PERFORMANCE EVALUATION OF ASPHALT MIXTURES WITH BITUMEN PARTIALLY REPLACED WITH WASTE ENGINE OIL AND CRUMB RUBBER

WAQAR ANWAR

(00000320120)

A thesis submitted in partial fulfillment of

the requirements for the degree

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in

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Performance Evaluation of Asphalt Mixtures with Bitumen Partially Replaced with Waste Engine Oil and Crumb Rubber

Submitted by

Waqar Anwar

(00000320120)

has been accepted towards the partial fulfillment

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Master of Science in Transportation Engineering

____

Dr. Muhammad Irfan

Professor,

Department of Transportation Engineering,

Military College of Engineering, Risalpur

National University of Sciences and Technology (NUST), Islamabad

DECLARATION

I certify that this research work titled "**Performance Evaluation of Asphalt Mixtures with Bitumen Partially Replaced with Waste Engine Oil and Crumb Rubber**" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged/referred.

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Signature: ______________________________

Name of Supervisor: **Dr Muhammad Irfan**

Date: _________________________________

Signature **(HOD)**: ________________________

Date: _________________________________

Signature **(Dean/Principal)**:_______________

Date: _________________________________

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<u>DEDICATION</u>

This thesis is dedicated to my beloved Father, who has always been there for me through the ups and downs of my life; my beloved brothers, who have always been there to cheer me up when I am feeling down; and my respected advisor, Brig. Dr. Muhammad Irfan, whose guidance has enabled me to complete my research work.

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(*Engr. Waqar Anwar)*

LIST OF ACRONYMS

AASHTO	-	American Association of State Highway and Transportation
AC	-	Asphalt Concrete
ARL	-	Attock Refinery Limited
ASTM	-	American Standard Test Method
BS	-	British Standard
CIPR	-	Cold-In-Place Recycling
WEO	-	Waste Engine Oil
HMA	-	Hot-Mix Asphalt
TSR	-	Tensile Strength Ratio
ITS	-	Indirect Tensile Strength
M_R	-	Resilient Modulus
LDPE	-	Low Density Polymer Ethylene
HDPE	-	High Density Polymer Ethylene
JMF	-	Job Mix Formula
LOS	-	Level of Service
CRMA	-	Crumb Rubber Modified Asphalt

NHA	-	National Highway Authority
NMAS	-	Nominal Maximum Aggregate Size
OAC	-	Optimum Asphalt Content
OBC	-	Optimum Bitumen Content
PG	-	Performance Grade
CR	-	Crumb Rubber
UTM	-	Universal Testing Machine
VFA	-	Voids Filled with Asphalt
VMA	-	Voids in Mineral Aggregate
WMA	-	Warm Mix Asphalt

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ABSTRACT

Crumb Rubber Modified Asphalt (CRMA) has many benefits such as increased rutting resistance and reflective cracking resistance, but there are also major concerns that limits its further application. These major concerns include low solubility of Crumb Rubber (CR) in asphalt, high viscosity when it is incorporated in higher amounts and poor storage stability. To tackle these limitations of CRMA, a hybrid approach was adopted in this study by introducing Waste Engine Oil (WEO) in CRMA to create a balance between stiffness and fluidity and to optimize the utilization of WEO along with CR to reduce the quantity of base bitumen by increasing the contribution of waste materials. A laboratory-based study was conducted to ascertain resilient modulus, Tensile strength Ratio (TSR), and permanent deformation of modified asphalt mixtures. The chemical composition of waste materials was determined using X-Ray Fluorescence test, and it was found that Zinc was found to be present in abundance in CR, while sulfur was present in higher amounts in WEO as depicted by its high concentration. It was observed that WEO can regulate the role of CR in asphalt because it facilitated the swelling action of CR in asphalt as indicated by enhanced performance properties. It was also found that the resilient modulus and rutting resistance was increased by 44% and 54% respectively as compared to control mixtures, whereas the moisture resistance was increased by 7%. However, higher dosages of the modifier led to decrease in resilient modulus, rutting resistance, and moisture resistance. Finally, the results of ANOVA and Tukey's analysis revealed that, at the confidence level of 95%, the modifier has a significant influence on the performance indicators of modified asphalt mixtures.

CHAPTER 1

INTRODUCTION

1.1 General

Pakistan is the fifth-most populous country in the world. The nation is quickly urbanizing because of social and economic forces. Pakistan has the highest rate of urbanization in South Asia, with 36.4% of the population residing in urban areas. Nearly half of the people of the United States will live in urban areas by 2025. This dramatic escalation in need to repair and maintain our present pavements has been driven by a loss in budgetary funds for an efficient, safe, and cost-effective roadway transportation system during the last several decades. In the past 25 years, asphalt reclamation and recycling have shown tremendous improvement, which is both technically and naturally desirable.

There is a growing infrastructure deficit in Pakistan due to the country's spending of approximately 2.1 percent of its GDP on road development. A worrying scenario seems to be emerging in Pakistan because of a downward trend in the development expenditures made by the government and the little role played by the private sector in the development of infrastructure. It is possible that Pakistan would fall short of its target of 124 billion dollars in funding for the construction of its road infrastructure between 2016 and 2040. The magnitude of this deficit is greater than Pakistan's entire outstanding obligations to its foreign creditors. Therefore, it is essential to use materials that do not harm the environment in this case to bring down the cost of the road infrastructure. The greater the proportion of bitumen modifiers in the asphalt mix that has acceptable properties, the greater the savings for the government and the less of a burden it will be financially.

Reclaiming and recycling asphalt meets all our societal goals of delivering efficient and safe thoroughfares while also drastically reducing energy consumption (oil consumption) and environmental impact compared to conservative pavement restoration. To that aim, procurement agencies may increase their available funds by using this method, but it must be done carefully since not all roads are viable candidates for asphalt recycling. As a result, the roaming public benefits by having an asphalt driving surface that they can trust. Considering our nation’s present economic situation, it is imperative that to cut investment expenses and establish a low-cost, efficient, and intelligent roadway system. The technology has significantly increased the requirement for pavement repair and management. Asphalt reclamation and recycling has made great development in the previous 25 years, and it is currently a preferred way of repairing old pavements in terms of both technological and natural advantages.

As the population of cities grows, so does the amount of economic and social activity, and transportation is a critical component of both. Passenger and freight traffic on Pakistan's highways make up around 92 and 96 percent, respectively. Because of the importance of preserving this infrastructure, it is necessary to employ effective preservation techniques that are both inexpensive to implement and long-lasting, to reduce rehabilitation and maintenance costs while also providing passengers with reliable transportation options.

Across the globe, asphalt concrete is the most often utilized paving medium for new roads. Since roads are vital to the country's social and economic well-being, they must be preserved. In a society where roads are the primary transportation route, the lifetime of asphalt pavements is essential. Because of the high cost of bitumen, long-lasting asphalt blends are becoming more popular. Pavement distresses occur due to the pavement's long-term exposure to high motor traffic and environmental deterioration. Researchers have spent the last several decades attempting to find ways to prolong the service life of pavement materials and so save money.

Hot Mix Asphalt (HMA) is primarily composed of aggregate and bitumen. To make asphalt concrete more durable and resistant to the degrading effects of traffic and the environment, a variety of modifiers are used. Rutting and cracking may occur on pavements that are subjected to heavy traffic regularly. Mainly due to water damage, pavements are degrading at an alarming rate. In the presence of water/moisture, the binder will not adhere to the aggregate. The pavement will collapse fast if the binder cannot bond the aggregate, which is referred to as stripping.

CRM may be an effective additive for easing the disposal of discarded tires. As a result of its incorporation the rutting resistance is improved, the flexibility of HMA mixes is increased, and asphalt binder ageing is delayed. Using thin layers of modified binder HMA mixes to create long-lasting roads may be a huge benefit. SBS and SBR are commercial polymers, and their usage in road and pavement building raises construction costs since they are costly materials. On the other hand, CRM has the potential to be both ecologically friendly and cost-effective and improve the bitumen binder’s characteristics and durability.

1.2 Problem Statement

The highway authorities of Pakistan spend vast amounts of money each year on the design, building, rehabilitation, and maintenance of roads to achieve the appropriate levels of service, prevent frequent difficulties, and, as a result, limit the suffering. Uncontrolled axle loads and extreme weather conditions are the leading causes of early pavement breakdown on asphaltic surfaces. Ruts are one of the most prevalent pavement problems in Pakistan because of uncontrolled excessive axle loads and considerable temperature fluctuations. Summers are blisteringly hot, and winters are bone-chillingly freezing here. Asphalt pavements are more likely to crumble and deteriorate over time in this climate. Rutting in asphaltic concrete is mainly addressed by Crumb Rubber Modified Bitumen (CRMB), which is made from recycled rubber. However, polymers and other additions to Bitumen are not used in Pakistan, and all adjustments are made by altering the aggregate grade and binder amount. Because it's made from used tires, Crumb Rubber in bitumen extends the useful life of flexible pavement while improving ride quality, lowering noise levels, and minimizing pollution caused by tire piles or burning.

To enhance the qualities of bitumen, its properties have been modified using a variety of waste materials, including crumb rubber. When incorporated into bitumen, crumb rubber raises the temperature at which the bitumen softens, as well as its viscosity. This decreases the bitumen's ability to penetrate and its thermal susceptibility. In addition, asphalt rubber mixtures have the potential to greatly improve the permanent deformation resistance and improve rutting resistance at low temperatures. This could increase the durability of the pavements, even though these mixtures typically use a greater quantity of binder. Previous research has revealed that crumb rubber cannot be degraded or melted into asphalt binder, as indicated in the study of the relevant literature. There will be a higher difference in density between the binder and the undissolved rubber when fewer rubber components are decomposed in the binder than when more rubber components are decomposed. Phase separation is more likely to occur because of this. In addition, several studies have brought up the possibility of using used engine oil as a bitumen extender or modifier.

Adding used engine oil may enhance the bitumen's penetration, which in turn lowers the temperature at which the bitumen's softening point occurs and its viscosity, which in turn lowers the temperatures at which asphalt mixes are produced and compacted. However, because of its inclusion, there is a possibility that the elastic recovery and permanent deformation resistance may be reduced. Because of this, the mixed design of these materials must be carefully considered. Waste engine oil may be use as a binder modifier. However, its absorption rate into asphalt mixes is often kept to a minimum to ensure that the final product will have satisfactory performance. As a result, to solve the previously mentioned issue associated with rubberized asphalt, waste engine oil and crumb rubber were combined to produce a CR-WEO modifier, which partially replaced the base bitumen.

1.3 Scope

To accomplish the goals that were set for this study, a strategy was developed, and the most important aspects of the research were highlighted. A thorough literature research was conducted about pre-treatment of Crumb Rubber and the inclusion of CR-WEO in base bitumen. To meet the stated goals of the study, a thorough research strategy was devised, which is outlined in the following sections:

- In-depth investigation of asphalt mix design, covering prior research publications on CR-WEO as a modifier for asphalt mixtures and scientific journals, as well as technical literature.
- Consistency tests such as Penetration test, ductility test, fire and flash point and softening point tests were utilized to characterize the binder that will be employed in this research.
- X-Ray Fluorescence test was conducted to determine the elemental and chemical composition of WEO and CR.
- Indirect tensile strength test, Resilient modulus test, Tensile Strength Ratio (TSR) and Hamburg Wheel tracking Test (HWTT) were used to determine Strength, stiffness, moisture susceptibility, and rutting resistance of unmodified and CR-WEO modified Superpave gyratory compacted HMA samples.

1.4 Research Objectives

The following is a list of the objectives that the research project aims to accomplish:

- To assess moisture susceptibility of CR-WEO modified asphalt through Tensile Strength Ratio (TSR).
- To evaluate the effect of CR-WEO as a modifier on stiffness by evaluating the Resilient Modulus (MR) using Universal Testing Machine (UTM).
- To investigate Rut resistance of CR-WEO modified HMA using Hamburg Wheel Tracking Test (HWTT).

1.5 Organization of Thesis

This thesis is divided into 5 different segments. The way this thesis is structured is shown in Figure 1.1.

Chapter 1 includes an introduction, a problem description, a discussion of research goals, and a discussion of the scope of the study.

Chapter 2 offers a literature study and in-depth examination of the different characteristics of CR-WEO when used in Pavements. This chapter highlights the applicability of past work on CR-WEO to the subject of pavement engineering. The comprehensive literature study done for the research is also presented in Chapter 2.

Chapter 3 discusses the materials that have been utilized, the testing that has been done, as well as the background of those tests, and it explains the significance of the findings that have been acquired from performance tests.

Chapter 4 offers a description of the outcomes of experimental work. This chapter contains a complete compilation of results. This chapter provides a comprehensive explanation of the experimental program's graphs, charts, and tables, as well as all relevant data. The findings and interpretations are also discussed in Chapter 4.

Chapter 5 provides the findings and suggestions. Previous chapter was focused on future research horizons and how researchers may use the results of this research study. In this chapter, we will continue this line of inquiry.

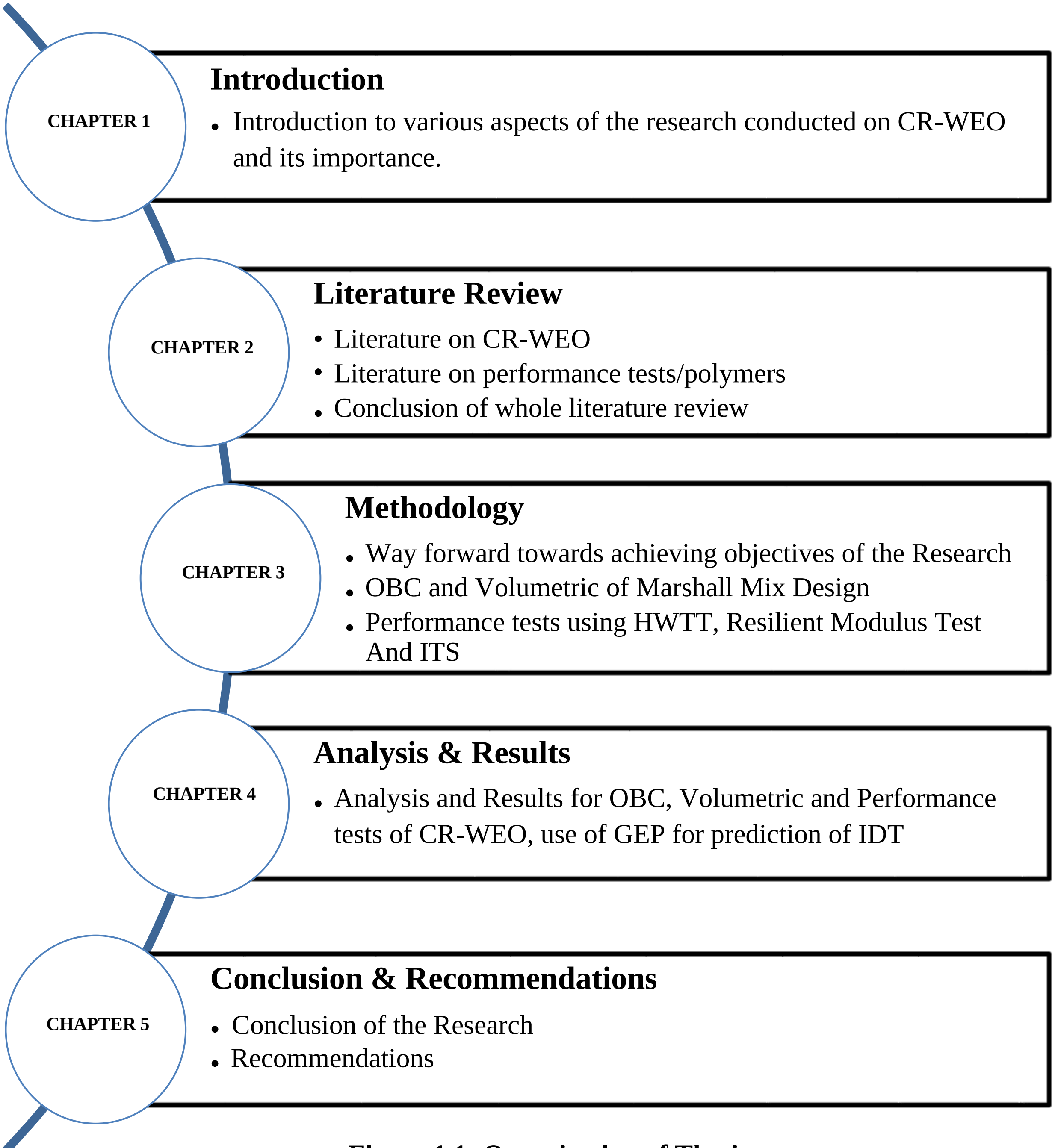


Figure 1.1: Organization of Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a summary of the research and theory related to the properties of asphalt binder, containing Waste Engine Oil (WEO) and Crumb Rubber (CR). According to the findings of previous studies, the effects of adding WEO and CR on the Rheological and different performance parameters have been discussed.

2.2 Background

The social and economic well-being of a nation is directly tied to the quality of its road network and how effectively it is maintained. It is common practice to use the number of kilometers of paved roads in a country as a measure of that nation's level of development. As a result, it is essential to make investments in the continuation and improvement of the road transportation infrastructure. Bitumen is the primary component of asphalt, which has been used extensively in the construction industry for quite some time. However, commonly utilized pavements are unable to fulfil the practical needs of both the existing traffic loadings and the traffic loadings that will be generated in the future. As a result, there is an immediate need for pavement materials that are of a better quality, safer, more trustworthy, and more environmentally friendly. Aging effects, temperature susceptibility, and viscoelasticity are three features of the asphalt binder that play a very essential role in the performance of asphalt mixture.

Because of a rise in service traffic density, high axle loadings, and a decrease in the number of services supplied for maintenance, road structures have collapsed at a faster rate during the last several years. Conventional bitumen binder needs to have improvements made to its performance-related properties, primarily in the areas of resistance to permanent deformation and fatigue cracking, to minimize the distresses that are developed in pavements and to increase the longevity of asphaltic pavements. This will help to keep the distresses that are developed in pavements to a minimum. Numerous studies have been conducted to investigate the different ways in which bitumen binder may be modified, which, in turn, leads to improvements in the performance of pavement.

2.3 Modification of Pavement Binders

Modifications are made to the binder to accomplish any of the following improvements:

- A high viscosity (or stiffness) during the summer months to prevent the formation of ruts or pushing.
- To prevent thermal cracking, the material should have a low stiffness and relaxation properties at low temperatures.
- Peeling may be minimized by increasing adhesion between aggregate particles and asphalt.
- To increase the temperature range in which asphalt can function effectively.
- To generate an elastic blend at a low temperature while simultaneously reducing non-load-associated thermal cracking.
- To make blends more rigid when they are heated to a high temperature.
- To enhance fatigue resistance.
- To make the material more oxidation- and age-resistant.
- To make the pavement more resistant to gasoline when it is subjected to fuel spills.
- To enhance the overall functionality of the pavement

At any one moment, a modifier might enhance one feature while degrading another. For example, a fuel-resistant modifier may inhibit fuel solubility and rutting at high temperatures, but it may not work well in low temperatures or the other way around. To be clear, not all modifiers are appropriate for every case.

2.4 Asphalt Modification Using Crumb Rubber

Crumb Rubber modified asphalt (CRMA) is often made from waste tire rubber that has been reduced to sizes even smaller than 1 mm using mechanical shredding, grinding, and reduction processes. It has been shown to improve resistance to rutting, promote flexibility in HMA mixes, slow the ageing process of asphalt binder, and cut down on reflective cracking. It is possible to gain significant success in lengthening the durability of roadways by utilizing thinner films of layers of modified binder HMA mixes. The Crumb Rubber that was employed as a polymer in this investigation is shown in Figure 2.1.

Figure 2.1: Crumb Rubber for Asphalt Modification

The plants that really produce rubber are the source of natural rubber. The most well-known of these plants is the Hevea brasiliensis species, which is indigenous to South America. Plantations in Indonesia, the Malay Peninsula, and Sri Lanka are responsible for the production of more than 90 percent of all-natural rubber on the market today. Para rubber is the general term that is given to this specific kind of plant rubber. Polymerization is the chemical process that is most often used to manufacture synthetic rubber, which is generated in a manner that is analogous to that of the production of plastics. Neoprene, Buna rubbers, and butyl rubber are examples of these synthetic rubbers that may be found. In most cases, they are designed with certain characteristics in mind to fulfil functions. Styrene butadiene rubber and butadiene rubber are the two types of synthetic rubber that are used in the production of tires the most often.

Charles Mac Donald in 1960 made the discovery that novel material qualities may be developed by combining crumb rubber with ordinary bitumen and allowing the mixture to be mixed for a period ranging from 45 to 60 minutes. Because of this, the size of the rubber particles increased when exposed to higher temperatures, which made it possible for pavement mixes to absorb more liquid bitumen. Midway through the 1980s, researchers in Europe started working on developing newer polymers and additives that may be used in bitumen binder modification.

2.5 Common Practices for Producing Crumb Rubber

Crumb tire rubber can be used in many different applications. The particle of rubber is graded, and it may be found in a wide variety of sizes and forms. The meshing screen or sieve size through which crumb rubber is passed throughout the manufacturing process serves as the standard by which it is recognized or measured. The manufacturing process for crumb rubber consists of the two processes that are listed below.

2.5.1 Shredding

Granulated scrap tire rubber is produced beginning with this stage of the manufacturing process. Tires that have been sliced up or left in their entirety are both able to be transported to shredding factories. They are subjected to processing, which results in a reduction in the particle size to the appropriate levels. Magnets and separators are used in the process of removing the steel belt and fiber reinforcements from the tires. The physical characteristics of a bitumen-rubber mix can be influenced by the crumb rubber particle size. In general, small differences in particle size have little influence on mix performance. The various sizes of CR that may be used for the modification of asphalt are shown in Figure 2.2.

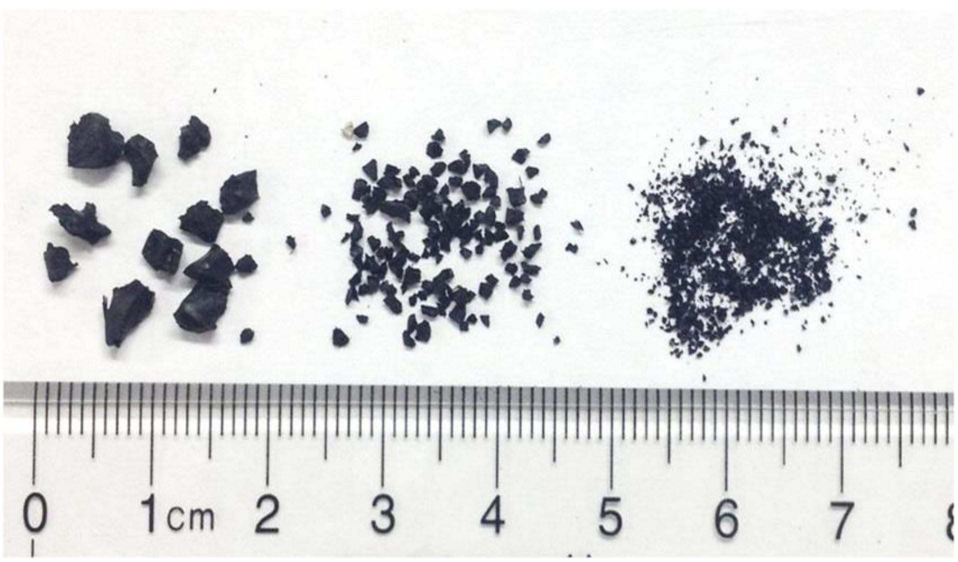


Figure 2.2: Different sizes of crumb rubber(Gheni et al., 2017)

2.5.2 Grinding and Granulation

The manufacture of crumb rubber may continue with any one of the following three procedures once the scrap tires have been shredded. Granulated Crumb rubber modifier is the product obtained from the granulator process, which results in cubical, evenly formed particles. The Cracker-mill process, which creates unevenly shaped and torn particles with sizes ranging from 4.75 mm (No. 4 sieve) to 11.42 mm (No. 40 sieve), is the method that is used the most often. This method is known as crushed Crumb rubber modifier. The third procedure is micro-milling technique, which produces an extremely fine powdered Crumb rubber modifier.

2.6 Performance Parameters of Crumb Rubber Modified Asphalt

The incorporation of CR results in low penetration values and higher softening points. Some of the general advantages of CR that have been reported include lower material costs, increased fatigue resistance, less reflective cracking, improved rutting resistance, stronger ductility, increased elasticity, and improved properties under cyclic loads. However, some researchers also reported some disadvantages of incorporating CR such as vulnerability to disintegration and oxygen absorption, as well as large molecular weight, which necessitated the need for mechanical homogenization and partial breakdown of the rubber compounds. Because of its chemical stability, tires rubber is difficult to degrade. Therefore, landfilling is the most frequent industrial methods of processing waste tire rubber.

In recent years, scrap tire rubber has been extensively used in asphalt pavement because of its excellent performance and environmental advantages. Crumb rubber is made from the shredded scrap tires and is added to asphalt to increase its overall performance. Airey et al., (2004) evaluated the effect of the interaction between rubber and bitumen on the short term and long-term ageing of asphaltic mixes utilizing the dry method. As part of the aggregate in a dense bituminous macadam with a maximum aggregate size of 20 mm, the levels of modification of crushed rock (CR) ranging from 3 percent to 5 percent were employed in the study. Granulated crumb rubber with a size ranging from 2mm to 8mm was used in this process. Following the fabrication of CRM mixes and Control mixtures using the Superpave Gyratory Compactor, samples were subjected to both short-term and long-term conditioning. The values of the stiffness modulus were found to have increased because of an increased percentage of CR in both short term and long-term aging. The incorporation of CR had also improved the rutting resistance. The use of rubberized bitumen binder lessens the impact of ageing on the rheological and physical properties of asphalt binder. The propeller mixer was used to combine the bitumen and the crumb rubber under consistent blending circumstances, which included a temperature of 180 degrees Celsius, a time of sixty minutes, and a rotational speed of two hundred revolutions per minute.

To investigate how oxidative ageing influences the rheological properties of rubberized modified bitumen, the aging resistance of the modified bitumen was analyzed by performing the Brookfield viscosity test at 135 ^{o}C, the penetration test at 25 ^{o}C, the softening point test at 25 ^{o}C, and the dynamic shear test using ASTM D-4. The findings showed that the use of a rubber-modified binder reduced the influence of ageing on the physical and rheological characteristics of the binder. This was shown by a lower ageing index of viscosity as well as a lower ageing index of G*/ sin at 76 degrees Celsius. Antioxidant was released into the asphalt from the particles of tire rubber, and this proved to be a significant factor in reducing the ageing effect, as the data results correctly observed and pointed out. Antioxidant was released at the same time as the proportion of crumb rubber increased. As seen by the ageing index of viscosity, CRMA held up better over time. As a result of short-term and long-term ageing, the value of the sample was reduced. The stiffness of the binder was improved by adding shredded rubber to it, which made it more resistant to rutting.

Some researchers have indicated that the Crumb Rubber in HMA is a good option for sustainable development since it makes use of waste material. This is because the solution involves the recycling of materials. It enhances resistance to rutting disintegration and produces pavements that have superior endurance by decreasing the distresses created in asphaltic pavement. This results in pavements that can withstand rutting for longer. Road users will soon have access to roadways that are both safer and smoother. In addition, issues relating to pollution will be mitigated, and the environment will be preserved, because of the use of crumb Rubber in HMA mixes.

According to the findings, the mixes with a greater shear rate were more effective at lower temperatures than the blends with a lower shear rate. Greater percentages of crumb rubber in CR modified binders result in greater viscosities, improved resistance to rutting, and reduced likelihood of cracking at low temperatures. In a research that was carried by Santos et al., (2020), the crumb rubber that was used in the production of Crumb Rubber Modifier (CRM) came from two distinct sources and was processed in two distinct ways. Both sources produced crumb rubber with a size of 0.425 millimeters. Before incorporating it into the asphalt concrete mixture, a wet method was used, during which the Crumb Rubber Modifier was combined with the basic asphalt binder for initial mixing. The temperature of the mixture was 177 degrees Celsius, and the mixing speed was 700 revolutions per minute. The viscosity test was one of the processes used in the evaluation of the qualities of these Crumb Rubber Modifier binders, which were determined using the Superpave binder test protocols. At a temperature of 25 degrees Celsius, samples were subjected to penetration, ductility, and elastic recovery tests. Rubber-modified binder's physical properties were shown to have improved because of the investigation. Penetration value and ductility both decreased, whereas elastic recovery increased. As a result, the binder was made more elastic and the rubber's resistance to rutting was increased. Adding crumb rubber to bitumen improved the rutting resistance of the rubberized pavement mix by improving the rutting factor.

According to the findings of Mashaan et al., (2012), the incorporation of waste tire rubber into asphalt concrete improves both the material's physical and mechanical properties. In this study, the typical bitumen with an 80/100 penetration grade was used, and Crumb Rubber (CR) with a size of 30 mesh was utilized (0.6mm). For the manufacture of the rubber modified mixture, a propeller mixer was utilized. This mixer could rotate at a speed of 200 rpm for a duration of 30 minutes throughout the blending process. According to the findings of the tests, increasing the amount of CR in the binder caused the penetration point values to decrease while simultaneously raising the softening point and the viscosity. This is because the CR has an interaction effect with the binder, which makes the binder stiffer and increases its capacity to recover after elastic deformation. The quantity of asphaltenes contributed to the rise in viscosity, which in turn enhanced the viscous flow of the binder at 135 degrees Celsius. The results of the tests on the stiffness modulus showed that increasing CR resulted in higher stiffness values than the control mixes.

2.7 Problems with Crumb Rubber Modified Asphalt

Crumb rubber cannot be completely degraded as well as melted down into a binder, according to previous studies. It is a well-known fact that the pace at which undissolved rubber passes through a binder is directly related to the radius of that rubber, as well as the difference in density between the rubber and the binder. Carbon black, which makes up most of the undissolved rubber in the binder, has a density that is between 1.8 and 2.1 times that of asphalt binder (1.15 grams per cubic centimeter). In addition, the process of de-polymerization and de-vulcanization causes some rubber components to be released into the binder, which causes a change in the binder's viscosity.

This means that when the rubber components in the asphalt are less degraded, the undissolved rubber particles will be larger and have a higher density difference with the binder. Phase separation is more likely to occur because of this. The rubber components may be dissolved and dispersed in the asphalt binder in the form of a network to optimize their compatibility with the asphalt binder. Because of this, the properties of rubber asphalt are affected by the presence of undissolved rubber particles. A more uniform look will be achieved if the rubber is dispersed more finely across the asphalt. Maintaining the integrity and independence of rubber particles is critical to rubber asphalt's high-temperature, low-temperature, and performance stability performance. Potentially detrimental to rubber asphalt performance are rubber particles that have flocculated or become agglomerated. When asphalt pavements are made with rubber, they may perform better in both hot and cold weather, while also extending their lifespan. However, since the additional rubber particles are distributed in an uneven and agglomerated manner, the performance of the asphalt pavement may be unreliable.

Asphalt modified with CR has the further benefit of reducing reflection cracks, reducing vehicle noise, and increasing a surface's resistance to skidding when wet, as well as eliminating "black pollution" created by waste tires accumulating on it. Light oil in HMA causes CR particles to expand during the production process for crumb rubber modified asphalt (CRMA). Due to partial desulfurization, these particles recover some of their original viscosity and flexibility. Meanwhile, the absorption of light oil thickens clean asphalt. As a result of the synergistic effects of CRMA, these properties have all been increased. As an addition to the asphalt, waste crumb rubber (CR) created from waste tires may not only help alleviate environmental concerns caused by these materials, but also enhance the characteristics of binders, which in turn improves the performance of asphalt pavement. The high temperature integrity of binders is improved by the CR's carbon black as well as Sulphur content. Road noise may be reduced while pavement life is extended, and vehicle comfort is enhanced. Despite this, traditional CRMA is prepared by adding CR to asphalt and then shearing at high speed, which results in most of the CR mainly swelling as well as other physical reactions, hurting the effectiveness of CRMA and reducing the quantity of CR, such that the percentage of CR in CRMA is typically approximately 20%(Riekstins et al., 2022). It is possible to enhance the treatment of CR content via the use of activation therapy and a final blend procedure Chemical, mechanical, engineering, and biological treatment procedures are used to alter the CR's physicochemical characteristics to increase the physical stability of CRMA.

Thermal treatment of the CR resulted in a considerable increase in the CRMA's ageing and fatigue resistance. In the past, researchers have employed radiation to activate and measure the activation properties of CR. Rubber-modified asphalt with high viscosity and a wet process has been linked to an increase in prices. Many researchers used life cycle cost analysis to assess the cost of Rubber modified asphalt as compared to conventional asphalt. Rubber-modified asphalt was first thought to costs nearly twice as much as regular asphalt, however since 2000, there has been a downward trend in the cost. Asphalt plant efficiency, bitumen modification, and higher production temperatures/WMA technologies are all cited as major contributors to the rise in prices. CR modified asphalt has a higher direct cost than regular asphalt, according to some studies since it has the potential to reduce the asphalt plant's efficiency by as much as 30%. Because of this, the cost of CR modified asphalt is between 10% and 20% more than that of regular asphalt. Studies have shown that CR asphalt may reduce maintenance expenses because of its increased durability and performance. Due to the similarity of the equipment needed to alter bitumen with polymers, this analysis did not take into account the cost of obtaining new equipment(Wang et al., 2022).

Because of the increased absorption of light oil in asphalt caused by CR at high doses, crumb rubber fragments embedded in asphalt cannot inflate to their maximum size. There is also an increase in the viscosity of CRMA, which has a negative impact on the performance of pavement. As a consequence, the CR dosage should be increased by no more than 10% to 20%(Jiao et al., 2022). Using physical methods like ultrasonic waves, some researchers tried to break the three-dimensional network structure of CR by breaking the surface activation of CR and facilitating swelling so that CRMA can be prepared with a more even and compact network structure and better performance. CRMA will benefit from this by having a more uniform and compact network structure, as well as improved performance. Although these techniques may improve CRMA's performance to some extent, it will be difficult to use them on a large scale due to the huge increase in product pricing(Tang et al., 2022).

Irfan et al., (2018) investigated crumb rubber-modified asphalt mixes to determine their resilient modulus, indirect tensile strength, as well as permanent deformation. On average, mixes created with crumb rubber-modified mixtures had a Marshall stability of 30 and a resilient modulus of 43 percent higher than the control mixtures. But as compared to unmodified control combinations, crumb rubber-modified ones showed a 12 percent improvement in permanent deformation. A reduction in the International Roughness Index of the crumb rubber-modified asphalt mixture of 36.16 percent was discovered in field studies on the treatment's short-term effectiveness. A drop of 24.20 percent in the International Roughness Index (IRI) was seen in the control mixed pavement.

However, conventional CRMA is well-known to have poor storage stability and thus is easy to split. The interaction of rubber and asphalt may be improved in several ways, according to several studies. These strategies include, enhancing the surface activity of the CR, and degrading the structure of crumb rubber to improve the rubber-asphalt system. Plasticization, palletization by mechanical extrusion, and microwave radiation are the three processes that contribute the most significantly to the pre-devulcanization and degradation of CR. However, none of these processes are carried out in liquid environments, which leads to the polluting of the surrounding air and water as a direct consequence of the release of hydrogen Sulphide gas that is produced during the devulcanization process. On the other hand, the inability to precisely regulate the degree to which CR degrades will severely restrict the properties of the modified asphalt. As a result of this, several researchers used distillates such as furfural oil as a swelling agent while pre-treating CR. Strategies like these might help the particles of CR to deteriorate more easily, which would increase both its surface activity and its compatibility with clean bitumen.

2.8 Role of Waste Engine Oil in Asphalt Mixtures

There is a growing quantity of WEO that is produced all over the globe due to the rise in the number of automobiles. WEO poses a risk to both the health of humans and the environment if it is not disposed of in an appropriate manner. It is difficult to reuse WEO since the performance of the oil degrades with time when an engine is used continuously. WEO is a byproduct of the combustion of fossil fuels and is released into the atmosphere when cars and trucks are driven. In the meanwhile, the petroleum sector has made several adjustments to the refining process to boost gasoline production while decreasing the amount of asphalt residue, resulting in an increase in the price of asphalt(Paliukaite et al., 2016). As a result, enhancing the asphalt binder's low-temperature performance is one of the most significant goals in pavement technology(Lei et al., 2017). Asphalt can be modified with waste oils to increase its low-temperature performance, lower its cost, and minimize pollution to the environment when utilized in this way.

As a result, the use of WEO has attracted a significant amount of interest in recent years as a reaction to waste management and economic advantages(Saffar et al., 2021). In the last ten years, a significant amount of investigation on asphalt that has been treated with engine oil has been carried out. Many researchers observed that the temperature susceptibility of asphalt can be lowered after using waste oil distillation bottoms as a simple extender for asphalt. Because of the wide variety of raw materials and processing methods, comprehensive research into the chemical and rheological characteristics of WEO-modified asphalt is needed before it can be used in real-world applications(Liu et al., 2022).

Waste engine oil are among the bio-oils that can be effectively used in asphalt binder. Bio-oil contains a wide range of organic molecules that are made up of a combination of chemical components from C to O, such as acids, alcohols and ketone compounds(Su et al., 2018). Three types of bio-oils may be distinguished based on the raw materials they are made from: plant oil, pyrolysis oil, and biodiesel. Extract, distillation or squeezing of plant oils such as soybean, peanut and/or rapeseed oils are all examples of plant oils. Fuel made from renewable oils and short carbon chain alcohols, known as biodiesel, and used as an alternative to diesel is called biodiesel. Oil derived from plants and pyrolysis is the most common kind of bio-oil utilized in bio-asphalt production. Traditional technologies like distillation were ineffective in removing oil from water. Following a thermal pretreatment/upgrading method, bio-oil produces biofuel, biomass heavy oil, and other byproducts. The waste engine oil that was used for this investigation is shown in Figure 2.3.

Figure 2.3: Waste engine oil used for asphalt modification

Bio-asphalt is made from biomass heavy oil, and biofuel is used to generate electricity. According to several studies, the amount of water and volatile compounds in bio-oil should be used to estimate the pretreatment temperature and time(Portugal et al., 2017). There are differences in the qualities of bio-asphalt based on the types and amounts of bio-oil used in it. Some research has been done in the last several years on agricultural and forestry waste biomass materials(Luo et al., 2017). Binders made from agricultural, or forest wastes have great viscosity, but poor performance at higher temperatures, according to recent studies. Bio-asphalt, which is made from plant waste, has also been shown to be resistant to fatigue and ageing. Adding bio-oil to bio-asphalt made from animal waste increases low temperature fracture resistance but decreasing viscosity and high temperature stability, as shown by this bio-asphalt. Viscosity of rejuvenated asphalt may be reduced by using animal waste bio-modifiers, and the rutting and fracture characteristics of rejuvenated asphalt are enhanced.

Lei et al., (2015) observed that waste engine oil residues considerably impacted the infrared spectrum and rheology of asphalt binder, which might lead to improved low-temperature performance of asphalt binder, according to his study of the engineering features of asphalt binder. Temperature-induced asphalt pavement cracking is a major problem in cold temperature areas. Therefore, it is important to improve the low temperature fracture and stiffness properties of binder. For example, some study has classed asphalt as the combination of polar and nonpolar molecules because of its chemical structure. As a result, increasing the amount of oil in asphalt is an option for improving the low-temperature capabilities of the binder(Liu et al., 2022).

2.9 Modern Research Trends in Crumb Rubber Modified Asphalt

The development and maintenance of road infrastructures need a significant number of natural resources that are limited in quantity, such as bitumen and aggregates. These materials are used in large quantities by the road paving sector. The paving industry is one of the largest users of fossil fuel within the construction sector. This is because bitumen, which is used in asphalt mixes, must be produced first. In addition, asphalt plants are recognized as substantial contributors to environmental degradation because to the large levels of greenhouse gas emissions that they produce. Therefore, waste, or recycled materials could potentially partially replace the raw materials that are used in asphalt mixtures. This would have several significant benefits, including a reduction in the volume of waste sent to landfills as well as the amount of consumption of natural resources and, as a result, the requirement for additional extraction. The incorporation of a variety of waste materials into asphalt mixes has previously been investigated over the course of the last several years, and the qualities of these mixtures have been evaluated in relation to the specification limitations, which are often met. To enhance the properties of bitumen, waste materials such as crumb rubber and plastic have been employed in the modification process.

The addition of plastic trash to bitumen causes the penetration values of the bitumen to decrease, while also raising the temperature at which the bitumen softens. Because of the improvement in resistance to both fatigue and permanent deformation, the relevant asphalt mixes' levels of stability and durability have been brought up to a higher standard. In addition, some plastic wastes are readily accessible in huge quantities at discounted prices, and these wastes might be employed for the modification of bitumen. In a similar fashion, the introduction of crumb rubber into bitumen raises the temperature at which the bitumen softens, which in turn lowers its thermal susceptibility and increases its viscosity. Because of how quickly it accumulates and how difficult it is to get rid of, this kind of trash is seen as a significant environmental concern; hence, innovative solutions that allow for its reuse would be welcomed with open arms. By adding used motor oil, one may enhance the bitumen's penetration, which in turn lowers the temperature at which the bitumen's softening point occurs as well as its viscosity, which in turn lowers the temperatures at which asphalt mixes are produced and compacted.

However, the elastic recovery and permanent deformation resistance may be lowered because of its incorporation. Because of this, considerable consideration must be given to the mix design of these materials. Recycled engine oil bottoms, on the other hand, are the non-distillable waste generated during the atmospheric distillation process of recycling waste motor oil. Recycled motor oil bottoms are often used as a binder addition in the United States and Canada because they are inexpensive and have become more widely available over time. Other kinds of asphalt mixes did not have this waste material's degree of resistance to permanent deformation, water susceptibility, and fatigue cracking, but the waste material-based mixtures did. The recycled engine oil bottoms in the modified binder, on the other hand, exhibited evidence of excessive ageing, which might lead to premature breaking of the paved surfaces early on. To keep asphalt mixes performing well, inclusion rates of binder extenders like used motor oil or recycled oil bottoms are typically maintained low to prevent overuse of these resources. The road paving industry's economic worth of waste motor oil-derived products may rise if they were utilized to partially replace bitumen in that material. Especially if the issues that arose because of their inclusion could be minimized or avoided. Waste motor oil products and polymers may be used to modify bitumen to make it more eco-friendly as well as cost-effective. Polymers are used to tackle some of those difficulties because they are used to solve some of those problems.

Xu et al., (2021) discovered that the inclusion of composite waste engine oil improved the solubility of crumb rubber in rubber asphalt. The highly dissolved rubber asphalt showed improvements in its performance at high temperatures as well as its performance at low temperatures and its storage stability. Up to 15% of bitumen can be substituted with waste cooking oil, tire rubber powder, and palm oil fuel ash in asphalt mixtures, according to Rahman et al., (2017), and this modification can achieve the same or better performance in terms of stability, flow, and rutting resistance than conventional asphalt. It was found by Lei et al., (2018) that the physical and chemical interactions in heated asphalt may improve the high-temperature performance of crumb rubber modified asphalt when bio-oils are added to the mix. They discovered that adding either 2 or 2.5 percent of the waste engine oil to the crumb rubber modified asphalt increased the binder's resistance to fatigue cracking at intermediate temperatures. This was accomplished by lowering the binders' stiffness and lowering the binders' fatigue parameter.

WEO added bitumen has a lower softening point and has a much higher penetration. A better self-healing characteristic of the bitumen was thus achieved by allowing the mixture to cure itself at lower temperatures. Using WEO as a bitumen modification also reduced OBC. Economic benefits (such as using less bitumen) and environmental benefits (such as repurposing hazardous waste) are therefore possible. Khan et al., (2019) conducted research in which they removed the bitumen and replaced it with varying percentages of waste cooking oil, bagasse ash, and crumb rubber powder. It was discovered that up to 20 percent of the bitumen can be successfully replaced without affecting the performance of the bitumen. The modified bitumen demonstrated strong resistance to rutting and sliding, in addition to cracking at low temperatures.

Yu et al., (2019) found that rubberized asphalt binders treated with recycled heavy bio-oil had greater rutting and fatigue resistance compared to standard rubberized asphalt binders, although their low-temperature performance was less than ideal. A variety of characterization techniques were used by Wang et al., (2020) to study the fatigue performance of CRMB with warm-mix additives. Although it had a higher resistance of permanent deformation, but a lower resistance of fatigue cracking, modified bitumen could be used in hot climates because it was less susceptible to temperature change.

Bio-oil was employed as a replacement for pavement bitumen by Sun et al., (2018), and it was discovered that the best bio-bitumen product is produced when specified mass proportions of components react at 100 C for 2 hours. Zhou et al., (2021) investigated the impact that Sulphur has on bio-modified rubberized bitumen. They discovered that the effect that Sulphur has on bio-modified rubberized bitumen is dependent on the chemical composition of the bio-modifier. Additionally, the incorporation of Sulphur resulted in a considerable decrease in the elastic properties of rubberized bitumen. Additionally, the interactions between Sulphur and bitumen may be increased with the use of certain bio-modifiers, which can also help boost the bitumen's viscoelasticity while also improving sustainability and resource conservation.

Ren et al., (2021) studied the effects of rubber size on the continuous swelling and degradation of crumb rubber modified bitumen (CRMB). Using CRMB binder dynamic viscosity changes, he was able to do this. According to his findings, as deterioration progressed, the CRMB binder's complex modulus, rutting susceptibility, viscoelastic property, and zero-shear viscosity all decreased. Asphalt quality may be improved by considering factors including the size of the crumb rubber being used, its surface characteristics, and the kind of desulfurization used on the crumb rubber. However, the uneven distribution of rubber particles in the asphalt surface might contribute to an unsteady performance. A lack of solubility in asphalt means that crumb rubber may be found in asphalt binder in the form of particles because of its extensive dispersion.

2.10 Summary of Literature Review

Based on the analysis of the relevant literature, it can be concluded that Waste engine oil (WEO) has the potential to regulate the role crumb rubber (CR) in the modified binder blend by creating a balance between the stiffness and fluidity of the binder. Table 2.1 summarizes the literature review that has been discussed in a comprehensive manner. From Table 2.1, it is clear that researchers are trying to use a polymer along with waste engine oil, as polymers can improve the rutting resistance of waste engine oil modified asphalt.

From Table 2.1 it can be observed that, in most of studies, rubber asphalt was found to increase asphalt mixtures' high-temperature and long-term performance and durability. However, higher percentage of CR can lead to an unstable performance of the asphalt pavement because of the unequal distribution of the rubber particles. As a result of poor solubility of crumb rubber in asphalt, the CR tend to be found in the asphalt binder in the form of undissolved particles due to its widespread distribution. As a result, conventional rubber asphalt suffers from a variety of drawbacks, the most notable of which are its high viscosity and poor storage stability.

Table 2.1: Summary of Literature Review

Research paper description	Polymer Type	Test Performed	Outcomes
Incorporating Waste Engine Oil Products and Polymers into Enhanced Modified Asphalt Products	Crumb Rubber (20%), Waste Engine oil (7.5%, 12.5%, and 15%)	Dynamic Viscosity MSCR Test Consistency Tests	Binder modified with EO, and CR demonstrated that they had a low thermal susceptibility, high values of high temperature PG, and high rutting resistance.
Highly dissolved Rubber Asphalt prepared using a composite Waste Engine Oil addition	Crumb Rubber, Waste Engine Oil (5%, 15%, 25%, 35%)	Solubility Test Storage Stability MSCR Test	In rubber asphalt, the inclusion of composite waste engine oil enhances the solubility of the crumb rubber.
The effect of bio-oil on the performance of rubberized asphalt at high temperatures	Crumb Rubber (Mesh 20 and Mesh 80), Bio oil (0%,5%, 10%, 15%)	MSCR Test RV test Temperature sweep test	Crumb rubber modified asphalt's elastic properties may be improved by a short-term ageing process that blends crumb rubber and bio-oil in a heated asphalt dispersion system during heating.
The effect of used engine oil on the rheological characteristics of various asphalt binder types	Waste Engine Oil (4% and 8%)	GS-MS Test GPC Test RV Test DSR Test	When WEO is incorporated into asphalt, the complex modulus decreases, but the phase angle increases. WEO has a negative impact on asphalt's rutting resistance and a beneficial impact on its fatigue performance.
Properties of Viscoelasticity of Recycled Asphalt Binders Containing Waste Engine Oil	Aged Binder, Waste Engine Oil (4%, 6%, 8%)	Brookfield Viscometer FTIR Test Relaxation Modulus	At any given moment, the relaxation modulus of all blends was lower when waste engine oil content was increased. In general, it was found that adding 24% of waste engine oil negated the benefits of the aged binder addition.

The influence of styrene-butadiene rubber (SBR) and waste oils on the physical characteristics of aged asphalt	SBR(1% and 3%), WEO/WCO (5%, 10%, 15%)	RV Test DSR Test FTIR Test BBR Test	WCO rejuvenated asphalt demonstrated some benefits in fatigue cracking resistance whereas WEO rejuvenated asphalt had greater resistance to rutting and creep recovery.
Modified bitumen production using Waste motor oil, coal tar, and waste tires	Used Engine Oil (20%), Coal Tar (30%), Waste tire (50%)	Consistency Tests Viscosity tests	Modified bitumen exhibited a stronger resistance to permanent deformation but a poorer resistance to fatigue cracking was less responsive to temperature change, contained fewer volatiles, and was less flammable.
Rubberized Binders with Recycled Heavy Bio-oil as a Performance Enhancer	Asphalt Rubber (18%), Heavy bio oil (3%)	Storage Stability Test RV Tests MSCR Tests	The bio–ARs demonstrated higher rutting and fatigue resistance, but somewhat worse low temperature performance compared to a traditional AR binder.
The effect of long-term ageing on the fatigue performance of crumb rubber modified bitumen	Crumb Rubber (5%, 10%, 15%, 22%), Warm Mix additive	Time sweep test DSR Test	CRMB binders outperform plain bitumen in terms of fatigue resistance. Adding warm-mix additives has distinct impacts on the fatigue performance of a neat bitumen binder than a CRMB binder.
Activating agent's effect on Crumb Rubber modified Asphalt's performance	Crumb Rubber (33%), WEO (10%-20%)	Viscosity Test DSR Test	For A-CRMA to work at its best, the dose of WEO must be carefully chosen to ensure that the WCR is fully swollen without diluting the asphalt and lowering its effectiveness.

Waste engine oil has a good resistance to ageing, and it also considerably cuts down on the number of pollutants that is released into the water. Additionally, the inclusion of waste engine oil may be utilized to improve the penetration of a bitumen while simultaneously lowering its softening point temperatures and viscosity. This results in a reduction in the temperatures required for asphalt mixture manufacturing and compaction. The liquid modifier is also helpful in enhancing the rubberized bitumen's workability and lowering the softening point.

As a result, to solve the problems that are associated with rubberized asphalt, waste engine oil and crumb rubber were combined to make a CR-WEO modifier that will partly replace the base bitumen. In accordance with the findings of previous research, the CR-WEO modifier was prepared by combining Crumb Rubber and waste engine oil. After that the resulting mixture was heated in an oven set to 100 degrees Celsius for two hours to pre-treat the rubber. To partly replace the base bitumen, different percentages of CR-WEO modifier was employed, and the performance of the CR-WEO modified asphalt mixtures was evaluated, using a variety of performance tests.

CHAPTER 3

RESEARCH MEHTODOLOGY

3.1 Introduction

This chapter provides a comprehensive analysis of the Research Methodology that was used to achieve the goals of the research. First, the material that was necessary for this research was collected. The optimum bitumen content was determined using Marshall mix design. The MS-2 manual was followed to conduct an analysis of the volumetric attributes Va, VMA, VFA, Flow, and stability. To prepare samples for performance testing, a Superpave Gyratory Compactor was used. Once the samples had been prepared, they were saw cut to perform Hamburg wheel tracking to determine rutting, resilient modulus, and moisture susceptibility.

This chapter presents the study technique that was executed to provide specifics about the mixing of CR-WEO with bitumen and further testing of the mix's performance, as described in chapter 1. The assessment of the performance of the samples created in the laboratory was carried out in four steps. In the first step, traditional testing of the binder was carried out. These tests included the penetration test, the ductility test, and the softening point test. The IDT and MR tests were carried out on the prepared Superpave Gyratory Compacted samples. After that, the rut resistance of modified and unmodified Superpave gyratory samples were evaluated.

Aggregates from Babozai Query, 60/70 bitumen from Attock Refinery, Waste engine oil from Toyota workshop and Crumb Rubber (Mesh # 40) from a local firm in Peshawar were materials that were chosen this research. To find the chemical composition of the waste materials X-Ray fluorescence test was conducted. After that, the materials were characterized in accordance with their predetermined criteria. To ascertain the performance of modified asphalt mixes, Gyratory compacted samples were utilized. Marshall samples were prepared for determining the OBC, while Superpave Gyratory compacted samples were prepared in order to ascertain the resilient modulus, Tensile Strength Ratio (TSR) and rutting resistance of CR-WEO modified samples. The research methodology that was adopted for this investigation is shown in figure 3.1.

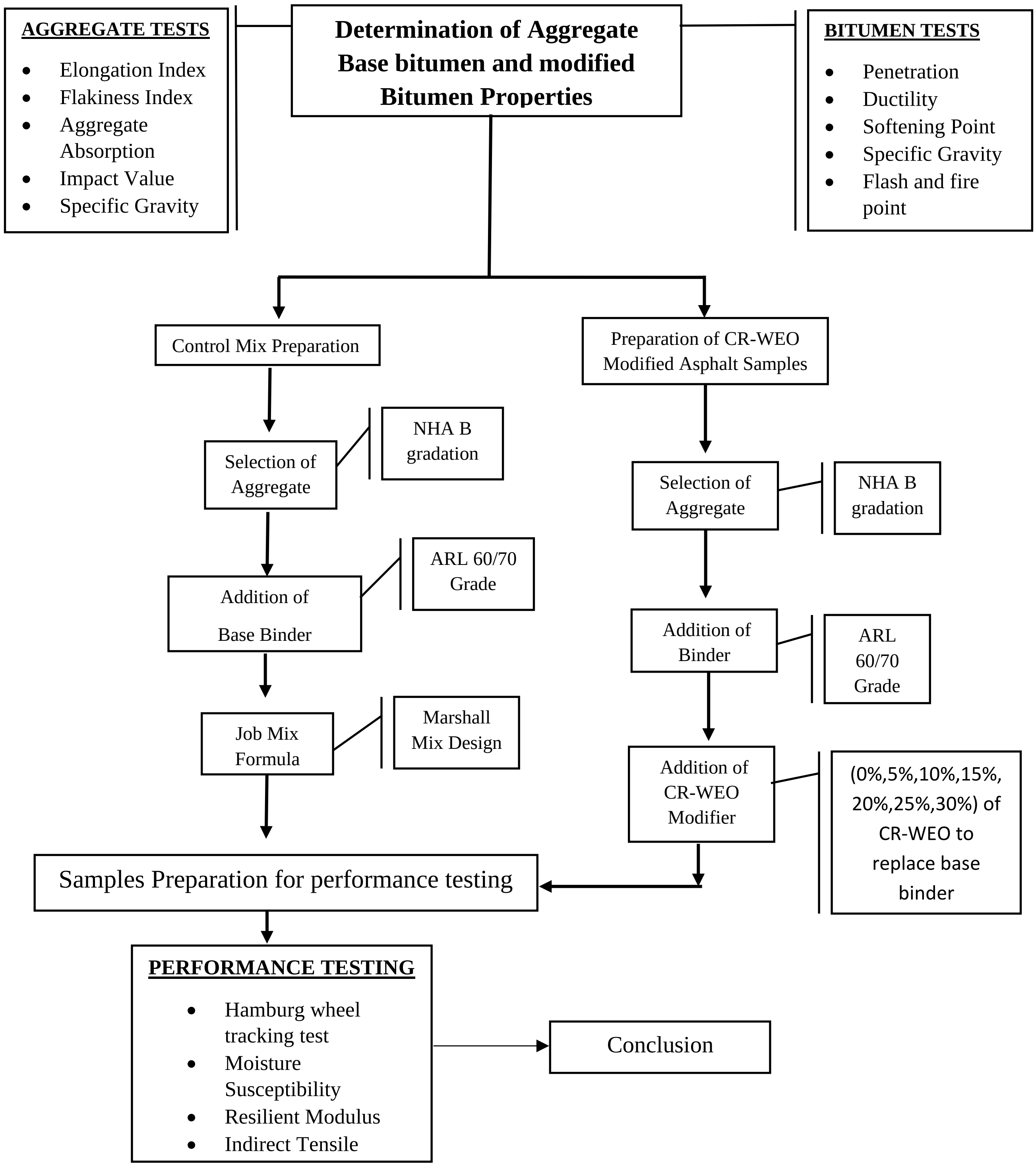


Figure 3.1: Research methodology

3.2 Aggregate Testing

Since the strength of asphalt mixtures is closely related to the properties of aggregates, such as their strength and durability, therefore, aggregate testing is an important part of the job mix formula. Several experiments were performed on the aggregate, including sieve analysis, aggregate gradation, the Los Angeles abrasion test, the aggregate impact value test, as well as specific gravity measurements for coarse and fine aggregates, amongst others. Aggregate samples will be put through a range of tests to establish their engineering capabilities. These fundamental attributes included water absorption, specific gravity, strength, and durability. Aggregate shape and texture affect aggregate strength as well as a slew of other technical characteristics. The gradation of the aggregates may also influence the properties of HMA.

3.2.1 Sieve Analysis and Gradation

Size, shape, texture, and grade of the aggregate are all important factors when it comes to strength of asphalt mixtures. Aggregates should also have low porosity and be strong and durable. Babozai query aggregates were sieved in the laboratory. The amount kept for each sieve was placed in individual bags. Table 3.1 shows details of the gradation that was selected for this investigation.

Table 3.1: Description of Aggregate Gradation

Sieve Designation		NHA Class-B Specification Range (% Passing)	Upper Limit	Lower Limit	Our Selection (% Passing)
mm	**inch**				
25	1	–	-	-	
19	3/4.	100	100	100	100
12.5	1/2.	75-90	75	90	82.5
9.5	3/8.	60-80	60	80	70
4.75	No. 4	40-60	40	60	50
2.38	No. 8	20-40	20	40	30
1.18	No. 16	5-15.	5	15	10
0.075	No. 200	3-8.	3	8	5.5
Pan	Pan	-	-	-	Pan

Figure 3.2 shows the graphical plot of NHA class B gradation. The Nominal Maximum Aggregate Size (NMAS) for this gradation is 19mm.

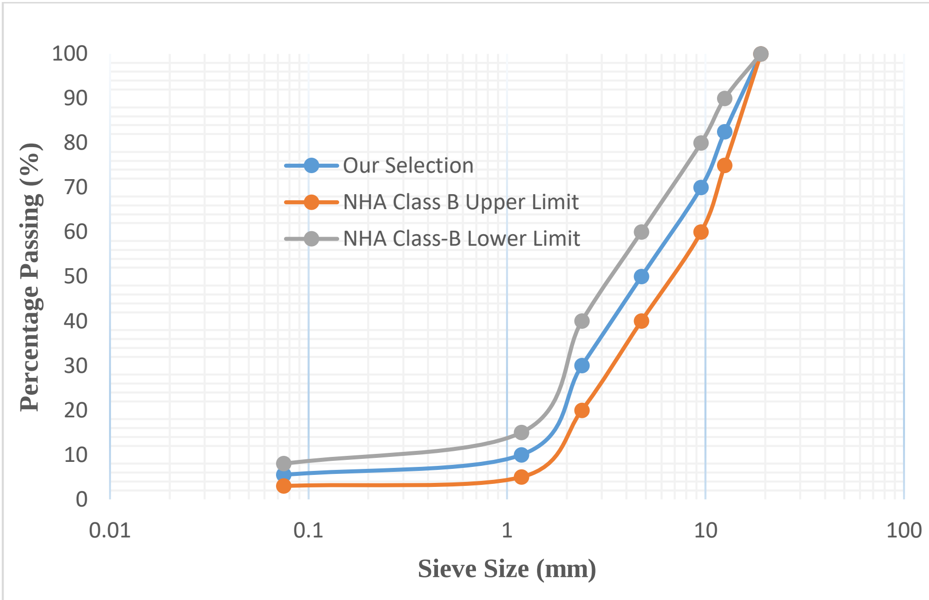


Figure 3.2: NHA class B gradation plot

3.2.2 Aggregate Impact Value Test

An aggregate may be broken into tiny pieces owing to the impact load and pounding action of traffic. As a result, aggregates must be sufficiently hard and tough to withstand fractures caused by traffic's impact loading effect. In accordance with BS 812 and IS 383, this test is carried out. Approximately 350 grams of aggregate were chosen for this test, passing through a 14mm screen, and retaining on a 10mm sieve. Three layers of aggregate were put in the Impact testing machine cup, and a tamping rod was used to agitate each layer 25 times. The aggregates were hammered with a 14 kg standard hammer dropped from a 38 cm height after compaction. To remove them from the cup, they had to be sifted through a 2.36mm sieve. The proportion of particles passing through a 2.36mm sieve is given. The percentage of aggregate retained on this sieve is used to determine the aggregate impact value.

3.2.3 Los Angeles Abrasion Test

Because significant loads of traffic may cause disintegration, deterioration, and crushing, asphalt mixes need to be able to withstand these types of damage. To accomplish this goal, a LA abrasion test is carried out on aggregates to measure their toughness and durability. This test is carried out in accordance with the requirements of AASHTO T 96-92.

After the aggregate had been subjected to abrasion in accordance with the normal operating procedure using the predetermined quantity of balls, the resulting material was sieved using sieve number 12. After this, the amount of weight lost due to abrasion was calculated, and according to the standards, this value must be lower than 40. The apparatus that was used to determine the Los Angeles abrasion value is shown in Figure 3.3.

Figure 3.3: Los Angeles abrasion test

3.2.4 Specific Gravity of Aggregates

The specific gravity of aggregates is the weight of a given volume of aggregates compared to water at 24°C. The specific gravity test was performed on coarse aggregate and fine aggregate in accordance with ASTM C127, (2004) and American Society for Testing and Materials, (2015). These weights include the weight of aggregates that have been oven dried, the weight of aggregates that have been completely submerged in water, and the saturated surface dry weight of aggregates. Tests for determining the specific gravity of fine aggregates and the amount of water they absorb were carried out in line with ASTM C 128. The specific gravities of the coarse aggregate particles must be carefully considered while preparing asphalt paving mixtures. Engineers often use it in the planning of both paved and unpaved regions. Bulk specific gravity may be used to determine both the amount of binder absorbed and the VMA. Specific gravity is another word for "relative density," which refers to aggregate material's weight-volume properties. For example, "relative density" is used to refer to the aggregate material's specific gravity. When an item is kept at a constant temperature, this is its mass to volume ratio. Coarse aggregates are those particles that remain visible on the sieve after filter No. 4. ASTM C127 was utilized to determine the specific gravity of coarse aggregate particles and their water absorption rate. After passing the aggregates through sieve #4, those that remained were dried in an oven and then immersed in water for twenty-four hours. After that, the aggregates were laid out on a fabric so that their saturated weight could be calculated. After that, the submerged weight of the aggregates, as well as their specific gravity and water absorption, was determined. The oven-dried sample does not have any water in it, but in the saturated surface-dry stage, water may be found filling the aggregate pores.

3.2.5 Aggregate Crushing Value

The apparatus that was utilized for the crushing value test included a steel cylinder with open ends, a base plate, a plunger with a piston that had a diameter of 150 mm and was provided with a hole across it, for lifting through a rod, a cylindrical measure, a balance, a tamping rod, and a 28 compressive testing machine. Aggregates that went through a 1/2-inch sieve but remained on a 3/8-inch sieve were chosen for further processing. After being carefully cleaned, dried in the oven, and weighed (W1), a sample of aggregate was then layered onto a cylindrical measure in three distinct increments, with 25 tamping performed on each successive layer. After that, the sample was placed in the cylinder with the base plate in three separate layers, and the plunger was put in place. After that, the cylinder was put inside of a compression testing machine, and a load was then added in a consistent manner at a pace of 4 tons per minute until the total load reached 40 tons. After that, the aggregate that had been crushed was removed from the steel cylinder and sieved through a 2.36mm mesh.

3.2.6 Shape Test of Aggregate

The shape test of aggregates is used to calculate the proportions of flaky and elongated particles present in aggregate stockpiles. In the context of aggregates, flaky particles are those aggregate particles that have their smallest diameter that is less than 0.6 times the average dimension of the sample aggregates. Elongated particles are aggregates that have a bigger size that is more than 1.8 times of the sample aggregates' average dimension. The flakiness and Elongated index were found according to the respective ASTM standards.

Fractured particles were found to be 98%. The aggregate was satisfying the criteria of all the standards. The results of the tests that was conducted on aggregate is shown in Table 3.2.

Table 3.2: Laboratory Test Results of Aggregate

Type of Description		Standards	Results	Specification
Fractured Particles Test		ASTM D 5821	98	90% (Min)
Aggregate impact value		BS 812	16.09%	30% (Max.)
Aggregate crushing value		BS 812	15.67%	30% (Max.)
Los Angeles Abrasion test		ASTM C 131	25.89%	45% (Max)
Flakiness Index		ASTM D 4791	7,09%	15% (Max)
Elongation Index		ASTM D 4791	2,37%	15% (Max.)
Deleterious Material Test	Coarse Aggregate	ASTM C 142	0.21%	-
	Fine Aggregate	ASTM C 142	1.30%	-
Specific gravity	Coarse Aggregate	ASTM C 127	2.650	-
	Fine Aggregate	ASTM C 128	2.56	-
	Mineral Filler	ASTM C 128	2.43	-
Aggregate water absorption	Coarse Aggregate	ASTM C 127	0.82%	3% (Max.)
	Fine Aggregate	ASTM C 128	1.76%	3% (Max.)

3.3 Bitumen characterization

For a binder to be successful, it must possess all three of the following properties: consistency, safety, and purity. Alterations in temperature bring to modifications in the asphalt binder's consistency. Therefore, the asphalt binder consistency must be compared at a temperature that is constant. The penetration test may be used to determine the consistency of the bitumen. As a result of this, several laboratory experiments were carried out to describe additional asphalt binder.

- Bitumen test for Flash and Fire Point.
- Bitumen test for Penetration Grade.

- Bitumen test for Softening Point.
- Bitumen test for Ductility.

Both the ARL 60/70 modified binder and the CR-WEO modified binder were put through consistency and Superpave performance testing (0 percent to 30 percent). The penetration test, the softening point test, the ductility test, and the flash and fire test were some of the consistency tests that were carried out.

3.3.1 Penetration Test

It is the most historically significant empirical test. The bitumen specimen is tested by vertically penetrating it with a standard needle under the loading, duration, and temperature that have been predetermined. A tenth of a millimeter is the unit of measurement for the penetration. With the use of this test, bitumen may be graded into a variety of distinct categories. It is only a method of categorization rather than a standard for evaluating quality. A higher penetration number implies that the sample has a more fluid consistency. Bitumen with a greater penetration rate is often favored for use in cooler climate zones, while bitumen with a lower penetration rate is generally recommended for use in warmer locations. The penetration test has a standard working temperature of 25 degrees Celsius, but it may also be carried out at different temperatures such as 0 degrees Celsius, 4 degrees Celsius, and 46 degrees Celsius by adjusting the needle load and the penetration. The tests were performed in accordance with ASTM D5 as well as AASHTO T 49-93 standards. Samples of base bitumen were subjected to a 25°C water bath temperature control to condition different CR-WEO percentages. A needle load of 100 grams and a testing time of 5 seconds were used to determine the penetration values of the bitumen samples after conditioning.

3.3.2 Softening Point Test

The Softening Point test is carried out in accordance with the standards provided by Drews, (2008) and AASHTO T 53-92. This test is carried out to determine the temperature at which the binder begins to soften, which may be anywhere between 30 and 150 degrees Celsius. The bituminous binder is poured into two horizontal discs that have been cast in shouldered brass rings. The rings are then heated at a regulated pace. The softening point of the binder is determined when the steel balls that are supported by each brass ring fall because the binder has become softer.

3.3.3 Ductility Test

The ductility test is carried out in compliance with both the (ASTM D 113-07, 2002) and the AASHTO T 51-93 specifications. This test involves stretching a standard asphalt specimen to its breaking point at a standardized rate of 5 centimeters per minute at a temperature of 25 Celsius. It is common knowledge that a binder with extremely low ductility is believed to have weak adhesive characteristics, which leads to poor performance when it is put into use. Pouring bitumen into ductility molds allowed for the preparation of sample bitumen that had either been changed or was unmodified. After being conditioned in a water bath at 25 degrees Celsius, each specimen sample was drawn at a rate of 5 centimeters per minute. Reading was captured, however just the samples' break down was recorded.

3.3.4 Fire and Flash Point Test

The Flash and Fire point is a way of calculating the highest temperature that asphalt may be heated to without the risk of ignition while still being in the vicinity of an open flame. After pouring the samples into open cups, they were heated at a predetermined pace to determine the flash point and the fire point. The point at which a little flame ignites at the surface is known as the flash point, and the point at which the sample catches fire is known as the fire point.

3.4 Preparation of CR-WEO Modified Bitumen

CR-WEO modifier was prepared according to the research that have done in the past, by combining 25 percent waste engine oil (by weight of the Crumb Rubber) and Crumb Rubber, after which the combination was taken in an oven at 100°C for 2 h to pretreat the rubber. Different percentages of CR-WEO modifier were utilized to partially replace base bitumen and the characteristics of modified bitumen and performance assessment of resulting asphalt mixes will be undertaken utilizing various performance tests.

3.5 Preparation of CR-WEO Modified Asphalt mixtures

Mixing Machinery and Sample Preparation to properly mix CR-WEO in bitumen, a high shear mixer, is necessary. However, the Laboratory does not have access to High Shear Mixers; thus, a drill machine with 1000 rpm was utilized to manually mix the two substances. To achieve maximal surface area of contact with bitumen, the ahead-most portion of its shaft was welded, and then it was reshaped to resemble a propeller. Table 3.3 shows the composition of various CR-WEO modified asphalt samples.

Table 3.3: Composition of Different CR-WEO Modified Samples

TYPE OF SAMPLE	ABBREVIATION	VIRGIN BITUMEN USAGE (%)	PERCENTAGE OF CR-WEO (%)
Virgin binder	Control Binder	100	0
Virgin binder+5% CR-WEO	5% CR-WEO	95	5
Virgin binder+10% CR-WEO	10% CR-WEO	90	10
Virgin binder+15% CR-WEO	15% CR-WEO	85	15
Virgin binder+20% CR-WEO	20% CR-WEO	80	20
Virgin binder+25% CR-WEO	25% CR-WEO	75	25
Virgin binder+30% CR-WEO	30% CR-WEO	70	30

Various amounts of CR-WEO as were used during the process of preparing the bitumen samples (5 percent, 10 percent, 15 percent, 20 percent, 25 percent & 30 percent). CR-WEO and bitumen were combined in a drill machine at a speed of 1000 rpm and a temperature of more than 180 degrees Celsius was maintained for a period of 15 minutes. During the process of mixing, it was essential to maintain a temperature that was above 180 degrees Celsius and a speed of at least 1000 revolutions per minute. The three most fundamentally significant factors in CR-WEO mixing are temperature, mixing duration, and mixing speed. Temperatures range from 180°C to 200°C, durations from 10 minutes to 30 minutes, and speeds from 1000 rpm to 250 rpm have been found to be the most often used numbers for these three parameters. These values were collected from a variety of worldwide studies and research projects. On such instances, adjusting both the time and the speed is always necessary since increasing the speed may be utilized to cut down on the amount of time spent mixing.

3.6 Marshall Mix Design

Marshall Stability is the maximum load that a mixed specimen can bear at a standard temperature of 60°C. As the applied force increases, the specimen deforms, and this process is known as flow. Using Marshall Apparatus, the Marshall Mixes required for locating the OBC are created in accordance with normal protocol. The criteria were used to identify and verify that all the volumetric properties, such as stability and flow, had been fulfilled. In the end, OBC was discovered.

After the sieve analysis, the aggregates were heated at 110 degrees Celsius in an oven until dry. To create a compacted sample with a diameter of four inches using the Marshall Mix design technique (ASTM D6926), 1200 grams of aggregates is needed. Calculations were made to determine the quantity of bitumen that would be required for each sample, and the results ranged from 3.5 percent to 4 percent, 4.5 percent to 5.0 percent, and 5.0 percent to 5.5 percent.

The following procedures were carried out to prepare the samples:

- The aggregate that would be utilized was chosen from the Babozai quarry, and its basic properties was determined. A suitable mixture of aggregates that was properly graded, hard, and sound yet rough in texture was developed.
- Following the completion of rheological experiments on the asphalt binder, such as the penetration test, the ductility test, and the softening point test, the asphalt binder was selected.
- To prepare the samples, heated binder and aggregate were mixed in large amounts so that standard-sized specimens could be made according to molds. During the process of preparing Marshal Specimens, different amounts of binder in percentages ranging from 3.5 percent to 5.5 percent were applied.
- To compact the Marshal Samples, 75 blows were delivered to each side of the specimen. According to ASTM D 1559, the falling height was 18 inches. After being prepared, samples were allowed to cool before being extracted from molds with the assistance of a hydraulic jack system.
- After the sample preparations were finished, the volumetric properties were calculated using the Marshal method.

3.7 Formulation of Job Mix Formula with Marshall Test

The OBC should be determined to prepare samples for performance testing. For this purpose, all the samples were carefully tested to find their stability, flow, density, Gmb, Gmm, Air voids, VMA and VFA. The results of these tests were compiled, and Graphical plots and curves were developed using this data. The binder's primary function is to thoroughly cover the aggregate's surface area. The aggregate will be protected against water damage because of this procedure. Figure 3.4 shows the steps that was adopted to determine Optimum bitumen content.

Figure 3.4: Formulation of job mix formula with marshal test

If the mixture contains insufficient bitumen content, uncoated aggregate will be visible. Eventually, this might lead to raveling or stripping because of the reduced strength and durability. A mix with an excessive amount of bitumen content will be very susceptible to bleeding, will have reduced skid resistance, and may cause rutting of the pavement. To put it another way, the pavement's performance is directly related to the amount of asphalt binder included in the mix. The mixture must meet a gradation criterion specified in the specification. To ensure that the aggregates form a good interlocking structure, the right percentage of various aggregate sizes must be provided.

Additionally, the aggregates must satisfy specified aggregate properties as well as source aggregate properties to be used. A good mix design will ultimately result in a combination that is approved, consisting of aggregate and asphalt binder. The term "job mix formula" is often used to refer to this suggested combination, which also considers the aggregate gradation and the kind of asphalt binder (JMF). The Marshall test does not use a standard technique for selecting and evaluating asphalt binder. A predetermined process or a local experience may be used to evaluate a binder. The Superpave PG binder system is the most widely used approach in this field. The temperature-viscosity connection of the asphalt binder is determined by a series of preparatory experiments. Table 3.4 shows the volumetric parameters that was evaluated using Marshall mix design.

Table 3.4: Determination of Optimum Bitumen Content

%age of bitumen content	Bulk Specific gravity (G_{mb})	Specific gravity (G_{mm})	%age Air voids in agg. (V_a)	%age voids in bitumen (V_b)	Voids in mineral agg. VMA	Voids filled with Asphalt VFA	Stability (KN)	Flow (mm)
3.5	2.340	2.499	6.36	7.95	14.31	55.55	14.25	1.85
4	2.362	2.480	4.76	9.17	13.93	65.85	15.35	2.48
4.5	2.363	2.438	3.08	10.32	13.40	77.04	15.05	2.87
5	2.352	2.410	2.41	11.42	13.82	82.59	14.07	3.31
5.5	2.348	2.399	2.13	12.54	14.66	85.50	13.20	3.91

Graphs were plotted against various parameters of Marshall Mix Design and the value of were checked to determine the Optimum Bitumen Content (OBC). Figure 3.8 shows the graphs that were plotted for stability, flow, VFA, VA, and unit weight against bitumen content to determine the OBC.

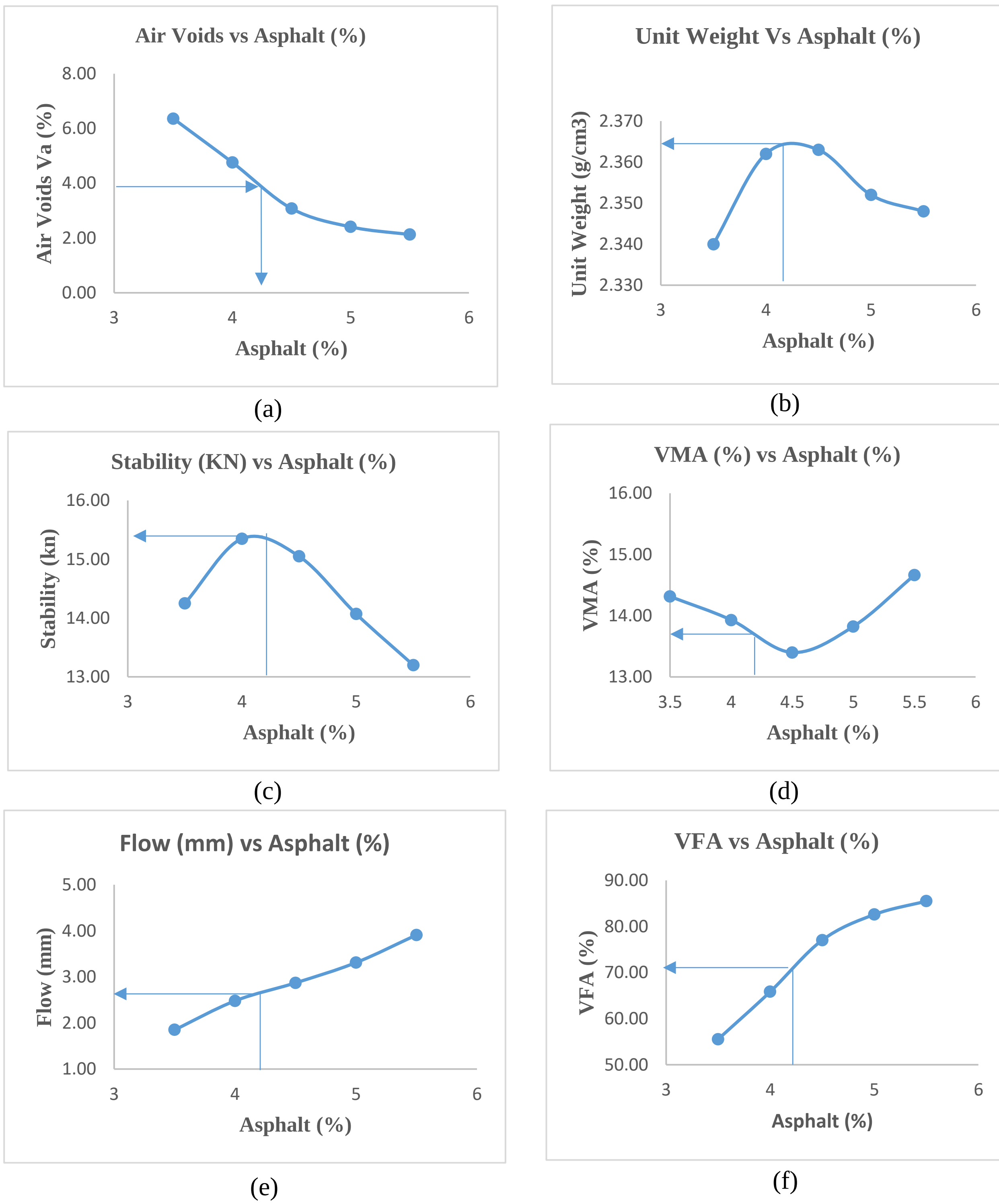


Figure 3.5: Marshall parameters for determination of OBC

From Figure 3.5, it can be seen that at 4% air voids, the OBC was found to be 4.18%. Table 3.5 summarizes the Marshall parameters that were used to confirm the optimum bitumen content. It was also found that other parameters such as Unit weight, VMA, VFA, Stability and flow were also satisfying the specified criteria. Figure 3.5(a) shows the graph between air voids against different asphalt content. It was found that at 4% air voids the optimum bitumen content was found to be 4.18%. Figure 3.5(b) shows the plot between unit weight and asphalt content. Figure 3.5(c) shows the graph between stability and asphalt content. It was found that at 4.18% asphalt content the stability was 15.4. Figure 3.5(d) display the graph between VMA and different asphalt content. The VMA at 4.18 percent air voids was found to be 13.8%. Figure 3.5(d) shows the plot between flow against different asphalt content. The flow at 4.18% air voids was found to be 2.79mm. Figure 3.5(f) shows the plot between VFA against different asphalt content. The VFA at 4.18 was found to be 70%.

Table 3.5: Marshall Parameters for determination of Optimum Bitumen Content

Marshall Parameters	Measured Value	Criteria	Remarks
OBC (%)	4.18	At 4 % air void	------
Unit Weight (g/cm3)	2.365	NA	------
VMA (%)	13.8	13 (min)	pass
VFA (%)	70	65-75	pass
Stability (KN)	15.4	8.006 (min)	pass
Flow (mm)	2.79	2.0-3.5	pass

Table 3.6 shows the results of Marshall test, that was conducted for samples containing different percentages of CR-WEO. It was found that the sample containing 10% CR-WEO has the maximum stability as indicated by the Marshall stability value of 15.45 KN. However, higher percentages of CR-WEO caused the stability values to decrease. Therefore, it can be concluded that the asphalt mix that contain 10 percent of modifier has the balance between stiffness and fluidity as indicated by its enhanced stability as compared to the control mix.

Table 3.6: Volumetrics parameters of CR-WEO modified asphalt

Binder	CR-WEO (%)	Voids (%)			Stability (KN)	Flow (mm)
		Air voids	VMA	VFA		
60/70	0	6.65	13.76	66.19	13.01	1.75
	5	5.71	13.65	58.11	14.29	1.95
	10	4.29	13.47	68.11	15.45	2.41
	15	3.71	14.03	73.62	15.08	2.95
	20	3.21	14.62	78.06	14.02	3.37
	25	2.81	15.34	81.64	12.91	3.97
	30	2.66	15.26	85.21	12.68	4.32

3.8 Sample Preparation for Asphalt Mix

The aggregates were heated to temperatures between 105 and 110 degrees Celsius to precondition the aggregates for making the asphalt mixtures. For HMA mix, a mixing temperature of 160 degrees Celsius and a compacting temperature of 135 degrees Celsius are utilized. It used 6000gm of aggregate and a gyratory compactor to produce gyratory compacted specimens with a diameter of six inches. To compact the specimens, 125 revolutions were conducted on them while the gyratory angle was set at 1.16 degrees and 600 kPa of pressure was applied. To produce a standard sample for the wheel tracker testing, each specimen was cut with a saw cutter into required dimensions.

3.9 Physical properties of Waste Engine Oil

Combustion engines utilize engine oil to minimize friction between moving parts. It's made up of heavy hydrocarbons and other additives combined together(Devulapalli et al., 2020). The engine oil's viscosity creates a thin coating between moving components. WEO is a byproduct of the transportation and manufacturing industries, derived from used engine oil. There are several environmental advantages to using WEO, including reduced soil and water contamination(Yan et al., 2022). Additives in the WEO include polymers that may improve the performance of the binder, as well as viscosity modifiers that may improve lubrication. It mixes readily and activates the aged binder since its chemical composition is comparable to asphalt (as both are petroleum-based materials).

3.10 Investigations of Sample Potential for Rutting

Rutting are the longitudinal depressions that are created by cyclic traffic loads and by the accumulation of small deformations in asphalt materials over time. Pavement rutting is a frequent sort of long-term wear and tear on roads. The specimens were put through a series of tests using a HWTT to evaluate how resistant they were to permanent deformation as part of the examination into the rutting propensity. HWTT is an electrically driven device that can move a tire that is 203 millimeters in diameter and 50 millimeters broad across 230 millimeters. The weight on the steel wheel is 700 Newtons, and the pressure that these steel wheels create is equivalent to the pressure that is produced by the rear tire of a double axle. The contact stresses become vary as a direct consequence of an increase in the rut depth's corresponding rise in the contact area. The steel wheel rotates forward and backward over the specimen as it goes through its paces. The apparatus used for determining the rutting of samples is shown in Figure 3.6.

Figure 3.6: HWTT apparatus for determining rut depth of asphalt mixtures

When using a twin wheel tracker, there are two distinct modes of testing: the first mode is an air/dry mode, and the second mode is a wet mode. During this test, the specimen was evaluated under dry conditions. Because the steel wheel moves over the surface of the specimen, the Wheel Tracking Apparatus can determine how rutting has affected the surface. Because the size of the silicon mould used in the machine has a thickness of 63 millimeters and a diameter of 150 millimeters, the sample had to be saw cut to conform to the requisite size of the mould before the test could be carried out. Following the placement of the specimen into the mould, the empty areas were then filled with pieces of plastic or wood to ensure that the sample would not move in response to the rotation of the wheel. The steel tray was readjusted and positioned directly under the wheel so that it could be fixed. The wheel tracking device was turned on when the steel tray containing the sample was securely fastened in place. In the laptop that was coupled to the machine, certain example pieces of fundamental data such as the code, diameter, weight, and height were input. The movement speed of the wheels was set at 60 ppm (passes per minute). To determining the rutting potential of asphalt mixtures, the number of passes was set at 10,000 and maintained as indicated.

The last step of the test was moving the wheel back and forth to signify the progress that had been made. On the liquid crystal display (LCD) of the system that was connected to the machine, the number of passes was shown. The wheel was counted as passing twice if it made a full rotation in both directions. At the same time as the wheel is turning, a device called a linear variable differential transformer (LVDT) detects the depth of the impact of the rut in millimeters of unit.

3.11 Moisture Susceptibility Test

The tests were carried out in line with ASTM D 6931-07 to establish the moisture susceptibility of the material. Unconditioned tests were performed on three samples taken from each percentage of CR-WEO. Prior to the testing, the unconditioned specimens were conditioned in a water bath at 25.1 degrees Celsius (77.18 degrees Fahrenheit) for one hour. In addition, three samples of each mixture were examined after being conditioned. The conditioning of the samples was carried out in accordance with ALDOT-361, which specified that the specimens should first be soaked before being put in a water bath heated to 60 °C (140 °F) for 24 hours, followed by a water bath heated to 25 °C (77 °F) for one hour. Each specimen was put in the UTM machine in such a manner that the load would transfer in the sample diametrically at a rate of fifty millimeters per minute, regardless of whether the specimen had been conditioned or not. After that, the tensile strength was determined by using the measurements of the specimens and the loads at which they failed. To compute tensile strength ratios, the average conditioned tensile strength was divided by the average unconditioned tensile strength. A tensile strength ratio of 80% is required as per Superpave standards. A tensile strength ratio, abbreviated as TSR, is a comparison of the tensile strength of a conditioned sample to that of an unconditioned sample. Equation 1 shows the formula that was used to find the tensile strength of samples.

$$St = 2000P/\pi Dt \tag{1}$$

Here:

St = Tensile strength of sample (Kpa)

P = Maximum load applied on sample (N)

t = Specimen height before tensile test (mm)

D = Specimen diameter of sample (mm)

3.12 Resilient Modulus Test

Resilient modulus data may be used to measure how effectively a pavement structure reacts to traffic loads delivered by drivers. Resilient modulus also provides information for pavement design and assessment as well as analytical purposes. To predict pavement performance and analyses pavement reaction to traffic stress, the resilient modulus is considered an important parameter. Figure 3.7 shows the arrangement of resilient modulus apparatus. Universal testing machine was used to determine the resilient modulus of CR-WEO modified asphalt mixtures.

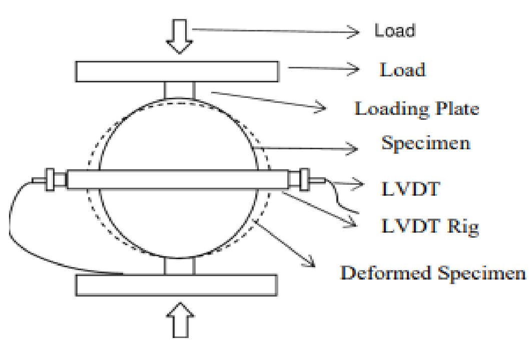


Figure 3.7: Arrangement of resilient modulus apparatus

Using Superpave gyratory compacted HMA samples, it was possible to perform resilient modulus tests on modified and unmodified asphalt mixtures. At 25°C, samples were taken out of the temperature container and loaded into the loading device, which was kept at that temperature. The repeated-load indirect tension test can be used to determine the resilient modulus of a cylindrical specimen, and a haversine waveform should be provided vertically in the specimen's vertical diametric plane. The application of load and the resilient modulus were determined using horizontal elastic deformation. Each load pulse's recovered horizontal deformation and horizontal deformation due to horizontal deformation is multiplied by equations to determine the resilient modulus. The apparatus that was used to evaluate the resilient modulus of CR-WEO modified asphalt mixtures is shown in Figure 3.8.

Figure 3.8: UTM for determination of resilient modulus

3.13 Summary

In this chapter, the laboratory characterization of aggregates and asphalt binder for the purpose of preparing asphalt mixes is discussed. For the creation of asphalt mix, only the kinds of materials that fulfilled the requirements of the standard criteria and specifications were employed. Calculations were done on the volumetric parameters of the asphalt mix samples that were created, and OBC was determined. At the conclusion of the chapter, the processes for sample preparation for performance testing, such as the moisture susceptibility, resilient modulus, and rutting resistance tests, were discussed.

This chapter provides an in-depth explanation of the approach that was used throughout the various stages of the experimental investigation. Both aggregate and bitumen were evaluated to ensure that they can be used for this investigation. To have a better grasp of the properties, tests on bitumen following the mixing of CR-WEO are presented with their respective ASTM standards. These tests measure the percentage of asphalt content in the bitumen. During the second phase, the NHA Class B gradation standards were used to produce a JMF. A concise explanation of the Marshall Test technique is provided, and volumetric characteristics of Marshall testing specimens are outlined with reference to applicable standards and specifications.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Rutting is the most frequent kind of pavement distress seen on hot mix asphalt (HMA) pavements across the world, and it is notably prevalent in Pakistan. Rutting is primarily caused by greater pavement surface temperatures in conjunction with increased axle loads. Therefore, doing the Hamburg double wheel tracker tests is not only rational and desirable from a technical standpoint but also from a practical one for the purpose of determining rutting susceptibility. In addition to rutting, moisture that is entrapped by the pavement may operate as a destructive agent. This most often leads to an early failure of HMA pavement and evaluating moisture-induced damage by UTM is a straightforward, easy, and the most common approach.

This research work is centered on the incorporation of CR-WEO as a substitute of asphalt binder in HMA mixture and analyzing the influence of this modification on the moisture susceptibility, resilience modulus, and rut resistance of CR-WEO modified asphalt mix. After calculating OBC and adding the optimal additive content, samples were prepared for performance testing. The NHA class B was utilized for this investigation. In this chapter, the results of various experiments, such as Moisture susceptibility (ITS), Resilient Modulus (MR), and rut resistance, are discussed in detail. Additionally, an analysis and comparison of the test data of conventional samples and CR-WEO modified samples is carried out and then discussed. With the assistance of Microsoft excel, an analysis of the findings collected from the various laboratory trials of HMA mix was carried out. X-Ray fluorescence test was conducted to find the chemical composition of WEO and CR. In the end, Hsu's and Tukey analysis was conducted to find the influence of CR-WEO on performance properties of modified asphalt.

4.2 Consistency Tests

For evaluating rheological properties such as penetrability and softening point, six different percentages of CR-WEO were used: five percent, ten percent, fifteen percent, twenty percent, twenty-five percent, and thirty percent by weight of bitumen. As the temperature rises and falls, the asphalt binder's consistency changes accordingly. In most cases, a test of the bitumen binder's penetration or viscosity is carried out to evaluate its consistency. The temperature that was used for penetration test was 25 degrees Celsius, the load that was used was 100 grammes, and the test period was 5 seconds. Bitumen is a substance that has a visco-elastic characteristic; nevertheless, as the temperature increases, it gradually gets softer, and its viscosity decreases. After conducting the consistency tests, it was found that the virgin 60/70 grade bitumen was satisfying all the criteria of all the test according to the respective standards. Table 4.1 Shows the results of consistency tests that was conducted on base bitumen. The penetration of the base bitumen was 69 at 25 ^oC, while the softening point of base bitumen was 50 ^oC.

Table 4.1: Consistency Test Results

Test Description	Result	Standards	Specifications
Penetration Test @ 25^oC	69	ASTM 5	60/70
Flash Point (^oC)	268	ASTM D 92	232 minimum
Fire Point (^oC)	291	ASTM D 92	232 minimum
Specific Gravity (kg/cm3)	1.03	ASTM D 70	1.01-1.06
Softening Point (^oC)	50	ASTM D36-06	49-56
Ductility Test (cm)	111	ASTM D 113-99	100 minimum

The softening point and penetration of base binder and CR-WEO modified asphalt was evaluated. It was found that as the percentage of CR-WEO was increased up to 10% the penetration values were slightly decreased, while the softening values were slightly increased. However, as the percentage of CR-WEO was employed in an amount greater than 10%, the penetration values were increased significantly, while the softening point values were decreased up to sample containing 30% CR-WEO. This shows that WEO has a dominant effect on consistency values as compared to Crumb rubber. Otherwise, softening point of CR modified asphalt increases as the CR content increases. The results of penetration and softening point tests for CR-WEO modified asphalt and base bitumen are shown in Figure 4.1.

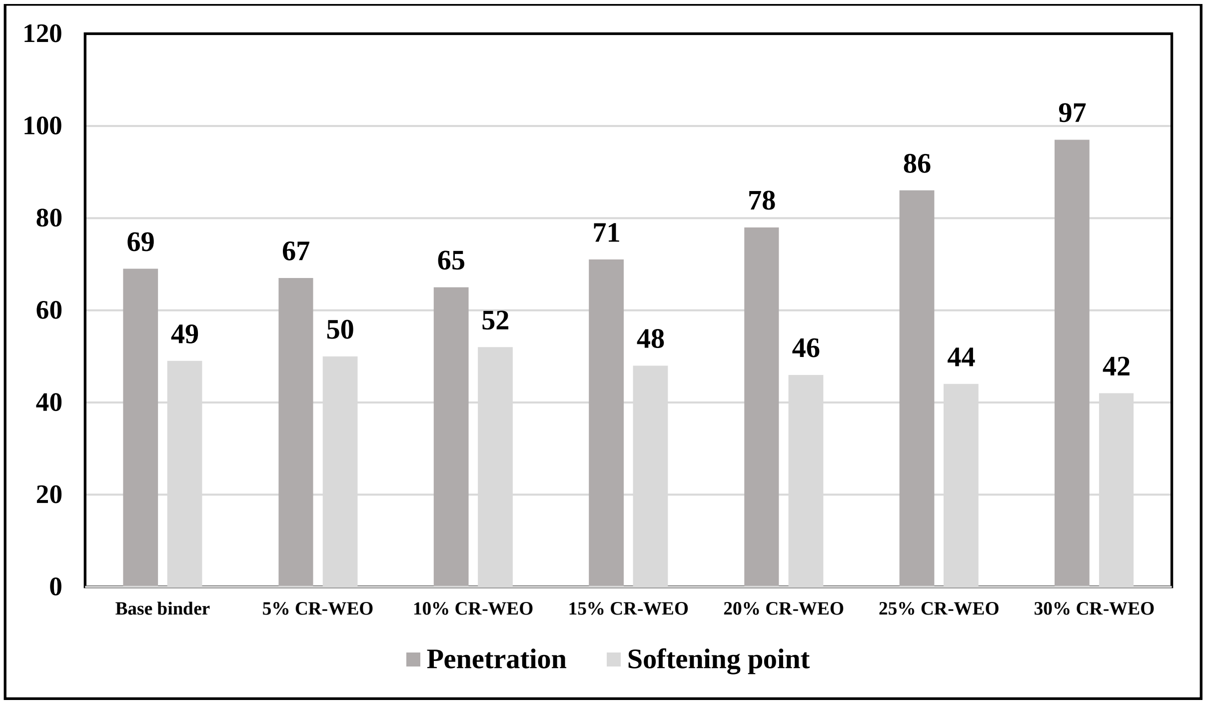


Figure 4.1: Results of consistency tests for CR-WEO modified binder

4.3 X-Ray Fluorescence Test

X-ray fluorescence spectroscopy is a technique that utilizes high-energy, short-wavelength X-ray radiation to identify the elemental composition of sample material. When it comes to detecting the surface concentration and spread of elements, X-ray fluorescence spectroscopy is an exceptionally helpful technique(A. Khan et al., 2021). When subjected to X-ray radiation, certain elements may be distinguished from one another based on the unique fluorescence energy that is emitted by each in response to the radiation. X-Ray Fluorescence test was conducted using EDX-7000 to determine the chemical composition of the waste engine oil and Crumb rubber. Fluorescent (or secondary) x-rays are produced when a solid or liquid sample is exposed to high-energy x-rays from a calibrated x-ray tube, as part of the XRF process.

Figure 4.2 shows the plot between Count per second/Unit area and Kilo electron volts for crumb rubber and Figure 4.3 shows the plot between Count per second/Unit area and Kilo electron volts for waste engine oil. From figure 4.2, ZnO has the most count per second per unit area, While Figure 4.3, indicates the presence of Sulphur trioxide in a larger amount in WEO.

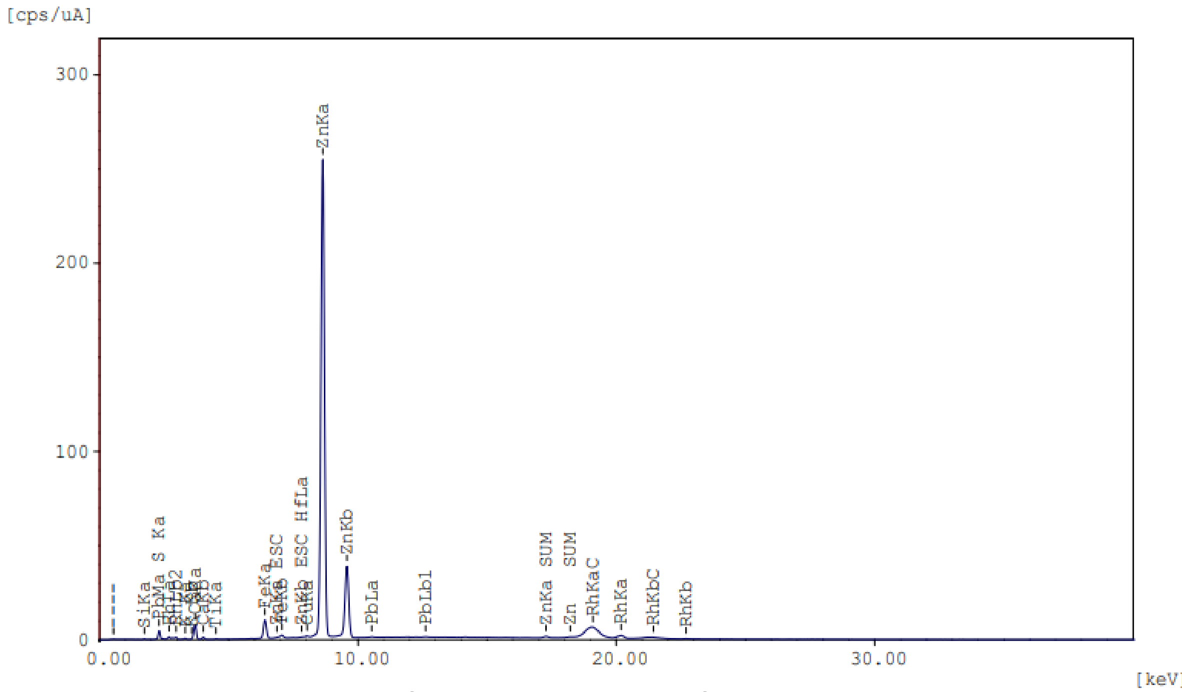


Figure 4.2: X-Ray fluorescence analysis for 40 mesh crumb rubber

Table 4.2 shows the chemical composition of crumb rubber. From Table 4.2, it can be observed that Zinc Oxide (ZnO) was found to be present in abundance in CR totaling up to 37.61%. This is because ZnO is an activator that is utilized all over the globe in a process called rubber vulcanization. ZnO as an activator promotes rapid curing kinetics as well as high cross-linking densities in rubber nanocomposites(Hadi & Kadhim, 2020).

Table 4.2: Chemical Compounds Present in Crumb Rubber

Compounds	Percentage (%)
ZnO	37.61
SO3	34.88
SiO2	14.58
CaO	9.51
Fe2O3	1.79
K2O	1.1
TiO2	0.19
PbO	0.16
CuO	0.11
HfO2	0.02

Also, it is frequently included in rubber compounds to speed up the vulcanization process and stimulate sulfur vulcanization. In addition to the influence that it has on the process of curing, ZnO also has several positive effects on the physicochemical properties of rubber.

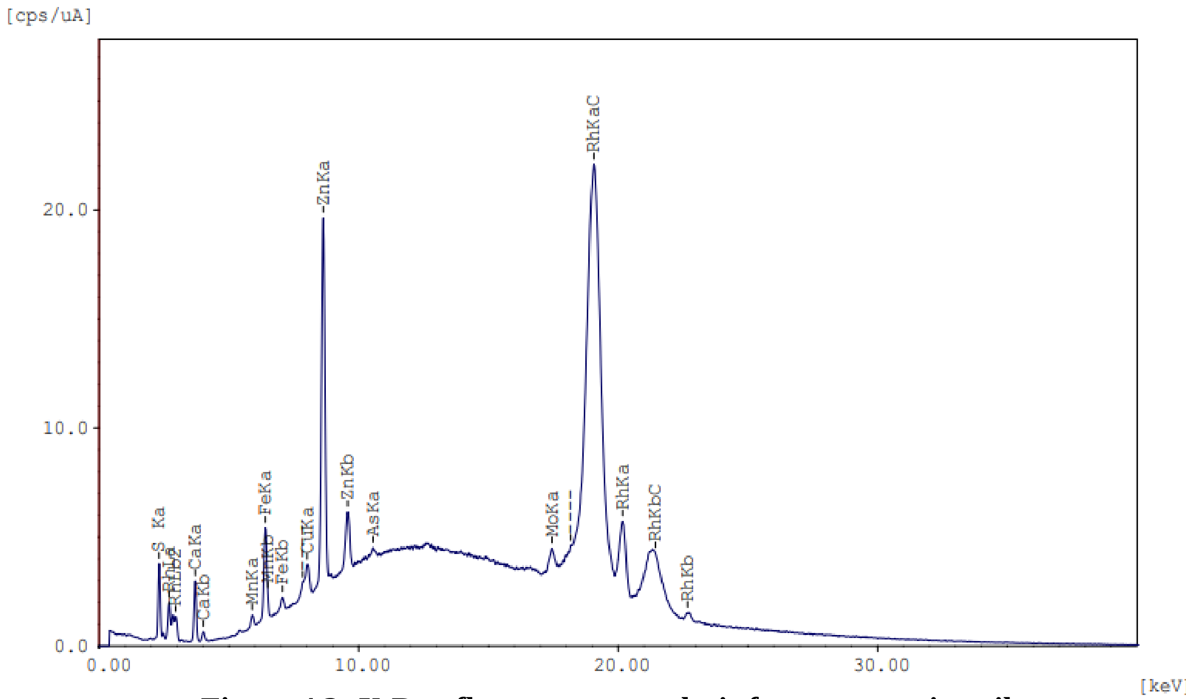


Figure 4.3: X-Ray fluorescence analysis for waste engine oil

From Figure 4.3, it can be confirmed that Sulphur trioxide was present in a larger amount in WEO. This is because Sulphur compounds are utilized in the chemistry of engine oil formulation as an addition for an antioxidant, as part of the anti-wear (AW) compounding, as part of the extreme pressure (EP) compounding, and as part of the increased lubricity qualities. Table 4.3 shows the chemical composition of waste engine oil.

Table 4.3: Chemical Compounds present in Waste Engine Oil

Compounds	Percentage (%)
SO3	61.76
ZnO	17.52
CaO	15.58
Fe2O3	3.39
CuO	0.87
MnO	0.52
MoO3	0.32

Also, Sulphur dioxide was further oxidized to Sulphur trioxide due to the usage of engine oil. This is also a reason that Sulphur dioxide was present in abundance in waste engine oil. Overall, the sulfur was found to be present in excessive amount in WEO, while Zinc was found to be present in abundance in CR.

4.4 HMA Performance Testing

To examine the performance of asphalt mixes comprising virgin binder and binder modified with varying amounts of CR-WEO, an evaluation of the performance of asphalt mix sample was carried out by conducting moisture susceptibility and rutting tests.

4.4.1 Moisture Susceptibility

For evaluating the moisture susceptibility, experimentation and testing were carried out in accordance with the ASTM D6931-07 standard. Three samples were prepared from the saw cutting of the cored HMA samples of Diameter of 4 inch and Thickness of 2 inch for the unconditioned indirect tensile strength test and three samples were prepared for the conditioned indirect tensile strength test for the hot-mix asphalt (HMA) mixture that included virgin asphalt binder. Samples were conditioned in accordance with ALDOT 361, which was followed throughout the process.

After carrying out the test using the UTM machine, the maximum load that the sample could withstand before breaking is recorded, and a calculation using the formula previously presented in chapter 3 is carried out to establish the sample's tensile strength. The formula is used to find the tensile strength of all the samples, both conditioned and unconditioned. This formula is then used to determine the tensile strength ratio, which is used to determine whether the samples prepared with CR-WEO modified binder meet the required criterion of tensile strength ratio (above 80 percent), as recommended by the standard. Because of the moisture-induced degradation, the ITS values of the samples that were conditioned were found to be lower than those of the unconditioned samples. When there is a greater proportion of CR-WEO in the HMA mixture, the TSR value decreases significantly.

Table 4.4 displays the IDT values of conditioned and unconditioned samples of CR-WEO modified asphalt mixtures. From table 4.4, it can be confirmed that the IDT values of conditioned samples are lower than the IDT values of unconditioned because of the moisture damage that occurred when the samples were conditioned.

Table 4.4: Tensile Strength Values of Different CR-WEO Modified Mixes

Base and Modified Binders	Average Unconditioned (KN)	Average Conditioned (KN)	Tensile Strength Ratio (%)
Base Binder	5.64	4.84	85.81
5 %CR-WEO	6.47	5.89	91.03
10 %CR-WEO	6.96	6.42	92.24
15 %CR-WEO	6.84	6.22	90.93
20 %CR-WEO	6.61	5.89	89.10
25 %CR-WEO	6.24	5.37	86.11
30 %CR-WEO	5.98	5.10	85.28

From Figure 4.4, it can be observed that when the CR-WEO content is increased to 10%, the TSR value rises to a maximum of 92, and then steadily drops. As a result, the sample containing 10% CR-WEO had the best moisture susceptibility. The stability of the overall mix decreases as CR-WEO content increases, and this has a negative impact on TSR values. To be fair, all samples met the Superpave criteria of minimum TSR value of 80 percent.

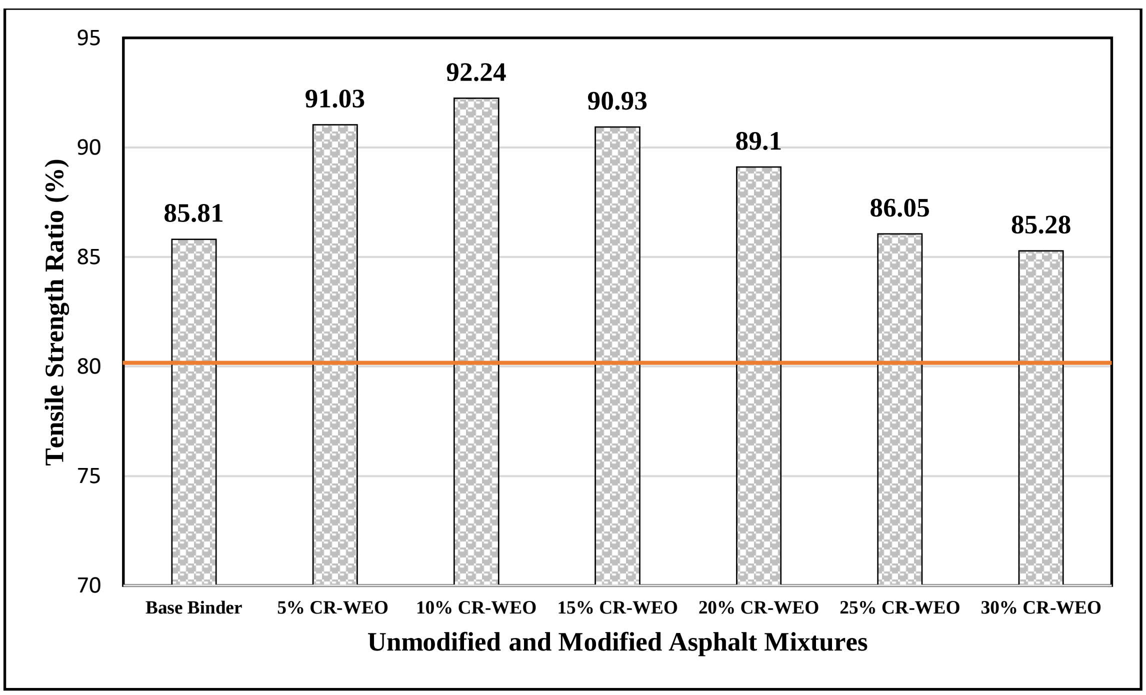


Figure 4.4: Results of TSR test

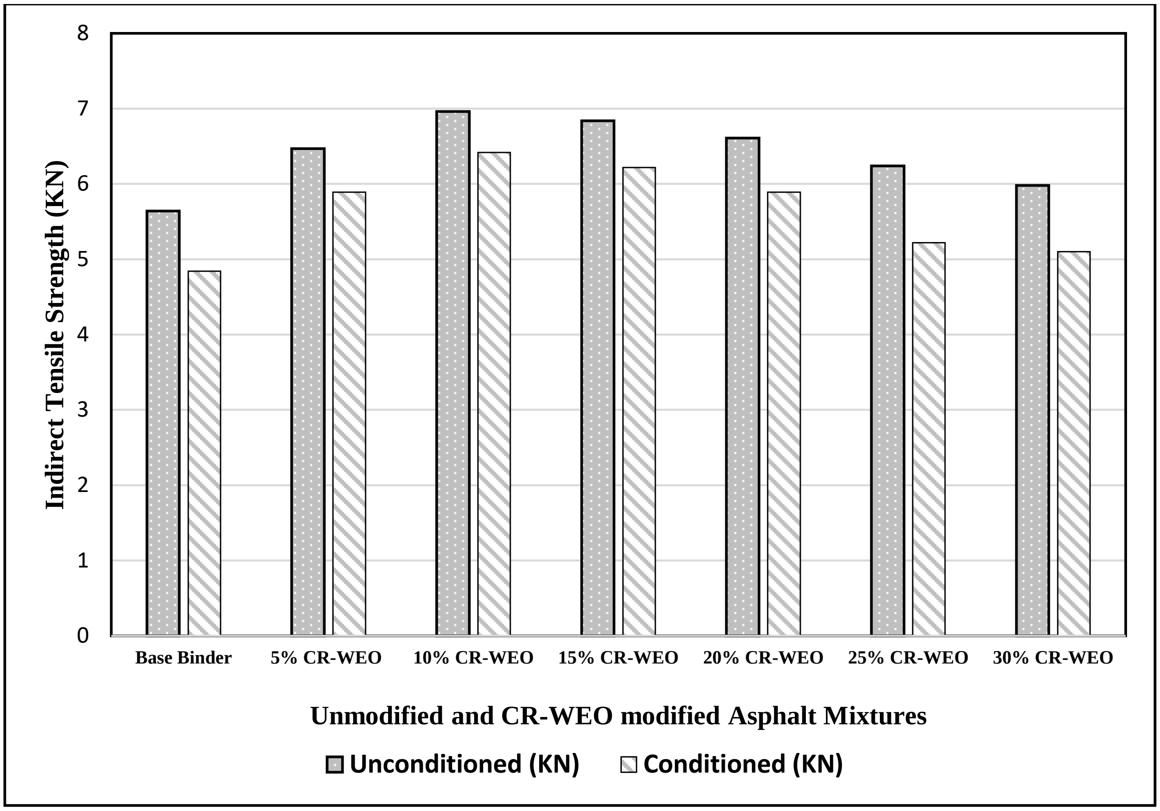


Figure 4.5: IDT values of conditioned and unconditioned asphalt samples

The IDT values of conditioned and unconditioned samples are shown in Figure 4.5. The sample containing 10% CR-WEO has the maximum IDT values as shown in Figure 4.5. However, when the percentage of CR-WEO as a modifier was employed in an amount greater than 10 %, the IDT values were dropped significantly. This indicates the higher amount of WEO has negative effects on the IDT values. Therefore, from the results of IDT, it can be concluded that 10 percent of modifier should be used to get optimum results.

4.4.2 Resilient Modulus Test

When a material is subjected to cyclic loading, resilient modulus is taken to determine the ratio of the applied stress to the recoverable strain. This ratio serves as a relative indication of the material's mixed stiffness. Using a performance test, it can ascertain the quality of the materials and gather data for the design of the pavement. One method for doing so is by using the resilient modulus. When it comes to estimating pavement performance and studying how pavement reacts to traffic loads, resilient modulus is an important statistic to consider. A contact peak loading of 20 percent of the IDT strength was used in the MR testing of samples produced by cutting cored samples. The experiments were carried out at a temperature of 25°C. Table 4.5 show the resilient modulus of modified asphalt mixtures. From table 4.5, sample containing 10 % CR-WEO has maximum resilient modulus values.

Table 4.5: Resilient Modulus Values of Different CR-WEO modified Mixtures

PERCENT	Mega pascals
BASE BINDER	3108
5% CR/WEO	4489
10% CR/WEO	5599
15% CR/WEO	4738
20% CR/WEO	4305
25% CR/WEO	3685
30% CR/WEO	3392

Figure 4.6 shows the resilient modulus of CR-WEO modified asphalt mixtures. It was also observed that higher dosages of CR-WEO led to decreases in the resilient modulus values, as the modifier was incorporated in an amount greater than 10 percent. This shows that the asphalt mixture that contain 10 percent CR-WEO has the best balance between stiffness and fluidity.

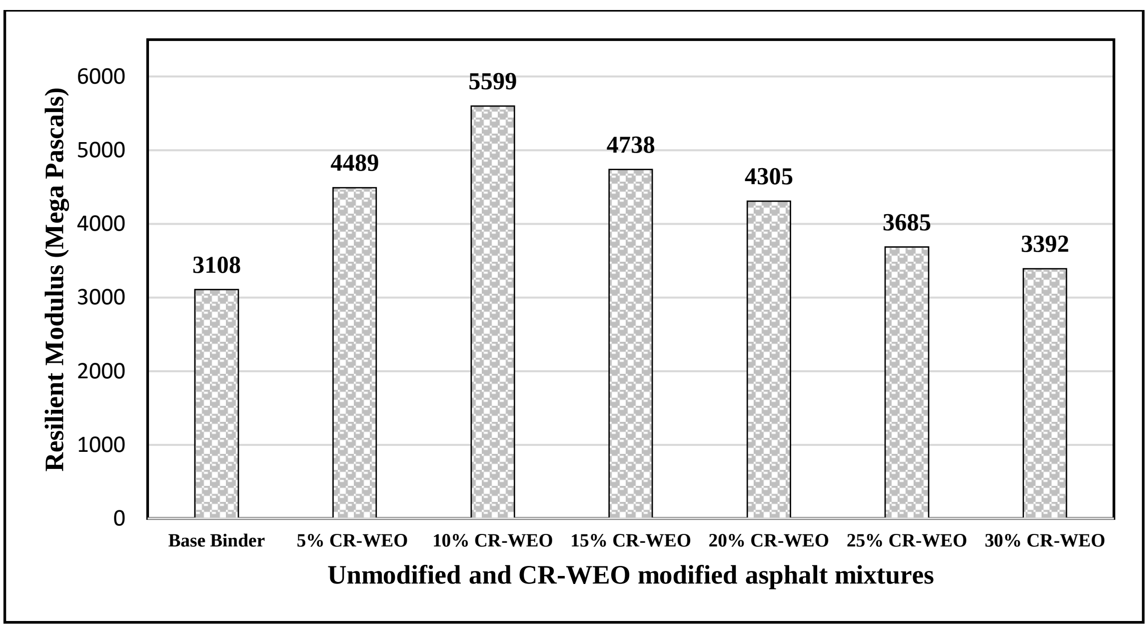


Figure 4.6: Resilient modulus values of different asphalt mixtures

Results show that the addition of 10 percent CR-WEO has enhanced the resilient modulus by 1.80 times. However, when the CR-WEO percentage was increased from 10 percent of CR-WEO, the value of resilient modulus started to decline. So, in the light of these results, it is indicated that modified sample with 10 percent CR-WEO has the best results.

4.4.3 Hamburg Wheel Tracking Test

The rutting test was carried out in accordance with the AASHTO T 324 standard. The gyratory compactor was used to prepare a total of samples for the rutting test. The unmodified and CR-WEO modified samples had a height of 6 inches and a diameter of 6 inches, and after cooling to room temperature for one day, the samples were saw cut to the required sizes of 2.4 inches height and 5.9 inches diameter to fit inside molds. After that, a comparison of the findings was carried out so that the difference in rutting susceptibility between unmodified asphalt and CR-WEO modified asphalt paving mix could be examined. Rutting experiments were carried out on specimens in air conditions using a wheel tracker.

Following the procedure described above, fourteen samples were prepared by utilizing different amounts of CR-WEO; these samples were then saw cut for wheel tracker testing to measure the rutting potential. The temperature within the chamber was always kept at 40 degrees Celsius, and the experiment was carried out in an environment with dry air. The criteria for failing were established at a rut depth of 12.5mm. The wheel passes on the samples totaled 10000 (5000 cycles), and the speed was maintained at 51 cycles per minute throughout the experiment. In addition to this, the specifics of the samples were added to the program that displays the data on the deformation. The rut depth increases as the number of cycles increases, and the experiment was designed to end either after 5000 cycles were finished or when a rut depth of 12.5 millimeters was reached, whichever comes first. At this criterion, none of the samples were rejected. After the test was finished, the samples were removed, and then the CR-WEO modified samples were fixed in the moulds of the HDWT device. Information was input into the software, and then the test was run under the same circumstances as before, including loading, cycles, and temperature.

Table 4.6 shows the rut depth values of CR-WEO modified asphalt mixtures. The rut depth was measured in millimeters. It was observed that when CR-WEO is used as a modifier, it has the potential to improve the rutting resistance and it can be confirmed in table 4.6.

Table 4.6: Rut Depth of Different CR-WEO Modified Asphalt Mixtures

Different binders	Rut depth in mm
BASE BINDER	3.31
5 %CR/WEO	2.21
10 %CR/WEO	1.52
15 %CR/WEO	2.31
20 %CR/WEO	2.55
25 %CR/WEO	2.80
30 %CR/WEO	3.17

Figure 4.7 displays the rutting values of CR-WEO modified asphalt mixtures. From the results, sample containing 10% CR-WEO have higher rut resistance than the other samples. The best balance between stiffness and fluidity was achieved by the sample that contain 10 % CR-WEO.

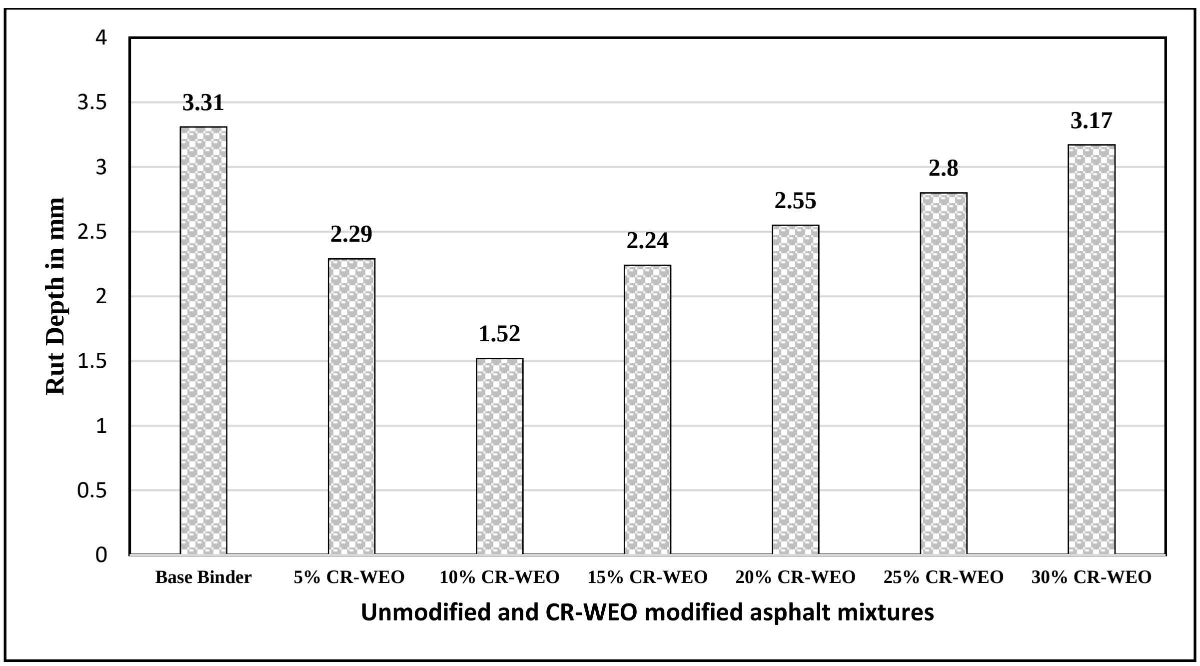
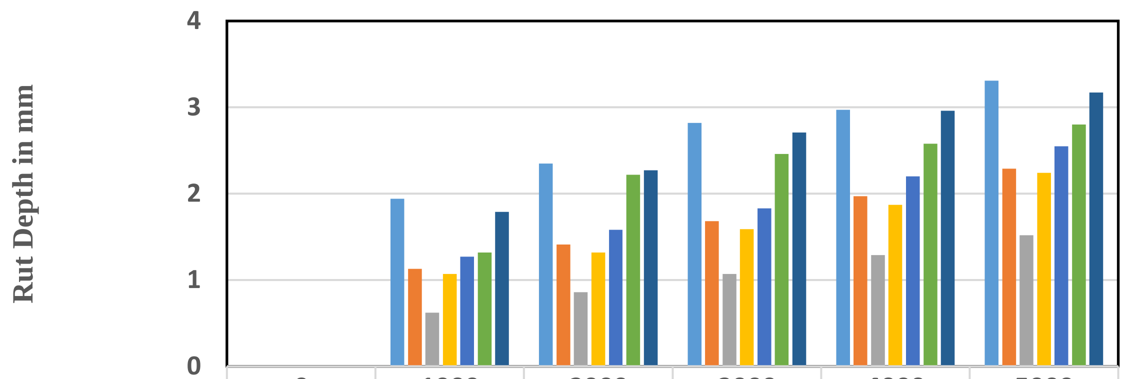


Figure 4.7: Rut depth values of control and modified asphalt mixtures

Therefore, the samples which contain higher content of CR-WEO show less rut resistance as compared to the sample that contains 10 % CR-WEO. Figure 4.8 shows the rutting resistance of modified asphalt mixtures at different number of cycles.



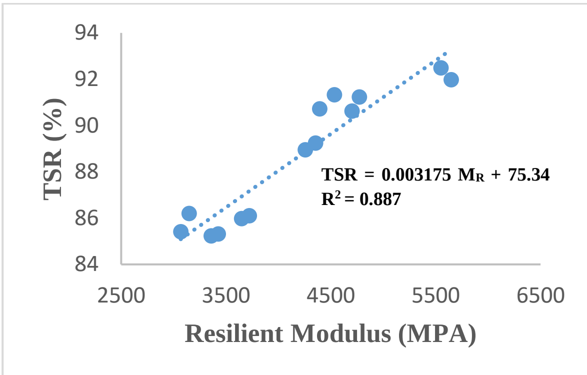
	0	1000	2000	3000	4000	5000
CR/WEO 0 %	0	1.94	2.35	2.82	2.97	3.31
CR/WEO 5 %	0	1.13	1.41	1.68	1.97	2.29
CR/WEO 10 %	0	0.62	0.86	1.07	1.29	1.52
CR/WEO 15 %	0	1.07	1.32	1.59	1.87	2.24
CR/WEO 20 %	0	1.27	1.58	1.83	2.2	2.55
CR/WEO 25 %	0	1.32	2.22	2.46	2.58	2.8
CR/WEO 30 %	0	1.79	2.27	2.71	2.96	3.17

Figure 4.8: Rut depth vs number of cycles

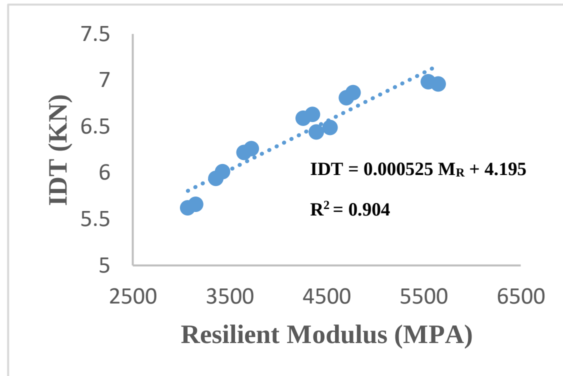
From Figure 4.8, it is evident that, when the percentage of CR-WEO exceeds 10%, the rut resistance characteristics of asphalt mixes decreased. This is because the percentage of waste engine oil increases as CR-WEO percentage in asphalt mix increases, which leads to reduction in rut resistance of asphalt mixes when employing higher amount of CR-WEO in asphalt mixtures.

4.5 Correlations Between Performance Tests

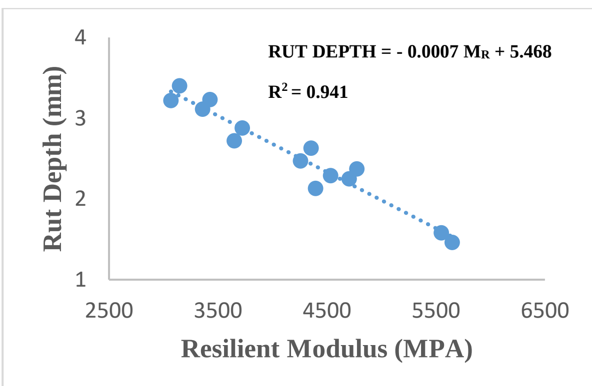
In the preceding section, the findings indicated that 10% CR-WEO should be used to modify the base bitumen. Tensile Strength Ratio, resilient modulus, and Hamburg wheel tracking tests were used to confirm the significance of these findings. The correlations were developed between results of TSR, resilient modulus, and HWTT results, to find the relation between these performance indicators. It was found that the performance indicators were strongly correlated as depicted by high R^2 values and it can be confirmed from Figure 4.9.



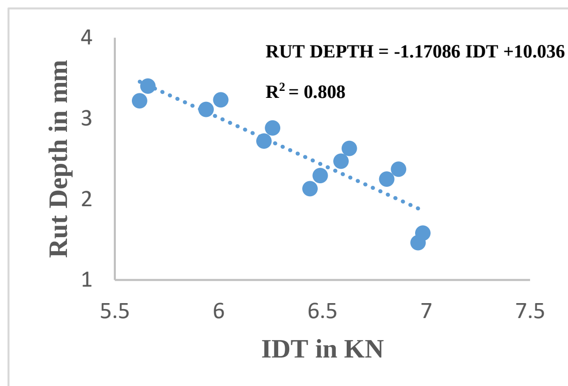
(a)



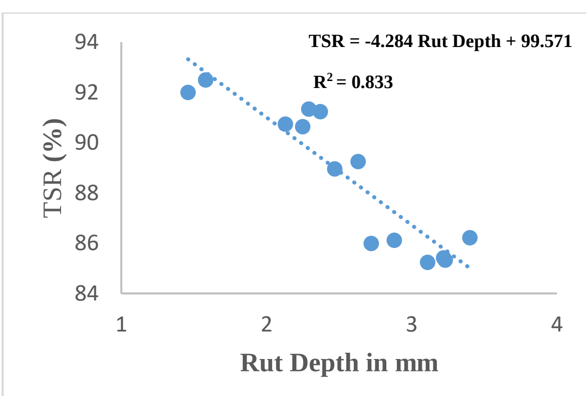
(b)



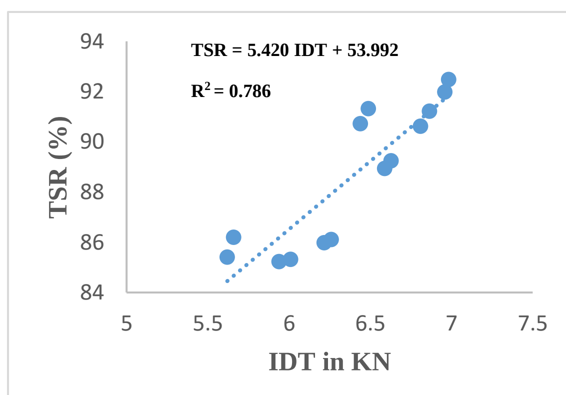
(c)



(d)



(e)



(f)

Figure 4.9: Correlation between HMA performance tests

Figure 4.9 shows the correlations developed between different HMA performance tests. It was found that all the variables were strongly correlated as indicated by the high R^2 values. Figure 4.9(a) shows the correlation between TSR and resilient modulus values. The correlation between TSR and resilient modulus was found to be strong as depicted by R^2 value of 0.887. Figure 4.9(b) shows the correlation between IDT values and resilient modulus. The correlation between these is also strong as the value of R^2 for this correlation was 0.904. Figure 4.9(c) shows the correlation between rut depth and resilient modulus. The correlation between these two was the strongest as compared to other correlations because of the R^2 value of 0.94, which was the highest as compared to other correlations. Figure 4.9(d) shows the correlation between IDT and rut depth values. It was found that they were negatively correlated with each other. Figure 4.9(e) shows the correlation between TSR and rut depth while Figure 4.9(f) shows the correlation between IDT and TSR. Both correlations were found to be strong as indicated by high R^2 values and it can also be confirmed in Table 4.7. Table 4.7 shows the summary of correlations developed. From Table 4.7, it can be confirmed that rut depth and resilient modulus were strongly correlated to each other as indicated by R square value of 0.94.

Table 4.7: Summary of Correlations developed

Equation No.	Correlation between	Expressions	R Square
1	IDT and M_R	IDT = 0.000525 M_R + 4.195	0.904
2	TSR and M_R	TSR = 0.003175 M_R + 75.34	0.887
3	RUT DEPTH and M_R	RUT DEPTH = -0.0007 M_R + 5.468	0.941
4	RUT DEPTH and IDT	RUT DEPTH = -1.17086 IDT +10.036	0.808
5	TSR and RUT DEPTH	TSR = -4.284 RUT DEPTH + 99.571	0.833
6	TSR and IDT	TSR = 5.420 IDT + 53.992	0.786

4.6 Analysis of Data

One-way ANOVA was used to examine the influence of different percentages of CR-WEO on rutting, moisture susceptibility, and stiffness-related performance properties of CR-WEO modified asphalt mixtures. The impact of CR-WEO as a modifier was examined using

ANOVA with a single factor. ANOVA revealed that CR-WEO modified HMA samples differed substantially from the control sample. Tukey's analysis and Hsu's MCB analysis were conducted to examine the significance of ANOVA results. The M_R, IDT, moisture susceptibility, and rut depth of asphalt mixes were taken into consideration as the dependent variables. The amount of CR-WEO was the constant factor that was evaluated.

4.6.1 Tukey's and Hsu's MCB Analysis for Rut Depth

An analysis of variance (ANOVA) was carried out to ascertain whether the Rut depth of CR-WEO modified asphalt samples was distinct from that of control sample. Equal variances were assumed for the analysis. ANOVA analysis is a useful parametric tool to find the influence of CR-WEO on performance of modified asphalt mixtures. The ANOVA analysis was conducted with null hypothesis that all means are equal and alternative hypothesis is that all means are not equal. However, it only tells whether the results are significant or not, it does not tell where the difference lies. Table 4.8 shows results of ANOVA analysis that was conducted for rut depth values.

Table 4.8: Results of ANOVA Analysis for Rut Depth Values

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	6	6.77563	1.12927	340.73	0.000
Error	14	0.04640	0.00331		
Total	20	6.82203			

From Table 4.8, it is evident that as the p-value is smaller than 0.05, it means that the modifier has significant influence on rut depth values. Also, the null hypothesis should be rejected as P-value is smaller than 0.05. So, the alternative hypothesis should be accepted that all means are not equal. In order, to find the significance of ANOVA results, Tukey's pairwise analysis and Hsu's multiple comparison from the means was conducted. Tukey's range test is a single-step multiple comparison procedure and statistical test. Tukey's technique applies to all pairwise comparisons simultaneously. Tukey's test eliminates the need for an ANOVA by automatically reducing the Type I error rate. Within and among the groups, the observations being examined are unaffected by each other. Table 4.9 shows the mean, Standard deviation of CR-WEO modified asphalt samples at 95% confidence interval.

Table 4.9: Means of Rut Depth values of different CR-WEO modified samples

CR-WEO %	N	Mean	St Dev	95% CI
CONTROL	3	3.3100	0.0600	(3.2387, 3.3813)
CR/WEO 5%	3	2.2100	0.0600	(2.1387, 2.2813)
CR/WEO 10%	3	1.5200	0.0700	(1.4487, 1.5913)
CR/WEO 15%	3	2.3100	0.0600	(2.2387, 2.3813)
CR/WEO 20%	3	2.5500	0.0500	(2.4787, 2.6213)
CR/WEO 25%	3	2.8000	0.0500	(2.7287, 2.8713)
CR/WEO 30%	3	3.1700	0.0500	(3.0987, 3.2413)

There is a normal distribution of groups associated with each of the test's mean values. If an interval does not contain zero, the corresponding means are significantly different. From Table 4.10, none of the interval share letter, which means that they are significantly different from each other.

Table 4.10: Grouping Information Using the Tukey's Method and 95% Confidence

CR-WEO%	N	Mean Rut Depth	Grouping				
CONTROL	3	3.3100	A				
CR/WEO 30%	3	3.1700	A				
CR/WEO 25%	3	2.8000		B			
CR/WEO 20%	3	2.5500			C		
CR/WEO 15%	3	2.3100				D	
CR/WEO 5%	3	2.2100				D	
CR/WEO 10%	3	1.5200					E

The findings of the ANOVA and Tukey tests demonstrate that the addition of CR-WEO as a modifier has a substantial impact on Rutting. Furthermore, the findings reveal that the rutting performance of the control and CR-WEO modified samples differs significantly.

Table 4.11 shows the results of Tukey's analysis that was conducted for rut depth values. Only two pairs were not found to be significant as the P value was greater than 0.05. While other pairs were found to be significant as indicated by the P values less than 0.05. This means Tukey's analysis supported the result of ANOVA that the modifier has significant influence on rut depth values.

Table 4.11: Tukey's Simultaneous Tests for Differences of Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CR/WEO 5% - CONTROL	-1.1000	0.0470	(-1.2605, -0.9395)	0.000
CR/WEO 10% - CONTROL	-1.7900	0.0470	(-1.9505, -1.6295)	0.000
CR/WEO 15% - CONTROL	-1.0000	0.0470	(-1.1605, -0.8395)	0.000
CR/WEO 20% - CONTROL	-0.7600	0.0470	(-0.9205, -0.5995)	0.000
CR/WEO 25% - CONTROL	-0.5100	0.0470	(-0.6705, -0.3495)	0.000
CR/WEO 30% - CONTROL	-0.1400	0.0470	(-0.3005, 0.0205)	0.107
CR/WEO 10% - CR/WEO 5%	-0.6900	0.0470	(-0.8505, -0.5295)	0.000
CR/WEO 15% - CR/WEO 5%	0.1000	0.0470	(-0.0605, 0.2605)	0.389
CR/WEO 20% - CR/WEO 5%	0.3400	0.0470	(0.1795, 0.5005)	0.000
CR/WEO 25% - CR/WEO 5%	0.5900	0.0470	(0.4295, 0.7505)	0.000
CR/WEO 30% - CR/WEO 5%	0.9600	0.0470	(0.7995, 1.1205)	0.000
CR/WEO 15% - CR/WEO 10%	0.7900	0.0470	(0.6295, 0.9505)	0.000
CR/WEO 20% - CR/WEO 10%	1.0300	0.0470	(0.8695, 1.1905)	0.000
CR/WEO 25% - CR/WEO 10%	1.2800	0.0470	(1.1195, 1.4405)	0.000
CR/WEO 30% - CR/WEO 10%	1.6500	0.0470	(1.4895, 1.8105)	0.000
CR/WEO 20% - CR/WEO 15%	0.2400	0.0470	(0.0795, 0.4005)	0.002
CR/WEO 25% - CR/WEO 15%	0.4900	0.0470	(0.3295, 0.6505)	0.000
CR/WEO 30% - CR/WEO 15%	0.8600	0.0470	(0.6995, 1.0205)	0.000
CR/WEO 25% - CR/WEO 20%	0.2500	0.0470	(0.0895, 0.4105)	0.002
CR/WEO 30% - CR/WEO 20%	0.6200	0.0470	(0.4595, 0.7805)	0.000
CR/WEO 30% - CR/WEO 25%	0.3700	0.0470	(0.2095, 0.5305)	0.000

When a certain interval does not have a value of zero, the means that correspond to that interval are drastically different. From Figure 4.10, it can be observed that only two of the intervals contain zero, and the other intervals do not contain zero, which demonstrates that they are statistically distinct from one another. It is thus possible to draw the conclusion that CR-WEO has a considerable influence on the values of rut depth.

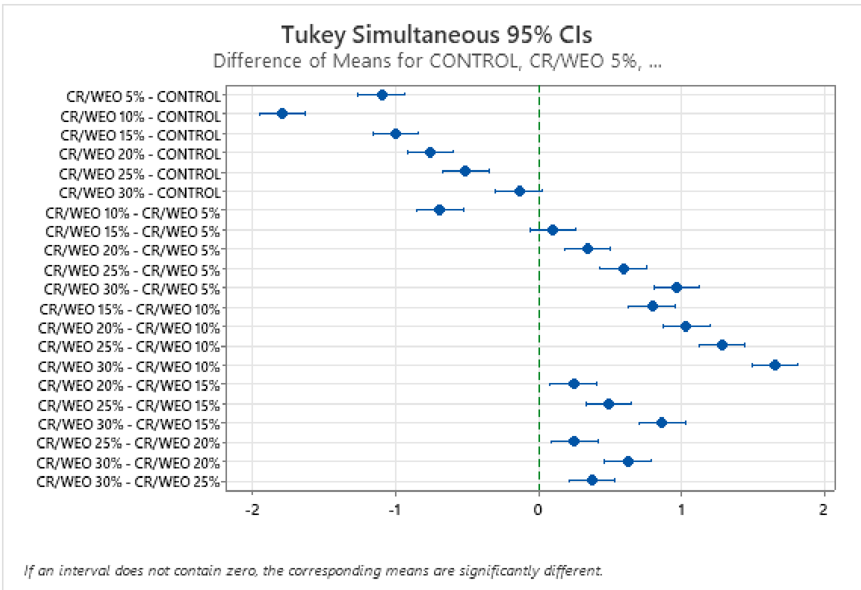


Figure 4.10: Tukey's pairwise analysis of rut depth with 95% confidence interval

After conducting the Tukey's analysis, Hsu's MCB test was conducted to identify factor levels that are the best, insignificantly different from the best, and those that are significantly different from the best. Researchers can define "best" as either the highest or lowest mean. This procedure is usually used after an ANOVA to analyze differences more precisely between level means. Hsu's MCB compares each sample mean to the "best" of all other means, where "best" denotes either the biggest or the lowest. If an interval has zero as an endpoint, there is a statistically significant difference between the corresponding means.

Table 4.12 shows the results of HSU's MCB test. Hsu's MCB approach compares all potential pairwise comparisons, while Hsu's simply compares a portion of them. Hsu's analysis provide narrower confidence intervals and it is more powerful tests for any given error rate. The best was defined as the mean that have highest value of rut depth and all the comparisons were made with the best. Hsu's analysis further supported the results of ANOVA that the modifier has significant influence on rut depth values.

Table 4.12: Hsu's Simultaneous Tests for Level Mean

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CONTROL - CR/WEO 30%	0.1400	0.0470	(0.0000, 0.2590)	0.022
CR/WEO 5% - CONTROL	-1.1000	0.0470	(-1.2190, 0.0000)	0.000
CR/WEO 10% - CONTROL	-1.7900	0.0470	(-1.9090, 0.0000)	0.000
CR/WEO 15% - CONTROL	-1.0000	0.0470	(-1.1190, 0.0000)	0.000
CR/WEO 20% - CONTROL	-0.7600	0.0470	(-0.8790, 0.0000)	0.000
CR/WEO 25% - CONTROL	-0.5100	0.0470	(-0.6290, 0.0000)	0.000
CR/WEO 30% - CONTROL	-0.1400	0.0470	(-0.2590, 0.0000)	0.022

From Figure 4.11 it can be observed that all intervals have a zero-ending point which means that they are statistically different, and therefore it can be concluded that CR-WEO has a significant impact on rut depth values.

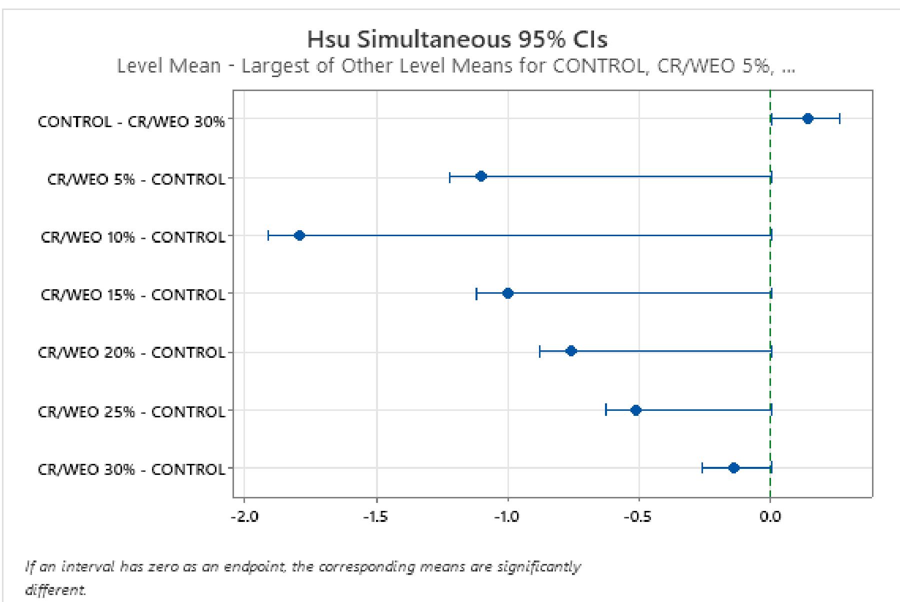


Figure 4.11: Hsu's MCB analysis of rut depth

Figure 4.12 shows the interval plot of rut depth values. The values of interval data are measured over a numerical scale that maintains consistent lengths between each pair of consecutive values.

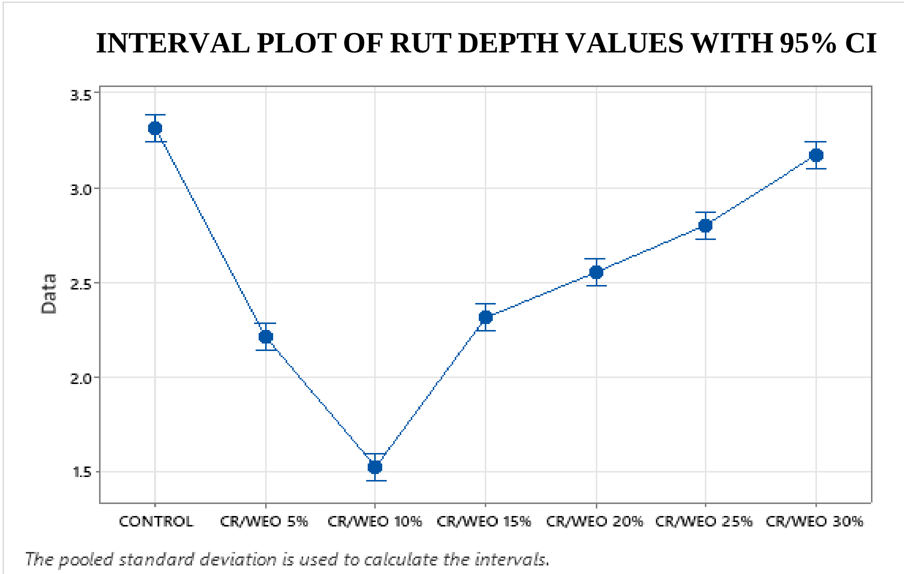


Figure 4.12: Interval plot for rut depth mean values

The difference between an interval scale and a ratio scale lies in the fact that an interval scale does not have a genuine zero. Zero is not the absence of the variable entirely on an interval scale; rather, it is an arbitrary position on the scale. When the data are continuous, this method is used. An interval plot displays the confidence interval for the mean of the rut depth values rather than presenting the individual data points.

4.6.2 Tukey's and Hsu's MCB Analysis for Resilient Modulus

A one-way Analysis of Variance (ANOVA) was used to compare the effects of varying percentages of CR-WEO on resilient modulus of modified asphalt samples.

Table 4.13: Results of ANOVA analysis-CR-WEO% vs Resilient Modulus

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	6	13352208	2225368	436.65	0.000
Error	14	71350	5096		
Total	20	13423558			

For the sake of this study, it was assumed that the variances were equal. The findings of the ANOVA analysis are shown in Table 4.13. It was found that the modifier has significant influence on resilient modulus values as depicted by P value of 0 which can be confirmed from Table 4.13.

Table 4.14: Means of different CR-WEO modified samples

Factor	N	Mean	St Dev	95% CI
CONTROL	3	3108.0	70.0	(3019.6, 3196.4)
CR/WEO 5%	3	4489.0	70.0	(4400.6, 4577.4)
CR/WEO 10%	3	5599.0	90.0	(5510.6, 5687.4)
CR/WEO 15%	3	4738.0	70.0	(4649.6, 4826.4)
CR/WEO 20%	3	4305.0	65.0	(4216.6, 4393.4)
CR/WEO 25%	3	3685.0	75.0	(3596.6, 3773.4)
CR/WEO 30%	3	3392.0	55.0	(3303.6, 3480.4)

Table 4.14 shows the mean of resilient modulus, Standard deviation of different All possible pairwise differences in means were made using Tukey's pairwise analysis. Table 4.15 shows the grouping information that was developed using Tukey’s test. All the intervals were found to be significantly different as they were not sharing any letter and it can be confirmed from Table 4.15.

Table 4.15: Grouping Information Using the Tukey’s Method and 95% Confidence

Factor	N	Mean	Grouping					
CR/WEO 10%	3	5599.0	A					
CR/WEO 15%	3	4738.0		B				
CR/WEO 5%	3	4489.0			C			
CR/WEO 20%	3	4305.0			C			
CR/WEO 25%	3	3685.0				D		
CR/WEO 30%	3	3392.0					E	
CONTROL	3	3108.0						F

Therefore, it can be found that CR-WEO as a modifier has significant influence on the resilient modulus, as shown by the ANOVA and Tukey tests. Also, CR-WEO modified samples have a significantly higher resilient modulus than the control samples. This can be confirmed from Figure 4.13, which shows that means of only one interval that was between

CR-WEO 20% and CR-WEO 5% was touching the zero line. However, the means of all the other intervals were significantly different as they were touching the zero line.

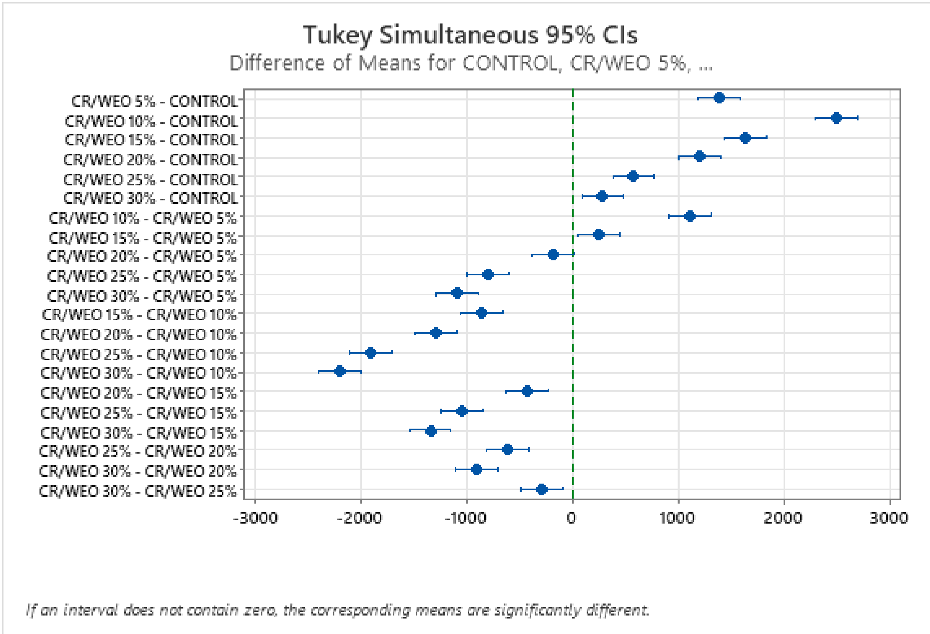


Figure 4.13: Tukey's pairwise analysis of resilient modulus

There are vastly different means for distinct intervals that don't have a value of zero. As can be seen in Figure 4.13, only one of the intervals has a value of zero, whilst the other intervals do not, proving that they are statistically different. It can be summarized that the resilient modulus values are significantly influenced by CR-WEO. From Table 4.16, P value of only one pair that was between 5% CR-WEO and 20% CR-WEO was greater than 0.05. This means that means of these two pair was not significantly different. However, all the other intervals have P value smaller than 0.05. This means that means of majority of the pairs shown in Table 4.16 are significantly different from each other. Therefore, it can be concluded that CR-WEO as a modifier has significant influence on the resilient modulus values as means of majority of the pairs significantly different and it can be confirmed from Figure 4.13 and Table 4.16.

After conducting Tukey's analysis, resilient modulus values were analyzed using Hsu's analysis to access the impact of CR-WEO as a modifier. Confidence intervals were created for the difference between each level's mean and all other levels' means. There is a statistically significant difference between the means if an interval has zero as its ending point.

Table 4.16: Tukey's Simultaneous Tests for Differences in Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CR/WEO 5% - CONTROL	1381.0	58.3	(1181.9, 1580.1)	0.000
CR/WEO 10% - CONTROL	2491.0	58.3	(2291.9, 2690.1)	0.000
CR/WEO 15% - CONTROL	1630.0	58.3	(1430.9, 1829.1)	0.000
CR/WEO 20% - CONTROL	1197.0	58.3	(997.9, 1396.1)	0.000
CR/WEO 25% - CONTROL	577.0	58.3	(377.9, 776.1)	0.000
CR/WEO 30% - CONTROL	284.0	58.3	(84.9, 483.1)	0.004
CR/WEO 10% - CR/WEO 5%	1110.0	58.3	(910.9, 1309.1)	0.000
CR/WEO 15% - CR/WEO 5%	249.0	58.3	(49.9, 448.1)	0.011
CR/WEO 20% - CR/WEO 5%	-184.0	58.3	(-383.1, 15.1)	0.079
CR/WEO 25% - CR/WEO 5%	-804.0	58.3	(-1003.1, -604.9)	0.000
CR/WEO 30% - CR/WEO 5%	-1097.0	58.3	(-1296.1, -897.9)	0.000
CR/WEO 15% - CR/WEO 10%	-861.0	58.3	(-1060.1, -661.9)	0.000
CR/WEO 20% - CR/WEO 10%	-1294.0	58.3	(-1493.1, -1094.9)	0.000
CR/WEO 25% - CR/WEO 10%	-1914.0	58.3	(-2113.1, -1714.9)	0.000
CR/WEO 30% - CR/WEO 10%	-2207.0	58.3	(-2406.1, -2007.9)	0.000
CR/WEO 20% - CR/WEO 15%	-433.0	58.3	(-632.1, -233.9)	0.000
CR/WEO 25% - CR/WEO 15%	-1053.0	58.3	(-1252.1, -853.9)	0.000
CR/WEO 30% - CR/WEO 15%	-1346.0	58.3	(-1545.1, -1146.9)	0.000
CR/WEO 25% - CR/WEO 20%	-620.0	58.3	(-819.1, -420.9)	0.000
CR/WEO 30% - CR/WEO 20%	-913.0	58.3	(-1112.1, -713.9)	0.000
CR/WEO 30% - CR/WEO 25%	-293.0	58.3	(-492.1, -93.9)	0.003

Table 4.17 shows the results of Hsu's multiple comparison from the best that was conducted by selecting the highest value of resilient modulus as best and after that the comparisons were made with the best. As, 10% CR-WEO has the highest resilient modulus value, therefore, 10% CR-WEO was chosen as the best. From Table, 4.17 it is evident that the P value of all the intervals is zero, therefore, it can be concluded that they are significantly different from each other.

Table 4.17: Hsu's Simultaneous Tests for Level Mean

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CONTROL - CR/WEO 10%	-2491.0	58.3	(-2638.6, 0.0)	0.000
CR/WEO 5% - CR/WEO 10%	-1110.0	58.3	(-1257.6, 0.0)	0.000
CR/WEO 10% - CR/WEO 15%	861.0	58.3	(0.0, 1008.6)	0.000
CR/WEO 15% - CR/WEO 10%	-861.0	58.3	(-1008.6, 0.0)	0.000
CR/WEO 20% - CR/WEO 10%	-1294.0	58.3	(-1441.6, 0.0)	0.000
CR/WEO 25% - CR/WEO 10%	-1914.0	58.3	(-2061.6, 0.0)	0.000
CR/WEO 30% - CR/WEO 10%	-2207.0	58.3	(-2354.6, 0.0)	0.000

CR-WEO has a considerable effect on resilient modulus values, as shown in Figure 4.14. All intervals in Figure 4.14 have zero ending points, which indicates that they are statistically distinct.

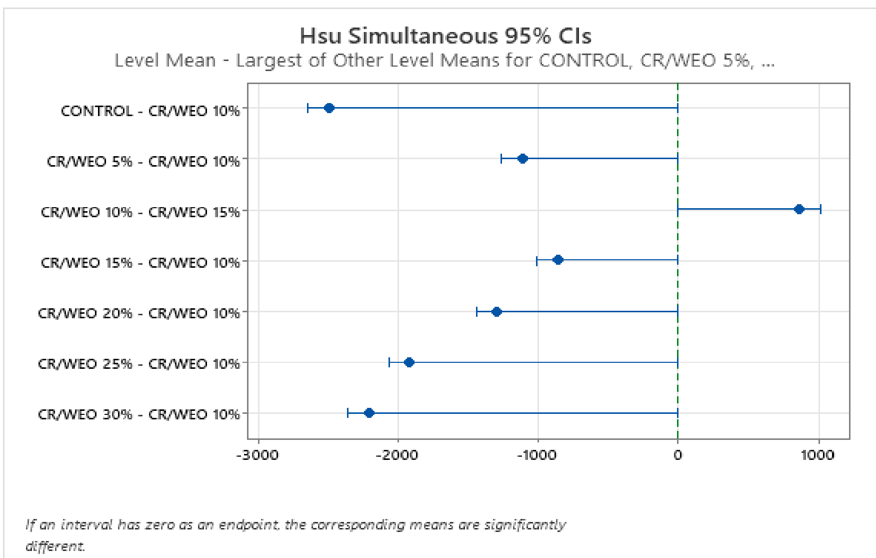


Figure 4.14: Hsu's MCB analysis of resilient modulus values at 95% CI

The interval plot of resilient modulus values is shown in Figure 4.15. Using a numerical scale, interval data values may be compared to each other. The distinction between an interval scale and a ratio scale is that an interval scale does not have a true zero. Rather than being a complete absence of a variable, zero is just an arbitrary point on the interval scale. This approach is used when the data is in a continuous form. Resilient modulus values are shown as intervals rather than as individual data points in an interval plot.

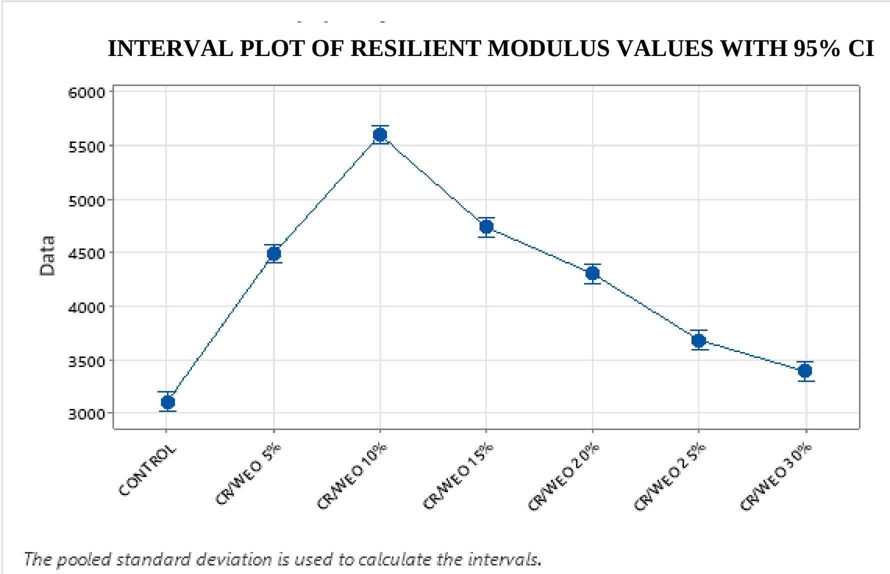


Figure 4.15: Interval plot for resilient modulus mean values

4.6.3 Tukey's and Hsu's MCB Analysis for Tensile Strength Ratio

To examine the impacts of varying percentages of CR-WEO on moisture susceptibility of CR-WEO modified samples, one-way analysis of variance was conducted. An analysis of variance (ANOVA) was performed to see whether the Tensile Strength Ratio of CR-WEO modified asphalt samples differed from that of the corresponding control asphalt sample. The variances were equal in this investigation. Table 4.18 displays the results of the ANOVA test. The P value in 4.18 is smaller than 0.05, which means that the null hypothesis should be rejected and the alternative hypothesis that all means are not equal should be accepted. Therefore, the result of ANOVA analysis shows that the CR-WEO as a modifier has significant influence on TSR values.

Table 4.18: Results of ANOVA analysis: CR-WEO% vs TSR values

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	6	149.481	24.9136	1107.27	0.000
Error	14	0.315	0.0225		
Total	20	149.796			

Table 4.19 shows the mean of TSR values and standard deviation of different CR-WEO modified asphalt samples. N donates the number samples that were used in conducting in this analysis.

Table 4.19: Means of TSR of different CR-WEO modified samples

Factor	N	Mean	St Dev	95% CI
CONTROL	3	85.8100	0.1500	(85.6243, 85.9957)
CR/WEO 5%	3	91.0300	0.1500	(90.8443, 91.2157)
CR/WEO 10%	3	92.2400	0.1500	(92.0543, 92.4257)
CR/WEO 15%	3	90.9300	0.1500	(90.7443, 91.1157)
CR/WEO 20%	3	89.1000	0.1500	(88.9143, 89.2857)
CR/WEO 25%	3	86.1100	0.1500	(85.9243, 86.2957)
CR/WEO 30%	3	85.2800	0.1500	(85.0943, 85.4657)

All possible pairwise differences in means are accounted for using Tukey's method at the same time. Observations are unaffected by each other inside and within the groups. A considerable difference in means occurs when an interval does not include a value of 0. From Table 4.20, it is evident that each interval does not share letter, therefore, they are statistically different from each other.

Table 4.20: Grouping Information Using the Tukey's Method and 95% Confidence

Factor	N	Mean	Grouping				
CR/WEO 10%	3	92.2400	A				
CR/WEO 5%	3	91.0300		B			
CR/WEO 15%	3	90.9300		B			
CR/WEO 20%	3	89.1000			C		
CR/WEO 25%	3	86.1100				D	
CONTROL	3	85.8100				D	
CR/WEO 30%	3	85.2800					E

ANOVA and Tukey's tests demonstrate that when CR-WEO is used as an additive, the Tensile strength ratio results are dramatically affected. In comparison to the control samples, the CR-WEO modified samples exhibit much greater moisture resistance. It applies concurrently to all pairwise comparisons and finds any difference between two means that is higher than the predicted standard error, which is what Tukey's test does. Table 4.21 shows the results of Tukey’s analysis that was conducted for TSR values. From Table 4.21, it can be observed that P values of only two pairs were greater than 0.05, which means that they were not statistically different. However, means of other pairs were significantly different as depicted by the P values of less than 0.05.

Table 4.21: Tukey’s Simultaneous Tests for Differences in Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CR/WEO 5% - CONTROL	5.220	0.122	(4.802, 5.638)	0.000
CR/WEO 10% - CONTROL	6.430	0.122	(6.012, 6.848)	0.000
CR/WEO 15% - CONTROL	5.120	0.122	(4.702, 5.538)	0.000
CR/WEO 20% - CONTROL	3.290	0.122	(2.872, 3.708)	0.000
CR/WEO 25% - CONTROL	0.300	0.122	(-0.118, 0.718)	0.249
CR/WEO 30% - CONTROL	-0.530	0.122	(-0.948, -0.112)	0.010
CR/WEO 10% - CR/WEO 5%	1.210	0.122	(0.792, 1.628)	0.000
CR/WEO 15% - CR/WEO 5%	-0.100	0.122	(-0.518, 0.318)	0.979
CR/WEO 20% - CR/WEO 5%	-1.930	0.122	(-2.348, -1.512)	0.000
CR/WEO 25% - CR/WEO 5%	-4.920	0.122	(-5.338, -4.502)	0.000
CR/WEO 30% - CR/WEO 5%	-5.750	0.122	(-6.168, -5.332)	0.000
CR/WEO 15% - CR/WEO 10%	-1.310	0.122	(-1.728, -0.892)	0.000
CR/WEO 20% - CR/WEO 10%	-3.140	0.122	(-3.558, -2.722)	0.000
CR/WEO 25% - CR/WEO 10%	-6.130	0.122	(-6.548, -5.712)	0.000
CR/WEO 30% - CR/WEO 10%	-6.960	0.122	(-7.378, -6.542)	0.000
CR/WEO 20% - CR/WEO 15%	-1.830	0.122	(-2.248, -1.412)	0.000
CR/WEO 25% - CR/WEO 15%	-4.820	0.122	(-5.238, -4.402)	0.000
CR/WEO 30% - CR/WEO 15%	-5.650	0.122	(-6.068, -5.232)	0.000
CR/WEO 25% - CR/WEO 20%	-2.990	0.122	(-3.408, -2.572)	0.000
CR/WEO 30% - CR/WEO 20%	-3.820	0.122	(-4.238, -3.402)	0.000
CR/WEO 30% - CR/WEO 25%	-0.830	0.122	(-1.248, -0.412)	0.000

When conducting an experiment, significance is a random variable that is specified in the experiment's sample space and may range from 0 to 1. According to the Tukey's test, the identical sample counts across groups (balanced data) as ANOVA is used to calculate Tukey's statistic. The multiple of the estimated standard deviation is the sole factor that causes a difference between the confidence limits derived from simultaneous comparisons and those derived from a single comparison.

As can be seen in Figure 4.16, only one of the intervals has a value of zero, whilst the other intervals do not have a value of zero. This demonstrates that the intervals are statistically distinct from one another. Therefore, it can be concluded that the values of the tensile strength are greatly impacted by incorporation of CR-WEO in asphalt mixtures.

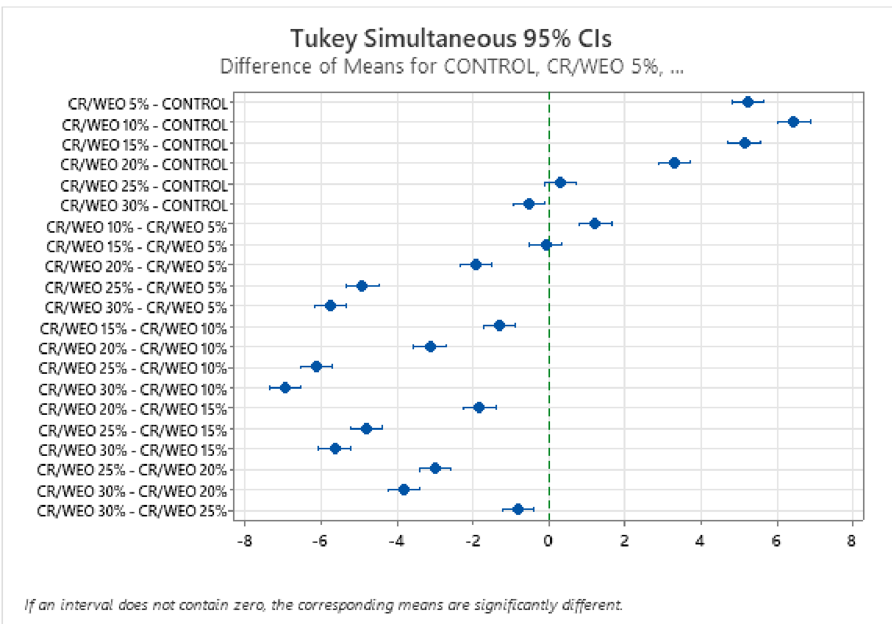


Figure 4.16: Tukey's pairwise analysis of TSR values with a 95% confidence interval

To evaluate the effect that CR-WEO has as a modifier, the TSR values were also evaluated utilizing Hsu's methodology. The difference in mean between each level and all the other levels was used to construct confidence intervals for those differences. If the endpoint of an interval is set to zero, then there is a statistically significant difference between the means of the interval's values. From Table 4.22, it can be observed that P value of all the intervals is less than 0.05, which means that they are significantly different from each. This also means that the modifier has great impact on the TSR values.

Table 4.22: Hsu's Simultaneous Tests for Level Mean

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CONTROL - CR/WEO 10%	-6.430	0.122	(-6.740, 0.000)	0.000
CR/WEO 5% - CR/WEO 10%	-1.210	0.122	(-1.520, 0.000)	0.000
CR/WEO 10% - CR/WEO 5%	1.210	0.122	(0.000, 1.520)	0.000
CR/WEO 15% - CR/WEO 10%	-1.310	0.122	(-1.620, 0.000)	0.000
CR/WEO 20% - CR/WEO 10%	-3.140	0.122	(-3.450, 0.000)	0.000
CR/WEO 25% - CR/WEO 10%	-6.130	0.122	(-6.440, 0.000)	0.000
CR/WEO 30% - CR/WEO 10%	-6.960	0.122	(-7.270, 0.000)	0.000

As it is shown in Figure 4.17, the influence of CR-WEO on the values of TSR is significant. The fact that all the intervals in Figure 4.17 finish with a zero value, which suggests that these intervals are statistically different from one another.

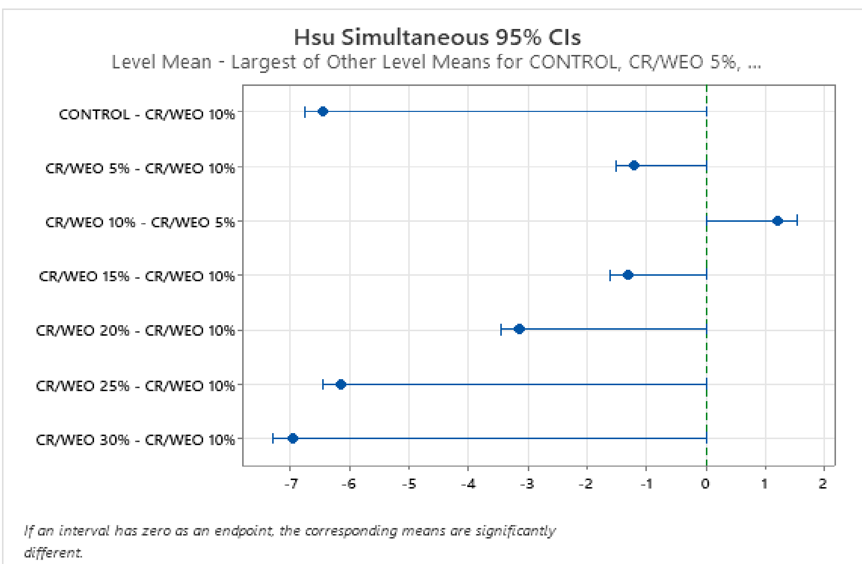


Figure 4.17: Hsu's MCB analysis of TSR values

An interval plot illustrates a confidence interval with a degree of certainty that is equal to or greater than 95% for each group's mean. When there are at least three observations available for each group, interval plots function most effectively. In general, the confidence interval was narrower and more exact when greater sample size was used to establish it. Figure 4.18 shows the interval plot of the values for the TSR.

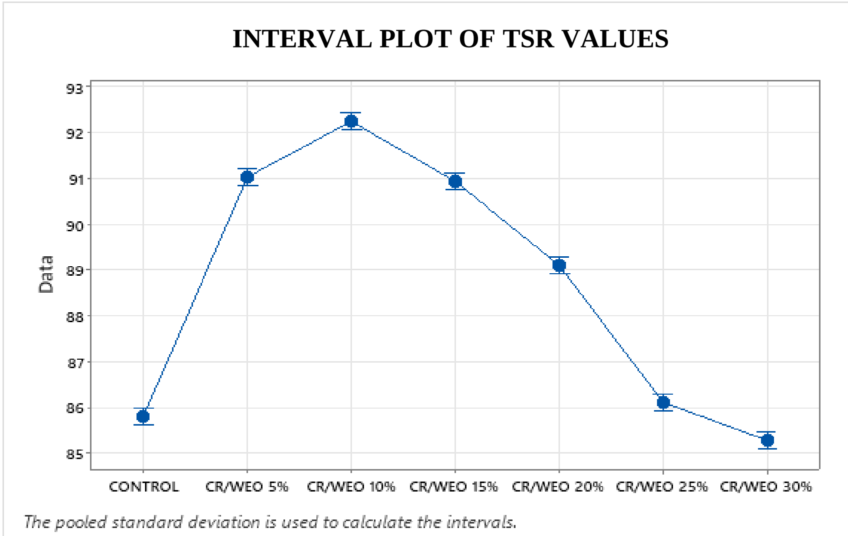


Figure 4.18: Interval plot for TSR mean values

4.6.4 Tukey's and Hsu's MCB Analysis for Indirect Tensile Strength

To examine the effects of various percentages of CR-WEO on indirect tensile strength, one-way analysis of variance was conducted. Analysis of variance (ANOVA) was used to evaluate whether the IDT values of CR-WEO modified asphalt samples differed from that of their corresponding reference asphalt samples. Table 4.23 shows the results of the ANOVA analysis. From Table 4.23, it can be observed that P value of IDT is smaller than 0.05, therefore, the modifier has significant influence on TSR values. The null hypothesis should be rejected, while the alternative hypothesis should be accepted because of the smaller P value.

Table 4.23: Results of ANOVA analysis (CR-WEO% vs IDT values)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	6	4.00431	0.667386	306.68	0.000
Error	14	0.03047	0.002176		
Total	20	4.03478			

Table 4.24 displays the mean and standard deviation of IDT values for several asphalt samples. The data is displayed with the confidence level of 95%, and N denotes the number

of samples that were used to conduct this analysis for each percentage of CR-WEO modified asphalt mixtures.

Table 4.24: Means of IDT of different CR-WEO modified samples

Factor	N	Mean	St Dev	95% CI
CONTROL	3	5.6400	0.0500	(5.5822, 5.6978)
CR/WEO 5%	3	6.4667	0.0451	(6.4089, 6.5244)
CR/WEO 10%	3	6.9600	0.0500	(6.9022, 7.0178)
CR/WEO 15%	3	6.8400	0.0400	(6.7822, 6.8978)
CR/WEO 20%	3	6.6100	0.0400	(6.5522, 6.6678)
CR/WEO 25%	3	6.2400	0.0500	(6.1822, 6.2978)
CR/WEO 30%	3	5.9800	0.0500	(5.9222, 6.0378)

Table 4.25 shows the grouping information using the Tukey's analysis with 95 percent confidence level. From Table 4.25, it can be observed every interval has only one letter, which means they are significantly different from each other.

Table 4.25: Grouping Information Using the Tukey's Method and 95% Confidence

Factor	N	Mean	Grouping					
CR/WEO 10%	3	6.9600	A					
CR/WEO 15%	3	6.8400	A					
CR/WEO 20%	3	6.6100		B				
CR/WEO 5%	3	6.4667			C			
CR/WEO 25%	3	6.2400				D		
CR/WEO 30%	3	5.9800					E	
CONTROL	3	5.6400						F

When CR-WEO is employed as an additive, ANOVA and Tukey's tests show a considerable change in the IDT findings The IDT values of the CR-WEO modified samples are much higher than those of the control samples and it can also be confirmed from Table 4.26.

Table 4.26: Tukey's Simultaneous Tests for Differences in Means

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CR/WEO 5% - CONTROL	0.8267	0.0381	(0.6966, 0.9568)	0.000
CR/WEO 10% - CONTROL	1.3200	0.0381	(1.1899, 1.4501)	0.000
CR/WEO 15% - CONTROL	1.2000	0.0381	(1.0699, 1.3301)	0.000
CR/WEO 20% - CONTROL	0.9700	0.0381	(0.8399, 1.1001)	0.000
CR/WEO 25% - CONTROL	0.6000	0.0381	(0.4699, 0.7301)	0.000
CR/WEO 30% - CONTROL	0.3400	0.0381	(0.2099, 0.4701)	0.000
CR/WEO 10% - CR/WEO 5%	0.4933	0.0381	(0.3632, 0.6234)	0.000
CR/WEO 15% - CR/WEO 5%	0.3733	0.0381	(0.2432, 0.5034)	0.000
CR/WEO 20% - CR/WEO 5%	0.1433	0.0381	(0.0132, 0.2734)	0.027
CR/WEO 25% - CR/WEO 5%	-0.2267	0.0381	(-0.3568, -0.0966)	0.001
CR/WEO 30% - CR/WEO 5%	-0.4867	0.0381	(-0.6168, -0.3566)	0.000
CR/WEO 15% - CR/WEO 10%	-0.1200	0.0381	(-0.2501, 0.0101)	0.080
CR/WEO 20% - CR/WEO 10%	-0.3500	0.0381	(-0.4801, -0.2199)	0.000
CR/WEO 25% - CR/WEO 10%	-0.7200	0.0381	(-0.8501, -0.5899)	0.000
CR/WEO 30% - CR/WEO 10%	-0.9800	0.0381	(-1.1101, -0.8499)	0.000
CR/WEO 20% - CR/WEO 15%	-0.2300	0.0381	(-0.3601, -0.0999)	0.000
CR/WEO 25% - CR/WEO 15%	-0.6000	0.0381	(-0.7301, -0.4699)	0.000
CR/WEO 30% - CR/WEO 15%	-0.8600	0.0381	(-0.9901, -0.7299)	0.000
CR/WEO 25% - CR/WEO 20%	-0.3700	0.0381	(-0.5001, -0.2399)	0.000
CR/WEO 30% - CR/WEO 20%	-0.6300	0.0381	(-0.7601, -0.4999)	0.000
CR/WEO 30% - CR/WEO 25%	-0.2600	0.0381	(-0.3901, -0.1299)	0.000

From Figure 4.19, it can be seen that only one interval has a value of zero. This shows that the intervals are statistically different from each other. As a result, it can be inferred that CR-WEO has a significant influence on IDT values.

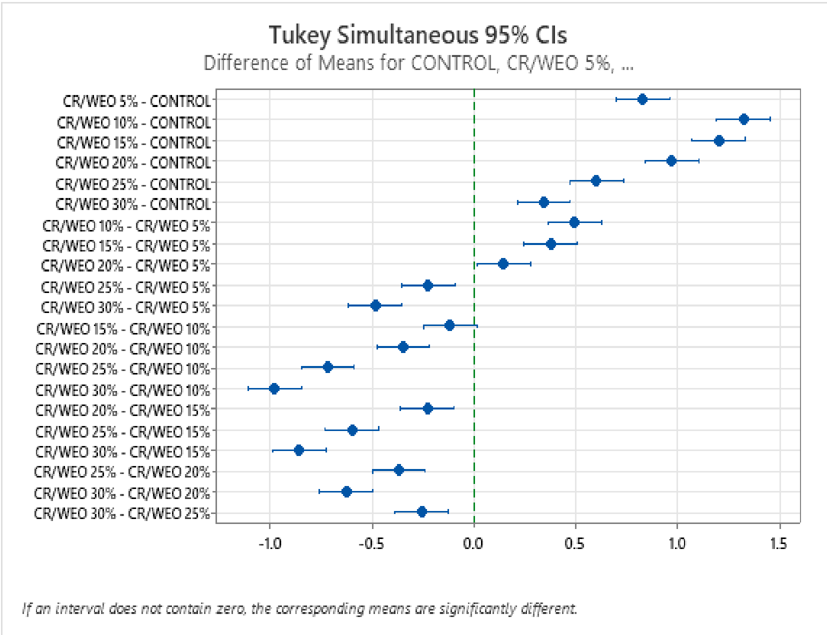


Figure 4.19: Tukey's pairwise analysis of IDT values with 95% confidence interval

The IDT data were analyzed using Hsu's technique to determine the influence of CR-WEO as a modifier. The results showed that CR-WEO has a significant effect on resilient modulus. Table 4.27 shows the results of Hsu's analysis that was conducted for IDT values.

Table 4.27: Hsu's Simultaneous Tests for Level Mean

Difference of Levels	Difference of Means	SE of Difference	95% CI	Adjusted P-Value
CONTROL - CR/WEO 10%	-1.3200	0.0381	(-1.4165, 0.0000)	0.000
CR/WEO 5% - CR/WEO 10%	-0.4933	0.0381	(-0.5898, 0.0000)	0.000
CR/WEO 10% - CR/WEO 15%	0.1200	0.0381	(0.0000, 0.2165)	0.016
CR/WEO 15% - CR/WEO 10%	-0.1200	0.0381	(-0.2165, 0.0000)	0.016
CR/WEO 20% - CR/WEO 10%	-0.3500	0.0381	(-0.4465, 0.0000)	0.000
CR/WEO 25% - CR/WEO 10%	-0.7200	0.0381	(-0.8165, 0.0000)	0.000
CR/WEO 30% - CR/WEO 10%	-0.9800	0.0381	(-1.0765, 0.0000)	0.000

The confidence intervals for these differences were constructed using the mean difference between each level and all the other levels. There is a statistically significant difference in the mean values of an interval if the endpoint is zero and it can be confirmed from Figure 4.20.

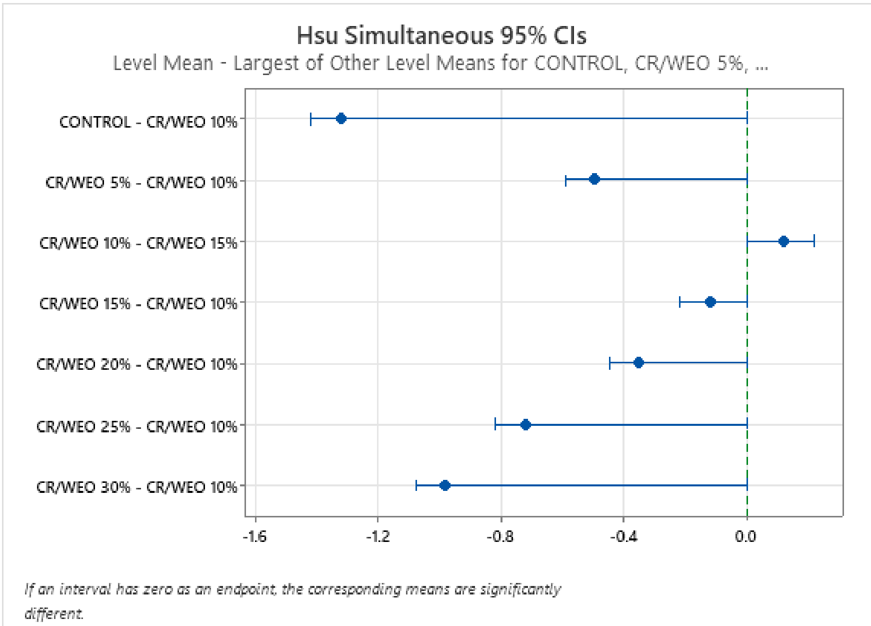


Figure 4.20: Hsu's MCB analysis of IDT values at 95% CI

Figure 4.20 illustrates the strong impact of CR-WEO on IDT values. Interval plot of IDT data is shown in Figure 4.21. A numerical scale may be used to compare the values of several intervals. An interval scale does not contain a true zero in its range of values, unlike a ratio scale, which does. As a point on the interval scale, zero is only a placeholder for a variable. This approach is utilized when the data is in a continuous format.

The value of IDT is represented in intervals rather than as individual data points in an interval plot. All valid interval graphs are included in the interval graphs; these are graphs that are defined in the same manner based on a collection of unit intervals. A confidence interval with a 95 percent level is shown using an interval plot for the mean of each group. When the sample size for each group is at least three, an interval plot functions most effectively. In general, the narrower and more accurate the confidence interval, the greater the sample size that was used to calculate it.

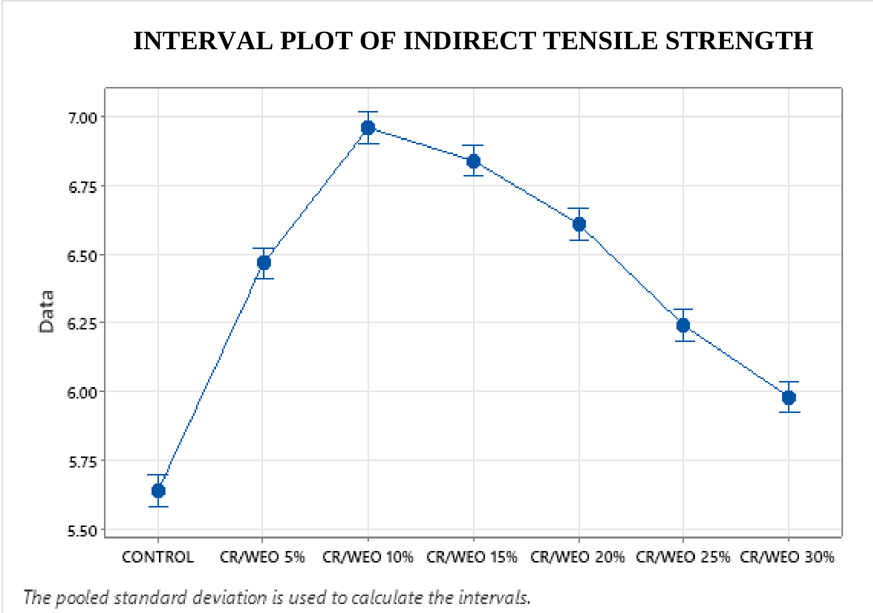


Figure 4.21: Interval plot for IDT mean values

4.7 Summary:

The findings of tests and analyses conducted on the performance assessment of CR-WEO modified and unmodified HMA samples were used as the foundation for this chapter. Microsoft Excel was used in the process of statistical analysis. IDT test and the resilient modulus tests are included in the first phase. Experiments were carried out to investigate the impact of elevating the CR-WEO content to a higher percentage. It was discovered that the IDT and MR value both increased with an increase in the CR-WEO percent (up to 10%) at a temperature of 25 degrees Celsius. In the second phase, samples of HMA were tested using a Hamburg Wheel Tracker machine to determine their tendency to develop ruts. Although all the samples were able to satisfy the established rutting threshold, the samples with 10 percent CRWEO exhibited the least amount of rutting. In the third phase, correlations were developed between different test results. From the correlations, it was observed that Rut depth and M_R have the highest R^2 value, which shows that they have a strong relationship. Finally, the correlation was developed between No. of cycles and the rut depth.

The rut resistance of an asphalt mix containing 10 percent CR-WEO is increased by up to 2.17 times when compared to the rut resistance of an unmodified asphalt mix. The resilient modulus of the samples that incorporated 10 percent CR-WEO was 1.80 times higher than the resilient modulus of the unmodified asphalt mix. When 10 percent CR-WEO is added to the asphalt mix, the TSR (Tensile Strength Ratio) increased by as much as 1.07 times the TSR value of the unmodified asphalt mix. It is possible to draw the following conclusion based on the findings: the asphalt mix that contains 10% CR-WEO performs the best.

Also, the effect of various modifier percentages on various performance indicators was examined using one-way ANOVA. There are several ways in which this section demonstrated how the CR-WEO modified asphalt binder performs in terms of rutting, moisture susceptibility, and stiffness. ANOVA with a single factor was used to assess the influence of CR-WEO as a modifier. To see whether CR-WEO modified HMA samples were significantly different from the control sample, an ANOVA was used. Using Tukey’s and Hsu's MCB analysis, the influence of the CR-WEO modifier on several performance metrics was studied.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

CR-WEO as a modifier in base bitumen was incorporated in this investigation to evaluate what effect it would have on the physical and performance of the modified asphalt mix. A road's service life increases because of improving its performance-related parameters. Detailed laboratory analysis was carried out with the purpose of determining which characteristics of bitumen change, and how these shifts, in turn, influence the road structure.

The first step involves the selection of materials from the Babozai quarry, the availability of bitumen grade ARL 60/70 crumb rubber and waste engine oil, and the testing of those materials by the requirements that have been established. The CR-WEO in both grades of binder were then subjected to a manual high-shear mixing method, after which the mixing process was completed. During the first round of testing, modified mixtures were subjected to consistency tests to evaluate the rheological characteristics (penetration, Softening point, ductility & flash point). The second step consisted of conducting Marshal Testing on an OBC based on the NHA Class B Specifications. It was determined how modified HMA samples behaved in terms of their strength and volume. The testing was carried out on standard specimens measuring four inches in diameter and two and a half inches in width. At a temperature of 25 degrees Celsius, an IDT test with a UTM machine was carried out to assess the cracking potential of HMA mixes and, also, the resilient modulus. On Superpave gyratory compacted samples, the Hamburg wheel Tracking Test was performed at 40^0 C to evaluate the potential for rutting. HMA samples of 6 inches in diameter and 2.5 inches thick were put through the Hamburg Wheel Tracking equipment.

According to the results of the HMA performance tests, for ARL 60/70 modified HMA samples, 10 percent CR-WEO modified samples demonstrated maximum IDT, $M_{R,}$ and rut resistance. An examination of the test data obtained with the Hamburg Wheel Tracker revealed the least amount of rutting to occur at 10 percent CR-WEO samples for 60/70 grade binder.

5.2 Conclusions

The purpose of the experimental work that was carried out was to investigate the impact of varying percentages of CR-WEO on the asphalt mixture. The characteristics of rutting, resilient modulus, and moisture susceptibility were meticulously focused on and developed upon. Following are some things that have been determined to be true after extensive investigation and analysis:

- It was found that the HMA mix that contains 10 percent CR-WEO has the best rutting resistance, resilient modulus, and moisture susceptibility values.
- Both the aggregates and the bitumen have passed the respective basic testing standard.
- When compared to an unmodified asphalt mix, the rut resistance was increased by as much as 2.17 times due to the addition of 10 percent CR-WEO.
- The asphalt mix was improved significantly by the addition of 10 percent CR-WEO, which resulted in a significant increase in the TSR value.
- The findings of the research provide evidence that the usage of CR-WEO results in improvements to the characteristics of modified asphalt concrete that serve as performance indicators. These improvements include an increase in rutting resistance, resilient modulus, and moisture damage resistance.
- According to the findings of the research that was carried out, it is possible to effectively use both crumb rubber and waste engine oil in Asphalt pavements.
- Also, the effect of various modifier percentages on various performance indicators was examined using one-way ANOVA.
- Using Tukey and HSU's MCB analysis, the influence of the CR-WEO modifier on several performance metrics was studied. It was found that the modifier has a significant influence on performance parameters.

5.3 Recommendations

Based on the study that was conducted and the findings that were acquired, the following suggestions have been created for our regional industry:

- Because most of the scrap tires in our nation are either incinerated or sent overseas, we need to encourage the development of crumb rubber in our industry so that we can make better use of old tires in the road building business.

- To save money on the initial building costs and prevent expensive rehabilitation operations in the future, our local industry is very committed to employing outdated construction methods and traditional bitumen in HMA. This must be modified right now.
- The adoption of CR-WEO modified binders in our local industry will improve road performance and will result in reduced expenses associated with road repair.
- According to the findings of the HMA performance tests, the samples containing 10 percent CR-WEO modification exhibited the optimum values of IDT, MR, and rut resistance among those containing ARL 60/70 modification.
- An analysis of the test data collected with the Hamburg Wheel Tracker found that 10 percent CR-WEO samples for 60/70 grade binder showed the least amount of rutting when compared to the other samples.
- Therefore, it is recommended that the asphalt binder should be modified with 10 percent CR-WEO to get the optimum properties of asphalt mixtures.

References

Airey, G., Rahman, M., & Collop, A. C. (2004). Crumb Rubber and Bitumen Interaction as a Function of Crude Source and Bitumen Viscosity. *Road Materials and Pavement Design*, *5*(4), 453–475. https://doi.org/10.1080/14680629.2004.9689981

Al-Saffar, Z. H., Yaacob, H., Satar, M. K. I. M., Kamarudin, S. N. N., Mahmud, M. Z. H., Ismail, C. R., Hassan, S. A., & Mashros, N. (2021). A review on the usage of waste engine oil with aged asphalt as a rejuvenating agent. *Materials Today: Proceedings*, *42*, 2374–2380. https://doi.org/10.1016/j.matpr.2020.12.330

American Society for Testing and Materials. (2015). ASTM C-128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. *ASTM International*, *i*, 1–6. https://doi.org/10.1520/C0128-15.2

ASTM C127. (2004). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. *Annual Book of ASTM Standards*, 1–5. https://doi.org/10.1520/C0127-15.2

ASTM D 113-07. (2002). Standard Test Method for Ductility of bituminous materials. *Annual Book of American Society for Testing Materiasl ASTM Standards*, *03*, 6–8. https://doi.org/10.1520/D0113-17.aware

Devulapalli, L., Kothandaraman, S., & Sarang, G. (2020). Effect of rejuvenating agents on stone matrix asphalt mixtures incorporating RAP. *Construction and Building Materials*, *254*, 119298. https://doi.org/10.1016/j.conbuildmat.2020.119298

Drews, A. (2008). Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus). *Manual on Hydrocarbon Analysis, 6th Edition*, *14*(Reapproved), 50-50–54. https://doi.org/10.1520/mnl10830m

Gheni, A., ElGawady, M., & Myers, J. (2017). Cyclic Behavior of Concrete Masonry Units Manufactured With Recycled Tires as an Aggregate.

Hadi, F. A., & Kadhim, R. G. (2020). A Study of the Influence of Zinc Oxide on Acid Resistance of Natural Rubber Composites. *IOP Conference Series: Materials Science and Engineering*, *871*(1). https://doi.org/10.1088/1757-899X/871/1/012076

Irfan, M., Ali, Y., Ahmed, S., & Hafeez, I. (2018). Performance Evaluation of Crumb Rubber-Modified Asphalt Mixtures Based on Laboratory and Field Investigations. *Arabian Journal for Science and Engineering*, *43*(4), 1795–1806. https://doi.org/10.1007/s13369-017-2729-2

Jiao, B., Pan, B., & Che, T. (2022). Evaluating impacts of desulfurization and depolymerization on thermodynamics properties of crumb rubber modified asphalt through molecular dynamics simulation. *Construction and Building Materials*, *323*(December 2021), 126360. https://doi.org/10.1016/j.conbuildmat.2022.126360

Khan, A., Khan, M. S., Hadi, F., Saddiq, G., & Khan, A. N. (2021). Energy-Dispersive X-ray (EDX) fluorescence based analysis of heavy metals in marble powder, paddy soil and rice (Oryza sativa L.) with potential health risks in District Malakand, Khyber Pakhtunkhwa, Pakistan. *Environmental Pollutants and Bioavailability*, *33*(1), 301–316. https://doi.org/10.1080/26395940.2021.1986427

Khan, J., Hussain, A., Haq, F., Ahmad, K., & Mushtaq, K. (2019). Performance Evaluation of Modified Bitumen with Replaced Percentage of Waste Cooking Oil & Tire Rubber with Bagasse Ash as Modifier. *Civil Engineering Journal*, *5*(3), 587. https://doi.org/10.28991/cej-2019-03091270

Lei, Y., Wang, H., Fini, E. H., You, Z., Yang, X., Gao, J., Dong, S., & Jiang, G. (2018). Evaluation of the effect of bio-oil on the high-temperature performance of rubber modified asphalt. *Construction and Building Materials*, *191*, 692–701. https://doi.org/10.1016/j.conbuildmat.2018.10.064

Lei, Z., Bahia, H., & Yi-Qiu, T. (2015). Effect of bio-based and refined waste oil modifiers on low temperature performance of asphalt binders. *Construction and Building Materials*, *86*, 95–100. https://doi.org/10.1016/j.conbuildmat.2015.03.106

Lei, Z., Bahia, H., Yi-qiu, T., & Ling, C. (2017). Effects of refined waste and bio-based oil modifiers on rheological properties of asphalt binders. *Construction and Building Materials*, *148*, 504–511. https://doi.org/10.1016/j.conbuildmat.2017.05.101

Liu, Q., Liu, J., Yu, B., Zhang, J., & Pei, J. (2022). Evaluation and optimization of asphalt binder and mixture modified with high activated crumb rubber content. *Construction* *and Building Materials*, *314*(PA), 125676. https://doi.org/10.1016/j.conbuildmat.2021.125676

Liu, Z., Li, S., & Wang, Y. (2022). Characteristics of asphalt modified by waste engine oil / polyphosphoric acid: Conventional, high-temperature rheological, and mechanism properties. *Journal of Cleaner Production*, *330*(June 2021), 129844. https://doi.org/10.1016/j.jclepro.2021.129844

Luo, W., Zhang, Y., & Cong, P. (2017). Investigation on physical and high temperature rheology properties of asphalt binder adding waste oil and polymers. *Construction and Building Materials*, *144*, 13–24. https://doi.org/10.1016/j.conbuildmat.2017.03.105

Mashaan, N. S., Ali, A. H., Karim, M. R., & Abdelaziz, M. (2012). An overview of crumb rubber modified asphalt. *International Journal of Physical Sciences*, *7*(2), 166–170. https://doi.org/10.5897/IJPSX11.007

Paliukaite, M., Assuras, M., & Hesp, S. A. M. (2016). Effect of recycled engine oil bottoms on the ductile failure properties of straight and polymer-modified asphalt cements. *Construction and Building Materials*, *126*, 190–196. https://doi.org/10.1016/j.conbuildmat.2016.08.156

Picado-Santos, L. G., Capitão, S. D., & Neves, J. M. C. (2020). Crumb rubber asphalt mixtures: A literature review. *Construction and Building Materials*, *247*, 118577. https://doi.org/10.1016/j.conbuildmat.2020.118577

Portugal, A. C. X., Lucena, L. C. de F. L., Lucena, A. E. de F. L., Costa, D. B., & Lima, K. A. de. (2017). Rheological properties of asphalt binders prepared with maize oil. *Construction and Building Materials*, *152*, 1015–1026. https://doi.org/10.1016/j.conbuildmat.2017.07.077

Rahman, M. T., Hainin, M. R., & Bakar, W. A. W. A. (2017). Use of waste cooking oil, tire rubber powder and palm oil fuel ash in partial replacement of bitumen. *Construction and Building Materials*, *150*, 95–104. https://doi.org/10.1016/j.conbuildmat.2017.05.216

Ren, S., Liu, X., Lin, P., Wang, H., Fan, W., & Erkens, S. (2021). The continuous swelling-degradation behaviors and chemo-rheological properties of waste crumb rubber modified bitumen considering the effect of rubber size. *Construction and Building Materials*, *307*(September), 124966. https://doi.org/10.1016/j.conbuildmat.2021.124966

Riekstins, A., Haritonovs, V., & Straupe, V. (2022). Economic and environmental analysis of crumb rubber modified asphalt. *Construction and Building Materials*, *335*(April), 127468. https://doi.org/10.1016/j.conbuildmat.2022.127468

Su, N., Xiao, F., Wang, J., Cong, L., & Amirkhanian, S. (2018). Productions and applications of bio-asphalts – A review. *Construction and Building Materials*, *183*, 578–591. https://doi.org/10.1016/j.conbuildmat.2018.06.118

Tang, N., Zhang, Z., Dong, R., Zhu, H., & Huang, W. (2022). Emission behavior of crumb rubber modified asphalt in the production process. *Journal of Cleaner Production*, *340*(December 2021), 130850. https://doi.org/10.1016/j.jclepro.2022.130850

Wang, H., Liu, X., van de Ven, M., Lu, G., Erkens, S., & Skarpas, A. (2020). Fatigue performance of long-term aged crumb rubber modified bitumen containing warm-mix additives. *Construction and Building Materials*, *239*, 117824. https://doi.org/10.1016/j.conbuildmat.2019.117824

Wang, S., Huang, W., Liu, X., & Lin, P. (2022). Influence of high content crumb rubber and different preparation methods on properties of asphalt under different aging conditions : Chemical properties , rheological properties , and fatigue performance. *Construction and Building Materials*, *327*(November 2021), 126937. https://doi.org/10.1016/j.conbuildmat.2022.126937

Xu, P., Gao, J., Pei, J., Chen, Z., Zhang, J., & Li, R. (2021). Research on highly dissolved rubber asphalt prepared using a composite waste engine oil addition and microwave desulfurization method. *Construction and Building Materials*, *282*, 122641. https://doi.org/10.1016/j.conbuildmat.2021.122641

Yan, S., Zhou, C., & Ouyang, J. (2022). Rejuvenation effect of waste cooking oil on the adhesion characteristics of aged asphalt to aggregates. *Construction and Building Materials*, *327*(October 2021), 126907. https://doi.org/10.1016/j.conbuildmat.2022.126907

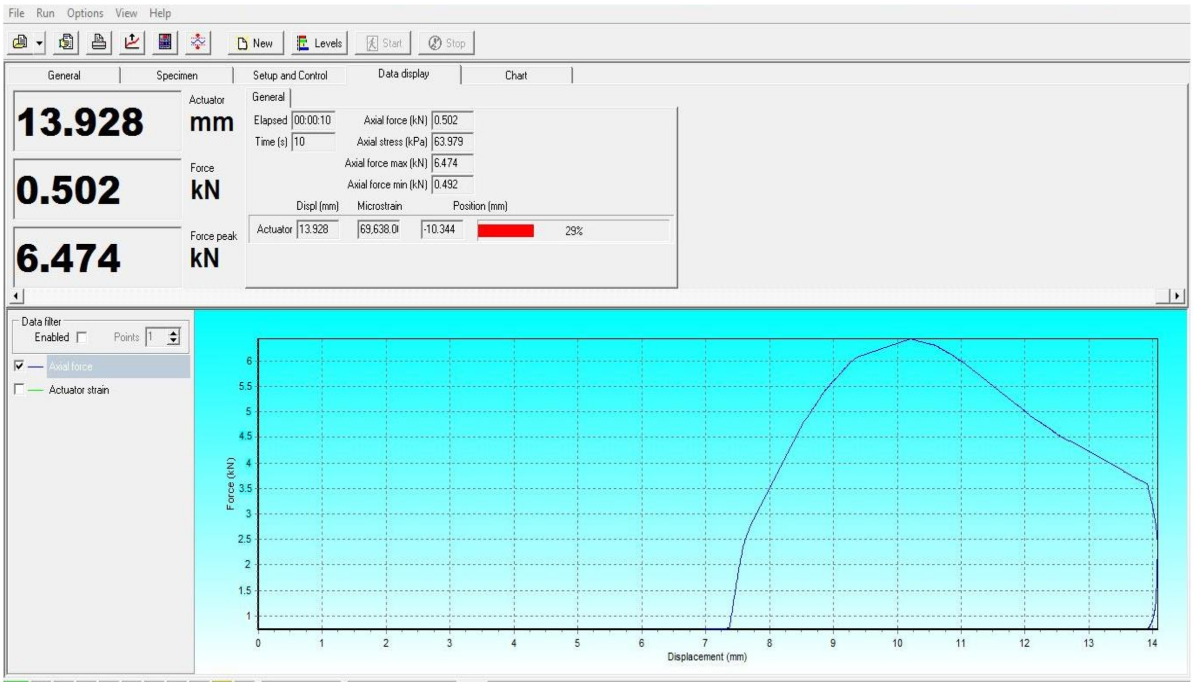
Yu, J., Ren, Z., Gao, Z., Wu, Q., & Zhu, Z. (2019). *Recycled Heavy Bio Oil as Performance Enhancer for Rubberized Bituminous Binders*. 1–15.

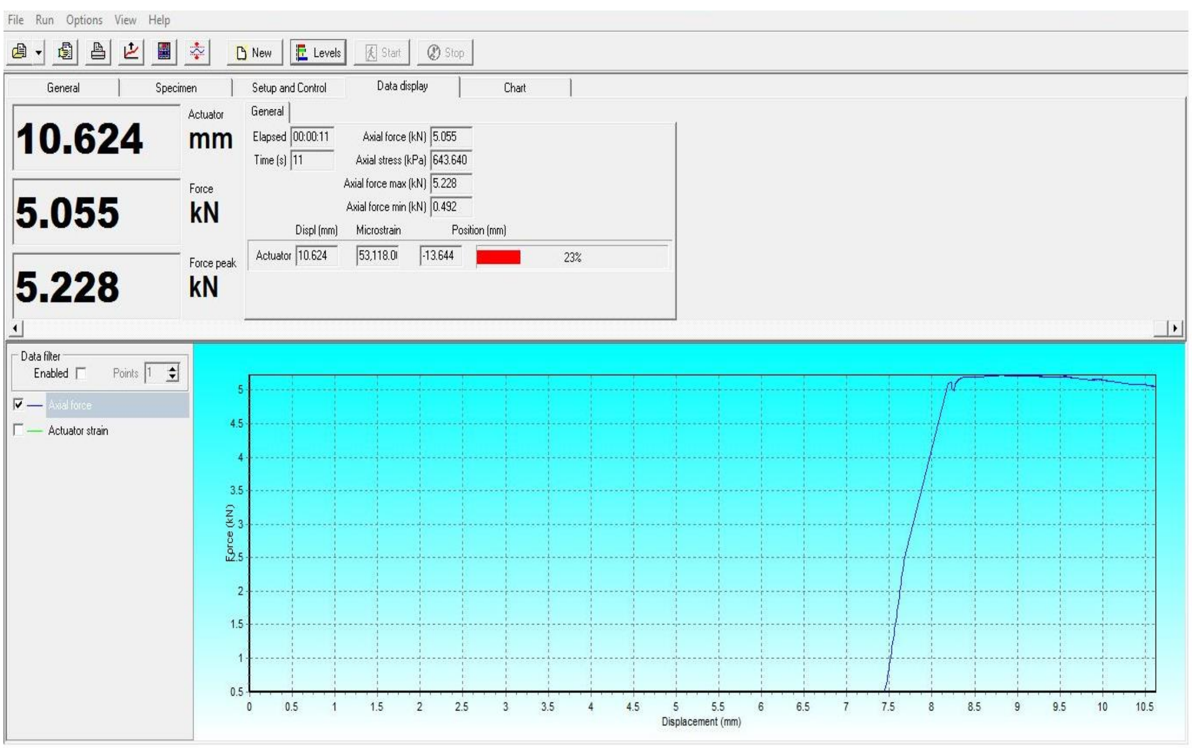
Zhou, T., Kabir, S. F., Cao, L., & Fini, E. H. (2021). Effects of ultraviolet exposure on physicochemical and mechanical properties of bio-modified rubberized bitumen: Sustainability promotion and resource conservation. *Resources, Conservation and Recycling*, *171*(April), 105626. https://doi.org/10.1016/j.resconrec.2021.105626

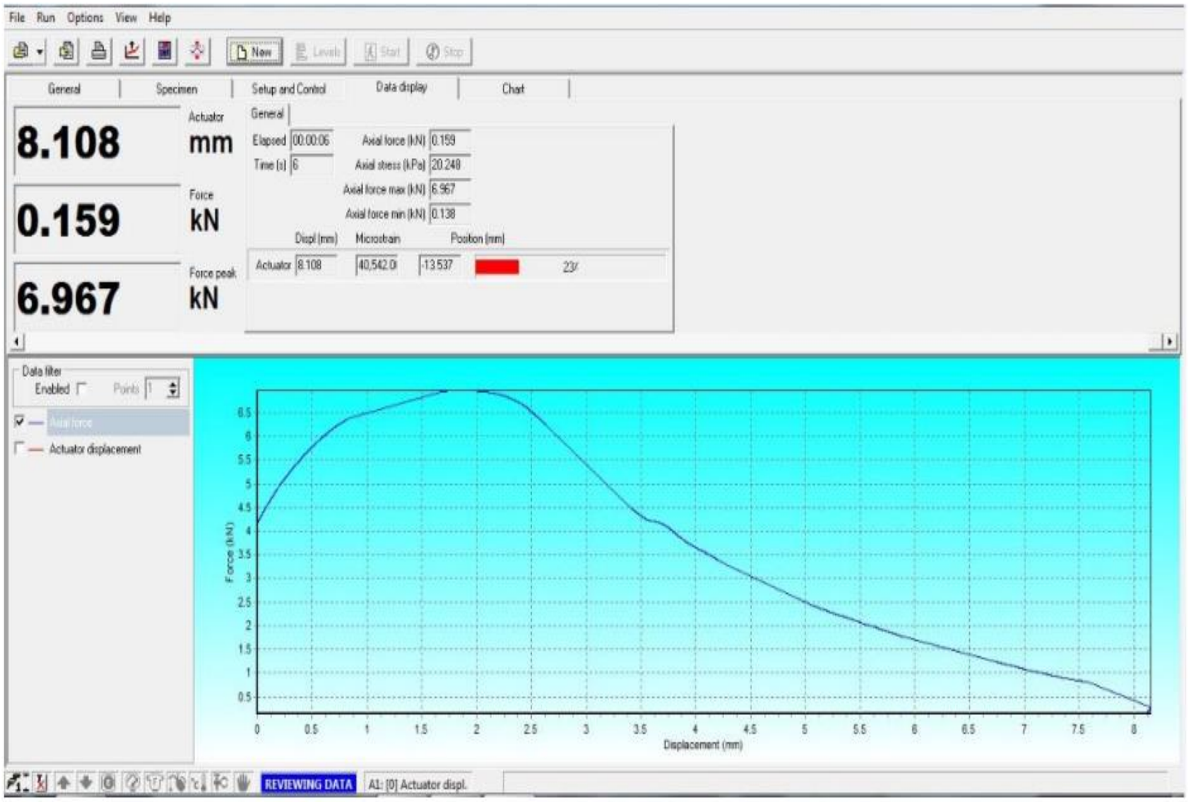
APPENDICES

APPENDIX-I

RESULTS OF TSR/IDT



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8.108
Actuator
mm
0.159
Force
kN
6.967
Force peak
kN
General
Elapsed 00:00:06
Time (s) 6
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Axial stress (kPa) 20.248
Axial force max (kN) 6.967
Axial force min (kN) 0.138
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Displacement (mm)
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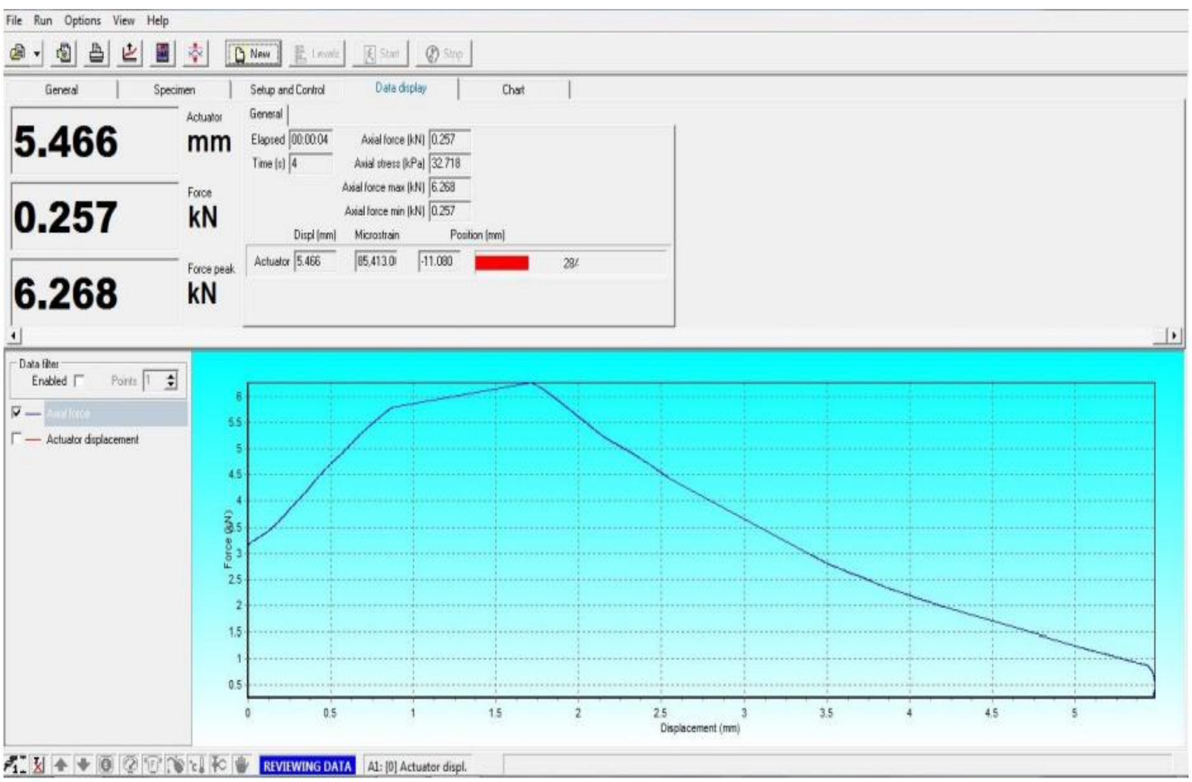
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mm
0.257
Force
kN
6.268
Force peak
kN
General
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Axial stress (kPa) 32.718
Axial force max (kN) 6.268
Axial force min (kN) 0.257
Displ (mm) Microstrain Position (mm)
Actuator 5.466 85,413.0 -11.080
Data filter
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Displacement (mm)
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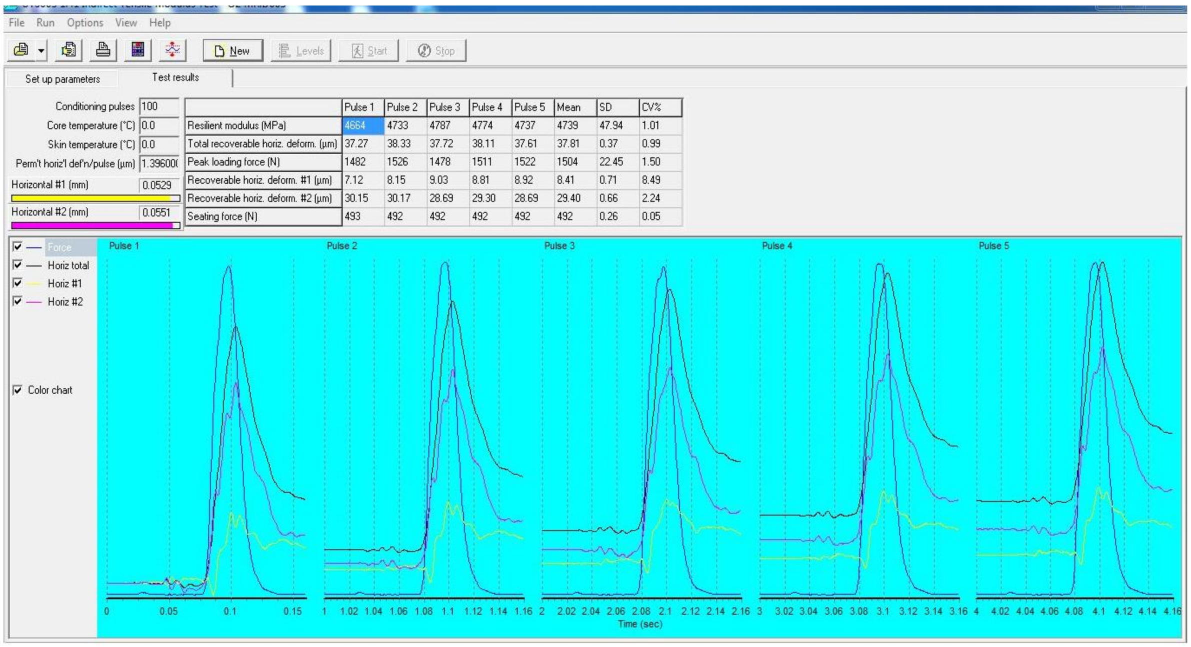
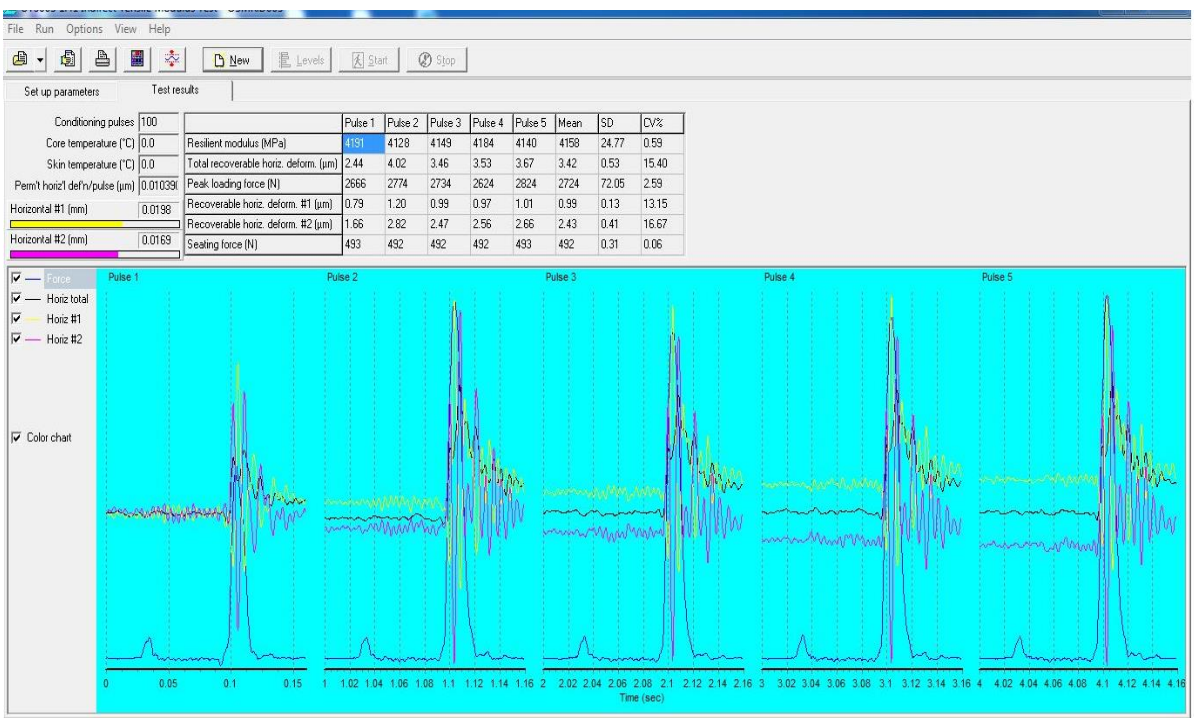
APPENDIX-II

RESULTS OF RESILIENT MODULUS



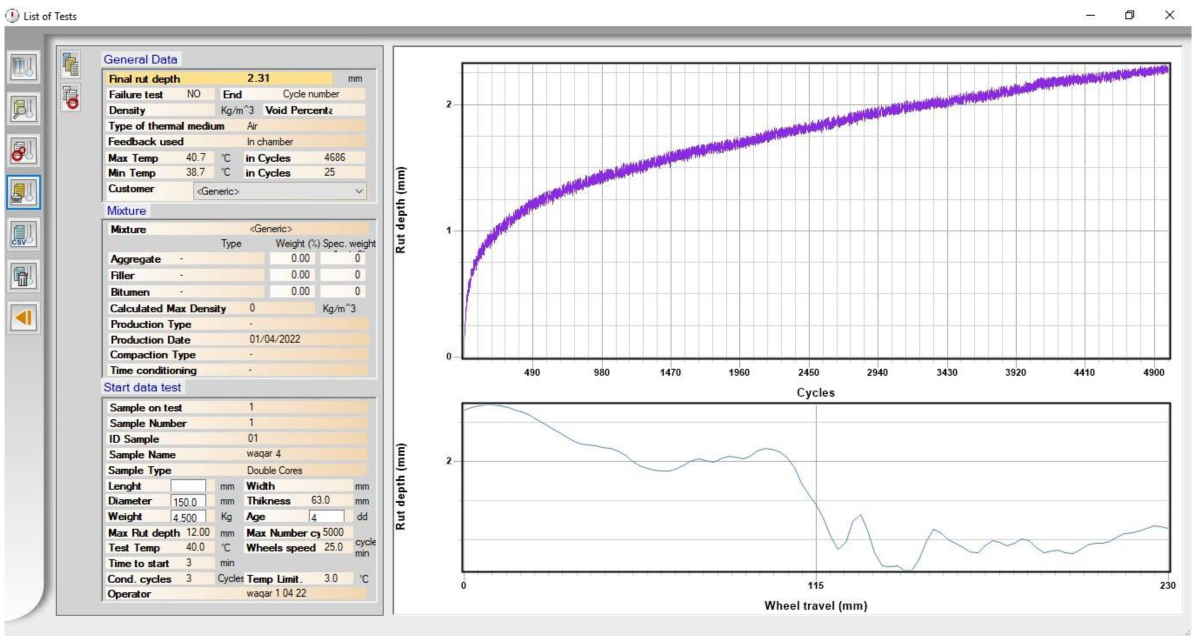
	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	4664	4733	4787	4774	4737	4739	47.94	1.01
Total recoverable horiz. deform. (µm)	37.27	38.33	37.72	38.11	37.61	37.81	0.37	0.99
Peak loading force (N)	1482	1526	1478	1511	1522	1504	22.45	1.50
Recoverable horiz. deform. #1 (µm)	7.12	8.15	9.03	8.81	8.92	8.41	0.71	8.49
Recoverable horiz. deform. #2 (µm)	30.15	30.17	28.69	29.30	28.69	29.40	0.66	2.24
Seating force (N)	493	492	492	492	492	492	0.26	0.05

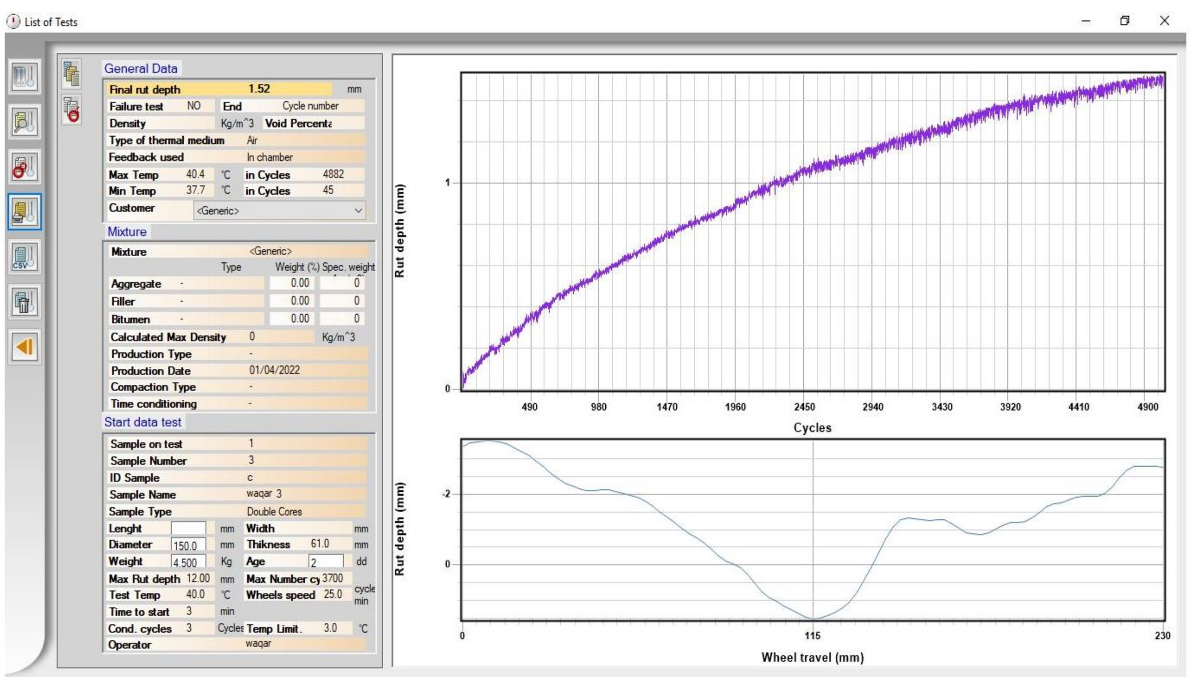


	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	4191	4128	4149	4184	4140	4158	24.77	0.59
Total recoverable horiz. deform. (µm)	2.44	4.02	3.46	3.53	3.67	3.42	0.53	15.40
Peak loading force (N)	2666	2774	2734	2624	2824	2724	72.05	2.59
Recoverable horiz. deform. #1 (µm)	0.79	1.20	0.99	0.97	1.01	0.99	0.13	13.15
Recoverable horiz. deform. #2 (µm)	1.66	2.82	2.47	2.56	2.66	2.43	0.41	16.67
Seating force (N)	493	492	492	492	493	492	0.31	0.06

APPENDIX-III

RESULTS OF HWTT





Rut Depth values at different number of Cycles (25% CR-WEO)

Cycle	Central ruth depth (mm)	Rut depth length 100 mm	Rut depth length 20.00 mm	Vector length	Vector data
1	0	0	0	84	-2.871489893
2	-0.025629077	-0.268142736	0.479405043	85	-2.866836566
3	-0.016309413	-0.249664199	0.512593338	87	-2.852876584
4	-0.067567568	-0.289019019	0.350852719	88	-2.827283285
5	-0.069897484	-0.296520986	0.222896619	89	-2.806343313
6	-0.065237651	-0.237840689	0.488431435	91	-2.817976631
7	0	-0.182563733	0.529414501	92	-2.806343313
8	0.020969245	-0.209981691	0.437285178	92	-2.794709995
9	-0.055917987	-0.145401268	0.52554215	94	-2.77842335
10	0.058247903	-0.178844974	0.454882483	94	-2.792383332
20	0.03028891	-0.123897984	0.54782844	97	-2.780750014
30	0.032618826	-0.105773566	0.548988519	97	-2.790056668
40	0.102516309	-0.081041911	0.614224138	97	-2.77842335
50	0.121155638	-0.061975051	0.610438024	97	-2.764463369
60	0.100186393	-0.06313544	0.606360671	97	-2.750503388
70	0.274930103	-0.070224676	0.560349706	97	-2.750503388
80	0.309878844	0.011485972	0.758096459	97	-2.73887007

90	0.149114632	-0.020281226	0.657327586	97	-2.710950107
100	0.319198509	-0.025207974	0.614806617	97	-2.734216743
200	0.510251631	0.19297725	0.951123537	98	-2.715603434
300	0.650046598	0.202489325	0.898182665	97	-2.696990126
400	0.910997204	0.3105458	1.116612302	97	-2.694663462
500	1.034482759	0.382734788	1.228157036	97	-2.685356808
600	1.181267474	0.4681168	1.342031687	97	-2.652783518
700	1.253494874	0.534925489	1.414259087	97	-2.599270256
800	1.44221808	0.626031022	1.55055918	97	-2.56902363
900	1.395619758	0.680811259	1.578518173	97	-2.534123676
1000	1.325722274	0.75523935	1.740738583	97	-2.510857041
1126	1.421248835	0.83731289	1.807432432	97	-2.464323769
1501	1.919850885	0.989293284	2.041589003	97	-2.378237217
2000	2.222739981	1.175447176	2.284773998	97	-2.250270721
3000	2.462721342	1.463298274	2.6444548	97	-2.068790963
4000	2.891425909	1.581957573	2.786579683	97	-1.975724421
5000	2.80055918	1.741834199	2.968313141	97	-1.840777934
5000	2.80055918	1.741834199	2.968313141	97	-1.840777934

Rut Depth values at different number of Cycles (10% CR-WEO)

Cycle	Central ruth depth (mm)	Rut depth length 100 mm	Rut depth length 20.00 mm	Vector length	Vector data
1	0	0	0	90	-3.292171482
2	0.058248	-1.32887	-0.03844	91	-3.22693383
3	0.086207	-1.29981	-0.0088	92	-3.313140727
4	0.069897	-1.26759	-0.01223	93	-3.243243243
5	0.00699	-1.30396	-0.01657	94	-3.343429637
6	0.060578	-1.27623	-0.00311	94	-3.271202237
7	0.037279	-1.2819	0.044268	95	-3.306150979
8	0.044268	-1.31158	-0.00786	95	-3.273532153
9	0.046598	-1.2494	0.016827	96	-3.352749301
10	0.039609	-1.24861	-0.00414	96	-3.268872321
20	0.074557	-1.23968	0.077761	97	-3.364398882
30	0.093197	-1.2277	0.089119	97	-3.338769804
40	0.083877	-1.22576	0.093197	97	-3.32945014
50	0.088537	-1.23119	0.088828	97	-3.359739049
60	0.109506	-1.22737	0.087954	97	-3.334109972
70	0.121156	-1.21844	0.103973	97	-3.268872321

80	0.132805	-1.21666	0.120573	97	-3.324790308
90	0.118826	-1.21649	0.116496	97	-3.271202237
100	0.121156	-1.20024	0.121738	97	-3.271202237
200	0.235322	-1.12746	0.201538	97	-3.240913327
300	0.293569	-1.10089	0.236486	97	-3.250232992
400	0.361137	-1.02333	0.362011	97	-3.327120224
500	0.456664	-0.95504	0.432199	97	-3.254892824
600	0.484623	-0.93069	0.447926	97	-3.271202237
700	0.54287	-0.87461	0.514329	97	-3.271202237
800	0.603448	-0.83783	0.549278	97	-3.280521901
900	0.647717	-0.80587	0.573159	97	-3.240913327
1000	0.703635	-0.76038	0.649464	97	-3.301491146
1126	0.768872	-0.71678	0.705673	97	-3.273532153
1501	0.915657	-0.6111	0.844886	97	-3.268872321
3000	1.11137	-0.44512	0.989923	97	-3.315470643
4000	1.39329	-0.21174	1.24534	97	-3.380708295
5000	1.523765	-0.07278	1.387756	97	-3.34109972