of impurity that are present in the plastics being used. 20% impurity followed similar trend which indicates that finding out the types of impurity is more important than the percentage of impurity present in the recycled plastics. At 30% impurity, the performace due to moisture reduces to half of the unconditioned situation (Figure 4.32).

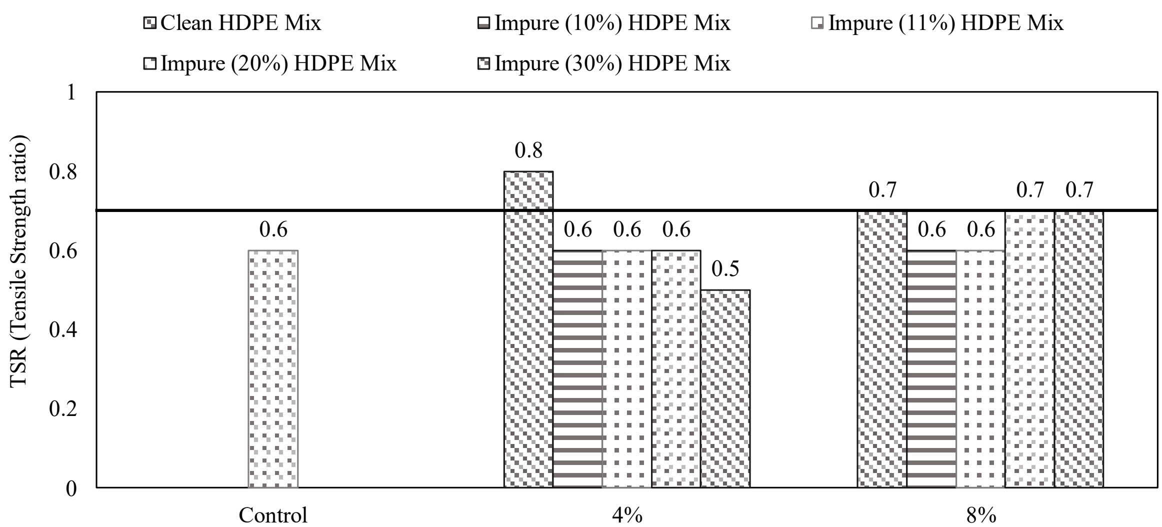


Figure 4.32 Tensile strength ratio of asphalt mix with HDPE at different levels of impurities

Figure 4.32 also indicates that with 8% plastics without impurity satisfies the criteria of TSR 0.7. However, 10% and initial 11% does not satisfy the TSR 0.7 criteria. At 8% addition of plastics with the aggregate takes in more impurity at 10% and 11% impurity level which hinders the plastics to have the cover with asphalt which is the reason for the performance degradation. moreover, air void remains more in such case and the moisture can easily percolate inside the aggregates and the mix becomes susceptible to moisture. However, at 20% and 30% impurity the performance elevates due to the amount of impurity affecting positively in the plastic mixed asphalt mix.

PP Plastics

PP as introduced clean can increase the performance against moisture susceptibility. However, if 4% PP contains 10% impurity, the performance against moisture deteriorates. However, 20% and 30% impurity actually enhance the performance which means more impurity contributes beneficially to the mix. In case of 8% impurity, this point can be proved. Up to 20% impurity, the TSR was found to satisfy the moisture susceptibility criteria. It can decrease the performance if there is 30% impurity as shown in Figure 4.33. Therefore, using PP in higher amount can result in positively.

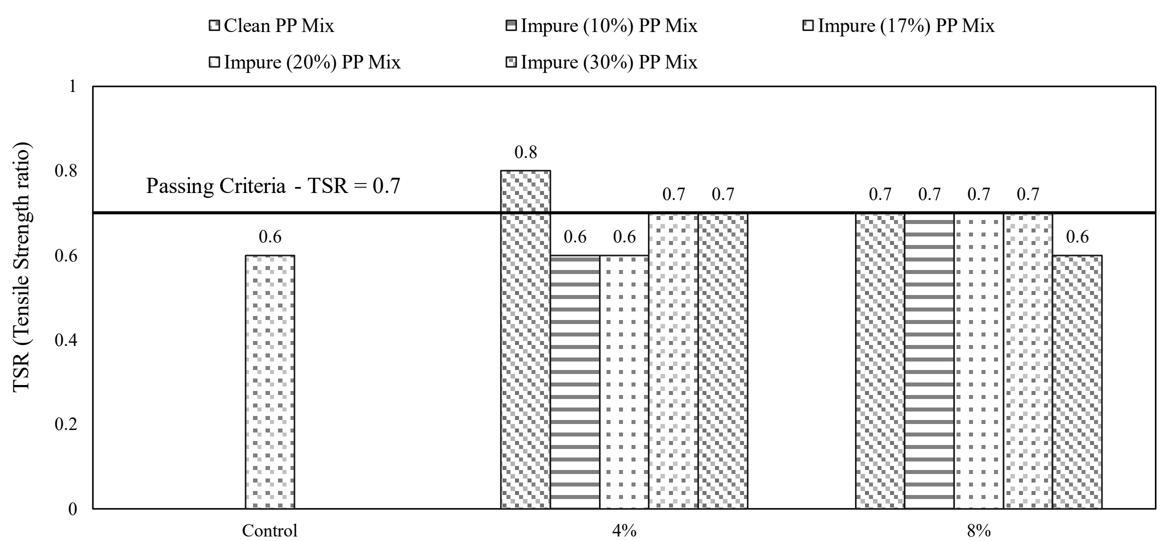


Figure 4.33 Tensile strength ratio of asphalt mix with PP at different levels of impurities

LDPE Plastics

Although HDPE and PP showed promising results, LDPE did not reciprocate the similar type. LDPE as 4% and 8% clean plastics showed deterioration in the performance against moisture. although higher percentage of impurity (more than 20%) made the asphalt mix better in moisture. This is similar in both 4% and 8% plastics, however, all the mixes failed to satisfy the criteria of TSR 0.7 (Figure 4.34). This is because LDPEs are thin and cover less surface area of aggregates, hence, the impurities take in those places and the bitumen fails make a homogenous asphalt mix. As a result, the voids are more in this asphalt mix in LDPE and become susceptible to moisture. Therefore, using LDPE alone in the asphalt mix even with good amount of impurity is not satisfactory.

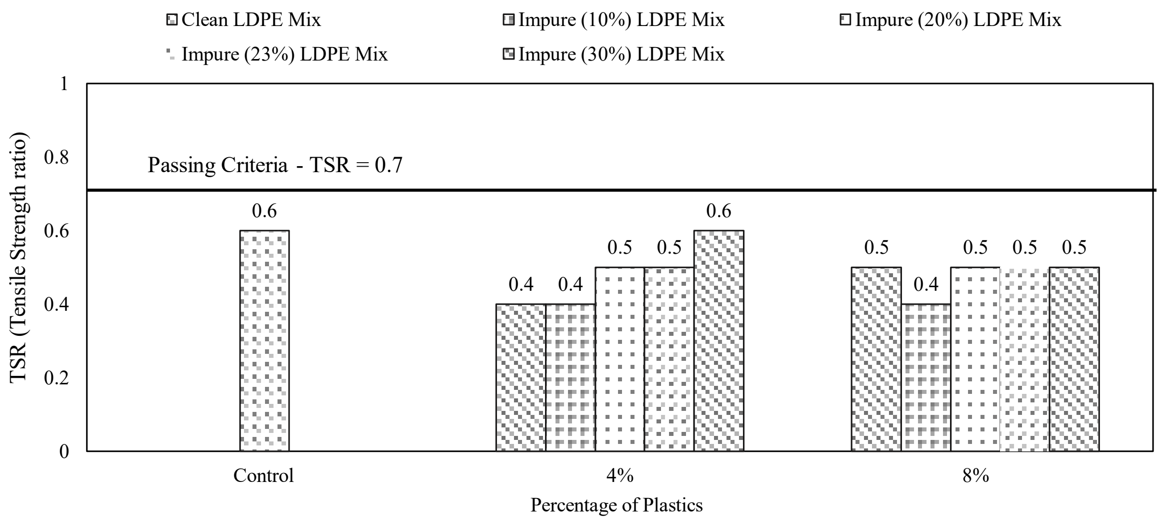


Figure 4.34 Tensile strength ratio of asphalt mix with LDPE at different levels of impurities

<u>LDPE (replacement of bitumen) + 0.5% PP (replacement of aggregate)</u>

LDPE with impurity did not satisfy the moisture resistance criteria, hence PP was mixed as replacement of aggregate. As the plastics were mixed after cleaning, the 4% and 8% LDPE with 0.5% PP, the resistance to moisture susceptibility increased. At 4% use of clean LDPE, the TSR reaches 0.9 meaning that the samples can retain 90% of its unconditioned strength. At 8%, the TSR stands 0.8 which also satisfies the moisture susceptibility criteria.

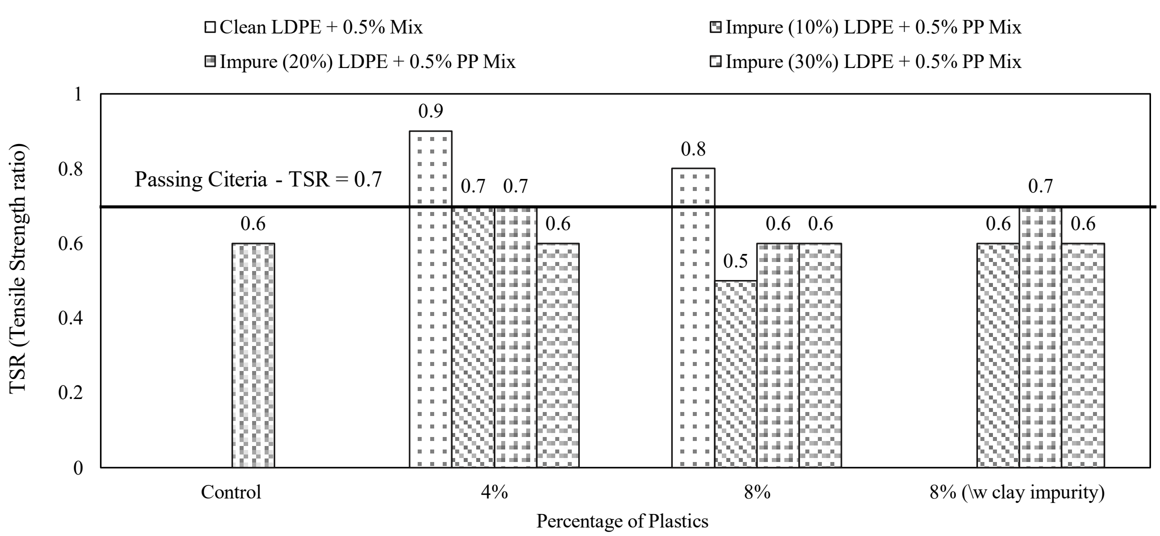


Figure 4.35 Tensile strength ratio of asphalt mix with LDPE+PP at different levels of impurities

At 4%, up to 20% impurity can be allowed as at 30%, the TSR value turned out to be 0.6 which clearly doesn't satisfy the criteria. When 8% LDPE is used, the TSR is invariably lower than 0.7 irrespective of how much impurity present in the plastics. Addition of clay to deplete the air voids inside the asphalt mix brings in some strength in conditioned samples and at 20% impurity, the strength can withhold up to 70%, however, in other percentage less or more than 20%, the TSR was found 0.6. Therefore, introducing clay did bring about TSR 0.7, nevertheless the types of impurities are the reasons for the degradation of the asphalt mix.

4.7 Skid Resistance Test Analysis

As plastics have been introduced in the asphalt mix, a potential issue comes up regarding skidding or slipping of the vehicle wheels on the road. To address this issue, skid resistance tests were performed on the control samples and the plastic mixed samples. According to TxDOT, skid resistance refers to the force generated when a tire, prevented from rotating, slides along the surface of the pavement. It depends on the micro and macro texture of the pavement. A skid score, denoting an index value, is assigned based on measurements obtained using a specialized truck towing a locked-wheel skid trailer. The trailer applies water spray to the pavement ahead of the left tire, and smooth-treaded tires are used on the trailer. Testing is conducted at a speed of 50 mph, periodically locking the left wheel of the trailer while a controlled amount of water is sprayed onto the pavement surface. Skid scores typically range from 10 to 40, with higher numbers indicating better skid resistance.

However, in the laboratory, ASTM E303-93 (2018) is followed to determine the slip resistance of a flooring surface or the skid resistance of a road surface using the pendulum (sometimes called the British Pendulum Tester). The pendulum is allowed to fall freely and make contact on the asphalt sample and the British Pendulum Number (BPN) is obtained. Later the following empirical equation is followed to find the skid number of the surface.

Skid Number, $SN = 1.32 * BPN - 34.9$

<u>Skid Resistance Test on Conditioned Samples</u>

Skid resistance tests were performed on the control samples and the plastic mixed samples. Among the plastic mixed samples, samples with impurities at different levels were also prepared and skid resistance tests were performed. Initially, the tests were performed on the samples that were prepared following the mix design proposed by Islam (2021). Figure 4.36 shows the skid resistance for 4 different plastic types at 4 different percentages. The plastics that were used for the asphalt mix were LDPE, HDPE, PP and LDPE and PP combined where LDPE was used as bitumen replacement and 0.5% PP was introduced as a replacement of aggregate. These samples were conditioned during the HWTT at 50° Celsius for over 6 hours which can be a reason for the plastics to get exposed on the surface of the asphalt samples.

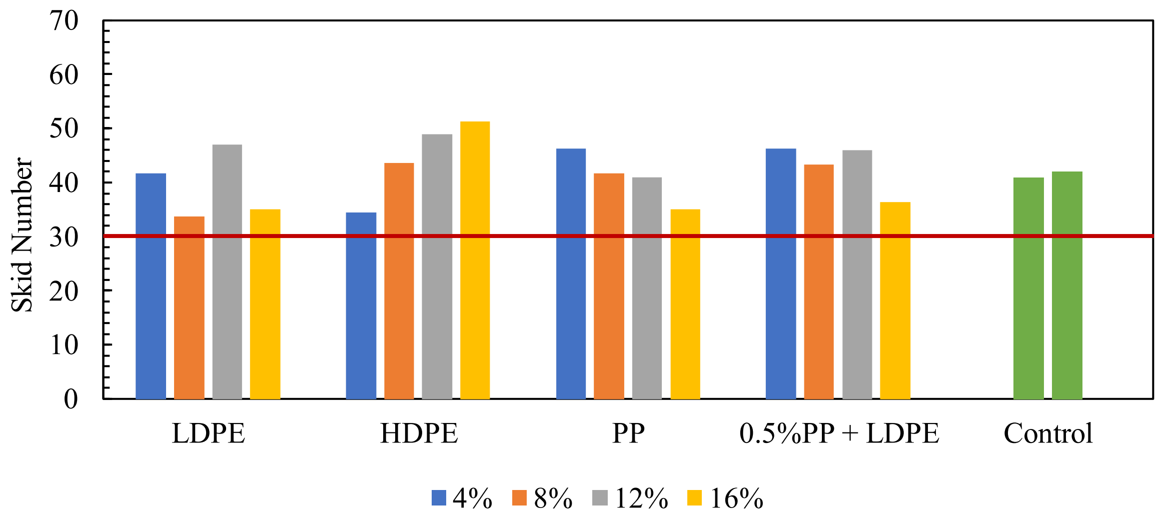


Figure 4.36 Skid number of different types of plastic mixed asphalt samples (conditioned) at various amount

LDPE shows variation in skid numbers depending on the percentage of plastics. at 8%, the LDPE plastic mixed asphalt showed skid number lower than 35 which can be acceptable only for low volume traffic according to Jayawickrama et al., (1996) and in the range of 25-35 which is considered as moderate slip potential surface UK Slip Resistance Group (UKSRG). However, at 12%, the resistance increased and again decreased at 16%. LDPE is a lightweight plastic and gets melted easily and the distribution of this type of plastic can be an issue which may result in the variance in the results at different percentages.

HDPE is the heaviest among all these types of plastics. As the percentage of HDPE in the asphalt mix increases, the skid resistance increases. After melting and covering the aggregates, the HDPE results in the increase in skid resistance. On the other hand, PP in the asphalt mix showed the opposite effect. The increase in the amount of PP technically decreased the skid number. However, in both HDPE and PP, the skid number is more than 30 which eliminates the potential slipping on the asphalt surface.

When 0.5% PP was introduced as aggregate with LDPE at different percentages, it showed the same results as of using other types of plastics. The skid number was in between 36-46 i.e., 36 at 16% LDPE and 46 was found in case of 4% plastics. However, it didn't show constant rate of decrease as the plastic content increased. Control samples had the skid number around 40. Table 4-11 summarizes the skid resistance test results for different combinations of plastics at 4 different percentages.

Table 4-11 Skid resistance test results of conditioned asphalt mix with plastic

		Percentage of Plastics			
		4%	**8%**	**12%**	**16%**
Type of Plastics	**LDPE**	42	34	47	35
	HDPE	34	44	49	51
	PP	46	42	41	35
	0.5%PP + LDPE	46	43	46	36
	Control	-	41	42	-

Later, similar tests were conducted using impurities in the asphalt mixed with different types of plastics. At first, 4% plastics of previously mentioned combination were utilized to prepared samples and these samples also have undergone the HWTT test at 50° Celsius temperature. All the plastics, when mixed at 4% replacement of the total bitumen, had 3 different percentages of impurities alike to the other tests (10%, 20% and 30%).

Table 4-12 Summary of skid resistance test results for 4% plastics in asphalt mix with impurity

		Percentage of Impurity		
		10%	**20%**	**30%**
Type of Plastics	**LDPE**	40	44	43
	HDPE	47	46	51
	PP	44	43	47
	0.5%PP + LDPE	46	42	43

Table 4-12 summarizes the skid number for using 4% of different combinations of plastics and the different levels of impurity contained by the plastics. All combinations have skid number more than 40. The graphical representation is shown in Figure 4.37.

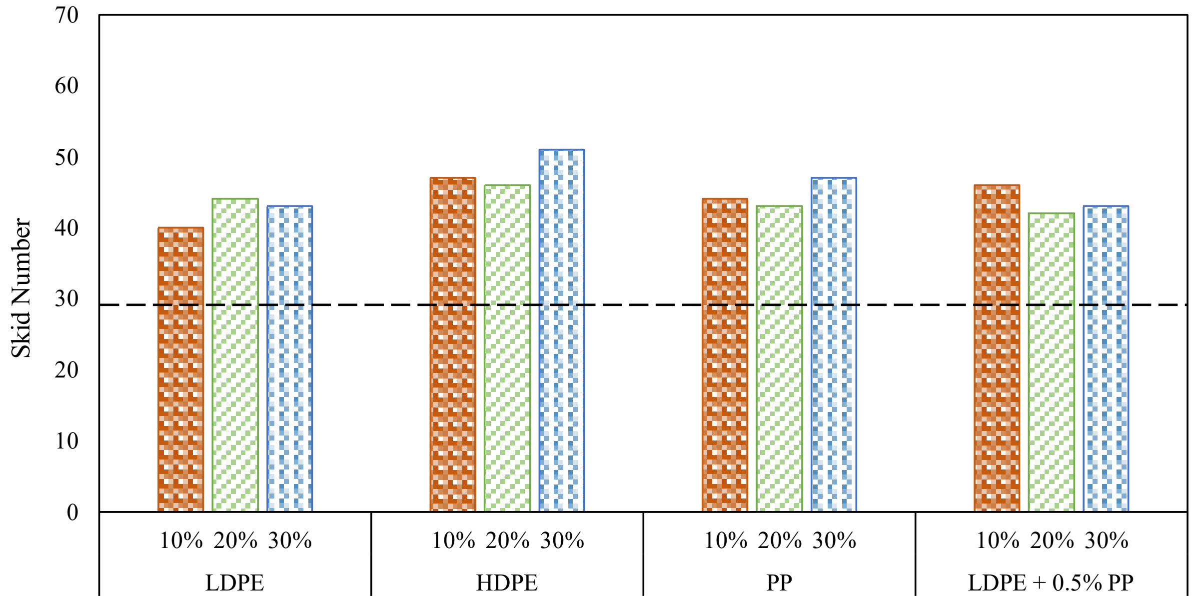


Figure 4.37 Skid resistance test results for 4% plastics in asphalt mix with impurity

In the case of mixing 8% plastic, the skid numbers were found more than it was found while using 4% plastics. Using 8% plastics means containing more impurity in amount than using 4% plastics, and the bitumen content also decreases. This allows the increase in surface area where frictional resistance increases. Hence, the skid number increases. In case of 8% plastic use in different combinations, the skid number ranges from 46-58 which is acceptable for heavy traffic load. Table 4-13 summarizes the test results.

Table 4-13 Summary of skid resistance test results for 8% plastics in asphalt mix with impurity

		Percentage of Impurity		
		10%	**20%**	**30%**
Type of Plastics	**LDPE**	48	46	52
	HDPE	50	49	47
	PP	56	58	53
	0.5%PP + LDPE	49	53	50

Figure 4.38 shows the graphical representation of 8% plastic addition in the asphalt mix and introducing impurity at 3 different percentages which are 10%, 20% and 30% respectively. All the combinations satisfy the criteria for a heavily travelled road. PP shows more resistance than other combinations.

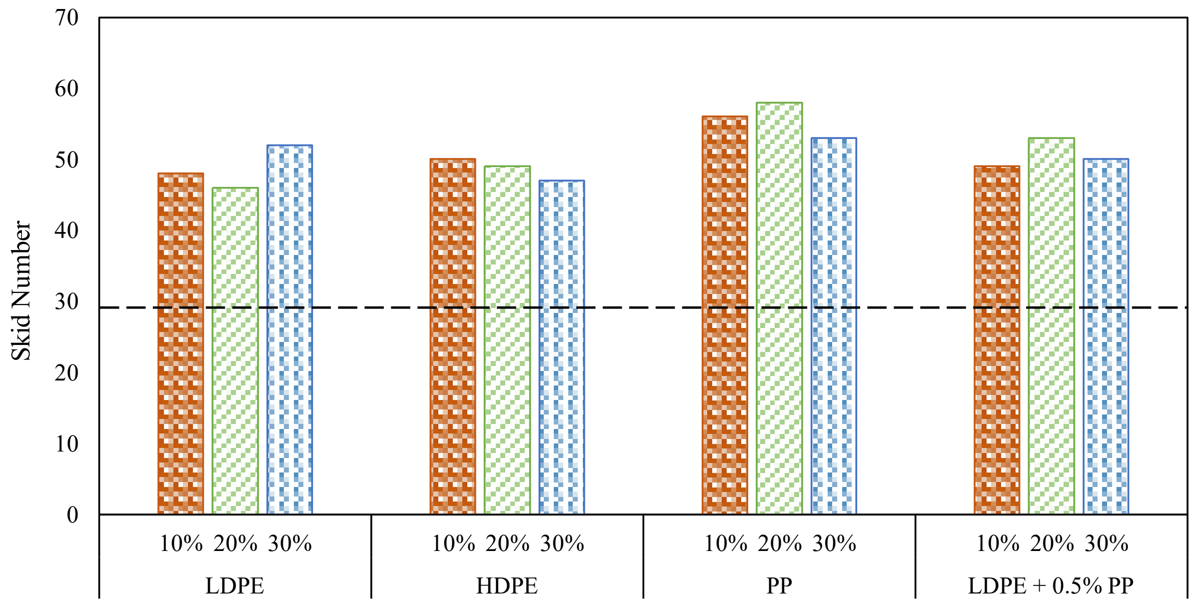


Figure 4.38 Skid resistance test results for 8% plastics in asphalt mix with impurity

Skid Resistance Test on Unconditioned Samples

Skid resistance test was also performed on the unconditioned samples. These samples have not gone through the conditioning procedure as mentioned previously at high temperature. The 62 mm diameter samples were used only for the skid resistance test. In this procedure, the resistance was technically found more than the conditioned samples.

In this case, the control samples were compared with 8% plastic mixed asphalt samples and the combinations were PP, HDPE and 0.5% PP with LDPE. There was no impurity in these samples. For each combination, 4 samples were prepared, and the skid test was done on these samples.

Figure 4.39 graphically represents the results obtained from the test. The average skid number is merely close to each combination. As far plastic mixed samples are concerned, it actually shows almost a similar value as of the control samples. Moreover, the alternate combinations also show similarity in the results. Therefore, it can be concluded that pavements constructed following the plastic road mix design has no additional effect on slipping or skidding in the wet condition of the road. It will be able to preserve the effect of adding plastic to the pavement.

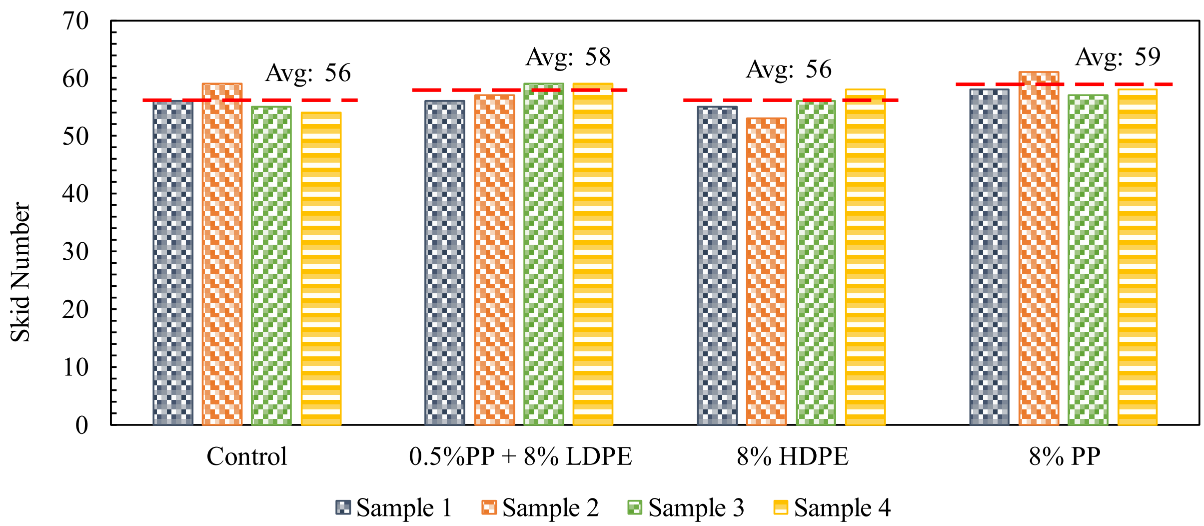
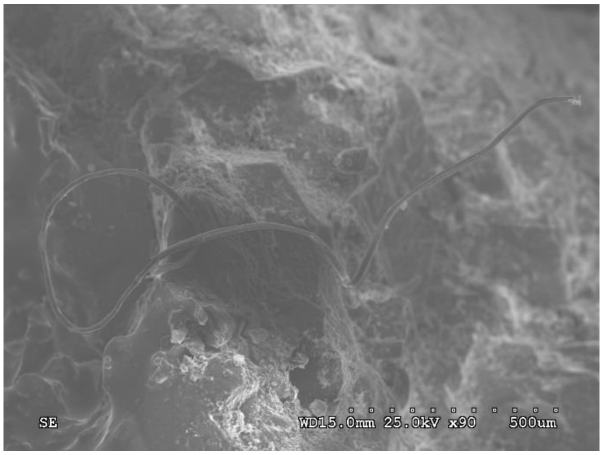
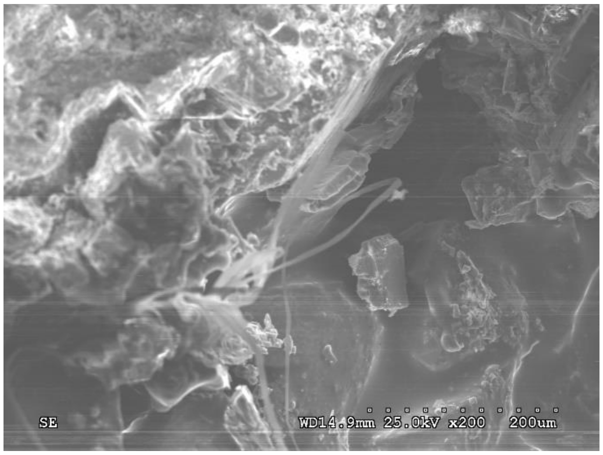


Figure 4.39 Skid number of different types of plastic mixed asphalt samples (unconditioned) at various amount

As a part of skid resistance test, asphalt mix was observed under microscope for potential exposure of plastics on the asphalt mix. This is however understandable that the dry mix of plastics in the asphalt mix can barely expose the plastics on the surface. The plastics are coating the aggregates first and on top of that the bitumen layer is covering the plastic mixed aggregates. Therefore, the chances of plastics coming out on the surface and making the asphalt mix vulnerable is impractical. Following are the photos containing plastics in the inside surface of the asphalt.





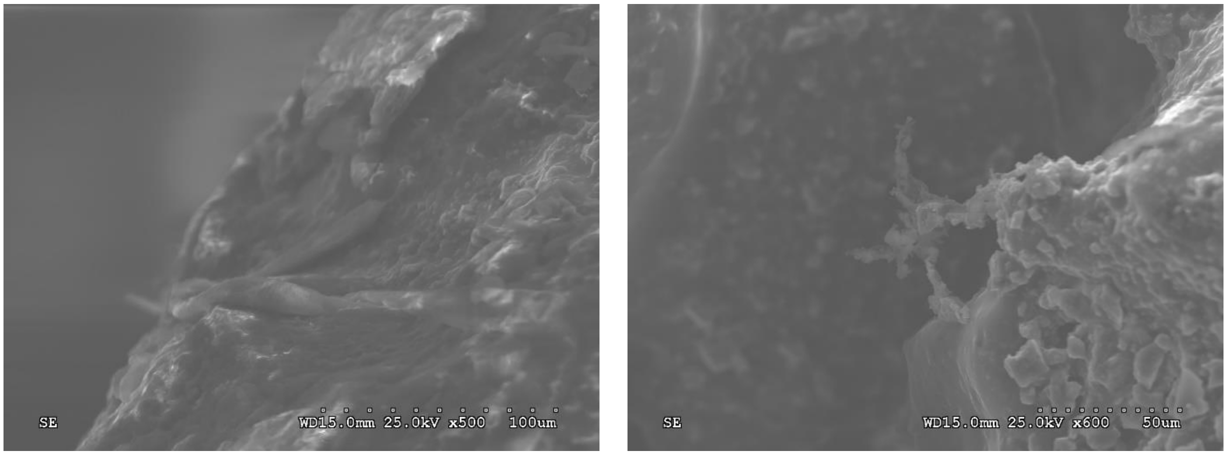


Figure 4.40 Plastics on the inner surface of aggregates observed in SEM

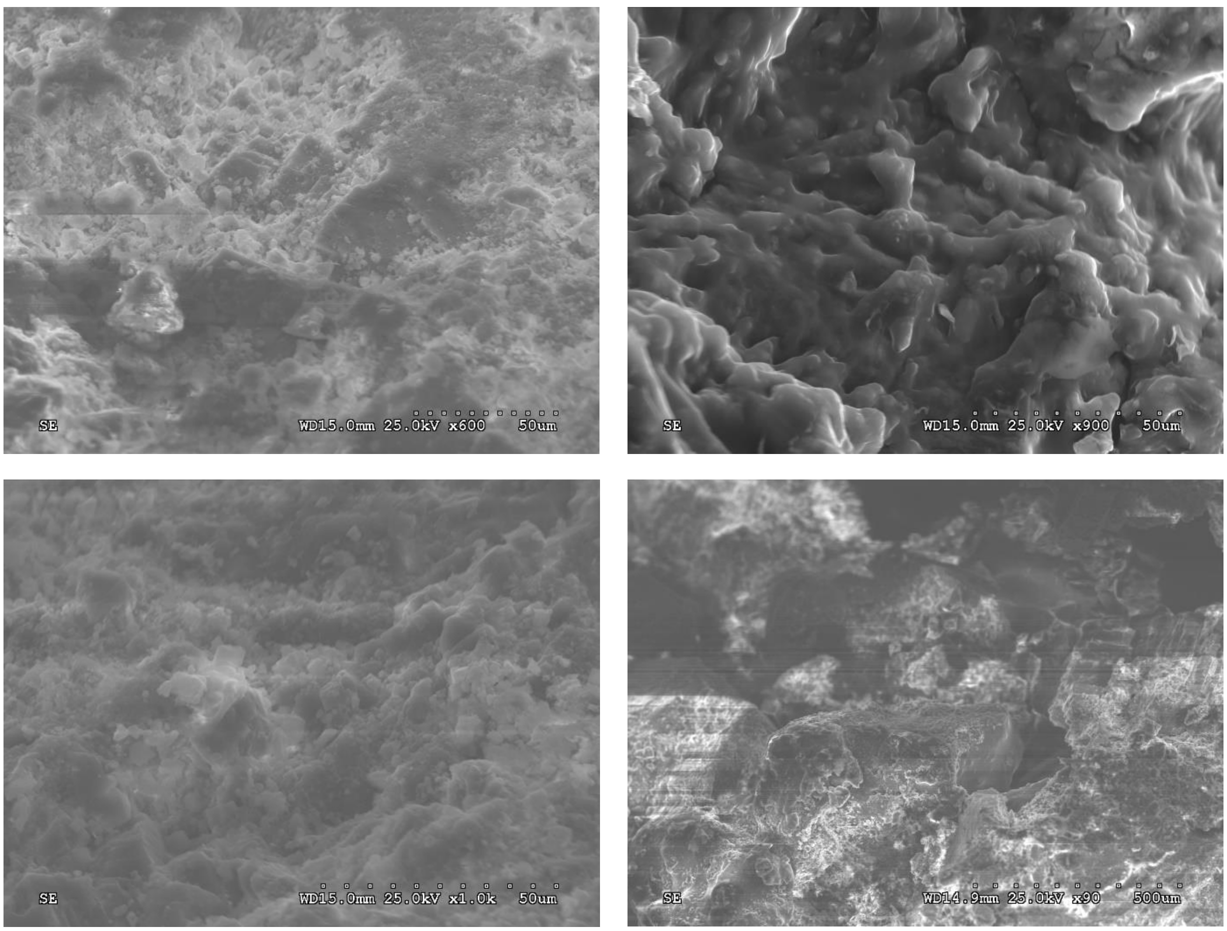


Figure 4.41 Absence of plastics on the top surface of the asphalt mix observed in SEM

CHAPTER 5

REGRESSION ANALYSIS

5.1 Introduction

The most important parameter for designing plastic roads with impurity is the Indirect Tensile Strength parameter (IDT). Although rutting is one of the most important parameters, there is not any significant change in the rutting parameter due to the impurities in the waste plastics in the performance of plastic road as much as the ITS values. Therefore, ITS values derived from the tests is subjected to observe for the change in the performance of plastic road asphalt mix with impurities. Moisture Susceptibility is one of the major parameters of superpave mix design which can be calculated by performing IDT on the conditioned samples after freezing and thawing. In this study, Plastic Type (PT), Plastic Content (PC), Impurity content in Plastic (IP), Rutting Depth (RD), Moisture Susceptibility TSR (MS) and Skid Number (SN) were the parameters used to develop the statistical model. A Multiple Linear Regression (MLR) model was developed to correlate these parameters with IDT value. Statistical modeling software, RStudio 2023.06.0 was utilized to conduct this analysis. The workflow of the analysis is presented Figure 5.1.

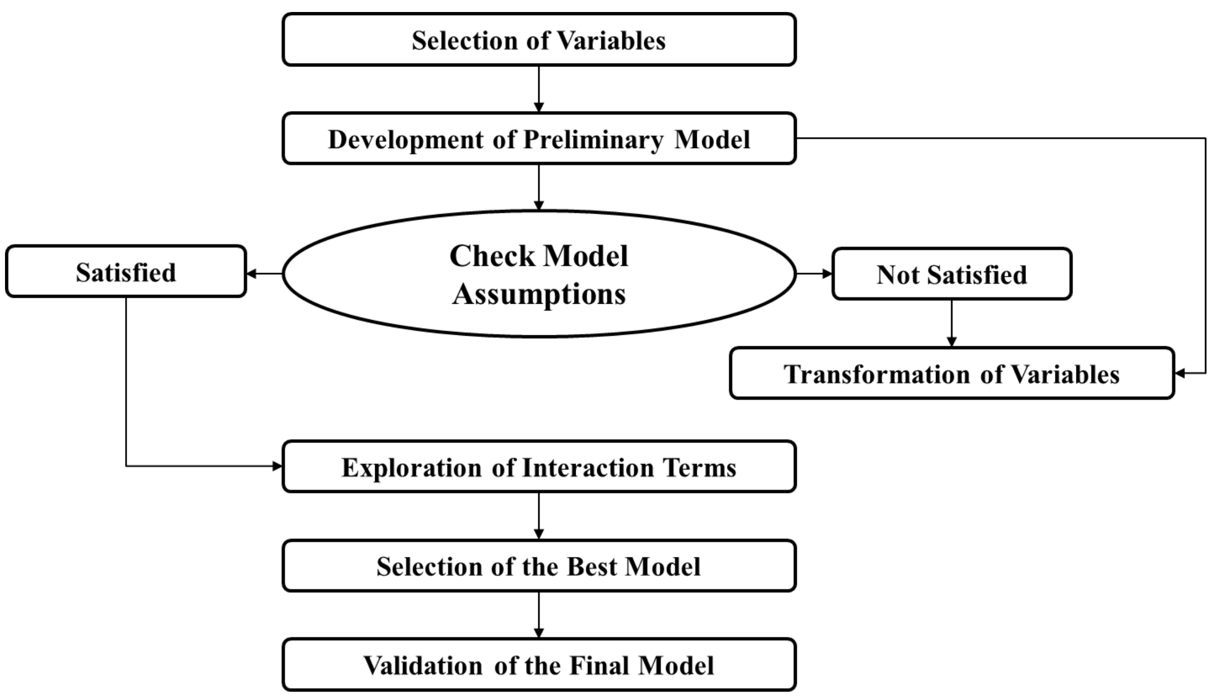


Figure 5.1 Statistical Analysis Flow for the Model Development

5.2 Parameter Selection for Model

The selection of predictors for the model was done in a way that ensured they were not strongly correlated with each other. It is important to avoid high collinearity among predictors because it can undermine the reliability of the developed model. This can result in smaller regression coefficients, increased variability, and challenges in explaining the impact of a predictor's unit change on the response variable (Pituch and Stevens, 2015). However, in real-life scenarios, it is not always possible to control the correlation among predictors, and some degree of interrelation does exist. This issue of interrelated predictor variables is known as multi-collinearity. When strong correlations exist among predictors, the model's outcomes become highly dependent on the specific predictors included. In such cases, interpreting the effect of a unit change in a predictor variable on the expected results may not be appropriate. Multi-collinearity can introduce three issues in a multiple linear regression (MLR) model: a) reduction in the regression coefficients, b) difficulty in determining variable importance, and c) increased variability (Stevens, 2012).

The objective of this study is to develop a Multiple Linear Regression (MLR) model to correlate Indirect Tensile Strength (IDT) of plastic modified bitumen mix with impurities with plastic type, plastic content, impurity content in the plastics, and consequent rutting value, moisture resistance and skid number so that IDT data can be obtained from these parameters, which requires a greater number of these tests to have a highly reliable value.

In this research, Indirect Tensile Strength (IDT) was modeled to be the response while Plastic Type (PT), Plastic Content (PC), Impurity content in Plastic (IP), Rutting Depth (RD), and Skid Number (SN) were the predictors.

Since all the independent predictors affect the response to some extent, it was decided to include all the parameters in the preliminary statistical model. The parameters were denoted as follows:

IDT = Indirect Tensile Strength (psi)

PT = Plastic Type (HDPE, LDPE, PP)

PC = Plastic Content (%)

IP = Impurity Content in Plastic (%)

RD = Rutting Depth (mm)

SN= Skid Number (unitless)

5.3 Multiple Linear Regression Analysis

This section includes a detailed description of the multiple linear regression analysis. Based on the lab test results, a MLR equation was developed to predict the tensile strength of the plastic modified bitumen mix with impurity as a function of Plastic Type (PT), Plastic Content (PC), Impurity content in Plastic (IP), Rutting Depth (RD), Moisture Susceptibility TSR (MS) and Skid Number (SN).

5.3.1 Correlation Analysis

To assess the relationship between the response variable and each predictor variable, a correlation analysis was conducted. Additionally, the predictor variables were subjected to correlation analysis to detect any signs of multicollinearity. It is crucial to ensure that there is no multicollinearity among the predictor variables (Kutner et al., 2005). Multicollinearity refers to the situation where two or more predictors can account for the same variation in the response variable. If there is a strong correlation among the predictor variables, it can create challenges for the multiple linear regression (MLR) model.

Response vs Predictor Plot

The response variable was plotted against each of the predictor variables, as shown in the following figures. The unit used for Indirect Tensile Strength are in psi, Plastic Content and Impurity Content in Plastic are in percentage, Rutting Depth in mm. The relationship between the response and predictors is not following any trend. The relationship between the response and predictors are not following any trend. Figure 5.2 to Figure 5.5 represents all of the response vs predictor plots.

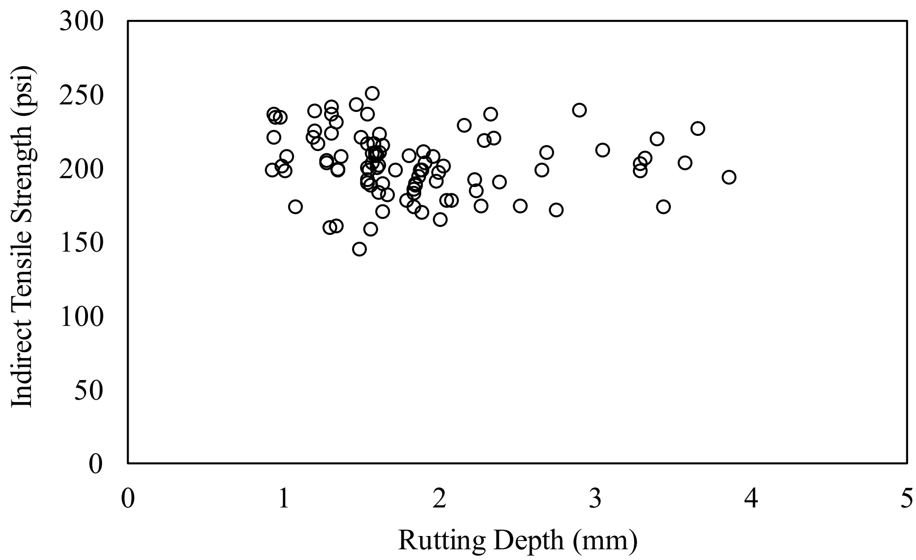


Figure 5.2 The correlation of indirect tensile strength (IDT) with rutting depth (RD)

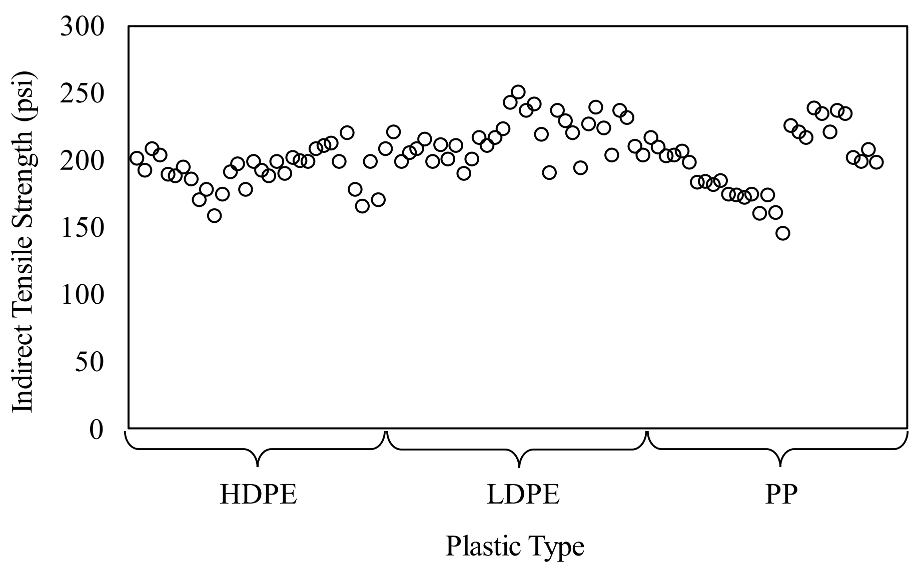


Figure 5.3 The correlation of indirect tensile strength (IDT) with plastic type

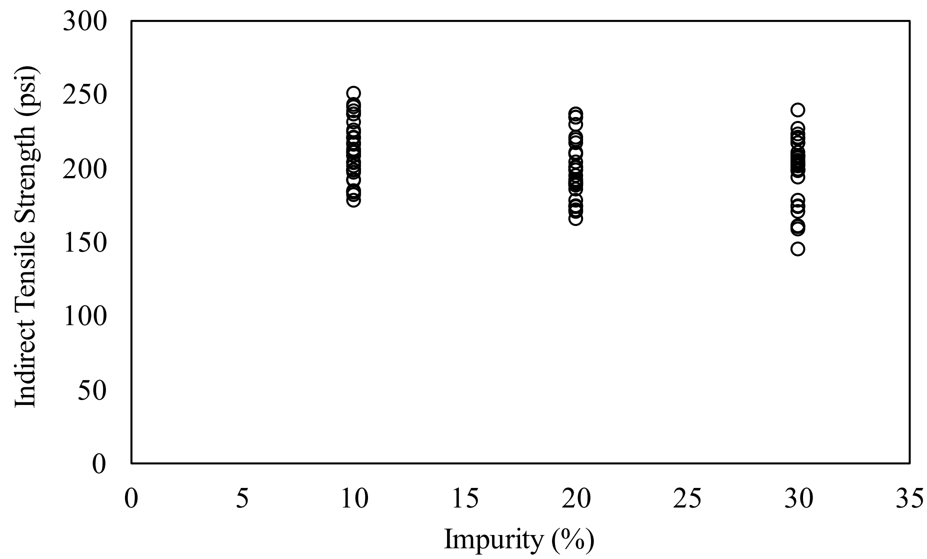


Figure 5.4 The correlation of indirect tensile strength (IDT) with impurity percentage

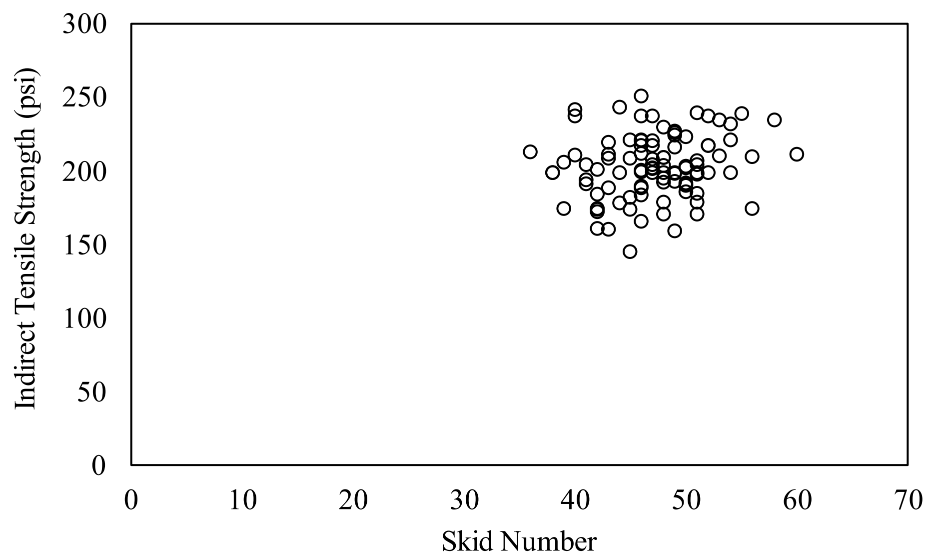


Figure 5.5 The correlation of indirect tensile strength (IDT) with Skid Number

<u>Predictor vs Predictor Plots</u>

Predictor vs predictor plots help us determine the multicollinearity between predictor variables. According to the predicting plot (Figure 5.6), no predictor variables have any substantial correlation between each other.

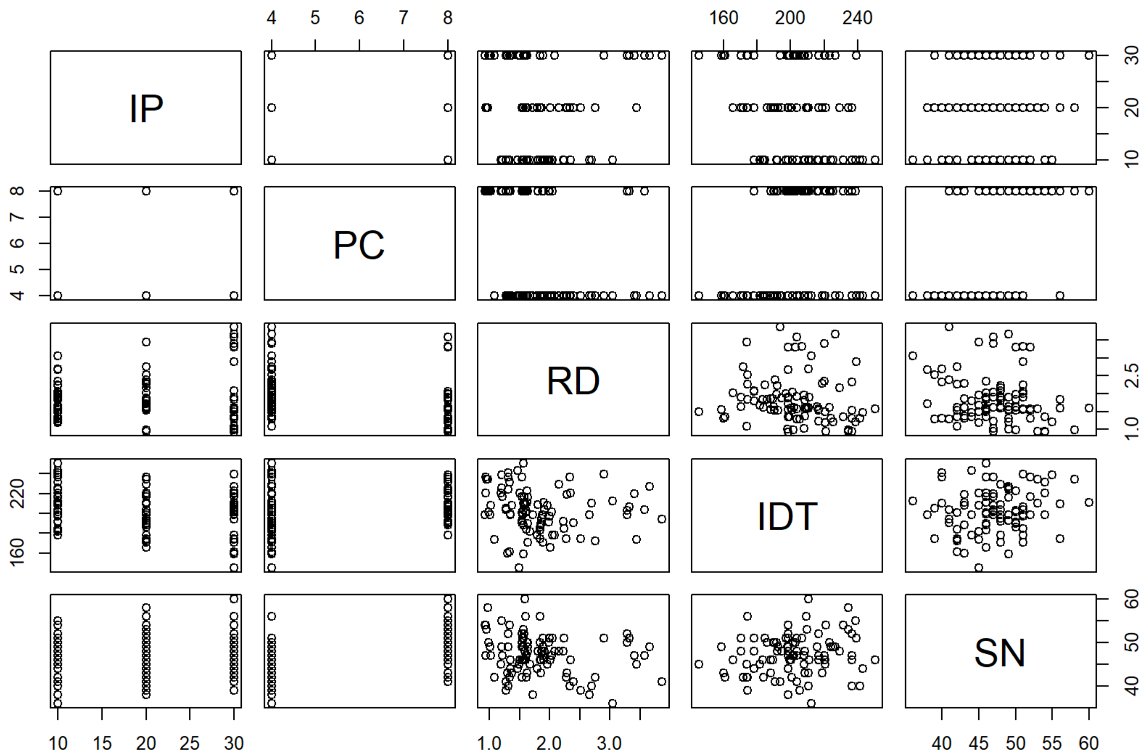


Figure 5.6 The correlation among the predictor variables

The Pearson Correlation Coefficients between the predictors are shown in Table 5-1. The highest correlation was found to be between the Plastic content and Rutting depth, i.e., -0.32. However, Kutner et al. (2005) states that any correlation less than 0.7 can be regarded as weak. Elastic modulus is also strongly correlated with unconfined compressive strength. The value of $r > 0.7$ for two of the predictor variables, which suggests that multicollinearity exists within the model. Thus, no significant collinearity was observed among the predictor variables.

Table 5-1 Correlation among the Predictor Variables

Variables	IP	PC	RD	SN
IP	1.000	0.000	0.093	0.111
PC	0.000	1.000	-0.324	0.531
RD	0.093	-0.324	1.000	-0.210
SN	0.111	0.531	-0.210	1.000

The linear strength between the response and the predictor variables were also measured using the correlation coefficient. Based on the statistical analysis (Table 5-2) plastic content has positive correlation with tensile strength. This means that an increase of plastic content will increase the tensile strength. Likewise, impurity content and rutting have negative correlation coefficients, such that an increase in this factor will reduce the tensile strength as well.

Table 5-2 Correlation between the Indirect Tensile Strength and Predictor Variables

IDT	IP	PC	RD	SN
1	-0.250	0.291	-0.116	0.187

5.3.2 Development of Preliminary Model

A preliminary multiple linear regression model was developed, correlating Indirect tensile strength (IDT) with Plastic content (PC), Plastic type (PT), Rutting depth (RD) and Impurity Content (IP). The Preliminary MLR Model was found as follows:

$$IDT = \beta_0 + \beta_1 PT + \beta_2 PC + \beta_3 RD + \beta_4 IP + \beta_5 SN + \varepsilon_i \quad (5.1)$$

Where, IDT = Indirect Tensile Strength (psi), PT = Plastic Type, PC = Plastic Content (%), IP = Impurity Content in Plastic (%), RD = Rutting Depth (mm) and SN= Skid Number are regression. β_0, β_1, β_2, β_3, β_4, β5 correlation coefficients which are determined through regression analysis by minimizing the sum of squared errors for the model data. ε_i is the random error. The physical meaning of the correlation coefficients is that they explain the variation in mean response per unit change of a predictor variable when all other predictor variables are kept constant. The regression parameters were estimated by minimizing the sum of squared errors for the sample. The predictor variables are quantitative in nature. Multiple linear regression was performed on the model data.

The parameter estimates and summary of the analysis of variance (ANOVA) are presented in Table 5-3 and Table 5-4, respectively. The sign conventions of the correlation coefficients are as expected and follow the results obtained from laboratory test data. Impurity content, rutting depth and using HDPE had negative coefficient, i.e., an increase in those coefficients decreased the tensile strength. The ANOVA summary showed that the adjusted R^2 was satisfactory and is acceptable. The p-value of the residuals was also very low. The preliminary fitted MLR equation can thus be presented as follows:

$$IDT = 185.717 - 3.209\ HDPE + 10.883\ LDPE + 28.863\ PP - 0.636\ IP - 7.051\ RD + 0.484\ SN + 1.788\ PC \quad (5.2)$$

The next step is to check if the MLR model assumptions are verified. The model should satisfy the constant error variance, normality of residuals, outliers, and multicollinearity among the predictor variables checks (Stevens, 1996; Kutner et al., 2005, Faysal, 2017).

Table 5-3 Parameter Estimates of the Preliminary Model

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	185.717	20.886	8.892	6.85e-14
Type HDPE	-3.209	4.962	-0.642	0.519
Type LDPE	10.883	4.969	2.190	0.031
Type PP	28.863	5.337	5.409	5.40e-07
Impurity Percentage	-0.0636	0.212	-2.994	0.004
Rutting Depth	-7.051	3.031	-2.327	0.022
Skid Number	0.484	0.466	1.040	0.301
Plastic Content	1.788	1.059	1.689	0.095

Table 5-4 ANOVA Summary of the Preliminary Model

Residual Standard Error	R^2	Adjusted R^2	F-statistic	p-value
6.72	0.6467	0.6027	10.15	2.299e-09

5.3.3 Verification of Preliminary Model

Multiple linear regression (MLR) models must satisfy some assumptions. Graphical plots and different statistical tests will be used to verify the following model assumptions:

- There should be a linear relationship between the response and predictor variables.
- The residuals should have constant variance.
- The residuals should be normally distributed.
- The residuals should not be auto correlated.

5.4 MLR Model Form

Residuals vs predictor variables and residuals vs fitted values plots are generally used to identify the applicability of linear regression for a data set. The appropriate situation for the applicability of a linear regression model is when the residuals are located within

a horizontal band centered on a horizontal axis. The points in the residuals vs predictors have to be scattered, and there is no systematic trend of the points. If any curvature is found in the plots, then the linear regression model is not appropriate, and a quadratic term is needed in the model.

Constant Error Variance

Plots showing residuals vs. predictor variables and residuals vs. fitted values help to determine constant error variance or homoscedasticity. The residuals should be randomly scattered without any trend when plotted against predictor variables. Similarly, there should be no specific trend of residuals when plotted against fitted values. This ensures that the constant error variance of an MLR model has been fulfilled. The presence of funnel shape or any curvilinear trend indicates presence of non-constant variance. The regression in such a case might not be valid. This condition can be mitigated by transformation of variables.

From Figure 5.7 residuals vs fitted values shows scattered plot. However, a clear curvilinear trend (marked by red) can be seen in the plot. This indicates absence of constant error variance and thus, points towards a need for transformation of the response variable. Further analysis was done by conducting the studentized Breusch-Pagan test in RStudio. The p-value from the test was 0.03678, which is greater than α = 0.01. So, the null hypothesis was not rejected indicating that the residuals are homoscedastic at α = 0.01.

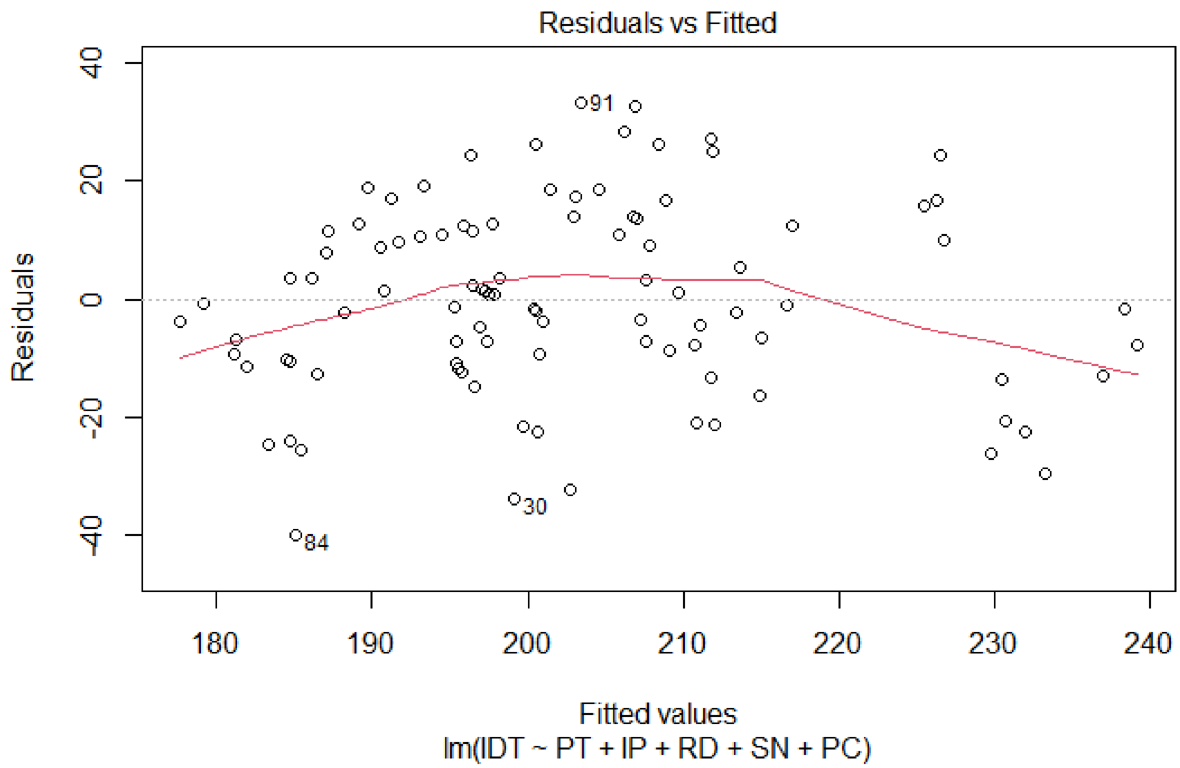


Figure 5.7 Residuals vs. Fitted Values Plot for the Preliminary Model

<u>Normality</u>

The error or the residuals of an MLR should be normally distributed. The normality of the residuals can be determined from a normal probability plot. A moderately linear plot signifies that the residuals are normally distributed. Figure 5.8 shows the normal probability plot for the preliminary MLR model.

A long tail on the right side and a short tail at the left side can be seen from the plot. This indicates that the distribution of the residuals might not be normal. To further verify the normality assumption, Shapiro-Wilk normality test was carried out in RStudio. The test estimated a p-value of 0.6311 which is greater than α = 0.01. So, the null hypothesis failed to be rejected indicating that the residuals are normally distributed at α = 0.01.

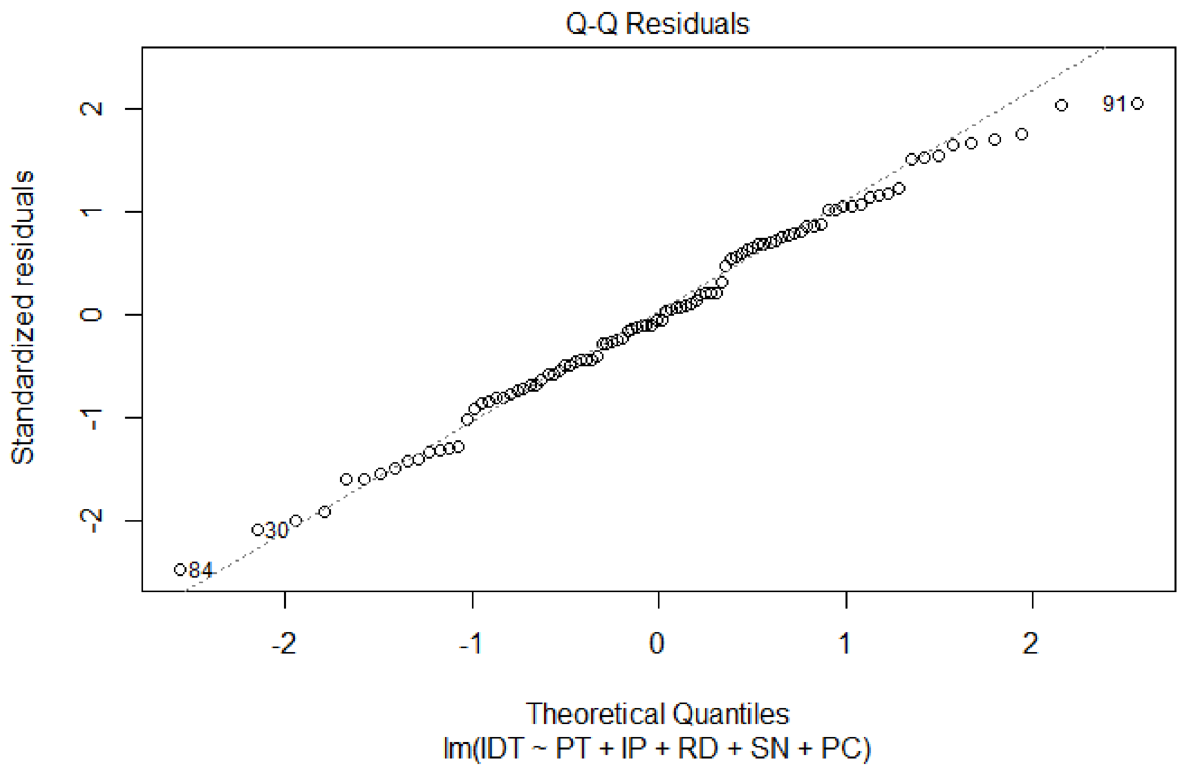


Figure 5.8 Residuals vs. Fitted Values Plot for the Preliminary Model

<u>Outlier Test</u>

Outliers are some extreme observations in a data set. They can mislead the regression by pulling the fitted line disproportionally towards the extreme observation (Kutner et al., 2005). The outliers, if any, were checked using several standard tests in RStudio. Bonferroni outlier test was used to detect outliers. DFFITS (Figure 5.9), DFBETAS (Figure 5.11), and Cook's Distance (Figure 5.10) were used to determine the influence of the outliers in the preliminary model. DFFITS (Difference in fits) estimates the influence of an observation in the predicted value. It is suggested that an absolute DFFITS value greater than 1 (for small to medium data set) for an observation is to be flagged for further check. An absolute DFBETAS value greater than 1 (for medium to large data sets) also suggests flagging the corresponding observation. Similarly, the observation with Cooks Distance (Di) > F (p, n − p) should also be flagged.

Based on the Bonferroni outlier test, one of the observations resulted in a p-value of 0.012306, which is greater than $\alpha = 0.01$, thus the corresponding observation was identified as an outlier. The observation was flagged as per DFFITS, DFBETAS, and Cooks Distance tests as well.

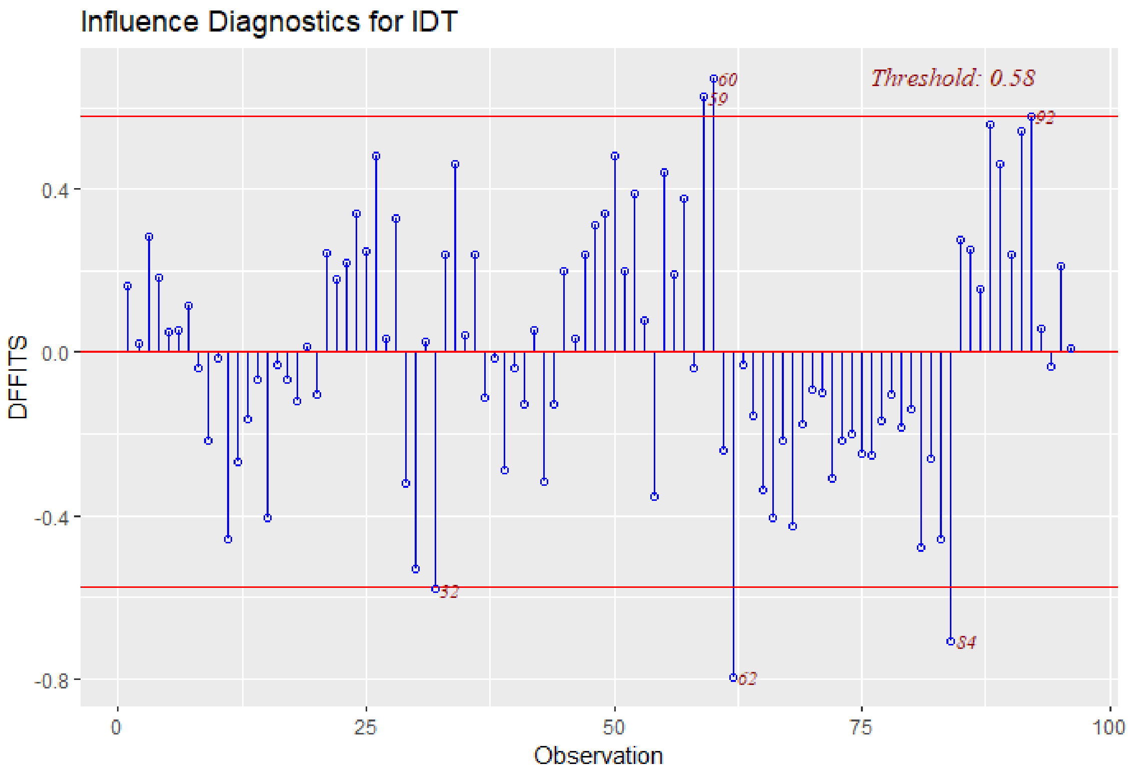


Figure 5.9 Outlier test by using DFFITS

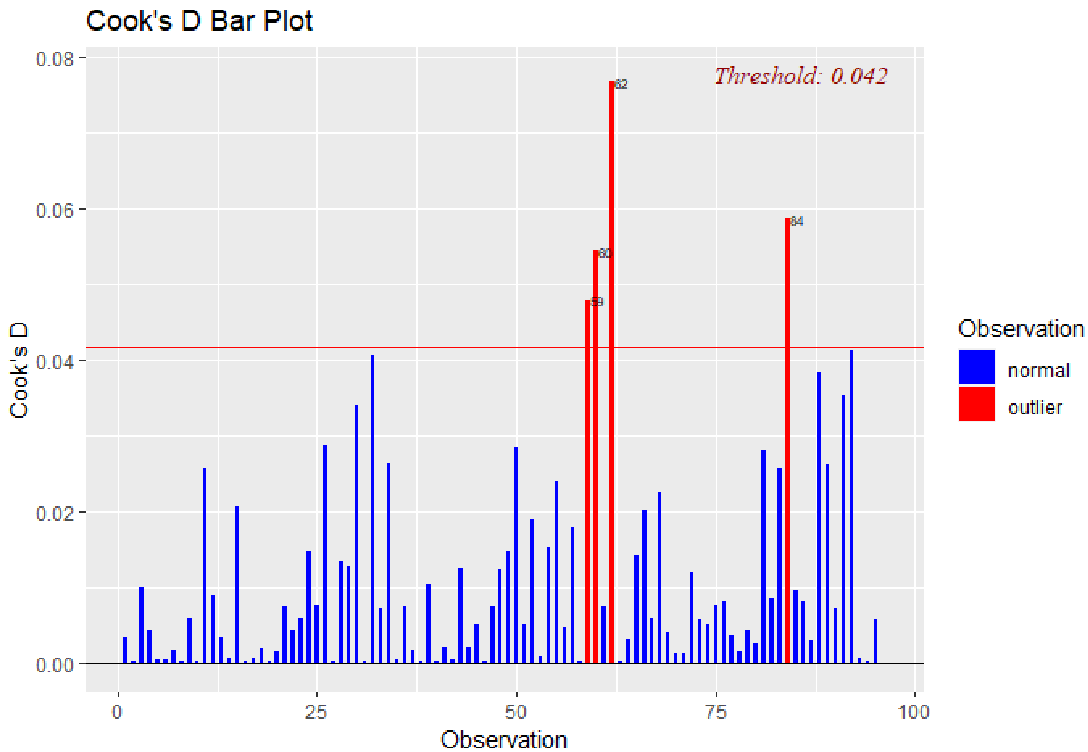
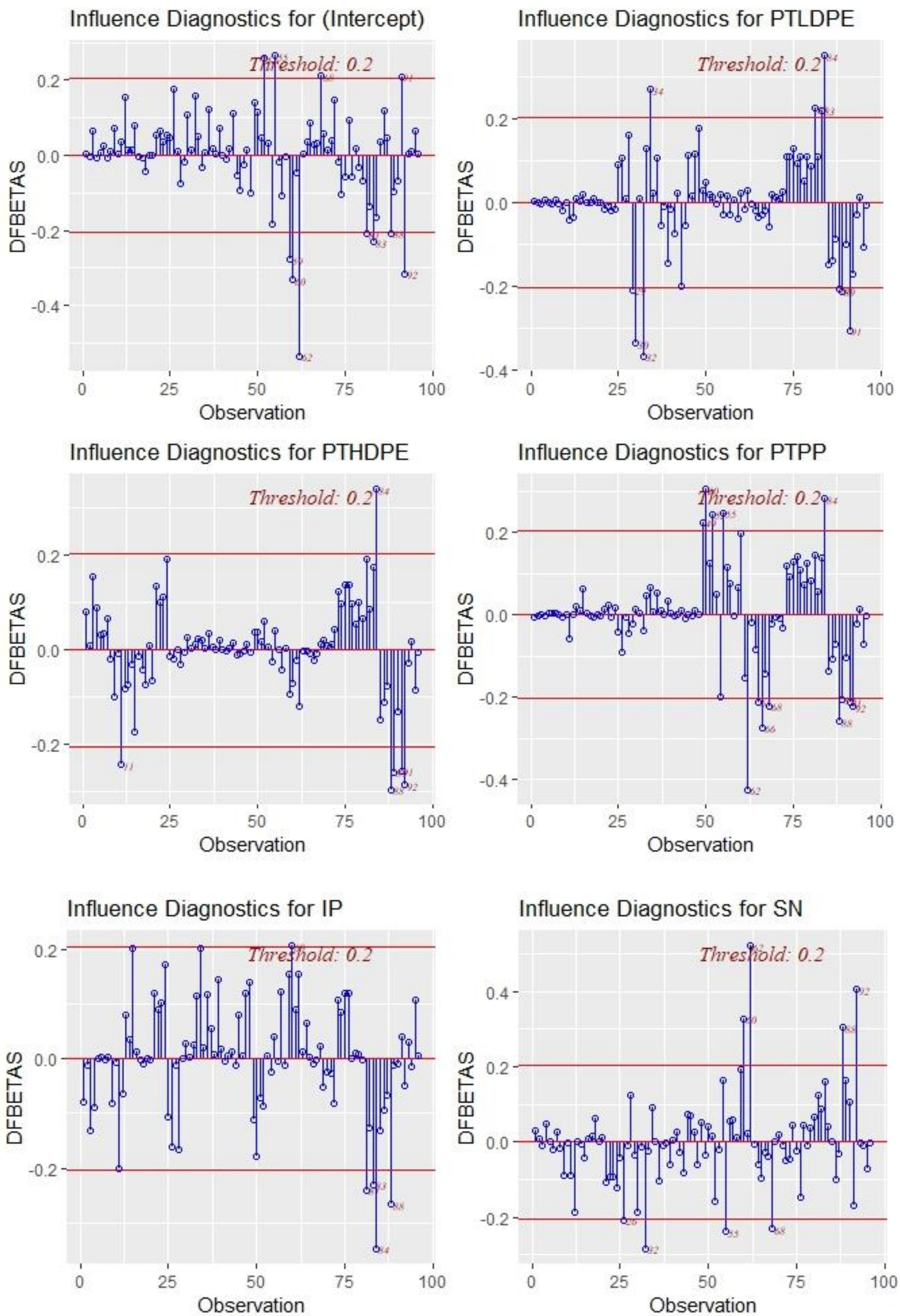


Figure 5.10 Outlier test by using Cook's Distance


Influence Diagnostics for (Intercept)
Threshold: 0.2
DFBETAS
Observation
Influence Diagnostics for PTLDPE
Threshold: 0.2
DFBETAS
Observation
Influence Diagnostics for PTHDPE
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Observation
Influence Diagnostics for PTPP
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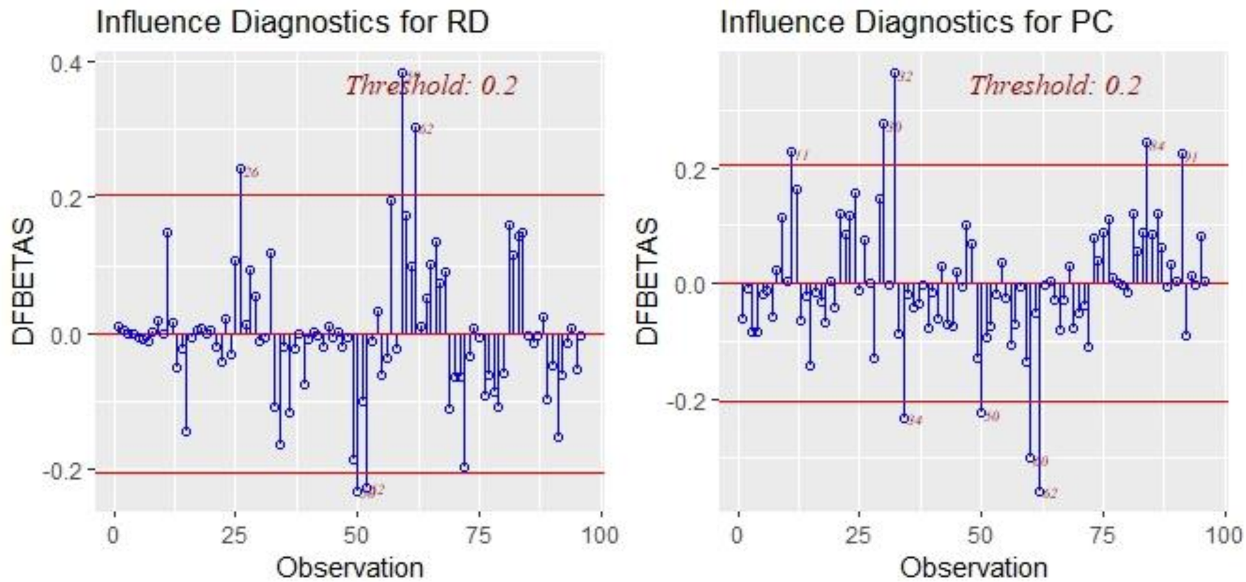

Figure 5.11 Outlier test by using DFBETAS

Multicollinearity

An important assumption of an MLR model is that the predictors should not be highly correlated among each other. Variation Inflation Factor (VIF), which quantifies how much the variation is inflated, can be used to detect multicollinearity in a model. If VIF > 1, multicollinearity occurs among the predictors. However, only predictors with a VIF > 5 may be problematic. A VIF > 10 suggests high multicollinearity and indicates a poor estimate of the response. Thus, the VIF is preferable to be less than 5. Based on the VIF in Table 5-5, all the VIFs are within the suggested range. Thus, no serious multicollinearity exists among the predictor variables.

Table 5-5 Variation Inflation Factors for the Preliminary Model

Variables	PT	IP	RD	SN	PC
VIF	1.339	1.034	1.386	1.567	1.539

5.4.1 Transformation of Variables and Check for MLR Assumptions

Since the preliminary model satisfied the constant error variance and normality assumptions, no transformation of the response variable was performed. Hence an outlier data was discovered, the preliminary model did not pass the outlier test.

Multiple linear regression was performed again without the outlier data. The parameter estimates and summary of the analysis of variance (ANOVA) for the model presented in Table 5-6 and Table 5-7, respectively. The sign conventions of the correlation coefficients are as expected and follow the results obtained from laboratory test study data. The ANOVA summary showed that the adjusted R2 was satisfactory and is acceptable. The p-value of the residuals was also very low. The final fitted MLR equation can thus be presented as follows:

$$IDT = 192.5561 – 2.296\ HDPE + 11.508\ LDPE + 29.640\ PP - 0.649\ IP – 8.459\ RD + 0.396\ SN + 1.67\ PC \quad (5.3)$$

Where, IDT = Indirect Tensile Strength (psi)

RD = Rutting Depth (mm)

PC = Plastic Content (%)

IP = Impurity Content (%)

PP

Table 5-6 Parameter Estimates of the Final Model

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	192.556	21.4580	8.974	8.12e-14
Type HDPE	-2.296	4.9437	-0.464	0.64352
Type LDPE	11.507	5.025	2.290	0.025
Type PP	29.640	5.379	5.509	4.05e-07
Impurity Percentage	-0.649	0.215	-3.024	0.003
Rutting Depth	-8.459	3.203	-2.641	0.009
Skid Number	0.396	0.472	0.842	0.402
Plastic Content	1.671	1.051	1.590	0.116

Table 5-7 ANOVA Summary of the Final Model

Residual Standard Error	R^2	Adjusted R^2	F-statistic	p-value
16.37	0.745	0.709	9.819	7.835e-09

The next step is to check if the MLR model assumptions are verified.

5.4.2 Verification of Final Model

Constant Error Variance

Figure 5.12 shows the residuals vs. fitted values plot for the final MLR model.

No curvilinear trend or funnel shape was detected from the plot. The residuals seem to be randomly scattered. Further analysis was done by conducting the studentized Breusch-Pagan test in RStudio. The p-value from the test was 0.0552, which is greater than $\alpha = 0.01$. So, the null hypothesis failed to be rejected indicating that the residuals are homoscedastic at $\alpha = 0.01$. The constant error variance assumption was fulfilled for the final model.

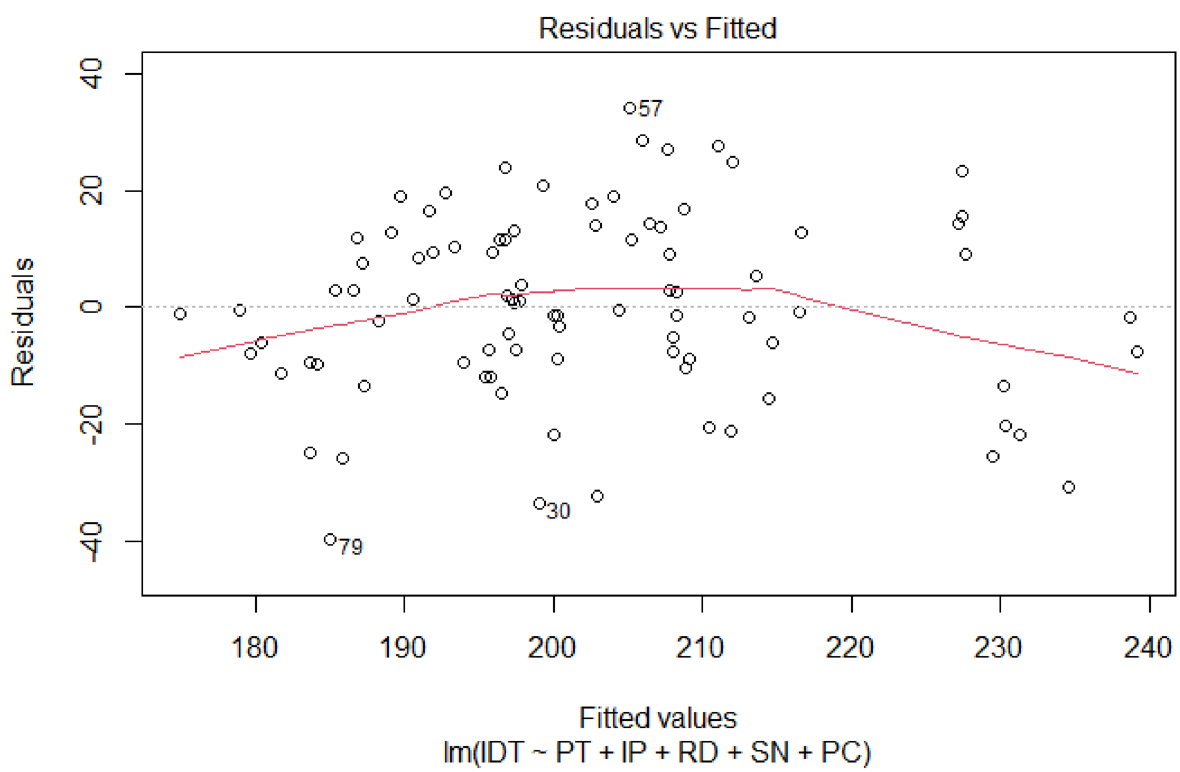

Figure 5.12 Residuals vs. Fitted Values Plot for the Final Model

Normality

Figure 5.13 shows the normal probability plot for the final MLR model.

Short tails on both sides can be seen from the plot. To further verify the normality assumption, Shapiro-Wilk normality test was carried out in RStudio. The test estimated a p-value of 0.706, which is greater than $\alpha = 0.01$. So, the null hypothesis failed to be rejected indicating that the residuals are normally distributed at $\alpha = 0.01$.

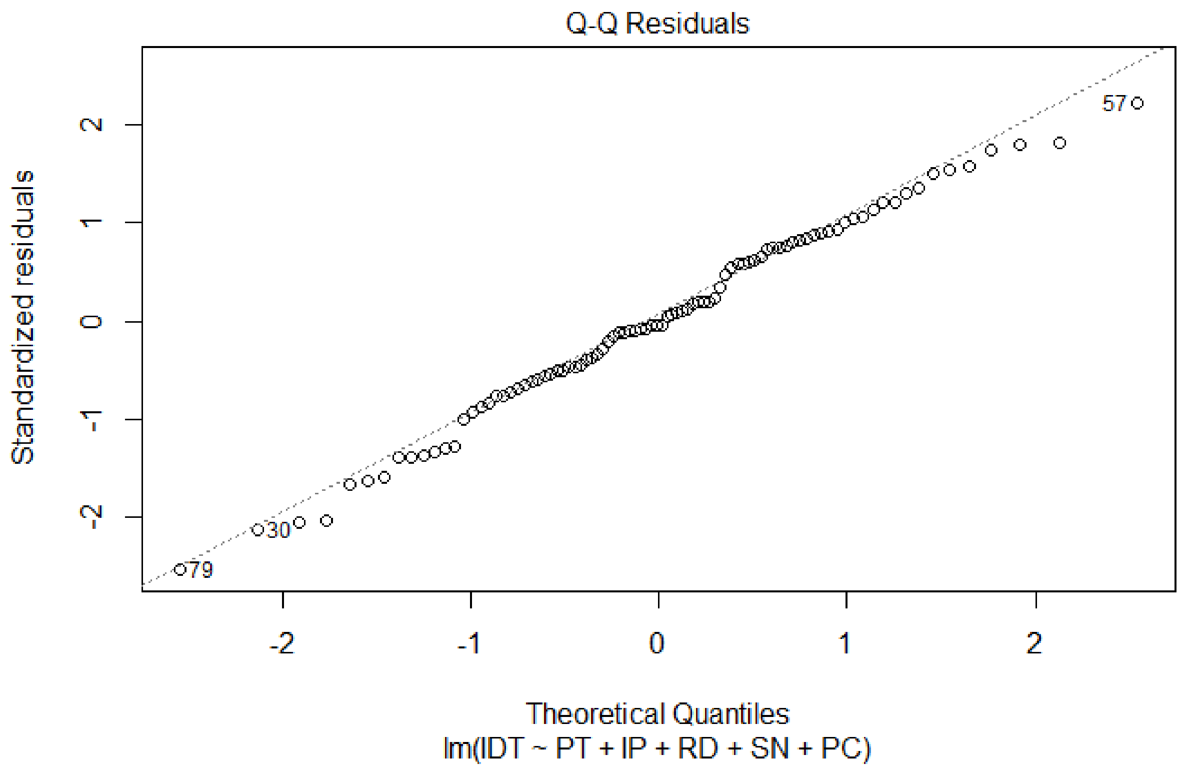

Figure 5.13 Normal Probability Plot for the Final Model

Outlier Test

The outliers, if any, were checked using several standard tests in RStudio. Bonferroni outlier test was used to detect outliers. DFFITS, DFBETAS, and Cook's Distance were used to determine the influence of the outliers in the final model. It is also suggested that Di greater than 0.5 should be investigated, as it may be influential (Faysal, 2017).

Multicollinearity

All the VIFs, except Plastic type and Plastic content, are within the suggested range. The high VIF of Plastic type and Plastic content are expected since they are extracted from the same laboratory test, so a relation is inevitable. Thus, no serious multicollinearity exists among the predictor variables.

Based on the Bonferroni outlier test, none of the observations were flagged as potential outliers. All the observations satisfied the assumptions as per DFFITS, DFBETAS, and Cook's Distance tests as well.

5.4.3 Final Model Selection

The Best subset method, stepwise regression, and backward elimination were performed in RStudio to finalize the best prediction model.

Best Subset Selection

The parameters under consideration for the best subset selection method are R^2, adj. R^2, Mallows C_p, and Bayesian Information Criteria (BIC). The method selects the best model with the highest R^2 and adj. R^2, and the lowest Mallows C_p and BIC. The summary of the results is represented in Table 5-8. Based on this method, the combination with five predictor variables was the best model.

Table 5-8 Summary of Best Subset Selection Method

Predictor variables					R^2	Adj. R^2	C_p	BIC
Plastic Type	PC	RD	IP	SN				
-	-	-	-	-	0.611	0.603	33.44	-13.6
-	-	✓	-	-	0.699	0.684	21.51	-20.4
-	✓	-	✓	-	0.635	0.638	13.98	-24.4
-	-	✓	✓	-	0.697	0.671	9.79	-25.8
✓	✓	✓	✓	-	0.738	0.707	5.33	-27.9
✓	✓	✓	✓	✓	0.744	0.706	6.41	-24.4
✓	✓	✓	✓	✓	0.747	0.702	8.00	-20.3

Backward Elimination

The backward elimination method starts with all the predictor variables in the model. Then, it incrementally removes statistically insignificant variables. The analysis is completed when there is no insignificant variable remaining in the model. Based on this method, all the predictor variables were significant at $\alpha = 0.01$ significance level.

Stepwise Regression

Stepwise regression method utilizes both the backward selection and forward selection algorithms. The model starts with the most significant predictor variable. The regression is carried out and the parameters under consideration are calculated. Then, other variables are incrementally added as per their significance. The procedure is repeated until the model with the best criteria parameters is obtained. The F-statistic test is used to conduct statistical significance tests (Kutner et al., 2005). Based on this method, the five predictor variables formed the best model.

However, the model with all four predictor variables obtained the best R^2 value. C_p and BIC values were very close to those of the five variables model. Determining tensile strength required the plastic type, plastic content, impurity content and rutting depth, which is why all predictor variables were kept in the model.

5.4.4 Validation of the Final Prediction Model

The experimental test results were used to evaluate the predictive capacity of the developed multiple linear regression model for Indirect tensile Strength (IDT) value of plastic modified bitumen mix with impurity. The rutting values were used for different combinations of plastic content, plastic type, and impurity contents. According to Figure 5.14, the developed model can predict 85% of the variation in resilient modulus at different combinations.

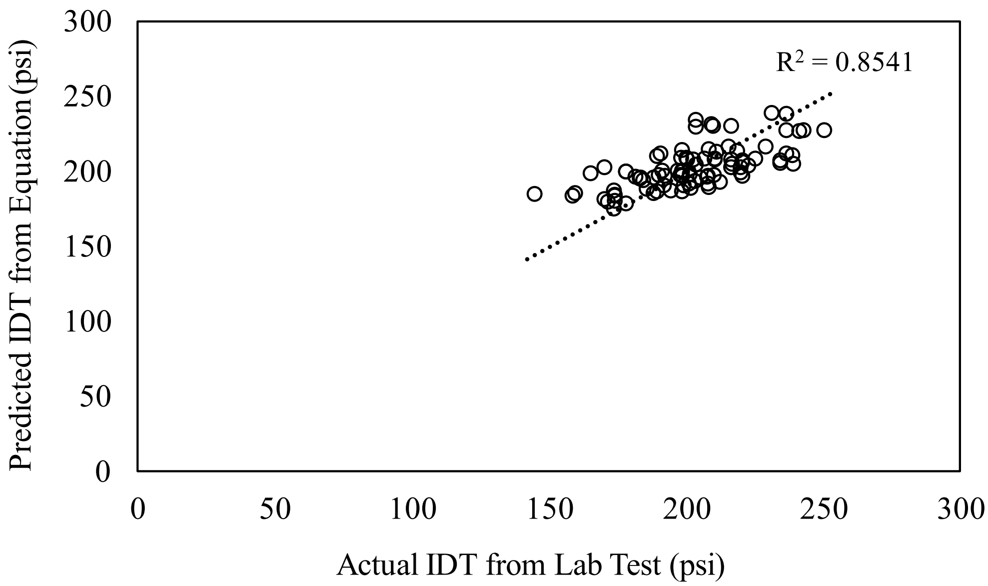

Figure 5.14 Validation of the Final Prediction Model

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 Introduction

Plastic roads have been a germane topic in the research and development field of construction materials. Since waste plastic is abundant and there is no suitable place for the plastic waste to end up, reusing, and recycling have become the most pertinent option. Plastic road indeed can be the most viable solution for reusing the plastics. However, research studies have proved that impurities and contamination can be an issue in dealing with material research. The use of waste plastic in the plastic road is nonetheless within this discussion. As a part of the preliminary study, it was rudimentarily found out that the impurities in the plastic waste can be an issue in the mix design of plastic road. At the same time, the percentages of impurity that could be present in the waste plastics were determined. Later, specific percentages of impurity were considered in the research to find the outcome in the asphalt mix design. An experimental program was developed to find out the effect of impurities in plastic in plastic road design. The effect was intensively observed in the volumetric and performance test of the asphalt mix design of plastic road. In this chapter, we present a summary of the laboratory test results and data analysis findings. Additionally, we offer recommendations for future studies.

6.2 Summary

The following are the major activities undertaken so far according to the current study:

- Plastic waste was collected from 2 locations. The first location was Irving Hunter Ferrell Landfill, and the second location was the University of Texas at Arlington campus. Landfill was considered as secondary source and the university campus was considered primary source.
- Three types of recycled plastics which were High density polyethylene (HDPE), polypropylene (PP) and Low-density polyethylene (LDPE) plastic were sorted from the collected waste plastics.
- As preliminary study, the plastic waste collected from the Irving Landfill was considered. The amount of impurity was found out by the process of cleaning and drying. Plastics were then cleaned and shredded for the volumetric and performance test to find out if there is an effect

of the impurities in the test results. It was affirmative that the effect was present. Hence, further study was conducted.

- A total number of 211 plastics collected from the landfill and 106 plastics were cleaned to find out the impurity content contained by the 3 types of plastics.
- After cleaning and drying process, the impurity contained by plastics were found. The plastics collected from the landfill were found to have contained 11%, 17% and 23% impurity in HDPE, PP and LDPE respectively. The plastics which were collected from the university had 5%, 10% and 16% impurities in HDPE, PP and LDPE respectively.
- As impurities were visually observed, food, paper, soil, grease, liquids, yard waste were mostly found on the surface of the plastics.
- From statistical analysis, it was found that primary source contains less amount of impurities in plastics than the secondary source. In the case of PP, primary source contained 7%-14% impurity, however secondary source contained 15%-24% impurity. In the case of LDPE, primary source contained 12%-21% impurity, however secondary source contained 20%-29% impurity. In the case of HDPE, primary source contained 4%-7% impurity, however secondary source contained 10%-16% impurity.
- Another 105 plastics were shredded with the impurity initially found out to mix them in the asphalt mix to find out if there is an effect of the impurities in the asphalt mix.
- Four different types of aggregate were collected from Austin Asphalts, Dallas for the surface course testing. These were Type C rock, Type D rock, Man sand, and recycled asphalt pavement (RAP). PG 64-22 bitumen was also collected from there.
- For surface course, four combination of plastic such as LDPE (replaced as bitumen), LDPE (replaced as bitumen) + 0.5% PP (replaced as aggregate), PP (replaced as bitumen), and HDPE (replaced as bitumen), are used along with recycled asphalt pavement (RAP). All the plastics are used in different amounts to replace up to 8% by weight of bitumen.
- In the final study, 3 specific percentages of homogenous impurities were introduced to the asphalt mix with the plastics. 10%, 20% and 30% replacement of plastics by the impurity were introduced in the mix to find out the effect of impurities in the asphalt mix.
- Optimum asphalt content was 4.8% used as per found by Islam, 2021.

- Volumetric tests and performance tests (Rutting, Indirect tensile strength (IDT), Overlay, Moisture susceptibility) are conducted to evaluate the usage of plastic with impurity in asphalt mix.
- In preliminary study, air void for 4% and 8% HDPE with 11% and PP with 17% impurity increased. Having PP in the mix with impurity kept the air voids with 5% limit, however, in case of HDPE it was more than 5%. Clean LDPE had air voids more than 5% and LDPE with impurity was no exception.
- Air void at 4% plastic with different amount of impurities were found satisfactory for PP and LDPE + 0.5% PP in the asphalt mix. However, HDPE and LDPE did not satisfy the 5% air void criteria. Air void at 8% plastic with different amount of impurities were found satisfactory up to 20% impurity in PP and LDPE + PP combination.
- Rutting depth remains similar in case of using 4% HDPE at different percentages of impurity and 8% HDPE shows a non-uniform pattern however the rutting depth is very less which indicates the stiffness of the mix. In case of LDPE, the increase in impurity content in the mix for 4% and 8% plastic decreases the rutting. Therefore, impurity makes the mix stiff in this case as well. In case of PP, the rutting depth increase due to the increase in the impurity percentage. Although, the rutting increases, however, it remains in the limit of 12.5 mm. However, in case of using PP, the stripping inflection point initiates at 9000 cycles for 30% impurity.
- Preliminary study showed that mixing HDPE and PP with impurity in the asphalt mix barely changes the strength of the asphalt mix, however, using LDPE with 23% impurity showed more than 30% decrease in the asphalt mix while using 4% and 8% of LDPE.
- It was found after incorporating different percentages of impurity that in case of HDPE while using 4% of it, the ITS decreases up to 15%, however, increasing the plastic dosage to 8% helps increase the ITS while increasing the impurity. For PP, the ITS decreases as the impurity increases for 8% plastic introduction in the asphalt mix. In the case of using LDPE, the ITS decreases more than 30% while using it at 4% and 8% with 23% impurity. However, 30% impurity can do better in the asphalt mix with LDPE by increasing the strength by 20%.
- Impurity in the plastics hampers the moisture susceptibility test. 4% HDPE with impurity reduces the TSR below 0.7, while for clean plastic the strength would retain 80% of its unconditioned samples. However, for 8%, 20% and 30% impurity can increase the TSR.

- Using PP at 8% shows the best results in moisture resilience with up to 20% impurity. In the case of LDPE, at 4% and 8%, the samples fail in moisture susceptibility test. LDPE and PP together can enhance the performance if LDPE is at 4% with up to 20% impurity.
- Skid resistance test was done on both clean plastics and plastic with impurities. In all the cases, the skid number is more than 35 which signifies that there is no potential skidding chance of vehicles on the plastic road.
- To determine the value of the indirect tensile strength (IDT) for different combinations of recycled materials which is plastic with impurities, MLR models were developed using rutting depth (RD), plastic type, plastic content (PC) and impurity in those plastics. As a final model, we have the following:

  $$IDT = 192.5561 - 2.296\ HDPE + 11.508\ LDPE + 29.640\ PP - 0.649\ IP - 8.459\ RD + 0.396\ SN + 1.67\ PC$$

This model had a regression coefficient of 85%. Thus, 85% of the variation in indirect tensile strength (psi) is explained by the model in relation to plastic type, plastic content, impurity in the plastic, rutting depth and moisture TSR value.

6.3 Recommendations for Future Studies

- Plastics from different locations should be analyzed to find out the impurity percentages in the waste plastics. The bigger the dataset is, the more reliable the data will be.
- Determination of the types of impurity affecting the performance of plastics road should be undertaken.
- Further studies should be conducted to fix the optimum asphalt content so that the performance of the plastic road does not alter due to introducing the impurities in the asphalt mix with recycled plastics.
- Microscopic analysis should be conducted to quantify the amount of impurities in the waste plastics.
- Other types of plastics apart from HDPE, LDPE and PP should be incorporated in the experimental program to find out the quantity of impurity those plastics can contain and find out the effect of impurities in them in asphalt mix with plastics.
- The effect of impurity can be observed in the Crack Attenuating Mix (CAM) layer.

- A detailed life cycle analysis and cost analysis can be done in future studies to know about the sustainability and cost effectiveness of plastic use in pavement.

CHAPTER 7

REFERENCE

1. Ahmad, M. S. (2014). Low density polyethylene modified dense graded bituminous macadam. International Journal of Engineering Trends and Technology, 16, 366-372.
2. Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Shafigh, P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. Materials & Design, 32(10), 4844-4849.
3. Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Ahmadinia, E. (2012). Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. Construction and Building Materials, 36, 984-989.
4. Ahuja, S., & Alsante, K. M. (Eds.). (2003). Handbook of isolation and characterization of impurities in pharmaceuticals (Vol. 5). Academic press.
5. Akinpelu, M., Dahunsi, B. I., Olafusi, O., Awogboro, O., & Quadri, A. (2013). Effect of polythene modified bitumen on properties of hot mix asphalt. ARPN Journal of Engineering and Applied Sciences, 8(4), 290-295.
6. Ali, N., Chan, J., Potyondy, A., Bushman, R., and Bergen, A. (1995). "Mechanistic Evaluation of Asphalt Concrete Mixtures Containing Reclaimed Roofing Materials," Transportation Research Record, No. 1515, Journal of the Transportation Research Board, Washington, D.C.
7. Ali, S. S., Ijaz, N., Aman, N., & Noor, E. M. (2017). Feasibility study of low-density waste plastic in non-load bearing asphalt pavement in District Faisalabad. Earth Sciences Pakistan, 1(2), 17-18.
8. Al-Adham, K., & Wahhab, H. A. A. (2018). Influence of temperature on Jnr values of polymer modified asphalt binders. International Journal of Pavement Research and Technology, 11(6), 603-610.
9. Al-Hadidy, A. I., & Yi-qiu, T. (2009). Effect of polyethylene on life of flexible pavements. Construction and Building Materials, 23(3), 1456-1464.
10. Al-Hadidy, A. I., & Yi-Qiu, T. (2009). Mechanistic approach for polypropylene-modified flexible pavements. Materials & Design, 30(4), 1133-1140.

11. Al-Salem, S. M. (2009). Influence of natural and accelerated weathering on various formulations of linear low-density polyethylene (LLDPE) films. Materials & Design, 30(5), 1729-1736.
12. Angelone, S., Casaux, M. C., Borghi, M., & Martinez, F. O. (2016). Green pavements: reuse of plastic waste in asphalt mixtures. Materials and Structures, 49(5), 1655-1665.
13. Appiah, J. K., Berko-Boateng, V. N., & Tagbor, T. A. (2017). Use of waste plastic materials for road construction in Ghana. Case studies in construction materials, 6, 1-7.
14. Arabani, M., & Pedram, M. (2016). Laboratory investigation of rutting and fatigue in glassphalt containing waste plastic bottles. Construction and building materials, 116, 378-383.
15. Asare, P. N. A., Kuranchie, F. A., & Ofosu, E. A. (2019). Evaluation of incorporating plastic wastes into asphalt materials for road construction in Ghana. Cogent Environmental Science, 5(1), 1576373.
16. Asutosh, A. T., & Nawari, N. O. (2017). Integration of recycled industrial wastes into pavement design and construction for a sustainable future. Journal of Sustainable Development, 10(1), 9-23.
17. Attaelmanan, M., Feng, C. P., & Al-Hadidy, A. I. (2011). Laboratory evaluation of HMA with high density polyethylene as a modifier. Construction and Building Materials, 25(5), 2764-2770.
18. AURPA, S. S. (2021). CHARACTERIZATION OF MSW AND PLASTIC WASTE VOLUME ESTIMATION DURING COVID-19 PANDEMIC (Doctoral dissertation, UNIVERSITY OF TEXAS AT ARLINGTON).
19. Aurpa, S. S., Hossain, S., & Islam, M. A. (2022). Effect of Plastic Waste on Volume Consumption of Landfill during the COVID-19 Pandemic. Sustainability, 14(23), 15974.
20. Awwad, M. T., & Shbeeb, L. (2007). The use of polyethylene in hot asphalt mixtures. American Journal of Applied Sciences, 4(6), 390-396.
21. Baaj, H. (2007). “Asphalt Pavement Modified with Recycled Roofing Asphalt Shingles in Municipal Environment,” The 13th Congress of Urban Infrastructure (INFRA), Laval, QC, Canada.
22. Babafemi, A. J., Šavija, B., Paul, S. C., & Anggraini, V. (2018). Engineering properties of concrete with waste recycled plastic: A review. Sustainability, 10(11), 3875.

23. Bale, A. S. (2011). Potential reuse of plastic waste in road construction: a review. International Journal of Advances in Engineering & Technology (IJAET), 2, 233-236.
24. Beena, K. S., & Bindu, C. S. (2010). Waste plastic as a stabilizing additive in Stone Mastic Asphalt.
25. Becker, Y, Mendez, M,& Rodriguez, Y 2001,'Polymer modified asphalt,' Vision Tecnologica, 9(1).
26. Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., ... & Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. Marine pollution bulletin, 142, 189-195.
27. Button, J. W., Williams, D., and Scherocman, J. A. (1995). "Shingles and Toner in Asphalt Pavements," Research Report FHWA/TX-96/1344-2F, Texas Transportation Institute, College Station, TX.
28. Cao, W. (2007). Study on properties of recycled tire rubber modified asphalt mixtures using dry process. Construction and Building Materials, 21(5), 1011-1015.
29. Chakraborty, A., & Mehta, S. (2017). Utilization & minimization of waste plastic in construction of pavement: A review. International Journal of Engineering Technology Science and Research, 4(8), 2394-3386.
30. Chavan, M. A. J. (2013). Use of plastic waste in flexible pavements. International Journal of Application or Innovation in Engineering and Management, 2(4), 540-552.
31. Chee, C. Y., Azahari, H., & Rehan, M. (2014). Modification of bitumen characteristics by using recycled polyethylene. Molecular Crystals and Liquid Crystals, 604(1), 33-40.
32. Chukaa, B. G. and Carr, J. (2016). Use of plastic waste in construction of roads. International James G. Speight PhD, DSC, in Asphalt Materials Science and Technology, 2016.
33. CIWMB (2007). "Asphalt Roofing Shingles Recycling: Introduction," California Integrated Waste Management Board.
34. Costa, L. M., Silva, H. M. R. D., Oliveira, J. R., & Fernandes, S. R. (2013). Incorporation of waste plastic in asphalt binders to improve their performance in the pavement. International journal of pavement research and technology, 6(4), 457-464.

35. David L Swearingen, Newton C Jackson, Keith W Anderson (1992), Use of recycled materials in highway construction, retrieved from Washington State Department of Transportation.
36. Delongui, L., Matuella, M., Núñez, W. P., Fedrigo, W., da Silva Filho, L. C. P., & Ceratti, J. A. P. (2018). Construction and demolition waste parameters for rational pavement design. Construction and Building Materials, 168, 105-112.
37. Dixit, S., & Rastogi, D. (2013). Studies on the improvement of characteristics of bitumen with use of waste plastic. International Journal of Emerging Technology and Advanced Engineering, 3(3), 895-900.
38. Doh, Y. S., Yun, K. K., Amirkhanian, S. N., & Kim, K. W. (2007). Framework for developing a static strength test for measuring deformation resistance of asphalt concrete mixtures. Construction and Building Materials, 21(12), 2047-2058.
39. Duggal, P., Shisodia, A. S., Havelia, S., & Jolly, K. (2020). Use of waste plastic in wearing course of flexible pavement. In Advances in Structural Engineering and Rehabilitation (pp. 177-187). Springer, Singapore.
40. Edjabou, M. E., Jensen, M. B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., & Astrup, T. F. (2015). Municipal solid waste composition: Sampling methodology, statistical analyses, and case study evaluation. Waste Management, 36, 12-23.
41. Eon-Duval, A., Broly, H., & Gleixner, R. (2012). Quality attributes of recombinant therapeutic proteins: an assessment of impact on safety and efficacy as part of a quality by design development approach. Biotechnology progress, 28(3), 608-622.
42. EPA, 1991. Plastic waste: management, control, recycling, and disposal. Pollution Technology Review No. 201, Noyes Data Corporation, Park Ridge, NJ.
43. Eriksen, M. K., Pivnenko, K., Olsson, M. E., & Astrup, T. F. (2018). Contamination in plastic recycling: Influence of metals on the quality of reprocessed plastic. Waste management, 79, 595-606.
44. Fakhri, M., & Azami, A. (2017). Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. Journal of Cleaner Production, 165, 1125-1132.

45. Fang, C., Wu, C., Hu, J., Yu, R., Zhang, Z., Nie, L. & Mi, X. (2014). Pavement properties of asphalt modified with packaging-waste polyethylene. Journal of Vinyl and Additive Technology, 20(1), 31-35.
46. FHWA (2009). "Reclaimed Asphalt Pavement," Federal Highway Administration.
47. Foo, K. Y., Hanson, D. I., and Lynn, T. A. (1999). "Evaluation of Roofing Shingles in Hot Mix Asphalt," ASCE, Journal of Materials in Civil Engineering, Vol. 11, pp.15-20.
48. FVD (2006). "White Paper on Results of Recycled Asphalt Shingles in Hot Mix". Asphalt Compost Pad Construction," Foth & Van Dyke and Associates Inc., Champaign, IL.
49. Gawande, A., Zamare, G., Renge, V. C., Tayde, S., & Bharsakale, G. (2012). An overview of waste plastic utilization in asphalting of roads. Journal of Engineering Research and Studies, 3(2), 01-05.
50. Germann, F. P., & Lytton, R. L. (1979). Methodology for predicting the reflection cracking life of asphalt concrete overlays. Interim Report, Sep. 1974-Mar. 1979 Texas A&M University, College Station.
51. Geyer, R., Jambeck, R.J., and Law K.L., 2017, Production, Use, and Fate of all Plastics ever Made, Science Advances 19 Jul 2017: Vol. 3, no. 7, e1700782, Retrieved from: https://advances.sciencemag.org/content/3/7/e1700782
52. Ghabchi, R. (2014). Laboratory characterization of recycled and warm mix asphalt for enhanced pavement applications.
53. González, V., Martínez-Boza, F. J., Gallegos, C., Pérez-Lepe, A., & Páez, A. (2012). A study into the processing of bitumen modified with tire crumb rubber and polymeric additives. Fuel processing technology, 95, 137-143.
54. Grilli, G., & Curtis, J. (2021). Encouraging pro-environmental behaviours: A review of methods and approaches. Renewable and Sustainable Energy Reviews, 135, 110039.
55. Grzybowski, K. F. (1993). "Recycled Asphalt Roofing Materials-A Multi-Functional, Low Cost Hot-Mix Asphalt Pavement Additive," Use of Waste material in Hot-Mix Asphalt, ASTM STP 1193, ASTM West Conshohocken, PA.
56. Gupta, S., & Veeraragavan, A. (2009, January). Fatigue behaviour of polymer modified bituminous concrete mixtures. In Journal of Indian Road Congress (Vol. 70, No. 1).

57. Gürü, M., Çubuk, M. K., Arslan, D., Farzanian, S. A., & Bilici, I. (2014). An approach to the usage of polyethylene terephthalate (PET) waste as roadway pavement material. Journal of hazardous materials, 279, 302-310.

58. Habib, N. Z., Kamaruddin, I., Napiah, M., & Isa, M. T. (2011). Rheological properties of polyethylene and polypropylene modified bitumen. International Journal Civil and Environmental Engineering, 3(2), 96-100.

59. Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. Journal of hazardous materials, 344, 179-199.

60. Hassani, A., Ganjidoust, H., & Maghanaki, A. A. (2005). Use of plastic waste (poly-ethylene terephthalate) in asphalt concrete mixture as aggregate replacement. Waste Management & Research, 23(4), 322-327.

61. Hınıslıoğlu, S., & Ağar, E. (2004). Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. Materials letters, 58(3-4), 267-271.

62. Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. Resources, conservation, and recycling, 52(1), 58-73.

63. Imtiaz, T. (2021). Reusing of Recycled Plastic as Pavement Base and Sub-base Materials. Ph.D Dissertation, University of Texas Arlington.

64. Inzerillo, L., Di Mino, G., Bressi, S., Di Paola, F., & Noto, S. (1995). Image Based Modeling Technique for Pavement Distress Surveys: a Specific Application to Rutting. International Journal of Engineering and Technology, 16(5), 1-9

65. Islam, M. R. (2015). Thermal fatigue damage of asphalt pavement. The University of New Mexico.

66. Islam, T. (2021). Reuse of Recycled Plastic for Plastic Road Design. The University of Texas at Arlington.

67. Ismail, Z. Z., & Al-Hashmi, E. A. (2009). Recycling of waste glass as a partial replacement for fine aggregate in concrete. Waste management, 29(2), 655-659. https://doi.org/10.1016/j.wasman.2008.08.012.

68. Jacobson-Kram, D., & McGovern, T. (2007). Toxicological overview of impurities in pharmaceutical products. Advanced drug delivery reviews, 59(1), 38-42.

69. Jain, P.K., Sangita, Bose, S., and Arya, I.R., (1992). Characterization of Polymer Modified Asphalt Binders for Roads and Airfields, ASTM STP 1108, pp. 341-356.
70. Jayaraman. Waste Plastics for Road Laying-Good, Bad, or Ugly. The Logical Indian. 12.20.2015. Accessed 02.14.2019.
71. Jayaraman, K., & Bhattacharyya, D. (2004). Mechanical performance of woodfibre–waste plastic composite materials. Resources, Conservation and Recycling, 41(4), 307-319.
72. Jones, C. L. (2008). "Summit on Increasing RAP Use in Pavements Sate's Perspective," Presented at MoreRap Conference, North Carolina Department of Transportation, Auburn, AL.
73. Jones, L. D., & Jefferson, I. (2012). Expansive soils.
74. Kalantar, Z. N., Karim, M. R., & Mahrez, A. (2012). A review of using waste and virgin polymer in pavement. Construction and Building Materials, 33, 55-62.
75. Karami, M., Nikraz, H., Sebayang, S., & Irianti, L. (2018). Laboratory experiment on resilient modulus of BRA modified asphalt mixtures. International Journal of Pavement Research and Technology, 11(1), 38-46.
76. Khan, T. A., Sharma, D. K., & Sharma, B. M. (2009). Performance evaluation of waste plastic/polymer modified bituminous concrete mixes.
77. Khawaja, H., & Tanveer, A. (2018). Review of Low-Temperature Crack (LTC) Developments in Asphalt Pavements.
78. King, G, Johnston, J 2012, 'Polymer modified asphalt emulsions (composition, uses, and specifications for surface treatments)', Federal Highway Administration (FHWA), FHWA-CFL/TD-12-004.
79. Kök, B. V., & Çolak, H. (2011). Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt. Construction and Building Materials, 25(8), 3204-3212.
80. Kutner, M. H., Nachtsheim, C. J., Neter, J., Li, W., et al. (2005). Applied linear statistical models, volume 5. McGraw-Hill Irwin Boston.
81. Lahimer, A. A., Alghoul, M. A., Yousif, F., Razykov, T. M., Amin, N., & Sopian, K. (2013). Research and development aspects on decentralized electrification options for rural household. Renewable and Sustainable Energy Reviews, 24, 314-324.

82. Lastra-González, P., Calzada-Pérez, M. A., Castro-Fresno, D., Vega-Zamanillo, Á., & Indacoechea-Vega, I. (2016). Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste. Construction and Building Materials, 112, 1133-1140.
83. Leal Filho, W., Voronova, V., Kloga, M., Paço, A., Minhas, A., Salvia, A. L., ... & Sivapalan, S. (2021). COVID-19 and waste production in households: A trend analysis. Science of the Total Environment, 777, 145997.
84. Liang, M., Xin, X., Fan, W., Wang, H., Ren, S., & Shi, J. (2017). Effects of polymerized sulfur on rheological properties, morphology and stability of SBS modified asphalt. Construction and Building Materials, 150, 860-871.
85. Malizia, A., & Monmany-Garzia, A. C. (2019). Terrestrial ecologists should stop ignoring plastic pollution in the Anthropocene time. Science of the Total Environment, 668, 1025-1029.
86. Mashaan, N., Chegenizadeh, A., & Nikraz, H. (2021). Laboratory Properties of Waste PET Plastic-Modified Asphalt Mixes. Recycling, 6(3), 49.
87. Menaria, Y., & Sankhla, R. (2015). Use of waste plastic in flexible pavements-green roads. Open Journal of Civil Engineering, 5(03), 299.
88. Mistry, R., & Roy, T. K. (2016). Effect of using fly ash as alternative filler in hot mix asphalt. Perspectives in Science, 8, 307-309.
89. Mitra, B. Poverty, Wealth, and Waste. Perc. 03.01.2000. Accessed 03.03.2019.
90. Journal of Research, Volume 03, Issue 17, November 2016
91. Moazami, D., Sahaf, A., & Mohamadzadeh Moghaddam, A. (2019). Investigating the Rutting Behavior of Modified Asphalt Mixtures with Waste Materials. International Journal of Numerical Methods in Civil Engineering, 3(4), 53-65.
92. Modarres, A., & Hamedi, H. (2014). Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. Materials & Design, 61, 8-15
93. Montanelli, E. F. (2013). Fiber/polymeric compound for high modulus polymer modified asphalt (PMA). Procedia-Social and Behavioral Sciences, 104, 39-48, Chicago.
94. Mohammed Altaweel, A. M., Ranganathaiah, C., Kothandaraman, B., Raj, J. M., & Chandrashekara, M. N. (2011). Characterization of ACS modified epoxy resin composites

with fly ash and cenospheres as fillers: mechanical and microstructural properties. polymer composites, 32(1), 139-146.

95. Moreno, F., Sol, M., Martín, J., Pérez, M., & Rubio, M. C. (2013). The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. Materials & Design, 47, 274-280.
96. Motlagh, A. A., Kiasat, A., Mirzaei, E., & Birgani, F. O. (2012). Improving technical characteristics of asphalt pavement using wastes of polystyrene disposable dishes. World Applied Sciences Journal, 18(5), 605-612.
97. Movilla-Quesada, D., Raposeiras, A. C., Silva-Klein, L. T., Lastra-González, P., & Castro-Fresno, D. (2019). Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen. Waste Management, 87, 751-760.
98. Naghawi, H., Al-Ajarmeh, R., Allouzi, R., AlKlub, A., Masarwah, K., AL-Quraini, A. and Abu-Sarhan, M. (2018). Recycled Plastic Waste Utilization as Asphalt Binder Modifier in Asphalt Concrete Pavement. World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering Vol:12, No:5, 2018.
99. NAHB (1998). "From Roofs to Roads: Recycling Asphalt Roofing Shingles into Paving Materials," National Association of Home Builders.
100. Najafi, S. K. (2013). Use of recycled plastics in wood plastic composites–A review. Waste Management, 33(9), 1898-1905.
101. NAPA (2009). "How to Increase RAP Usage and Ensure Pavement Performance," National Asphalt Pavement Association,
102. NAPA (2011). "Mix Production Survey Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, Warm-mix Asphalt Usage: 2009-2010," Technical Report, National Asphalt Pavement Association, Washington, DC.
103. Napiah, M., Habib, N. Z., & Kamaruddin, I. (2014). Creep behavior of polyethylene modified bituminous mixture. APCBEE procedia, 9, 202-206.
104. Nasser, O. A., & Petranikova, M. (2021). Review of achieved purities after li-ion batteries hydrometallurgical treatment and impurities effects on the cathode performance. Batteries, 7(3), 60.

105. Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2021). An overview of plastic waste generation and management in food packaging industries. Recycling, 6(1), 12.
106. Nouali, M., Derriche, Z., Ghorbel, E., & Chuanqiang, L. (2018). Plastic bag waste modified bitumen a possible solution to the Algerian road pavements. Road Materials and Pavement Design, 1-13.
107. Obbard, R., Iliescu, D., Cullen, D., Chang, J., & Baker, I. (2003). SEM/EDS comparison of polar and seasonal temperate ice. Microscopy research and technique, 62(1), 49-61.
108. ODOT (2009). "Standard Specification for Highway Construction," Oklahoma Department of Transportation, Office of Solid Waste and Office of Water, 1990. Methods to manage and control plastic waste. Report to Congress (EPA/530-XW-89-051.
109. Onyango, F. O. (2015). Rubber tyre and plastic waste used in asphalt concrete pavement (Doctoral dissertation).
110. Palit, S. K., Reddy, K. S., & Pandey, B. B. (2004). Laboratory evaluation of crumb rubber modified asphalt mixes. Journal of Materials in Civil Engineering, 16(1), 45-53.
111. Pamungkas, R. A., Bagaskara, C., Prabanto, B. A., Rahmat, A. N., Pambayun, W. B., Anggoro, Y. S., & Setyawan, A. (2019, September). Design and properties of asphalt concrete with various plastic waste in dry processed. In IOP Conference Series: Materials Science and Engineering (Vol. 578, No. 1, p. 012079). IOP Publishing.
112. Panda, M., & Mazumdar, M. (2002). Utilization of reclaimed polyethylene in bituminous paving mixes. Journal of materials in civil engineering, 14(6), 527-530.
113. Pivnenko, K., Eriksen, M. K., Martín-Fernández, J. A., Eriksson, E., & Astrup, T. F. (2016). Recycling of plastic waste: Presence of phthalates in plastics from households and industry. Waste Management, 54, 44-52.
114. Pituch, K. A. and Stevens, J. P. (2015). Applied multivariate statistics for the social sciences: Analyses with SAS and IBMs SPSS. Routledge.
115. Prata, J. C., da Costa, J. P., Girão, A. V., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2019). Identifying a quick and efficient method of removing organic matter without damaging microplastic samples. Science of the total environment, 686, 131-139.

116. Priyanka, B. A., Sarang, G., & Ravi Shankar, A. U. (2019). Evaluation of Superpave mixtures for perpetual asphalt pavements. Road Materials and Pavement Design, 20(8), 1952-1965.

117. Punith, V. S., & Veeraragavan, A. (2007). Behavior of asphalt concrete mixtures with reclaimed polyethylene as additive. Journal of Materials in Civil Engineering, 19(6), 500-507.

118. Punith, V. S., & Veeraragavan, A. (2010). Behavior of reclaimed polyethylene modified asphalt cement for paving purposes. Journal of Materials in Civil Engineering, 23(6), 833-845.

119. Rahman, F., & Hossain, M. (2014). Review and analysis of Hamburg Wheel Tracking device test data (No. KS-14-1). Kansas. Dept. of Transportation. Bureau of Materials & Research.

120. Rajasekaran, S., Vasudevan, R., & Paulraj, S. (2013). Reuse of Waste Plastics Coated Aggregates-Bitumen Mix Composite for Road Application—Green Method. American Journal of Engineering and Research, 2, 1-13.

121. Rajib, B. Mallick, T., Matthew, R., and Mogawer, W. S. (2000). "Evaluation of Use of Manufactured Waste Asphalt Shingles in Hot Mix Asphalt," Technical Report No. 26, Chelsea Center for Recycling and Economic Development, University of Massachusetts Lowell, Chelsea, MA.

122. Arandia, E., O'Donncha, F., McKenna, S., Tirupathi, S., & Ragnoli, E. (2019). Surrogate modeling and risk-based analysis for solute transport simulations. Stochastic Environmental Research and Risk Assessment, 33, 1907-1921.

123. Rebeiz, K. S., & Craft, A. P. (1995). Plastic waste management in construction: technological and institutional issues. Resources, conservation, and recycling, 15(3-4), 245-257.

124. Rossi, C. O., Spadafora, A., Teltayev, B., Izmailova, G., Amerbayev, Y., & Bortolotti, V. (2015). Polymer modified bitumen: Rheological properties and structural characterization. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 480, 390-397.

125. Sabina, K. T. A., Sangita, S. D., & Sharma, B. M. (2009). Performance evaluation of waste plastic/polymer modified bituminous concrete mixes. Journal of Scientific and Industrial Research, 68, 975-979.

126. Sandhiya, K., Sanjay, K. L., Rajkumar, K.N., Sandhya, R. and Sukumar, S. (2018), "Partial Replacement of Bitumen by Using Plastic in Bitumen Concrete," International Journal of Pure and Applied Mathematics, Volume 119 No. 12 2018, 2913-2920.
127. Sangita, Khan, T. A., Sabina, Sharma and D.K. Effect of waste polymer modifier on the properties of bituminous concrete mixes. Elsevier Construction and Building Materials 25 (2011) 3841–3848.
128. Santagata, E., Riviera, P. P., Dalmazzo, D., Lanotte, M., Zanetti, M., Fiore, S., & Ruffino, B. (2012). Design and construction of a full-scale test section with asphalt rubber gap-graded wearing course mixture. Procedia-Social and Behavioral Sciences, 53, 524-534.
129. Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., & Dunphy-Daly, M. M. (2020). Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. Environment international, 144, 106067.
130. Sengoz, B., and Topal, A. (2005). "Use of Asphalt Roofing Shingle Waste in HMA," Journal of Construction and Building Materials, Vol. 19, Issue: 5, pp. 337-346.
131. Shiva, P. K., Manjunath, K. R. K., & Prasad, V. R. (2012). Study on Marshal Stability Properties of BC Mix Used in Road Construction by Adding Waste Plastic Bottle. JUSR Journal of Mechanical and Civil Engineering (IOSRJMCE), 2(2), 12-23.
132. Shopnil, M. S. R., Imtiaz, T., Mahjabin, S., & Hossain, M. S. (2023). Hydraulic Conductivity Prediction of Cement Stabilized Pavement Base Incorporating Recycled Plastics and Recycled Aggregates. International Journal of Structural and Construction Engineering, 17(6), 260-264.
133. Siddique, R., & Naik, T. R. (2004). Properties of concrete containing scrap-tire rubber–an overview. Waste Management, 24(6), 563-569
134. Singh, S. (2022). Design of Crack Attenuating Mix using Waste Plastic (Doctoral dissertation).
135. Sobolev, K., Flores, I., Bohler, J. D., Faheem, A., & Covi, A. (2013, April). Application of fly ash in ASHphalt concrete: from challenges to opportunities. In Proceedings of World of Coal Ash Conference.
136. Sousa JB, Weissman SL (1994). Modeling permanent deformation of asphalt-aggregate mixes. J. Assoc. Asphalt. Paving. Technol., 63: 224-257.
137. Stevens, J. P. (2012). Applied multivariate statistics for the social sciences. Rout- ledge.

138. Szekely, G., Amores de Sousa, M. C., Gil, M., Castelo Ferreira, F., & Heggie, W. (2015). Genotoxic impurities in pharmaceutical manufacturing: sources, regulations, and mitigation. Chemical reviews, 115(16), 8182-8229.
139. Tasnim, J. (2022). Reuse of Recycled Plastic for Subgrade Treatment (Doctoral dissertation, The University of Texas at Arlington).
140. Tsakona, M. and Rucevska, I (2020). UNEP Baseline report on plastic waste.
141. Vasudevan, R. N. S. K., Velkennedy, R., Sekar, A. R. C., & Sundarakannan, B. (2010). Utilization of waste polymers for flexible pavement and easy disposal of waste polymers. International Journal of Pavement Research and Technology, 3(1), 34-42.
142. Venkat, R. R. V (2017). Report on the utilization of waste plastic materials in asphalt pavements
143. Walubita, L. F., Faruk, A. N., Das, G., Tanvir, H. A., Zhang, J., & Scullion, T. (2012). The overlay tester: a sensitivity study to improve repeatability and minimize variability in the test results (FHWA/TX-12/0-6607-1). Texas Transportation Institute, Texas A&M University System.
144. Wilschefski, S. C., & Baxter, M. R. (2019). Inductively coupled plasma mass spectrometry: introduction to analytical aspects. The Clinical Biochemist Reviews, 40(3), 115.
145. Yin, J., & Wu, W. (2018). Utilization of waste nylon wire in stone matrix asphalt mixtures. Waste Management, 78, 948-954.
146. Yin, F., Arambula, E., Lytton, R., Martin, A. E., & Cucalon, L. G. (2014). Novel method for moisture susceptibility and rutting evaluation using Hamburg wheel tracking test. Transportation Research Record, 2446(1), 1-7.
147. Zhou, F., & Scullion, T. (2003). Upgraded overlay tester and its application to characterize reflection cracking resistance of asphalt mixtures (FHWA/TX-04/0-4467-1). Texas Transportation Institute, Texas A&M University System.
148. Zhou, F., & Scullion, T. (2005a). Overlay tester: a rapid performance related crack resistance test (FHWA/TX-05/0-4467-2). Texas Transportation Institute, Texas A&M University System.
149. Zhou, F., & Scullion, T. (2005b). Overlay tester: a simple performance test for thermal reflective cracking (with discussion and closure). Journal of the Association of Asphalt Paving Technologists, 74.

150. Zhou, F., Hu, S., & Scullion, T. (2007a). Development and verification of the overlay tester-based fatigue cracking prediction approach (FHWA/TX-07/9-1502-01-8). Texas Transportation Institute, Texas A&M University System.

151. Zhou, F., Hu, S., & Scullion, T. (2009). Overlay tester: a simple and rapid test for HMA fracture property. Road Pavement Material Characterization and Rehabilitation selected papers from the 2009 GeoHunan International Conference. 65-73.

152. Zhou, F., Hu, S., Chen, D. H., & Scullion, T. (2007b). Overlay tester: simple performance test for fatigue cracking. Transportation Research Record: Journal of the Transportation Research Board, 2001(1), 1-8.

153. Zoorob, S. E., & Suparma, L. B. (2000). Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Cement and Concrete Composites, 22(4), 233-242.

154. https://techstartups.com/2019/12/20/india-built-21000-miles-road-ways-using-plastic-waste/