JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

HIGHWAY ENGINEERING STREAM

RUTTING PERFORMANCE EVALUATION OF ASPHALT MIXTURE CONSTITUTE WASTE MARBLE POWDER FILLER: AN EXPERIMENTAL AND NUMERICAL ANALYSIS APPROACH

A Final Thesis Submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

(Highway Engineering Stream)

By

Giza Teshome Lemma

June, 2024

Jimma, Ethiopia

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DECLARATION

I, Giza, hereby declare that this research paper titled "***Rutting Performance Evaluation of Asphalt Mixture Constitute Waste Marble Powder Filler: An Experimental and Numerical Analysis Approach***" is my original work and has not been submitted for any other degree or qualification at any other institution. I have acknowledged all the sources of information and data that I have used in this paper.

Candidate: Giza Teshome ______________ 10 / 07 / 2024

Signature Date

As Master research advisors, we hereby certify that we have read and evaluated this MSc research prepared under our guidance, by Mr. Giza Teshome entitled: "**Rutting Performance Evaluation of Asphalt Mixture Constitute Waste Marble Powder Filler: An Experimental and Numerical Analysis Approach**."

Anteneh Geremew (Ass. Prof)		02 / 07 / 2024 G.C
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ABSTRACT

The asphalt industry grapples with enhancing rutting resistance, promoting sustainability, and effectively utilizing waste. Rutting poses significant risks to flexible pavements, leading to damage and safety hazards. Sustainable road pavements are essential for conserving natural resources, necessitating innovative approaches. The industry must develop solutions for creating durable, environmentally friendly pavements. One of the primary challenges in asphalt paving construction is ensuring an adequate and available high-quality filler material. To overcome this, it is vital to identify and employ alternative filler materials that are readily available and meet stringent performance standards. This study evaluates the rutting resistance of asphalt mixtures modified with waste marble powder through comprehensive experimental and numerical analyses. Laboratory tests were conducted on asphalt mixtures with varying percentages of waste marble powder (0-50%) in increments of 10% to determine their rutting performance, while finite element modeling using Abaqus software simulated the deformation behavior under a 0.7MPa tire contact pressure. Key findings from the laboratory experiments revealed that all components (aggregate, bitumen, and waste marble powder) met the necessary quality standards. Marshall mix design is used to determine optimum bitumen content. Optimal bitumen and crushed stone dust (CSD) filler contents were identified as 5.24% and 5.25%, respectively. At these levels, the control mix exhibited a maximum Marshall stability, flow, VMA, VFA, bulk density, TSR, E_{mod} and rut depth of 10.87 KN, 2.959 mm, 15.69%, 74.64%, 2.304 g/cm³, 81.3%, 4276.88MPa and 0.394 mm respectively. Waste marble powder was found to optimally replace conventional filler at 30%, enhancing stability, flow, VMA, VFA, bulk density, TSR, E_{mod}, and rut depth by 11.41%, 2.33%, 2.29%, 1.58%, 0.35%, 18.23%, 23.33% and 4.06%, respectively. Simulation results indicated rut depths of 0.381 mm for the control mix and 0.375 mm for the optimized mix, closely aligning with the experimental results of 0.394 mm and 0.378 mm, respectively. This consistency validates the reliability of both the experimental and numerical methodologies. Furthermore, these results demonstrate compliance with the EN 13108 specification. The average rut depths, combining experimental and simulated data, were 0.388 mm for the control mix and 0.377 mm for the modified mix. Notably, the asphalt mixture incorporating 30% waste marble powder achieved a rut depth of 0.377 mm, highlighting its efficacy in enhancing performance and sustainability. These findings provide significant insights for advancing asphalt engineering with eco-friendly solutions using industrial waste, promising practical applications for future research.

Keywords: *Asphalt Rutting resistance, Waste Marble powder, experimental evaluation, Numerical evaluation, Rut depth, waste utilization and performance parameter*

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ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACV	Aggregate Crushing Value
AI	Asphalt Institute
AIV	Aggregate Impact Value
APT	Accelerated Pavement Testing
ASTM	American Society for Testing and Materials
BC	Bitumen Content
BS	British standard
CSD	Crushed Stone Dust
DBM	Dense Asphalt Macadam
EPDM	Ethylene Propylene Dien Monomer
ERA	Ethiopian Road Authority
ESA	Equivalent Standard Axle
EVA	Ethylene Vinyl Acetate
FEM	Finite element Method
HMA	Hot Mix Asphalt
HWT	Humberg Wheel Tracking
ITS	Indirect Tensile Strength
JMF	Job Mix Formula
LAAV	Los Angeles Abrasion Value
LTPP	Long-Term Pavement Performance monitoring
MD	Marble dust
MP	Marble Powder
MS-2	Asphalt Institute Manual Series -2
MSW	Municipal Solid Waste
OBC	Optimum Bitumen Content
OCSD	Optimum Crushed Stone Dust
OPC	Ordinary Portland Cement
OWMP	Optimum Waste Marble Powder
PE	Polyethylene
PET	polyethylene terephthalate
PEW	Polyethylene Wax
PLM	Product Lifecycle Management
RAP	Recycled Asphalt Pavement
RWP	Recycled waste plastic
SBR	Styrene Butadiene Rubber
SMA	Stone Mastic Asphalt
SWM	Solid Waste Management
SWTT	Single Wheel Track Test
VIM	Air Voids in Mineral
VMA	Voids in Mineral Aggregate

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Asphalt pavements are the predominant type of road pavement worldwide [1]. To construct and maintain road pavement, high-quality materials are essential in large quantities [2]. Typically, the cross-sectional structure of conventional flexible pavements includes a top pavement layer followed by aggregate layers supported by a natural subgrade. The surface layer of the asphalt pavement consists of hot-mixed asphalt (HMA) [3, 4]. The performance of this hot mix asphalt (HMA) is primarily influenced by the properties of its components. Such as, mineral aggregate, bitumen and mineral filler [2]. Using low quality material in flexible road surfaces leads to various types of damage, such as rutting, fatigue, and others. Among the road surface distress rutting is the major problem.

Rutting is a form of permanent deformation that appears on the surface of flexible pavements and is a significant concern for highway engineers. It is characterized by depressions that form along the wheel path due to the accumulation of irrecoverable strains from repeated load cycles. Advancements in truck load-carrying capabilities have exacerbated the issue, leading to increased wheel load and tire pressure on the pavement surface. Rutting can pose a hazard, as water-filled ruts can cause vehicles to hydroplane, losing contact with the road and potentially sliding out of their lane. It`s a significant concern in road maintenance and safety, as severe rutting can affect vehicle handling and lead to an increased risk of accidents [3, 5].

Repeated loadings cause rutting, a significant performance issue in hot mix asphalt (HMA) pavements. Two factors external and internal influence the rate and depth of this permanent deformation. External factors include the load and volume of truck traffic, tire pressure, temperature, and construction practices. Internal factors encompass the thickness of the pavement, bitumen, aggregate, and mixture properties [6].

The characteristics of aggregates are often recognized as the most influential factor causing rutting in asphalt pavements [6]. Subgrade ruts and hot mix asphalt (HMA) ruts are the two types of ruts. Thin asphalt pavements, for example, frequently cause repeated stresses on the layers beneath the asphalt layer, causing subgrade ruts. In contrast, issues such as compaction or mixed design within the asphalt layer cause HMA rutting, resulting in permanent deformations [3]. So, using quality material in road construction is the crucial method of length the life of pavement and minimize maintenance cost.

Mineral fillers are a critical component in the performance of hot mix asphalt (HMA). Specifically, fine aggregates passing a No. 200 sieve play a vital role in asphalt mixtures, significantly impacting the behavior and performance of asphalt pavements. These fillers enhance the workability, reduce moisture sensitivity, increase the hardness, and mitigate the aging process of hot mix asphalt (HMA) [7]. The lack of crushed dust, a common filler in HMA, resulting from the crushing of aggregates, is a major obstacle in pavement construction. As more blasting of mine sites for mineral fillers leads to environmental degradation, it is important to search for alternative mineral fillers.

Hot Mix Asphalt (HMA) can be produced using waste and secondary materials [8]. Materials such as municipal waste incinerator ash [9], power plant fly ash [10], coal waste powder [11, 12], Bellessa kaolin [2], industrial waste and by-product materials, such as marble, granite, steel slag, and hydrated lime powder, as mineral fillers [13] and rice husk ash [14] have been recognized for their mechanical and environmental advantages. The addition of mineral fillers improved the oxidation resistance of asphalt binder [15]. To save the natural assets used for road construction, utilizing materials that are readily available in the local area is an essential aspect of road construction.

Marble dust, a locally available material, is one of the most important fillers for enhancing the properties of hot mix asphalt. Marble, renowned for its physical qualities and glossy finish, is a prevalent stone worldwide [16, 17]. This metamorphic rock originates from the transformation of sedimentary carbonate rocks, such as limestone or dolomite under high heat and pressure. It is found in various geological settings around the world.

A significant portion of the world's marble, nearly 50%, is extracted from mines in countries like China, Italy, Iran, Spain, and India [18, 19]. The major producers of marble in the world are China, India, Italy, Turkey, Spain, Brazil, Iran, Egypt, and Greece. The major consumers of marble are China, the United States, India, Italy, Germany, France, and the United Kingdom [20, 21].

In African continent the largest producer of marble is Egypt, Morocco, and South Africa, which accounts for about 40%, 15% and 10% of the continent's output, respectively. Other African countries that produce marble include Ethiopia, Tunisia, Algeria, Nigeria, Namibia, Zimbabwe, Angola, Kenya, Uganda, and Tanzania [22, 20].

Marble is widely distributed across Ethiopia, with significant deposits found in various regions. Notable locations include: Tigray region in northern Ethiopia is known for its marble deposits, particularly around the town of Adigrat, Amhara region around the town of Debre Birhan, has marble reserves that are being actively exploited, Oromia region, particularly around the town of Harar, has marble deposits that are being utilized for construction and decorative purposes, Southern Nations, Nationalities, and Peoples' Region has marble resources in areas such as Yirgalem and Hawassa, Benishangul-Gumuz: Home to marble sites like Mora, Daletei, Baruda, Parzeite, Manden, and Bulene [20].

Recently, Marble industry is growing rapidly in Ethiopia [23]. As the marble processing and mining industry increases there is also an increment of waste marble dust which is deposited on open land in

Ethiopia. Its direct disposal can cause severe and irreversible environmental pollution, health problems and lead to climatic change. Therefore, many countries include Ethiopia are conducting research on reusing marble waste materials to mitigate environmental hazards and establish a safe disposal pathway. On way to mitigate waste marble dust is using as filler in hot mixed asphalt [4].

However, in Ethiopia reusing waste marble dust in road construction is rarely. Now a days, natural asset use for construction is decreasing and costly. So, using marble waste in road construction can save natural assets, minimize environmental hazard and climate change as well as cost of construction materials.

Many researchers have conducted experimental investigations using different industrial products such as filler in hot mix asphalt. However, most of them have not investigated using numerical methods. Numerical (finite element) methods are the most crucial method of identifying the performance of asphalt mix design by discretizing into small parts. It is a numerical technique to analyze the behavior of complex structures under various loading and boundary conditions. FEM can be used to study the rutting resistance of asphalt mixes by simulating the stress-strain response and permanent deformation of the mix under repeated wheel loading. It can also help to optimize the mix design and evaluate the performance of varied materials and additives. Tong, Ma [24] proposed a criterion for asphalt pavement rutting based on a thermal-viscos-elastic-plastic model, considering temperature and traffic load. This study demonstrates the potential of FEA in predicting and evaluating rutting resistance in hot mix asphalt.

This study evaluated the impact of substituting traditional filler material with waste marble powder in Hot Mix Asphalt (HMA). Laboratory samples were prepared by replacing varying percentages of conventional filler with waste marble powder. The Marshall stability of the samples was determined by subjecting them to loading and measuring their resistance to deformation. The flow properties were assessed by quantifying the samples' deformation under a specified load. Volumetric properties, including density and void content, were measured to understand the internal structure of the samples. Moisture susceptibility was evaluated through indirect tensile strength tests conducted under both dry and wet conditions. Rutting resistance was assessed using a single wheel track test, which simulated traffic conditions by applying repeated wheel loads. Additionally, finite element analysis was employed to further analyze the rutting characteristics of the HMA mixture.

Overall, this study provides valuable insights into the potential benefits of incorporating waste marble powder into asphalt mixtures to improve rutting resistance. By combining experimental and numerical approaches, the research design enabled a comprehensive evaluation of the performance of the modified asphalt mixtures, contributing to the development of sustainable and durable pavement materials.

1.2. Statement of the Problem

The asphalt industry faces significant challenges in enhancing the rutting resistance of asphalt mixes while promoting sustainability and effective utilization of waste materials. The selection of road construction materials is critical for infrastructure development, with implications for cost reduction and environmental impact. Halushko, Halushko [25], highlighted the potential of using waste materials, such as crushed slag and various industrial by-products, as substitutes for conventional materials. Aleroeva, Magomadov [26] further emphasizes the importance of selecting the most effective and economical materials, while Bamigboye, Bassey [27] underscores the environmental and economic benefits of using waste materials in road construction. These studies collectively suggest that the selection of effective materials for road construction should consider factors such as cost, quality, and sustainability.

Hot Mix Asphalt (HMA) is typically composed of aggregate, asphalt binder, and filler. A major obstacle in pavement construction is the shortage of crushed dust, a common filler in HMA derived from the crushing of aggregates. As the extraction of mineral fillers through mining leads to environmental degradation, it is crucial to seek alternative mineral fillers. Sharma, Naga [8] indicated that HMA could be produced using waste and secondary materials.

Hamza, El-Haggar [28] and Aliabdo, Elmoaty [29] demonstrated that marble and granite waste could be used in the production of concrete bricks and in cement and concrete production without compromising the physical and mechanical properties of the materials. Sang, Idowu [30] further showed that waste marble dust could enhance the performance of HMA, particularly in terms of stability, strength, and void characteristics.

While those studies have explored the use of various fillers in asphalt mixtures, a research gap exists in specifically examining the potential benefits and limitations of marble powder filler in terms of rutting resistance using finite element analysis (FEA) simulations. FEA allows for a detailed analysis of the mechanical behavior and performance of asphalt mixtures under different loading conditions.

Ethiopia is currently facing a significant issue with the accumulation of waste marble powder on open land, leading to environmental pollution and health risks for nearby communities [23]. Previous studies have not investigated the potential use of waste marble powder in HMA in Ethiopia, nor have they explored the impact of altered components on the rutting performance of asphalt mixes using FEA.

Therefore, conducting a comprehensive experimental and FEA evaluation of the rutting performance of asphalt mixes incorporating waste marble powder will be essential to address these research gaps. This evaluation will provide valuable insights for developing durable and efficient asphalt mixes with improved rutting performance, contributing to the sustainability of road construction in Ethiopia.

1.3. Research Question

1. What is the engineering properties of HMA constituents (aggregate, bitumen and fillers)?
2. How does the incorporation of marble powder filler affect the rutting resistance of asphalt mixtures?
3. How do the mechanical properties, such as stiffness and strength, of the modified asphalt mixtures change with the addition of marble powder filler?
4. What is the comparative analysis of the numerical and experimental performance of the HMA containing waste marble powder filler?
5. What is the optimal percentage of marble powder filler that can enhance the rutting resistance of asphalt mixtures?

1.4. Objectives

1.4.1. General objective

This research aims to evaluate asphalt rutting performance modified by waste marble powder experimentally and numerically (Finite element analysis).

1.4.2. Specific objectives

1. To determine the engineering properties of HMA constituents (aggregate, bitumen and fillers)
2. To assessing the impact of marble powder filler on the resistance of asphalt mixtures to rutting
3. To investigate the influence of marble powder filler on the overall mechanical behavior and performance of asphalt mixtures
4. To conduct a comparative analysis of the numerical and experimental performance of HMA containing waste marble powder filler.
5. To determine the optimal dosage of marble powder filler that enhances rutting resistance of the asphalt mixtures.

1.5. Limitation of the study

1. The findings of this study are specific to the use of white waste marble powder filler and a specific asphalt mixture composition. Diverse sources of marble powder and variations in asphalt mixtures may yield different results. Therefore, caution should be exercised when generalizing the findings to other scenarios or materials.
2. The study not extensively address the economic aspects of incorporating waste marble powder filler in asphalt mixtures.
3. The FEA simulations was validated through laboratory findings rather than field trials.

1.6. The Outcomes of this Research

The outcomes of the study "Rutting Performance Evaluation of Asphalt Mixture Constitute Waste Marble Powder Filler: An Experimental and Numerical Analysis Approach" included several key findings and contributions to the field of asphalt pavement engineering:

1. Enhanced understanding of modified mixes: The study provided insights into the mechanical properties and rutting resistance of asphalt mixes incorporating waste marble powder. It offered a deeper understanding of how these modified constituents influence pavement performance.

2. Optimal content: The research identified the optimal content of waste marble powder to achieve improved rutting resistance without compromising the overall performance of the asphalt mixes. This information can guide future pavement design and construction practices.

3. Validation of finite element modeling: The study validated the reliability and accuracy of the finite element model in predicting rutting behavior. This contributes to advancements in numerical modeling for pavement analysis.

These outcomes provide valuable knowledge, data, and guidance for engineers, researchers, and practitioners in the design, construction, and maintenance of asphalt pavements, particularly concerning the use of recycled materials to enhance pavement performance and sustainability.

1.7. Scope of the Study

This study examined the rutting resistance of asphalt mixes modified with waste marble powder as a mineral filler. The goal was to optimize the marble powder content to enhance rutting resistance without compromising performance, and to develop a 3D model of the asphalt mix modified with waste marble powder. Laboratory testing evaluated mechanical properties using Marshall mix design procedures by varying the percentage of waste marble powder (WMP). Performance tests, such as the wheel track test (rutting test) for validation and moisture susceptibility assessment, were conducted. Finally, finite element analysis was used to simulate and analyze the rutting behavior of the mixes.

1.8. Significance of the Study

The purpose of this study was to investigate the influence of modified constituents on rutting resistance in hot-mix asphalt. The road construction industry requires appropriate materials for building flexible pavements, and fillers are among the most crucial components of hot-mix asphalt. Currently, producing fillers for hot-mix asphalt involves many re-crushing cycles, which not only consumes significant time but also adds to the overall cost. Additionally, the use of fillers made from crushed rocks, cement, and lime have limitations in terms of performance and environmental impact. Therefore, finding alternative filler materials that can overcome these challenges is crucial for improving the efficiency and sustainability of road construction.

A study conducted by Awol [23] found that waste marble powder is abundantly available in local areas of Addis Ababa. This abundance makes it a promising candidate for utilization as a filler in hot mix asphalt, potentially reducing reliance on imported or expensive materials. Furthermore, utilizing this locally available material can contribute to waste reduction and promote recycling efforts, aligning with sustainable practices in pavement construction.

To investigate the influence of modified constituents on rutting resistance, the study employed comprehensive laboratory testing and numerical analysis. Various tests, such as the wheel tracking test and the indirect tensile strength test, were conducted to evaluate how different filler compositions affect the performance of asphalt mixes. These tests aimed to determine the optimal combination of constituents to improve rutting resistance. By using rigorous testing methods, the study aimed to provide reliable data and insights into the durability and longevity of asphalt mixes, ultimately contributing to the improvement of flexible pavements.

The study also utilized finite element analysis (FEA), a numerical modeling technique widely used in engineering, to simulate and predict the rutting behavior of asphalt mixes using Abaqus software. This technique involves dividing the pavement structure into small elements and analyzing the interactions between these elements under different loading conditions. By incorporating relevant material properties and pavement characteristics, the FEA provided valuable insights into the performance and behavior of modified asphalt mixes.

Additionally, laboratory experiments were conducted to validate the findings from the numerical analysis and ensure their applicability in real-world conditions. Lastly, the research provided important guidance and recommendations for incorporating waste marble powder in asphalt mixes, influencing decision-making processes, and driving policy changes toward more sustainable and resilient pavement solutions.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

Sustainable road pavements are designed and constructed with the aim of conserving and protecting natural resources, while also addressing the environmental issues associated with the disposal of hazardous solid waste [31]. The construction of new roads has significant environmental implications, requiring substantial amounts of materials and energy. The rising cost of crude oil, a key component of bituminous binder, has led to an increase in the overall price of bituminous mixtures [32].

To enhance sustainability and cost-efficiency, innovative materials and technologies are being developed to incorporate greener materials, waste, and recycled materials into the production cycle of asphalt mixes. As people become more concerned about environmental impacts, sustainable materials are increasingly being used in road construction. However, the search continues for the most suitable sustainable materials for road pavement development. The findings suggest that using secondary material not only provides an effective waste disposal method but also reduces the need for traditional material and lowers the overall construction cost. An effective and appropriate transportation system is crucial for the development of any nation [32].

Flexible pavements are multilayered structures that include pavements with unbound granular aggregate layers and pavements with aggregate layers that are bound together with bitumen and hot mix asphalt (HMA) on the top layer [3, 33]. Hot mix asphalt is a mixture of aggregate and asphalt binder that has different properties depending on the ingredients and how they interact. The quality, quantity, and grading of the aggregate affect how strong and stable the HMA is. Fillers are very fine aggregate particles passing sieve No.200 size that enhance the asphalt pavement performance. They are mixed with the HMA to make it more solid and stable by filling the gaps between the larger aggregate. They also help lower the temperature sensitivity of the asphalt binder layer. So, pavement materials characteristics are important factors that affect the performance of pavements [2].

Filler materials play a crucial role in the performance of flexible pavements, particularly in hot climates. A range of studies have explored the use of various waste materials as fillers in hot mix asphalt, with promising results. Saltan, Öksüz [34] found that cullet and waste glass bottle dust can be effective alternatives to traditional crushed stone dust, while Arabani, Babamohammadi [35] demonstrated the potential of seashells in improving the fatigue life and permanent deformation of asphalt. Shamsaei, Khafajeh [36] further supported the use of waste materials, showing that ceramic waste can enhance the mechanical properties of asphalt. Sargın, Saltan [37] also found that rice husk ash can be a suitable mineral filler in asphalt concrete.

Guha and Assaf [38] found that cellulose fiber and Ordinary Portland Cement (OPC) fillers can improve the mechanical and volumetric performance of hot mix asphalt, with cellulose fiber performing better than OPC. The use of OPC as a filler substitute was also shown to enhance the stability and resistance to rutting in asphalt mixtures in hot climates. Similarly, Olaiya, Tolulope [39] highlighted the benefits of using waste materials as fillers, such as marble dust and calcium carbide residue, in bituminous mixes. Furthermore, the addition of polymers, such as Polyethylene Wax (PEW), Styrene Butadiene Rubber (SBR), Ethylene Propylene Dien Monomer (EPDM), and Ethylene Vinyl Acetate (EVA), can reduce permanent deformation in flexible pavements [40]. These studies collectively suggest that the use of waste materials as fillers in hot mix asphalt can improve performance and sustainability.

The use of fillers in hot mix asphalt (HMA) has been shown to improve its density and stability by reducing voids in the coarser aggregate [41]. This improvement is particularly significant in terms of fatigue and rutting resistance, as well as moisture sensitivity. The type and amount of filler used can have a significant impact on the technical properties of HMA, including its performance in terms of permanent deformation, fatigue cracking, and moisture susceptibility [42]. As a primary component of asphalt pavements, aggregate characteristics, particularly gradation, also significantly impact pavement performance [6]

While experimental methods are commonly used to evaluate the performance of hot mix asphalt with different fillers, they do come with certain limitations. For example, these methods subject to variations in test conditions, such as temperature and loading rate, which can introduce uncertainty in the results. Furthermore, experimental methods not always capture the full range of performance characteristics that can be evaluated using numerical analysis. However, it is important to note that numerical analysis should not replace experimental methods, but rather complement them by providing additional insights and supporting the findings obtained through experimentation.

2.2. Distress in Asphalt Pavement

Asphalt pavement is a critical component of transportation infrastructure, providing a smooth and durable surface for vehicles to travel on. The design and analysis of asphalt pavement structures are essential for ensuring their long-term performance and durability. Rutting is one of the key causes of pavement deterioration and an important design problem. It is a depression that occurs on the pavement surface along the wheel path because of repeated load cycles. It has become a key worry for highway engineers as truck weight-carrying capabilities have improved, resulting in an increase in wheel load and tire pressure on the pavement surface. This can result in an accumulation of irreversible stresses, resulting in rutting. The combined impacts of traffic loads and poor weather conditions cause persistent deformation in asphalt pavements, eventually resulting in the creation of ruts on the road surface [43, 44, 5, 45, 46, 47].

There are two types of ruts: subgrade ruts and hot mix asphalt ruts (HMA). Subgrade rutting is due to repeated loading on the layers below the asphalt layer due to structural problems (thin asphalt pavement), while HMA rutting is due to irreversible deformations. Recovery inside the asphalt layer when the base layer has not settled due to compression or mixing [3]. The study focuses on HMA rutting, which involves mixtures subjected to repeated heavy loading at high temperatures. The speed and degree of rotting are influenced by external and internal factors. External factors include truck load and traffic volume, tire pressure, temperature, and construction methods. On the other hand, internal factors include pavement thickness, asphalt, aggregate, and mix properties [6]. Rutting is characterized as a sustained deformation of the roadway due to the continuous accumulation of vertical viscose-plastic compressive stress in the path of the wheel. This can occur due to the use of an inappropriate asphalt binder, a poorly formulated mix, or a mix with a high percentage of asphalt binders. The performance of rutting is also strongly associated with the percentage of voids in asphalt mixtures and the shape, toughness, and angularity of both coarse and fine aggregates [48].

To mitigate the issue of rutting distress, significant efforts have been made to assess the performance of asphalt pavement rutting, identify key influencing factors, and develop models that link rutting depth with these factors [5]. During the past decades, experimental considerable efforts have been made to accurately determine the progression of ruts and establish their relationship with influencing factors. Rutting testing methods can be classified into three types: laboratory rutting testing, accelerated pavement testing (APT), and long-term pavement performance monitoring (LTPP) [44].

In addition, a range of studies have utilized numerical analysis to investigate rutting in asphalt pavements. Dong, Sun [49] found that frequent starting and braking of vehicles at urban intersections can significantly alter stress distribution, leading to rutting. Luo, Lu [50] proposed new pavement structures for steel deck bridges and evaluated their rutting resistance performance, with a focus on the surface layer. Saevarsdottir and Erlingsson [51] observed the impact of water on pavement performance and used numerical analysis to model the accumulation of permanent deformation, which manifests as rutting. Bakhshi and Arabani [52] explored the use of crumb rubber to reduce rutting in asphalt mixtures, employing finite element modeling based on experimental viscoelastic properties. These studies collectively highlight the potential of numerical analysis in understanding and mitigating rutting in asphalt pavements.

The other stress in flexible pavement is moisture induces damage. Moisture-induced damage in flexible pavements is a significant concern, as it can lead to reduced base resilient modulus, increased structural damage, and premature deterioration [53, 54, 55].

Recent research has focused on improving laboratory tests to forecast moisture damage problems in the field. To solve these problems effectively, both the chemical and mechanical factors that cause moisture damage need to be considered. The chemical factors influence how asphalt molecules bond with the aggregate surface and how this bond changes when water is present. The physical issues involve finding ways to prevent water from reaching the asphalt aggregate interface. Besides selecting and controlling the quality of materials, proper design and construction are also essential to keep moisture away from the pavement. This includes providing adequate drainage for water and compacting the asphalt mixture well to reduce air voids and pavement permeability [1].

Researchers found that, this damage is particularly pronounced in pavements with poor drainage systems, where the base layer can experience high degrees of saturation for extended periods [56]. The combined effect of moisture and mechanical loading can cause adhesive damage at the aggregate-mastic interfaces in asphalt mixtures, further exacerbating the problem [57]. The bond between asphalt and aggregate is crucial for pavement durability, with moisture reducing this adhesion and leading to pavement distress [58]. Jakarni, Rosli [59] highlighted the importance of aggregate mineralogy, bitumen characteristics, and anti-stripping additives in reducing moisture damage. Kakar, Hamzah [60] emphasized the need for new in-situ testing techniques and material selection criteria to address moisture susceptibility in asphalt mixtures.

Asphalt Institute [1] emphasized that the moisture sensitivity of a mix can be evaluated by different methods, which have been successful in different jurisdictions. The local conditions and materials affect the suitability of a specific method. The most common methods to measure the moisture sensitivity of an asphalt mixture are the indirect tensile test procedures, AASHTO T 283 and ASTM D4867, also called the modified Lottman and Root-Tunnicliff tests. These tests need at least six test specimens to be compacted to a certain air voids percentage that matches the expected in-place percentage of 7.0 percent air voids.

To reduce the moisture sensitivity of the final product, some precautions should be taken when building asphalt pavements. Moisture damage is not only caused by the material and mix design process. Poor construction methods related to stockpiles, asphalt plants, lay down operation and pavement drainage can also contribute to moisture damage [1, 61, 33].

The type and proportion of filler in asphalt mixtures can significantly impact their moisture susceptibility. Bidgoli, Naderi [62] found that different fillers can alter the thermodynamic and mechanical properties of the mix, potentially affecting its response to moisture. Singh and Jain [63] and Mistry and Roy [64] both demonstrated that the addition of lime, cement, or rice husk ash fillers can improve the moisture susceptibility of cold mix asphalt and dense graded bituminous mix, respectively. Xiao, Chen [65] further supported these findings, showing that the replacement of limestone filler with steel slag powder can enhance the moisture damage resistance of asphalt mixtures. These studies collectively suggest that the choice and proportion of filler can play a crucial role in mitigating moisture susceptibility in asphalt mixtures.

However, the effect of waste marble powder on moisture susceptibility in asphalt mix is not directly addressed in the available literature. Therefore, this research is needed to specifically investigate the impact of waste marble powder on moisture susceptibility in asphalt mix.

2.3. Application of Finite Elements Analysis in Asphalt Pavement

The finite element method (FEM) is a powerful tool for predicting the structural response of asphalt pavements. However, three-dimensional (3D) modeling in general-purpose FEM software systems is different. Recently, to accurately assess the impact of heavy traffic loads on asphalt pavements, it is important to have a computer model that can quickly and accurately calculate the pavement response [66].

Finite Element Analysis is a numerical technique used to solve complex engineering problems by dividing the structure or material into smaller, more manageable elements. These elements are interconnected at discrete points called nodes, forming a mesh that represents the geometry and material properties of the structure. By applying the principles of continuum mechanics and numerical methods, FEA can simulate the behavior of structures under various loading and boundary conditions. In the context of asphalt pavement, FEA can be used to analyze the response of the pavement structure to traffic loads, temperature variations, and moisture effects [67, 68, 69].

The application of FEA in pavement design involves the development of numerical models that represent the geometric and material properties of the pavement structure. These models can be used to evaluate different design alternatives, assess the impact of varying traffic loads, and optimize the thickness and composition of pavement layers. Furthermore, FEA can facilitate the analysis of rehabilitation strategies, such as overlay design, and the evaluation of innovative materials and construction techniques. By integrating FEA into the pavement design process, engineers can make informed decisions that lead to more sustainable and cost-effective pavement solutions. It offers several benefits, including the ability to predict pavement performance under diverse conditions, optimize design parameters, and assess the influence of material properties and construction quality. Additionally, FEA can provide insights into failure mechanisms such as fatigue cracking, rutting, and thermal cracking, enabling engineers to develop proactive maintenance and rehabilitation strategies [70, 71, 72, 73].

In this study Abaqus software was used for modeling rutting of asphalt mixed. Abaqus is a general-purpose finite element software package that can be used for finite element analysis in mechanical and civil engineering. It is sold by Dassault Systems as part of the SIMULIA Product Lifecycle Management (PLM) software tool. Abaqus has a rich library of element types and material models capable of simulating stress and strain in isotropic and anisotropic metals at low and high temperatures, low and high strain rates, as well as minor and significant deformations. It can also simulate rubber and polymers, reinforced concrete, glass, and ceramics, crushable or elastic foam, and geotechnical materials such as soil and rock. It can simulate conductive and convective heat transfer, mass diffusion, acoustics, piezoelectricity, and electrochemistry independently, in sequential coupling, or in complete combination with stress analysis. It is also capable of simulating contact between significantly deformed parts. The Abaqus/Standard is ideally suited for steady-state, low-speed, and static conveying applications. It allows us to analyze a model in the time and frequency domains in a single simulation. Abaqus/Standard provides very accurate stress analysis [74].

In the realm of hot mix asphalt (HMA) analysis and design, Abaqus has found widespread application. The finite element method (FEM) has become a cornerstone in highway research, with numerous researchers turning to FEM software like ANSYS and Abaqus to investigate the permanent deformation characteristics of asphalt mixtures, ensuring the longevity and reliability of road infrastructures [75], [76]. Imaninasab, Bakhshi [77] used Abaqus to determine the rutting characteristics of rubber foam asphalt; [78] used Abaqus for 2D finite element modeling to predict the behavior of the rutting of the glass asphalt mixture.

In conclusion, the application of Finite Element Analysis in asphalt pavement has the potential to revolutionize the way pavement structures are designed, analyzed, and maintained. By leveraging the power of FEA, engineers can gain a deeper understanding of pavement behavior, optimize design parameters, and develop innovative solutions to address the challenges of modern transportation infrastructure. As FEA continues to evolve and improve, its role in pavement engineering will become increasingly prominent, leading to safer, more durable, and sustainable pavement systems for the future. This study is assessed rutting performance in asphalt mix by using waste marble powder as filler through experimental and numerical modeling using Abaqus software.

2.4. Volumetric Characteristics of Asphalt Mixes

When conducting mix design in the laboratory, the mix undergoes a thorough analysis to evaluate its potential performance in pavement structures. Regardless of the specific mix design method employed, a comprehensive volumetric analysis is typically performed on all mixtures. This analysis focuses on the following five key properties, which significantly influence the behavior and performance of the mixture:

1. Density: Determines the compactness of the aggregate particles and the overall mixture.

2. Voids in Mineral Aggregate (VMA): Measures the volume of the void spaces between the aggregate particles.

3. Air Voids: Assesses the volume of air pockets within the compacted mixture.

4. Voids Filled with Asphalt (VFA): Indicates the percentage of VMA that is filled with asphalt binder.

5. Asphalt Content: Represents the proportion of asphalt binder in the mixture by weight.

Each of these properties plays a crucial role in the performance characteristics of the pavement, influencing durability, stability, and resistance to deformation. [1, 33].

To achieve satisfactory pavement performance with HMA mixtures, the volumetric properties must be determined. Various studies have been conducted on the influence of mineral fillers on the Marshall properties of asphalt mixtures. Among them, the volumetric properties of HMA are necessary requirements to ensure good performance, and these properties are directly influenced by the particle size of the mixture, surface properties of aggregates, and compaction energy. Furthermore, the optimal asphalt binder content was found to increase as the filler content in the HMA content increases and is highly dependent on the filler type [2, 79, 80, 61]

2.5. Asphalt Pavement Wearing Course and its Composition.

The term "asphalt" has varying interpretations across the globe. For instance, in Europe, "asphalt" is equivalent to what is referred to as Hot Mix Asphalt (HMA) or Asphalt Concrete (AC) in the United State [1]. The hot mix asphalt wearing course is indeed the most critical layer in a pavement structure. It's the top layer that comes in direct contact with traffic loads and provides important characteristics such as friction, smoothness, noise control, rut and shoving resistance, and drainage [33].

HMA wearing courses should have high deformation, fatigue, and strain resistance, good stiffness, environmental degradation resistance, low permeability, good workability, sufficient skid resistance, and consistent performance [33]. Moreover, the purpose of hot mix asphalt design is to identify the blend of asphalt cement and aggregate that was ensure a durable and long-lasting performance when used in asphalt pavement [61, 1].

The ultimate objective of mix design is to choose a specific binder content that balances all desired properties. The performance of a pavement is linked to its durability, impermeability, strength, stability, stiffness, flexibility, resistance to fatigue, and workability. There is not a single asphalt content that will optimize all these properties. Instead, the asphalt content is chosen based on optimizing the properties needed for specific conditions [1].

The hot mix asphalt (HMA) types commonly utilized in tropical regions are produced in an asphalt plant through the process of heating and blending specific ratios of the following components:

- ❖ Coarse aggregate: characterized by particles larger than 2.36 mm but less than 25 mm
- ❖ Fine aggregate: characterized by particles smaller than 2.36 mm but larger than 0.075 mm
- ❖ Filler: characterized by particle sizes smaller than 0.075 mm, which can either be derived from the fines in the aggregate or added separately in the form of cement, lime, or ground rock
- ❖ A paving grade bitumen: with viscosity characteristics suitable for the specific HMA type, as well as the climatic and loading conditions where it will be applied [1, 33, 61].

2.5.1. Aggregate

The American Society for Testing and Materials (ASTM) defines aggregates as granular materials of mineral composition like sand, gravel, shell, slag, or crushed stone. These materials can be used with a cementing medium to form mortars or concrete or alone in applications such as base courses or railroad ballasts [81, 82, 83].

The characteristics of the material significantly impact the performance of the mix. The necessary attributes of aggregates are defined by their shape, hardness, durability, cleanliness, affinity for bitumen, and porosity. Besides these properties, the microtextured nature of the aggregate particles also greatly affects the performance of a compacted HMA layer. For instance, smooth-surfaced river gravel, even if partially crushed, may not create as much internal friction as a completely crushed aggregate with a coarse micro texture. Aggregate consists of a combination of fine and coarse pieces of hard crushed stone, crushed slag, crushed or uncrushed gravel mixed or mixed with natural sand, and crushed screens. [33, 83, 84, 1].

The coarse aggregates used in HMA production should be derived from crushing sound, unweather rock, or natural gravel. It's recommended that gravel be crushed to ensure that each particle has at least two fractured faces [61, 33, 85]. The mix design for asphalt surfacing materials was based on the recommendations given in the Asphalt Institute Manual Series, MS-2, and conducted using the Marshall test procedure. In general, the aggregate used in hot mix asphalt was strong enough to resist crushing, wearing, or hardness under traffic wheel load [85, 1, 84].

The effect of aggregate gradation in hot mix asphalt is a significant factor in determining the performance properties and mixture design parameters [86]. The impact of aggregate gradation variations on various properties of asphalt concrete mixtures has been investigated, with the fine-coarse and coarse-fine gradation variations having the greatest impact. The type of aggregate also plays a role, with coarse grading with a 25 mm maximum size found to give the most satisfactory results in terms of stability, stiffness, and void characteristics [87]. Therefore, the gradation of the aggregate used in hot mix asphalt for wearing course must fulfill the standard requirements indicated in Table 2.1.

Table 2.1: Particle size distributions for HMA [61, 84]

Sieve size (mm)	Nominal maximum stone size (mm)		
	Percentage passing sieve		
	19	12.5	9.5
25	100	-	-
19	90-100	100	-
12.5	-	90-100	100
9.5	56-80	-	90-100
4.75	35-65	44-74	55-85
2.36	23-49	28-58	32-67
0.3	5-19	5-21	7-23
0.075	2-8	2-10	2-10
Bitumen content (%)	4-10	4-11	5-12

2.5.2. Asphalt binder (Bitumen) properties

The performance of asphalt mixtures is significantly influenced by three key properties of asphalt binders: temperature sensitivity, viscoelasticity, and aging characteristics. The performance-graded (PG) system incorporates tests that address these properties to predict high-temperature rutting, low-temperature thermal cracking, and aging-related fatigue. Bitumen binder exhibits viscoelasticity, demonstrating both viscous and elastic behavior. As an organic chemical substance, asphalt undergoes oxidation when exposed to environmental oxygen, altering its molecular structure and composition. This oxidation process increases brittleness, commonly referred to as age hardening [1, 88, 89].

Bitumen is predominantly used in road construction, accounting for approximately 70% of its application. It serves as a binder, either alone or mixed with aggregate particles to form asphalt concrete. Typically, bitumen consists of around 80% carbon, 10% hydrogen, up to 6% sulfur by weight, and contains 5-25% asphaltenes dispersed in 90-65% maltenes. Given the vast number of different molecules present in asphalt, separating and identifying each component is nearly impossible [90].

2.5.3. Non-conventional mineral filler

The scarcity of crushed stone dust, a common filler in HMA due to aggregate grinding, poses a significant challenge in pavement construction. This leads to environmental degradation due to the need to create more quarry areas to produce enough mineral filler. Therefore, it is essential to consider an alternative mineral filler. There are many mineral fillers used as alternatives to hot mix asphalt (HMA), including stabilized bottom ash, a byproduct of municipal waste incineration, and steel slag from electric arc furnaces [9], fly ash from power plants [10], construction and demolition waste [91], old glass powder [92], recycled asphalt pavement (RAP) [93] and marble dust (MD).Using industrial by product as filler is another way to preserve the natural resources, reduce climatic change, sustainable and enhance pavement performance.

The rapid globalization of the economy, population, and urbanization has increased waste production. Worldwide in 2016, municipal solid waste (MSW) generation reached 2.01 billion tons. This figure is expected to rise significantly, reaching 3.40 billion tons by 2050 [94]. However, globally, waste generation is on the rise, with an estimated 2.24 billion tons of solid waste produced in 2020, equivalent to 0.79 kilograms per person per day. This figure is projected to surge by 73% to 3.88 billion tons by 2050 due to population growth and urbanization [31].

The regions that produce the most waste in the world is, from large to small, east Asia and pacific, South Asia, Sub-Saharan Africa, Europe and Central Asia, North America, Latin America and Caribbean and middle east and North Africa. Poorly managed waste disproportionately affects developing countries, particularly the urban poor. In low-income countries, over 90% of waste is often disposed of in unregulated dumps or openly burned, leading to serious health, safety, and environmental issues [94], [31]. Effective waste management, which is crucial for sustainable and livable cities, remains a challenge for many developing countries and cities including Ethiopia.

Waste management in Ethiopia, as in many African countries, faces significant challenges. Industrial waste, particularly in Addis Ababa, is a major concern due to inadequate management and pollution [95]. Medical waste, often disposed of through incineration, poses health and environmental risks, with a lack of national guidelines exacerbating the issue [96, 97].

In Ethiopia, the waste management system requires significant improvement, as current practices are inconsistent, insufficient, and ineffective. One promising approach to waste management is the reuse of waste products in infrastructure development.

2.6. Utilizing Waste Marble Powder (WMP) as Mineral Filler in Asphalt Pavement

Marble is a metamorphic rock composed of carbonate minerals that recrystallize under the influence of heat, pressure, and an aqueous solution (usually calcite ($CaCO_3$) or dolomite (CaMg (CO_3)) and exhibit textured crystals of varying thickness. Marble is not layered, although there are exceptions. In geology, the term marble refers to metamorphosed limestone, but its use in stone construction is broader, including unmetamorphosed limestone [98].

Marble is a low-grade metamorphic rock used in a variety of industrial applications and has potential value as a calcium supplement for animal feed [99, 100]. It is a natural stone that is widely used in construction for its beauty and durability [101, 102]. Using a combination of marble powders in concrete production can help mitigate environmental effects and produce compound concretes with the same or improved mechanical properties [103]. It is also used to improve pavement performance in road construction. Figure 2.1: The Taj Mahal Crown of the Palace is an ivory-white marble mausoleum located on the Yamuna river's right bank in Agra, Uttar Pradesh, India.

Figure 2.1: A Marble portal of the Taj Mahal in Agra, India [98]

2.6.1. Waste marble powder resource estimation in Ethiopia

Waste marble dust, a by-product of the marble industry, constitutes a significant portion of industrial waste in Ethiopia, with notable dumping practices [4, 104]. The direct disposal of this material poses severe and enduring environmental risks.

Ethiopia boasts abundant marble resources across various regions, including Benishangul Gumuz, Tigray, Amhara, and Oromia. However, the burgeoning marble industry exacerbates the challenge of waste marble powder accumulation on open land, leading to a surge in the cost of natural road construction materials. Despite this, there is a conspicuous lack of research on leveraging waste marble powder for hot mix asphalt in Ethiopia. Therefore, this study evaluated the rutting performance of hot mix asphalt through the incorporation of waste marble powder, by employed a finite elements model.

CHAPTER THREE

MATERIALS AND RESEARCH METHODOLOGY

3.1. Descriptive of the Study Area

Sendafa (Oromo: Sandafaa) is a town and distinct woreda in Ethiopia's Oromia Region. It gets its name from the Oromo word for a thick, jointed grass or reed that thrives in swampy locations. Sendafa is in the Oromia special zone surrounding Finfinnee in the Oromia Region, with coordinates of 9° 09′ N, 39° 02′ E, and an elevation of 2514 meters above sea level. The town is located 38 kilometers North of the city on the paved Addis Abeba-Debre Brihan route. Sendafa is well-known for its diversified species and abundant biodiversity found in its swampy areas. Concerning weather, Sendafa has a moderate temperature; June, July and August are principal rainy season [105].

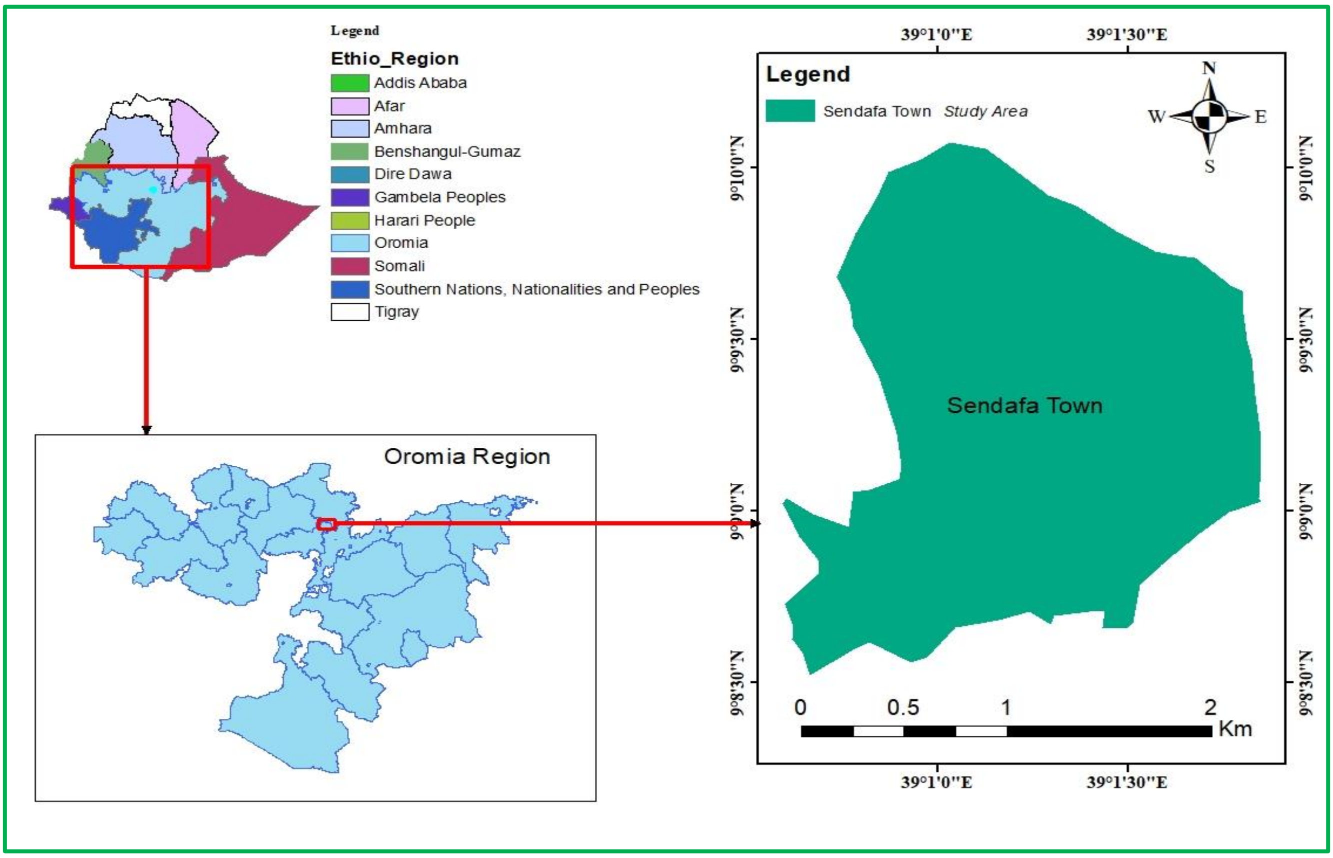


Figure 3.1: Study Area (ArcGIS)

3.2. Types and Source of Data

To carry out this research, primary and secondary data was used. Secondary data were collected from relevant literature, existing documents, books, and relevant standards such as ASTM, AASHTO, and ERA to analyze issues related to the relevant research objectives. On the other hand, primary data are the results of assessed properties identified during laboratory evaluation and software simulations.

3.3. Study Variables

This research employs two types of study variables: dependent variables and independent variables.

3.3.1. Dependent variable

Rutting resistance of asphalt

3.3.2. Independent variables

The amount of waste marble powder added to asphalt

3.4. Research design

In this study, the aim is to evaluate the rutting performance of asphalt mixtures modified with waste marble powder (WMP). The research employed both experimental and numerical analyses to assess the impact of WMP on the performance of the asphalt mix. Laboratory tests was conducted on asphalt mixtures with a control mix and varying optimum percentages of WMP to determine their rutting resistance properties. Additionally, finite element modeling (using Abaqus 6.14) was simulated the vertical deformation properties of the asphalt mixtures.

3.4.1 Experimental Setup

The experimental evaluation involves several laboratory tests. Initially, materials such as aggregate, bitumen, and WMP were collected, and their physical properties were tested according to ASTM, AASHTO, and ERA specifications. Following this, a trial Marshall mix design was conducted with various binder contents to determine the optimum binder content (OBC) for the conventional asphalt mixture. Standard Marshall specimens were prepared by applying 75 blows to each face as per ERA 2013 and ASTM D1559 standards, with four different bitumen contents (4.5%–6%) in 0.5% increments by weight of the total mix and varying crushed stone dust filler contents (4.25%-5.75% in 0.5% increments. Three Marshall specimens, each weighing 1150 gram, were prepared for each filler content, followed by Marshall stability-flow testing and volumetric parameter determination. These specimens helped determine the OBC and optimum filler content.

Next, WMP was used to partially replace conventional filler (crushed stone dust) at varying proportions: 0- 50% in 10% increments by weight of the optimum crushed stone dust filler. The impact of this replacement on Marshall properties was analyzed. Performance tests such as indirect tensile strength for moisture-induced damage and rutting tests were conducted at the OBC and optimum crushed stone dust obtained from the Marshall mix for the control mix, as well as at OBC, OCSD, and optimum waste marble powder (OWMP) for the modified asphalt mixture.

3.4.2 Numerical Simulation

In addition to the experimental testing, numerical simulations were conducted to further evaluate the rutting performance of the modified asphalt mix for both the control mix and the WMP-modified asphalt at optimum values. Abaqus 6.14V software was used for Finite Element Analysis (FEA) to model the vertical deformation (rutting depth). The simulations incorporated the material properties of the asphalt mix, including the effects of WMP on the mechanical properties. Parameters such as the elastic modulus, poison's ratio, and layer thickness were input into the FEA software to accurately model the behavior of the mix.

The results were presented in both tabular and graphical formats, followed by a comprehensive analysis and discussion. The study provided detailed insights into the effects of WMP on asphalt mixture properties. Based on these findings, conclusions and recommendations were drawn. The overall work of research is summarized as Figure 3.2.

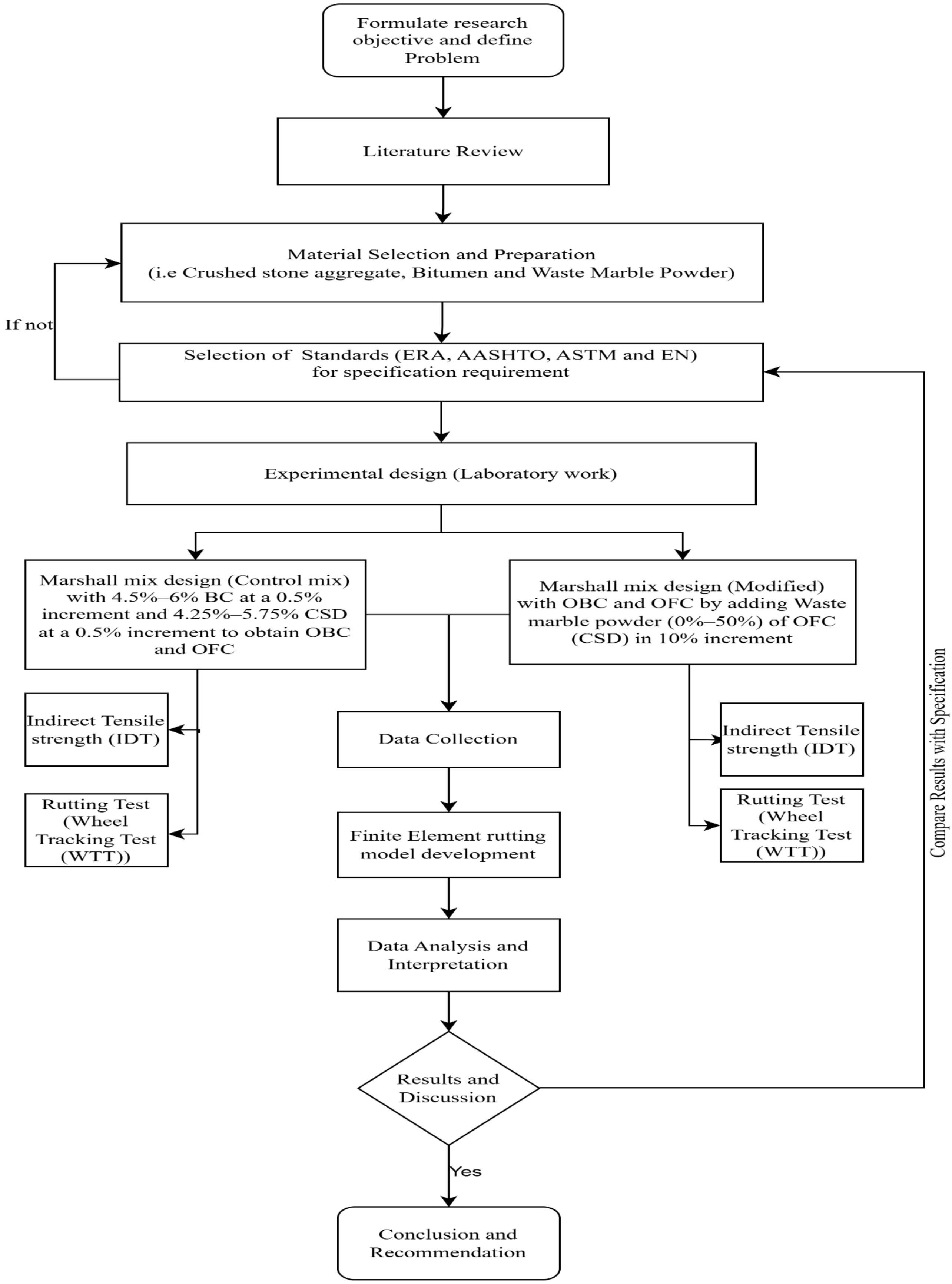


Figure 3.2: Research design flowchart

3.5. Materials

3.5.1 Characterization of materials

Hot mix asphalt is constituted of aggregate, asphalt binder and mineral filler [1]. Each component selection and characterization are critical in the design of HMA mixtures and the adjustment of manufacturing doses to achieve the desired quality and attributes of the generated combination. Various tests have been conducted on the material to determine its physical and mechanical qualities.

A) Aggregate

Aggregate is the primary component of hot mix asphalt, significantly influencing the mix's performance due to its physical and mechanical properties [1, 84] The mineral aggregate chiefly provides the bearing capacity of the pavement is shown in (Figure 3.3). The physical properties of the aggregate used in the mixture adhere to AASHTO, BS and ASTM specifications. The selected aggregate is well graded, strong, tough, and durable. Besides meeting gradation requirements, the aggregate must also possess sufficient strength to carry and transmit applied loads effectively [1]. The aggregate used in hot mix asphalt includes:

- ❖ Coarse Aggregate: Sized from 25 mm to 2.36 mm
- ❖ Fine Aggregate: Sized from 2.36 mm to 0.075 mm
- ❖ Filler: Crushed stone passing through a 75 μm IS sieve

In this study, the aggregate and crushed stone dust was sourced from the Ethiopian Road Construction Corporation (ERCC) Deneba quarry in the Jmma zone of the Oromia region.

B) Asphalt Binder:

Asphalt binder is a crucial component of asphalt pavement, responsible for providing strength, durability, and flexibility to the road surface. In order to achieve optimum performance, it is important to understand and study the key properties of asphalt binder [1].

The asphalt binder, classified with a grade of 60/70, was sourced from the Ethiopian Road Construction Corporation (ERCC) as depicted in Figure 3.3. Comprehensive physical quality assessments were conducted on the asphalt, including tests for specific gravity, softening point, ductility, penetration, and flash and fire points. These evaluations were performed in accordance with ASTM, AASHTO, and ERA 2013 standards. The purpose of these tests is to ascertain the asphalt's quality, ensuring the selection of appropriate binders for specific pavement applications and facilitating the design of optimal asphalt mixtures.

C) Mineral filler (Waste marble powder)

Filler type and content significantly impact the mechanical properties of asphalt mixtures. The specific properties of the filler, such as its interaction with bitumen and its contribution to the mixture's performance, play a crucial role in determining the overall mechanical performance of the asphalt mixture [106]. Crushed dust stone and waste marble powder passing through a No. 200 square mesh sieve were employed as mineral fillers in the preparation of Hot Mix Asphalt (HMA) (Figure 3.3). The waste marble powder used as a filler was obtained from the Addis Ababa Bole/Gullele branch of the Ethio-Marble Industry.

Marble, a metamorphic rock, primarily consists of recrystallized carbonate minerals, predominantly calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$). Renowned for its aesthetic appeal, marble is extensively utilized in sculpture, architecture, and interior design [98]. Below are the detailed physical properties of the crushed stone dust and marble powder used in this study.

Table 3.1: Physical properties of crushed stone dust and waste marble powder

Physical Properties	Mineral filler		Specification Requirement
	CSD	WMP	
Specific gravity	2.690	2.661	2.6-2.86 [107]
Plastic Index	NP	NP	<4 [108]
Particle size distribution	Mostly <75µm	Mostly <75µm	70-100 [108]
Density (Kg/m3)	2690	2661	2600-2800 [107]
Color	gray	white	

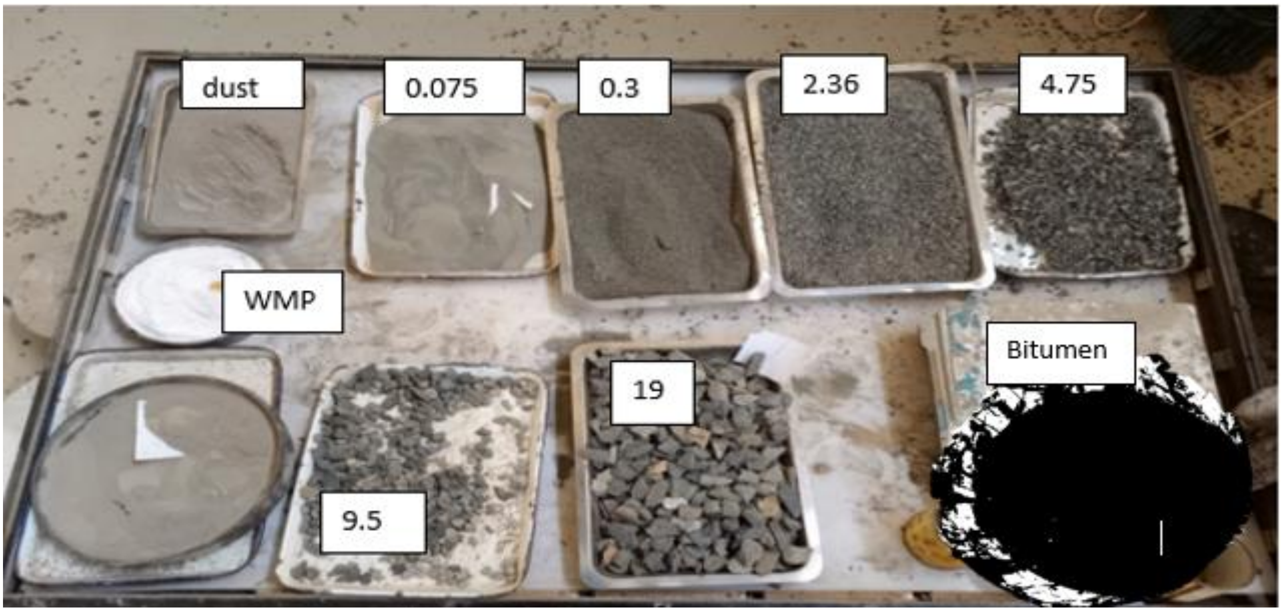


Figure 3.3: Aggregate, marble powder and bitumen used for asphalt mix batch

3.6. Sampling Size

The study by M. S. Eisa [109] investigated the effects of various waste materials as mineral fillers on asphalt mix properties, focusing on marble dust. The research examined the properties of asphalt modified with marble dust at eight different percentages (10%, 15%, 20%, 25%, 30%, 35%, 50%, and

75%) by weight of limestone dust conventional filler. Asphalt binder content ranged from 4.5% to 6.5% in 0.5% increments. The findings indicated that asphalt with 25% waste marble dust achieved the highest stability.

Levy Sang [110] explored the mechanical properties of hot mix asphalt incorporating waste marble dust. Sang's study used marble dust at 0%, 2%, 4%, and 6% by weight of total aggregates, with four different bitumen percentages. The Marshall stability test results demonstrated that 4% marble dust was the optimal filler content, while 6% marble dust provided the best rutting resistance.

According to ASTM standards, a minimum of three specimens is required for Marshall mix design. Sixteen samples (three for each bitumen percentage) were prepared to determine the optimum bitumen content (OBC), with bitumen percentages ranging from 4.5% to 6% in 0.5% increments without additive modification. Conventional Marshall samples, 101.6 mm in diameter and 63.5 mm in height, were used to measure density, Marshall stability, flow, volumetric parameters, moisture-induced damage via indirect tensile strength (ITS), and rutting potential through wheel tracking tests. The mixing and compaction temperatures were 125°C to 145°C and 140°C to 170°C, respectively.

For hot mix asphalt with crushed stone dust at 4.25% to 5.75% in 0.5% increments, 48 samples were produced. The study identified the optimum bitumen content (OBC) and optimum conventional filler (OCF) using three samples for each waste marble powder (WMP) percentage (0-50) %, in increments of 10% by weight of OCF). Six compacted Marshall samples were used to determine moisture susceptibility for mixtures with OBC and OCSD in both control and waste marble modified HMA at the optimum waste marble powder content. Twelve compacted Marshall samples (six wet and six dry) were used to evaluate the moisture susceptibility of the asphalt mixture.

3.7. Laboratory Test Method

3.7.1. Types of tests

The primary methodology employed to achieve the study's objectives was laboratory testing. All tests, except for the wheel tracking test (tested at Wolkite University, Highway lab), were conducted at Jimma University's Jimma Institute of Technology, within the highway materials laboratory. The properties of waste marble modified asphalt mixtures were evaluated and compared to conventional asphalt mixtures, both modified and unmodified, against specified standards.

Initially, the physical quality characteristics of the materials used, including aggregates and asphalt binder, were assessed. The asphalt binder underwent physical quality testing, including penetration, specific gravity, ductility, fire and flash point, and softening point tests. For the aggregates, tests conducted included the aggregate crushing value, Los Angeles abrasion test, water absorption test, and assessments of particle shape and specific gravity. Sieve analysis was performed for each aggregate type to determine size grading, followed by aggregate blending to create the binder course gradation curve used in the asphalt mix.

Subsequently, asphalt mixtures with various asphalt binder contents were prepared, and the Marshall test was conducted to determine the optimum binder content (OBC). Parameters such as density, air voids, Marshall stability, and flow were used to calculate the OBC of the conventional asphalt mixture. Asphalt mixtures incorporating waste marble powder in varying percentages (0-50%) at 10% increments were prepared using the determined optimum asphalt binder content. To evaluate moisture susceptibility and rutting resistance, indirect tensile strength tests and wheel tracking tests were conducted on both the mixtures with optimum bitumen content and the modified asphalt mixtures respectively.

3.7.2. Method of test

A) Aggregate tests according to their corresponding standards

i) Sieve analysis aggregate test: Sieve analysis was conducted to determine the particle size distribution of the coarse and fine aggregates, as well as fillers used in the asphalt mix. This test, compliant with ERA 2014 standards, involved pouring a known weight of aggregate into a well-arranged set of test sieves (Refer Table 3.2 and Appendix A, Table A1.1-A1.3). The aggregate retained on each sieve was used to calculate the grain-size distribution of each type of aggregate.

Table 3.2. Combined sieve analysis of course and fine aggregate

Test type: Average sieve analysis of fine and coarse aggregate						
Material description: Crushed Aggregate (Basalt) Material for: Asphalt Wearing course			Test Method AASHTO T- 27, ERA 2013 Tested Date: Nov 23/2023-Nov 25/2023			
Sieve Size (mm)	Bin #3 (2.36-0.075 mm)	Bin #2 (9.5-2.36 mm)	Bin #1 (19-9.5 mm)	Aver. Combined % Passing	Specification Limit	
	Ave.% Passing	Ave.% Passing	Ave.% Passing		Lower	Upper
25	100.0	100.0	100.0	100.0	100	100
19	100.0	100.0	76.0	92.0	90	100
9.5	92.1	57.5	42.0	63.8	56	80
4.75	79.1	36.8	17.3	44.4	35	65
2.36	60.0	23.0	4.0	29.0	23	49
0.3	16.4	9.6	0.0	8.7	5	19
0.075	8.0	5.7	0.0	4.6	2	8

ii) The Aggregate Crushing Value (ACV): This test determines the mass percentage of material crushed to sizes less than 2.36 mm under a compressive load of 400 KN. This test, performed on natural aggregates, adhered to BS 812: PART 110: 1990 standards (Appendix A, Table A2.1). This test simulates the aggregates' resistance under gradual applied load conditions.

iii) An Aggregate Impact Value (AIV): This test was also conducted on natural aggregates according to BS: 812 PART 112: 1990 standards (Appendix A, Table A2.2). The AIV represents the percentage of fines produced from an aggregate sample subjected to a standardized impact procedure. This test simulates the aggregates' resistance to impact under field conditions.

iv) The Los Angeles Abrasion Test (LAAV): evaluates the aggregate's resistance to abrasion and degradation [108]. (Refer Appendix A, Table A2.3).

v) Flakiness index test: It determine the flakiness of aggregate

vi) Specific gravity (Gs) and water absorption: for coarse and fine aggregates was carried out using the wire basket and pycnometer methods, in compliance with AASHTO T-85/ASTM C127 and AASHTO T-84/ASTM C128 respectively. Water absorption (W_{abs}) tests were performed to assess the aggregates' ability to absorb water, following AASHTO T85 standards (Appendix A, Table A3).

B) Bitumen quality tests and their corresponding standards

The asphalt binder, with a penetration grade of 60/70, was heated to 140-170°C until it became a free-flowing, semi-viscous liquid. The basic quality tests performed on the asphalt binder included:

1) Penetration Test: This test measures the hardness of the bitumen according to ASTM D5 standards (Appendix B, Table B1.1). It determines the distance in tenths of a millimeter that a standard needle penetrates vertically into the binder under specific conditions of temperature, load, and time. The average of three penetration readings was recorded as the representative value [1].

2) Ductility Test: The ductility of the asphalt binder was measured by the distance (in mm) to which a sample of bitumen elongates before breaking according to ASTM D5-86. This test uses a standard briquette specimen pulled apart at a specified speed and temperature (25°C ± 0.5) as regulated by the ductility machine [85] (Appendix B, Table B1.2).

3) Ring and Ball Test: Conducted according to ASTM D36 standards, this test evaluates the softening point of the bitumen (Appendix B, Table B1.3). It measures the susceptibility of the asphalt binder to temperature changes [85].

4) Specific gravity: Asphalt binder specific gravity is a crucial parameter in asphalt mix design and quality control. It refers to the density of the asphalt binder relative to the density of water [85] (Appendix B, Table B1.4)

5) Fire and flash point: Both the flash point and fire point are determined using standardized testing methods such as the Cleveland Open Cup (COC) method, which is specified in ASTM D92 (Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester) [85] (Appendix B, Table B1.5). These properties are crucial for ensuring safe handling, storage, and application of bitumen, particularly in high-temperature environments or during operations like paving, where bitumen is heated to elevated temperatures. These tests ensured that both the aggregate and the bitumen met the necessary quality standards for use in asphalt mixtures.

3.8. Marshall Hot Mix Design

The asphalt mixture is assessed in the laboratory before paving the field to check its mechanical properties and performance criteria based on different methods and standards. Two common and general techniques for compacting the asphaltic mixtures in the laboratory scale are:

i) Gyratory compaction and

ii) Marshall compaction.

In the gyratory method, the hot mix is compacted and gyrated simultaneously, while in the Marshall method, the asphaltic mixture is only compacted by several blows in a cylindrical mold. Marshall mixes design is a method used for designing asphalt mixtures. It involves determining the optimal combination of mix design parameters such as coarse aggregate, fine aggregate, mineral filler and bitumen content. The interaction between these parameters influences the properties of the asphalt mixtures [111].

Marshall mixes design is a widely used method for designing hot mix asphalt (HMA) to achieve desired performance characteristics. It was developed by Bruce Marshall in the 1930s and has since become a standard approach in the asphalt industry. The Marshall method only applies to hot-mix asphalt that has aggregates with a maximum size of 25mm (1 inch) or less and contains asphalt binder and mineral filler [61, 1]. Marshall test protocols are standardized by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM) [1].

The Marshall mix design process involves determining the optimal combination of aggregates, asphalt binder, and additives to produce an HMA mix that meets specific performance requirements. These requirements typically include factors such as stability, flow, density, rutting resistance, moisture susceptibility and durability.

Job mixes Formula (JMF) was used to get appropriate mix proportion. The Job Mix Formula (JMF) is a detailed specification used in the production of Hot Mix Asphalt (HMA). It outlines the proportions of various components to be used, including aggregate sizes, the amount of asphalt binder, and any additives required. The JMF is developed based on laboratory tests and mix design procedures to ensure that the resulting asphalt mix meets performance criteria and specification requirements. The goal of the JMF is to create a durable and high-quality pavement that can withstand traffic loads and environmental conditions [61, 84]

3.8.1. Marshall mixes design preparation

The Marshall mix design method was employed to determine the optimum binder content (OBC) for a conventional asphalt mixture without marble modification. This technique assesses the resistance to plastic deformation of a compacted cylindrical asphalt specimen when subjected to a loading rate of 50 mm/min [1, 84]. The preparation of cylindrical test specimens was conducted in accordance with (ASTM) [108] standards.

To fabricate the specimens, 1150 grams of preheated aggregate and binder were mixed for to ensure thorough integration (Figure 3.4a-b). The mixture was then placed into a mold, with each side compacted by applying 75 blows (Figure 3.4c). The samples removed from the molds after 24 hours (Figure 3.4d).

Figure 3.4: Marshall specimen preparation (a) pouring the heated bitumen to aggregate, (b) mixing, (c) compact and (d) compacted Marshall specimen

3.8.2. Compacted specific gravity of hot mix asphalt

Laboratory compacted specific gravity asphalt mixture testing is generally used to measure two essential asphalt mix properties: the bulk specific gravity of the mixture (G_{mb}) and the theoretical maximum specific gravity of the mixture (G_{mm}) [1].

A) Determine Bulk specific gravity test, G_{mb} using SSD method (ASTM 2726)

The bulk specific gravity of asphalt concrete is important in determining the volumetric properties of hot mix asphalt mixtures. These volumetric properties are good indicators of the performance of asphalt concrete. The compacted samples were allowed to cool at room temperature for 24 hours, and the bulk specific gravity was measured at 25°C according to ASTM D2726. The determination of the bulk specific gravity (Gmb) of lab-molded specimens and roadway cores is a critical component of asphalt mix design and testing [1]. The mass of the sample is determined in the air (dry), submerged in water, and then in the air again after drying the surface (saturated surface dry) after mixing, aging, and compacting the combination (Figure 3.5).

The bulk specific gravity is defined as the mass of the sample divided by the volume of water. The mass includes both the aggregate and the binder. The volume of a compacted specimen contains the effective volume of the aggregate, the volume of the binder, and the volume of air voids. The determination of bulk specific gravity expressed in Eqn.3.1.

$$Gmb = \frac{A}{B-C} \qquad \text{Eqn. 3.1}$$

Where, G_{mb}= Bulk specific gravity (g/cm^3)

A= dry mass of the specimen in air (g)

B= saturated surface-dry (SSD) mass of the specimen in air (g)

C= mass of the specimen in water at 77°F (25°C) (g)

Figure 3.5: Bulk specific gravity test

B) Determination of theoretical maximum specific gravity, G_{mm}

Determining the theoretical maximum specific gravity (G_{mm}) of loose asphalt mixtures is another basic component of asphalt mix design and testing that requires a mass divided by a volume multiplied by the unit mass of water. In this scenario, the mass includes both the aggregate and the binder masses. The volume solely includes the effective volume of the aggregate and the volume of the binder [1].

The theoretical maximum specific gravity of an asphalt concrete mixture is the specific gravity of the mixture at zero voids as shown in Figure 3.6. Maximum specific gravity of a mixture performed according to ASTM D 2041 or AASHTO T-209 method. The determination of the compressed weight and specific gravity of a mixture is expressed by the Eqn. 3.2 [33].

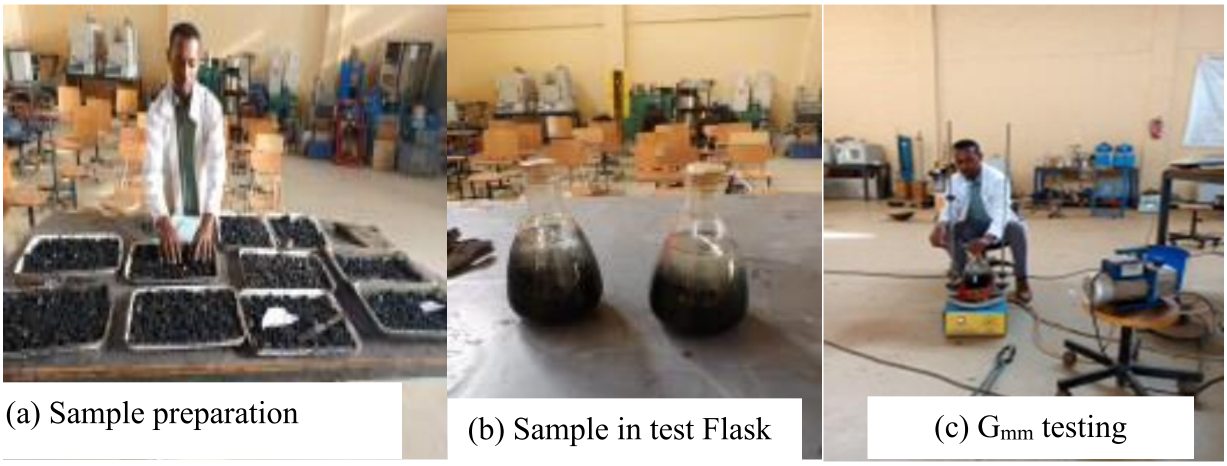
$$Gmm = \frac{A}{A-(E-D)} \qquad \text{Eqn. 3.2}$$

Where, G_{mm}= Theoretical maximum specific gravity

A=the mass of mix in air dry at room temperature (g)

B=the mass of flask with filled water at 25˚C (g)

E=the mass of container with mix sample and water (g)

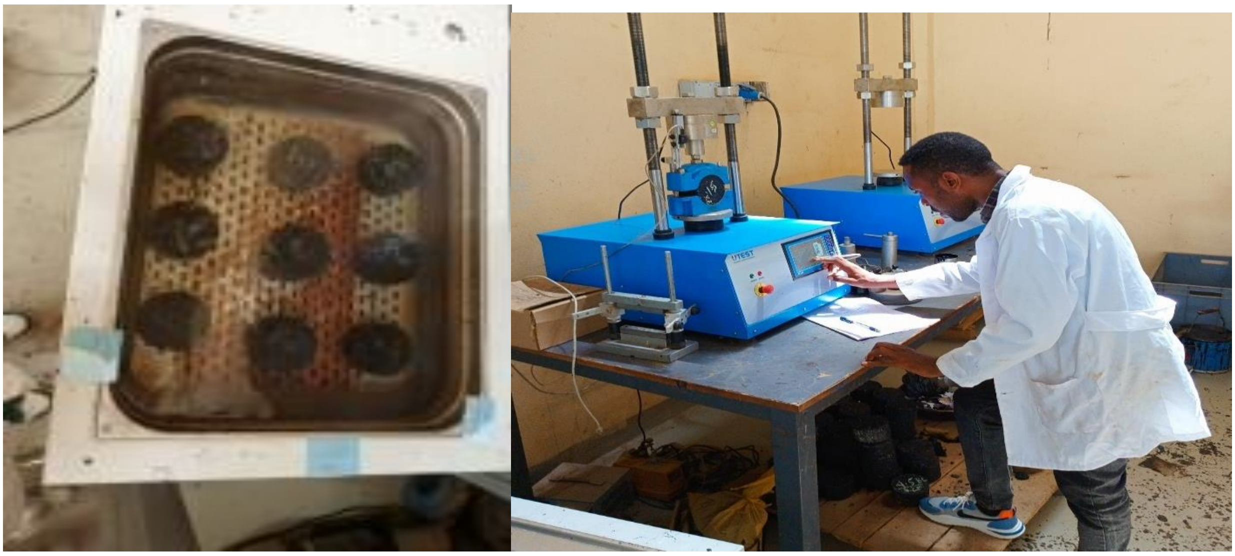


(a) Sample preparation (b) Sample in test Flask (c) G_{mm} testing

Figure 3.6: Maximum theoretical specific gravity test

3.8.3. Marshall stability-flow test

Following compacted bulk specific gravity determination, samples were conditioned at 60°C (Figure 3.7a) for 30-40 minutes for the Marshall stability-flow test, as per ASTM D1559 specification [1]. Figure 3.7b show that the test samples were then put through their spaces in the Marshall press at a displacement rate of 50.8 mm/min until they reached their maximum load. The flow is the value of deformation in mm that the sample registered upon attaining the maximum load value, and the resulting stability rate corresponds to the maximum load resisted.



a) Marshall specimen in 60°C water bath for 30-40 min b) Marshall stability-flow test

Figure 3.7: Marshall stability-flow test

In this investigation, five proportions of waste marble powder 0%-50% in 10 % increment by weight of conventional crushed stone dust filler material were chosen to be investigated for the manufacture of waste marble powder modified HMA samples and detection of OWMP as shown in the Figure 3.8. For adjusted combinations, the total percentage of binder (OBC) in the mix remained unchanged (5.24%).

Figure 3.8: Waste marble modified Marshall specimen

3.9. Volumetric Characteristics of Compacted Paving Mixtures

The volumetric characteristics of a compacted paving mixture refer to the properties and behavior of the mixture in terms of its volume and density. These characteristics play a crucial role in determining the performance and durability of the pavement. The volumetric characteristics of a compacted paving mixture, including bulk density, air voids, VMA, and VFA, are influenced by the compaction process. Proper compaction ensures a dense, impermeable, and durable pavement structure, which is essential for long-lasting and high-performance road surfaces [1, 61].

(Refer Appendix C, Table C4.1-C4.5 for detail).

3.9.1. Percent air void (Pa)

The air void (VIM) in the final compacted mixtures is a void between the coated aggregate particles. The air void of a compacted specimen is determined by the compaction method, compaction temperature, number of loadings on the mixtures, height, and weight of compaction [1]. According to the ERA 2014 technical specification [84], the air void in the hot mix should be between 3-5%. After calculating the loss and compressed specific gravity of the mixtures, the air void was examined. This outcome is expressed as a percentage (Refer Appendix C, Table C4.1-C4.5). The percent air void (P_a) is computed as shown in the Eqn.3.3.

$$Pa = 100 - \frac{100*Gmb}{Gmm} \quad \text{Eqn. 3.3}$$

Where, P_a= air voids in compacted mixture, percentage of total volume

G_{mm} = theoretical maximum specific gravity of paving mixture

G_{mb} = bulk specific gravity of paving mixture (g/cm^3)

3.9.2. Voids in mineral aggregate (VMA)

The voids in mineral aggregate (VMA) are defined as the intergranular void space between aggregate particles in a compacted paving mixture that comprises the air voids and the effective asphalt content, given as a percentage of total volume [1]. VMA is crucial because it affects the amount of asphalt binder that can be effectively coated onto the aggregate particles, which in turn influences the durability and performance of the asphalt mix. To achieve the desired VMA in HMA, several factors can be considered during mix design and production: Such as gradation, aggregate shape, aggregate packing, and asphalt binder content. The VMA is computed using the bulk specific gravity of the aggregate and expressed as a percentage of the compacted paving mixture's bulk volume [61]. VMA is computed using Eqn.3.4.

$$VMA = 100 - \frac{Gmb*Ps}{Gsb} \quad \text{Eqn. 3.4}$$

Where, VMA= voids in the mineral aggregate (%)

G_{mb}=bulk specific gravity of paving mixture (g/cm^3)

P_s = percentage of aggregate by total mix weight (%)

G_{sb} = bulk (dry) specific gravity of the aggregate (g/cm$_3$)

3.9.3. Percent VFA in compacted mixture

The term "Void Filled Asphalt" (VFA) refers to a type of asphalt mix designed to minimize the presence of air voids within the asphalt pavement. Void Filled Asphalt is often employed in areas where moisture infiltration can lead to premature pavement deterioration, such as the formation of potholes and cracks. By minimizing voids and improving impermeability, VFA helps enhance the longevity and performance of asphalt pavements in challenging environmental conditions. This is achieved through careful control of numerous factors in the mix design process: like proper aggregate gradation, binder content, compaction, and air voids control [1].

Asphalt-filled voids (VFA) represent volume percent of VMA and are percent filled with active binder. Like VMA, VFA also tends to increase as the mixture becomes finer and the total surface area of increases. VFA can be calculated using Eqn. 3.5.

$$VFA = 100 * \frac{VMA-Pa}{VMA}$$ Eqn. 3.5

where: VFA = voids filled with asphalt (%)

VMA = % of mineral aggregates voids

Pa = air voids in compacted mixture, percentage of total volume (%)

3.9.4. Percent binder absorption

Binder absorption in hot mix asphalt refers to the amount of asphalt binder that is absorbed by the aggregate particles during the mixing process. It is a crucial factor to consider in asphalt mix design as it directly affects the amount of binder needed to achieve the desired asphalt binder content in the final mix. Therefore, it is calculated based on the aggregate mass. P_{ba} is most readily calculated with the Eqn. 3.6 [1, 84].

$$Pba = 100 * \frac{Gse-Gsb}{Gse*Gsb}*G_b$$ Eqn. 3.6

Where, P_{ba} = absorbed binder, percentage by mass of aggregate (%)

G_{se} = aggregate's effective specific gravity (g/cm^3)

G_{sb} = bulk (dry) specific gravity of the aggregate (g/cm^3)

G_b = specific gravity of binder (g/cm^3)

3.9.5. Summary of Mix design specification

This study focuses on high-volume traffic, analyzing the properties of hot mix asphalt using the high-traffic criterion (Heavy traffic which is a design traffic between 1 to 5 million ESA). The mix design specification follows the ERA [33] methodology for flexible pavement design, and all mixtures must adhere to the Marshall standards for surface courses. Table 3.3 lists the requirement design standard specifications limits for each traffic class.

Table 3.3: Lists the limit design standard specifications for each traffic class [84]

Marshall Criteria for Asphalt mix design						
Category and design traffic (Million ESAL)	Number of Marshall Compaction	Minimum Stability (KN)	Flow (mm)	VMA (%)	VFA (%)	VIM @OBC (%)
Light (<0.4)	35	5.3	2-4.5	>=13	70-80	4
Medium (0.4-1)	50	5.3	2-4	>=13	65-78	4
Heavy (1-5)	75	8	2-3.5	>=13	65-75	4
Very Heavy (>5)	75	9	2-3.5	>=13	65-73	4

3.10. Asphalt Mixture Performance Tests

Asphalt mix performance tests are crucial evaluations conducted to assess the quality and characteristics of asphalt mixes, ensuring they meet specific engineering and performance standards. These tests help determine the suitability of the asphalt mix for its intended application in road construction. Performance testing of HMA mixes is done to determine the performance of HMA before it is used in a transportation facility, as well as to assess new materials and design techniques to improve the performance of HMA pavements [1]. To address various distresses, various testing and loading setups are applied. This study's goal is not to cover every conceivable performance test and test circumstance, but rather to provide a basic overview of mixed performance tests that can be utilized to solve specific pavement distresses (rutting resistance and moisture susceptibility).

3.10.1. Rutting (Permanent deformation) performance testing

Permanent deformation or rutting of asphalt mixtures is a problem that arises under loaded conditions at high pavement temperatures. As the pavement temperature rises, the asphalt mixture softens and becomes more prone to movement under load. When an asphalt mixture deforms underweight and does not rebound to its original, undeformed state, this is referred to as permanent deformation. Permanent deformation might result in channelization or rutting over time [1, 3].

Laboratory tests for rutting performance are performed at high temperatures to simulate the in-service temperature of the asphalt mixture during the summer months. Because mixture stiffness at high temperatures is considered crucial, most rutting tests frequently employed incorporate some sort of repetitive loading.

According to Asphalt Institute [1], loaded wheel testing is a typical approach used by certain designers to evaluate an asphalt mixture's rutting susceptibility. Although there are numerous varieties of loaded wheel tests, each with its own set of loading configurations and test conditions, the basic principles of the test remain the same.

1. Asphalt Pavement Analyzer (APA)

The Asphalt Pavement Analyzer (APA) is a popular loaded wheel test. This test is utilized for pavements with three million or more ESALs. A temperature of 64°C is commonly used as a standard test temperature. Asphalt mixture specimens are subjected to 8,000 cycles of testing or another specified endpoint [1].

2. Hamburg wheel tracking

The Hamburg wheel-tracking (HWT) test is another popular loaded wheel test. The HWT instrument, invented in Germany in the 1970s, evaluates the rutting and stripping resistance of asphalt mixtures. It tracks specimens with a heavy steel wheel, causing rutting. Dry or wet samples can be tested, with wet testing suggesting stripping susceptibility. The gadget assesses the susceptibility of bituminous material to rutting under wheel weight [1].

3. BS EN 12697-22 Bituminous mixture wheel tracking test

BS EN 12697-22 is a European standard for assessing the rutting susceptibility of asphalt mixtures using wheel tracking tests. This standard is widely adopted internationally and specifies three different test methods: two for small-sized devices (Procedures A and B) and one for a large-sized device (Table 3.4). The large size device is used for materials designed for wheel loads greater than or equal to 13t and therefore, this method did not consider in this research task.

Procedure A test method

- ❖ Utilizes six material samples.
- ❖ Samples are conditioned at the test temperature for 4-24 hours.
- ❖ Testing involves 1,000 cycles with a solid rubber tire, 50mm in width, under a 700N load.
- ❖ The cycle rate is maintained at 26.5 ± 1 cycles per minute, with the initial 5 cycles used for conditioning and deformation is measured at a single central point on the sample.
- ❖ The deformation rate is calculated over the final 300 cycles in μm/cycle.
- ❖ The total deformation determines the maximum rut depth.

Procedure B

- ❖ Utilizes two material samples.
- ❖ Samples are conditioned at the test temperature for at least 4 hours.
- ❖ Testing involves 10,000 cycles with a solid rubber tire, 50mm in width, under a 700N load.
- ❖ The cycle rate is maintained at 26.5 ± 1 cycles per minute, with the initial 5 cycles used for conditioning and deformation is measured as the average across 250 equally spaced points.
- ❖ The wheel-tracking rate is calculated over the 5,000 to 10,000 cycle range in millimeters [112].

Table 3.4: European categories for wheel tracking in EN13108 [113]

Device	Large size	Procedure A		Procedure B		
Measure	Proportional rut depth (%)	Rate (µm/ cycle)	Rut depth (mm)	Rate (µm/ cycle)	Proportional rut depth (%)	Rut depth (mm)
Categories	<5.0	<5.0	<3.0	<0.02[a]	<1.0[b]	<1.0
				<0.03	<1.5[b]	<1.5
		<7.5	<5.0	<0.04	<2.0[b]	<2.0
	<7.5			<0.05	<2.5[b]	<2.5
		<10.0	<7.0	<0.06	<3.0	<3.0
				<0.07	<4.0	<3.5
	<10.0	<12.5	<9.0	<0.08[c]	<5.0	<4.0
				<0.09[c]	<6.0	<4.5
		<15.0	<11.0	<0.10	<7.0	<5.0
	<15.0			<0.15	<8.0	<6.0
		<17.5	<13.0	<0.30	<9.0	<6.5
				<0.40	<11.0	<7.0
	<20.0	<20.0	<16.0	<0.50	<13.0	<8.0
				<0.60	<16.0	<9.0[d]

In this research, Procedure B of the single wheel tracking test was employed to determine the rut depth of bituminous mixtures, in accordance with the BS EN 12697-22:2020 standard using a Wheel Tracking Device. Set the machine in motion and take readings at the vertical displacement of the wheel, initially, then at least 6 or 7 times in the first hour, and at least one reading every 500 load cycles thereafter. The vertical position of the wheel is defined as the mean value of the profile of the specimen on a length of ± 50 mm about the center of the loading area at the midpoint of traverse, measured in at least 25 points approximately equally spaced. The vertical position of the wheel shall be measured without bringing it to a stop. Continue tracking until 10,000 load cycles are applied or until a rut depth of 20 mm is reached whichever is the rutting failure.

The contact area of the tire follows a simple harmonic motion relative to the specimen's top surface, traveling a total distance of (230 ± 10) mm at a frequency of (26.5 ± 1.0) cycles per minute. A vertical displacement sensor attached to the device records the rut depth (mm) at the specimen's surface. The device is equipped with a temperature control system to ensure uniform temperature throughout the testing period [112, 113].

Basic test procedure for Single Wheel Tracking Test

The test was conducted on control asphalt mixtures and waste marble powder asphalt mixtures at their respective optimum bitumen and waste marble powder contents. The procedure was as follows:

1. Preparation of asphalt mix components: Aggregate, bitumen, and filler were prepared at their optimum values.

2. Preheating and mixing: Aggregate and bitumen were preheated and mixed at high temperature of 175 °C using an automatic asphalt mixer.

3. Specimen formation: The mixed asphalt was added to a pre-prepared rectangular slab mold (320 mm x 260 mm x 50 mm) and compacted using an automatic roller asphalt compactor. Two slabs were prepared for each test. The air void values determined the number of rollers passes needed for proper compaction. The number of rollers passes 64 and 59 for control and modified mix respectively.

4. Conditioning: The compacted asphalt slabs were preheated at 60°C for a minimum of 4 hours in an oven dry prior to the rutting test.

5. Testing: The rutting test machine was calibrated, and the rut depth was measured using the single wheel tracking device. A 700N load was applied to the specimen, which was moved back and forth for 10,000 load cycles over 7 hours. Rut depth measurements were recorded every 250 load cycles. The rut depth and proportional rut depth is calculated as Eqn.3.7 and Eqn. 3.8 respectively [113].

$$WTSair = \frac{d10,000 - d5000}{5} \text{ (mm/}10^3\text{ load cycles)} \quad \text{Eqn. 3.7}$$

Where: WTS_{air} = wheel truck slope in air

d10000 = rut depth at 10,000 cycles

d5000 = rut depth at 5000 cycles

$$PRDair = \frac{dn - do}{h} * 100 \quad \text{Eqn. 3.8}$$

Where: PRD_{air} = the proportional rut depth of i^{th} replicate, in percent (%)

d_n = the vertical displacement after n load cycles, in millimeter (mm)

d_o = the vertical displacement initially, in millimeter (mm)

h = the specimen thickness, in millimeter (mm)

(1) Preheating aggregate at 175 °C

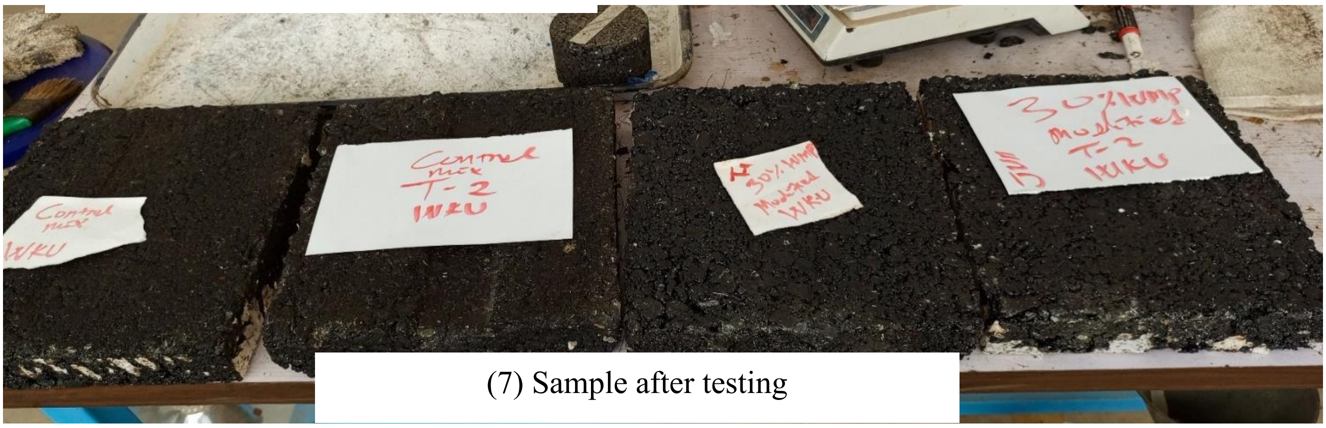
(2) Add heated bitumen to preheated aggregate

(3) Mixing by automatic asphalt mixture

(4) Sample under roller asphalt compactor

(5) Adjustment of specimen for test

(6) Testing



(7) Sample after testing

Figure 3.9: Rutting test procedure

3.10.2. Moisture induced damage (Indirect tensile strength test)

The moisture induced damage test evaluates how well an asphalt mix can resist the detrimental effects of moisture, such as stripping or loss of adhesion between the asphalt binder and the aggregate [1]. The test was conducted according to [114] test method, by preparing three Marshall specimen for each unconditioned (dry) and conditioned (wet) to evaluates the loss of strength of hot mix asphalt after moisture exposure. The indirect tensile strength test was used to assess this susceptibility.

This study used the tensile strength ratio (TSR) to analyze the moisture-induced damage properties of asphalt mixtures. The TSR test estimates water/traffic action and pore pressure effects on bituminous mixes performance. The study aimed to evaluate asphalt mixtures with and without waste marble powder filler at the optimum binder content and optimum waste marble powder. The test was carried out in accordance with [114] specifications (Figure 3.10), evaluating compressive strength after conditioning specimens in a 60°C water bath for 24 hours. A higher score indicates less moisture susceptibility (greater resistance to moisture damage). Indirect Tensile strength was computed as Eqn. 3.9 [85].

$$S_t = \frac{636.62 * Pmax}{t * D} \qquad \text{Eqn. 3.9}$$

Where: St= tensile strength (Kpa), t= specimen thickness (mm), P=maximum load (N) and D= specimen diameter (mm)

Tensile Strength Ratio (TSR)

$$TSR\ (\%) = \frac{St2}{St1} * 100 \qquad \text{Eqn. 3.10}$$

Where: S_{t1} = average tensile strength of unconditioned or dry subset

S_{t2} = average tensile strength of conditioned subset (wet)

Figure 3.10: Indirect tensile strength test

3.11. Numerical Analysis (Finite Element Method)

The Abaqus 6.14 version software was used to analyze the rutting depth of asphalt mix, a crucial parameter for pavement performance under heavy traffic loads. The software was comparing the rutting depths of the control and the modified mix, evaluating the effectiveness of the modification in improving rutting resistance. The goal of this simulation is to discover the layer reaction (vertical deflections) in pavement layers under projected traffic loads in constant static loading situations and varied pavement layer thicknesses. As a result, the pavement section's improvement can be assessed.

3.11.1. Basic software input variables

a) Modulus elastics

For various Abaqus models, the modulus of elasticity is used as the key indicator of stiffness. The elastic modulus based on recoverable strain under repeated load is known as Young's modulus or modulus of elasticity. For the purpose of this study the modulus of elasticity of asphalt layer obtained empirically from Eqn. 3.11 [85]

$E_{mod}=6.1*S_t+100$ (MPa) Eqn. 3.11

Where: S_t= indirect tensile strength (kPa)

To define the required parameters of the modified mixtures, indirect tensile strength test was conducted on the modified mixture as well as the control mixture. The indirect tensile strength test gives the tensile strength of the mixture which determine by the Eqn. 3.9 [85].

b) The Poisson's ratio

It is a material property that can be used to predict an asphalt mixture's horizontal movement. It is defined as the ratio of horizontal to vertical strain. Poisson's ratio values in most investigations were between 0.3 and 0.4 [33].

c) Flexible pavement layer

The flexible pavement layer characteristics such as thickness, depth, and width are the characteristics used in modelling. The subgrade, subbase, base course, and top asphalt layer make up a typical flexible pavement cross-section.

d) Tire pressure

For all models, the wheel load is simulated as applied pressure acting on a circular area with a radius of 0.20m between the pavement surface and the wheel load and a constant value of 0.7Mpa [33].

Table 3.5: Abaqus 6.14V software input parameters

Materials	Materials Characteristics		
	Young's Modulus elastics (MPa)	Poison ratio (v) [33]	Layer thickness (mm) [33]
Unmodified Wearing course	4276.88	0.35	50
WMP Modified Wearing course	5274.4	0.35	50
Granular road base, GB1 [33]	300	0.3	175, CBR>80%
Granular sub base, GS [33]	125	0.3	250, CBR>30%
Subgrade [33]	73	0.4	CBR 8-14%

Table 3.5 shows the flexible pavement layer such as base course, subbase and subgrade materials properties like young's modulus elasticity, poison ratio and layer thickness are taken from ERA 2013. Asphalt wearing course materials modulus of elasticity were obtained from Eqn. 3.11 and poison ratio was taken from ERA 2013. The young's modulus of asphalt mixes for both control and WMP modified HMA are analyzed from indirect tensile strength load by empirical method. This study was analyzed the effect of elastic modulus on the vertical deformation (U2) (Rutting depth) for the indicated pavement section using Abaqus software.

3.11.2. Development of a flexible pavement model using Abaqus/CAE modules

The finite element method (FEM) is a robust numerical technique for approximating solutions within the domain of continuum mechanics. Renowned for its versatility, FEM is extensively employed to simulate the response of structures under various engineering scenarios [74]. Flexible pavements exemplify complex engineering systems characterized by multiple layers, diverse materials, and intricate boundary conditions [33].

This study outlines a rigorous approach to analyzing flexible pavements using FEM, detailing the procedures for gathering the necessary data for comprehensive finite element analysis. Utilizing Abaqus software, the study employs the 8-node C3D8R element to conduct a three-dimensional solid structural analysis, effectively modeling and evaluating the behavioral responses of the pavement system.

This step involves defining the geometry of the pavement layers, assigning appropriate material models such as linear elasticity, poison ration, and setting up contact interactions between different layers to simulate the pavement's response to traffic loading. Subsequent sections focus on the simulation setup, detailing the application of loadings, boundary conditions, and meshing techniques essential for capturing the behavior of the pavement under various loading scenarios. Emphasis is placed on selecting suitable element types and mesh densities to ensure accurate and efficient simulation results.

A) Model geometry

Finite Element Analysis (FEA) has been demonstrated to be highly effective for complex pavement problems [74]. The finite element software Abaqus 6.14V is utilized to simulate displacements throughout the pavement structure, accurately replicating real-world conditions. Specifically, flexible pavements are modeled to simulate actual vehicle loading conditions, enabling precise estimation of structural responses.

A three-dimensions of the pavement model developed by using Abaqus are defined by its length in the X-direction, width in the Z-direction, and thickness in the Y-direction. Element sizes within the model were determined through convergence studies to ensure accuracy. For this study, the model adopts cubic dimensions of 500x500x500 mm in length, width, and depth respectively as shown in Figures 3.11.

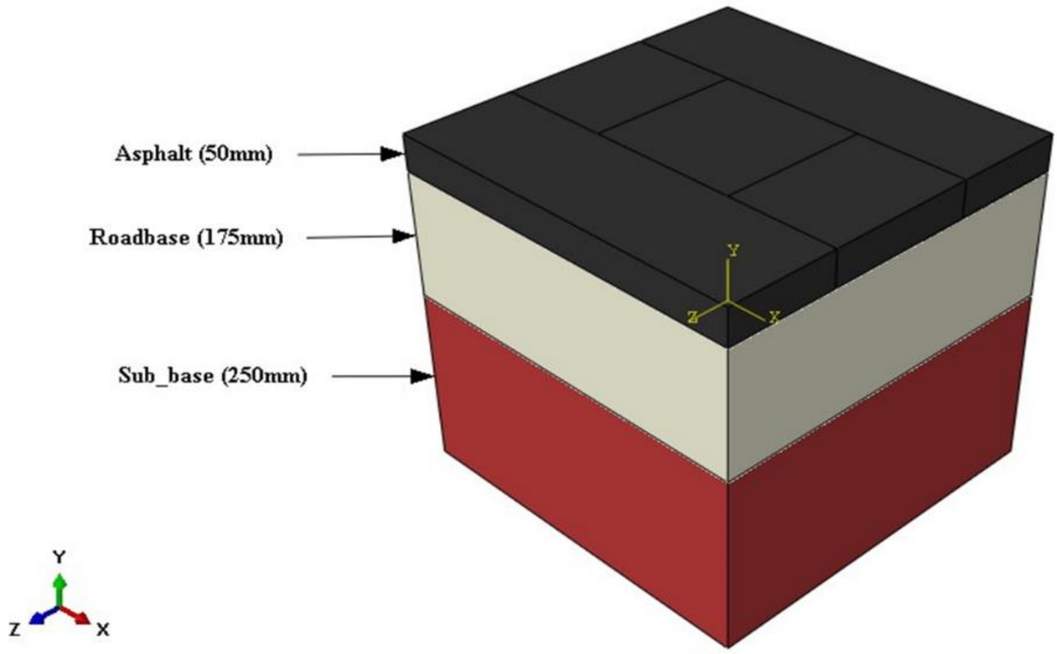


Figure 3.11: 3D FEM geometry

Figure 3.8 shows that the 3D model of geometry was composed of asphalt wearing course, roadbed and subbase of 50mm, 175mm and 250mm thickness respectively. The thickness of subgrade in this model is assumed to be infinite in dimension.

B) Finite element type and mesh

The model components are represented using the Hexahedra-8-node three-dimensional continuum brick element (C3D8R) in Abaqus 6.14V. This element, which incorporates reduced-order numerical integration, is adept at handling large deformations as well as geometric and material nonlinearities. Each C3D8R element possesses three degrees of freedom per node (X, Y and Z). Consistent element shapes are employed across all pavement layers to maintain nodal continuity between adjacent layers, ensuring accurate simulation of the structural behavior [115, 74]. The asphalt layer was finely meshed

(20x20 mm) along the wheel paths and coarsely meshed (40x40 mm) at the edges, roadbed, and subbase as shown in Figure 3.12. Each component's edges in the model geometry are constrained to move solely in the vertical direction (U2) in Abaqus while being fixed in the horizontal direction, ensuring the creation of an accurate mesh.

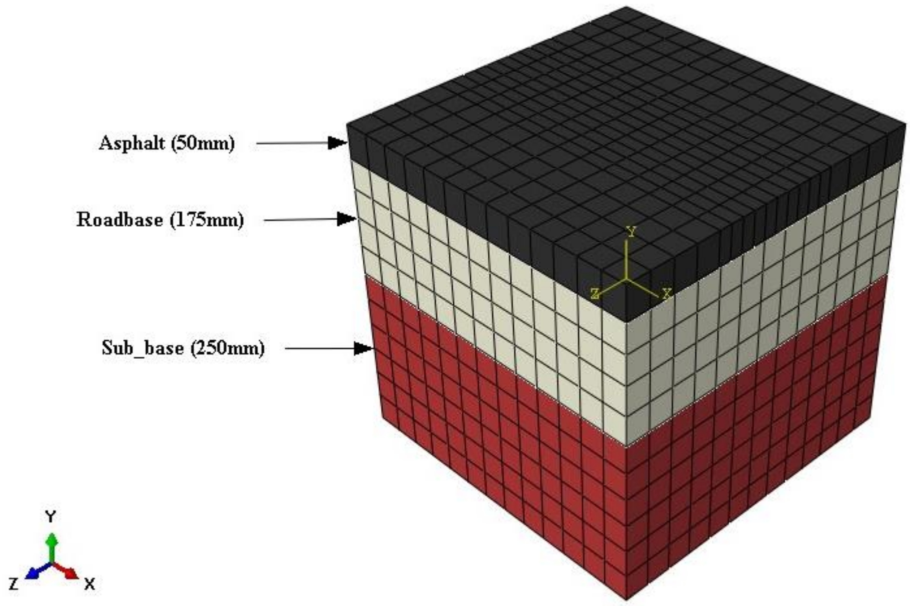


Figure 3.12: Layer model meshing

C) Boundary condition and load

Boundary conditions in Abaqus software modeling are essential for defining how a model interacts with its surroundings and for specifying constraints and loads. It is significantly impacting the accuracy of the model's response predictions [115, 116, 74]. Bottom plane has been restricted from the translational or rotational degrees of freedom as illustrated in Figure 3.13. Proper setting boundary conditions is crucial for achieving accurate and meaningful results in Abaqus simulation

The precision of the model is influenced by several parameters, including the material properties, the number of elements incorporated in the finite element (FE) model, the degrees of freedom, the distribution of contact stress, and the boundary conditions. As the number of structural elements and degrees of freedom in the FE model increases, so does the computational complexity. Different types of elements are employed in the FE model to accurately represent the geometry, with adjacent elements interconnected at nodes. Nodes serve as connection points within the FE model where degrees of freedom are specified [74, 117].

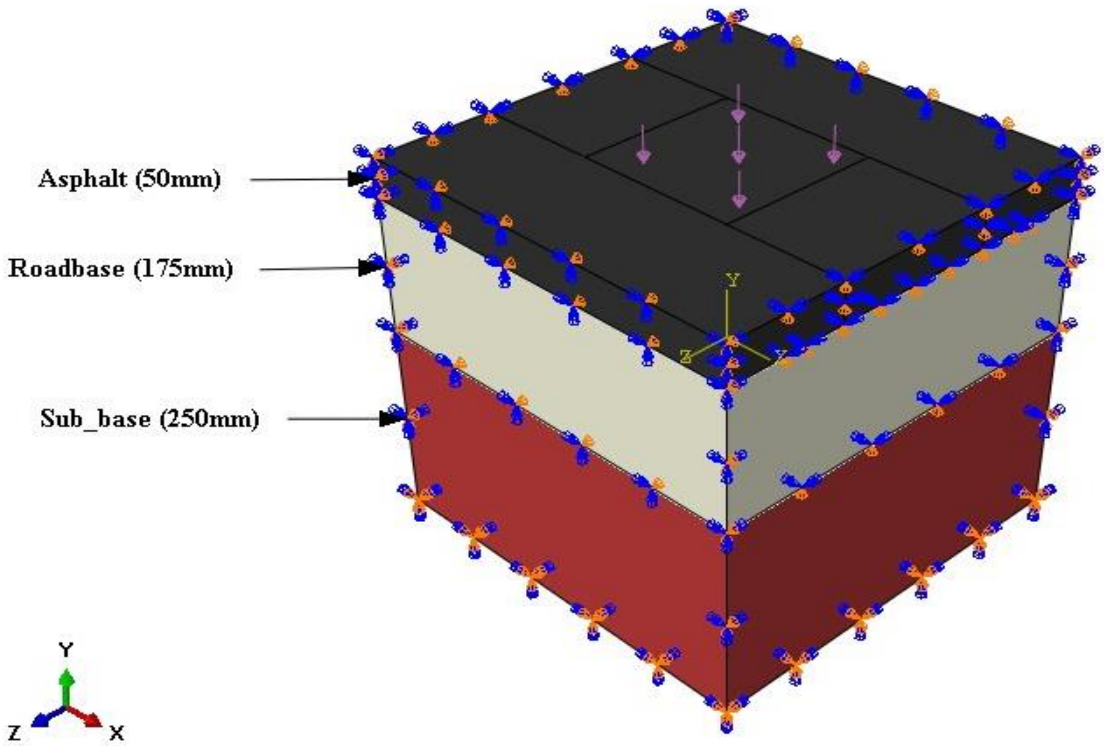


Figure 3.13: Boundary condition

D) Load condition and wheel path

Load cases are sets of loads and boundary conditions used to define a particular loading condition. Using 3D FE modeling of the flexible pavement was used to simulate a rectangular footprint of the contact area over which the tire pressure was distributed. The load was assumed to be transferred to the pavement over a rectangular contact area.

The tire pressure of 0.48 MPa (70 psi) used in the 1962 AASHTO road tests is relatively low compared to current standards. Today, over 90% of heavy trucks operate with higher tire pressures, commonly exceeding 0.7 MPa (102 psi), with some heavily loaded trucks reaching up to 1.03 MPa (150 psi) [33]. For this study, a tire pressure of 0.7 MPa was applied as a distributed load at the center of the pavement section of 200 mm-by-200 mm dimension in the longitudinal direction. Given the high traffic flow of passenger cars in the study area, a tire contact pressure of 0.7 MPa was deemed appropriate. Figure 3.14 illustrates the direction of the wheel path, with the green area indicating the region where the load is applied.

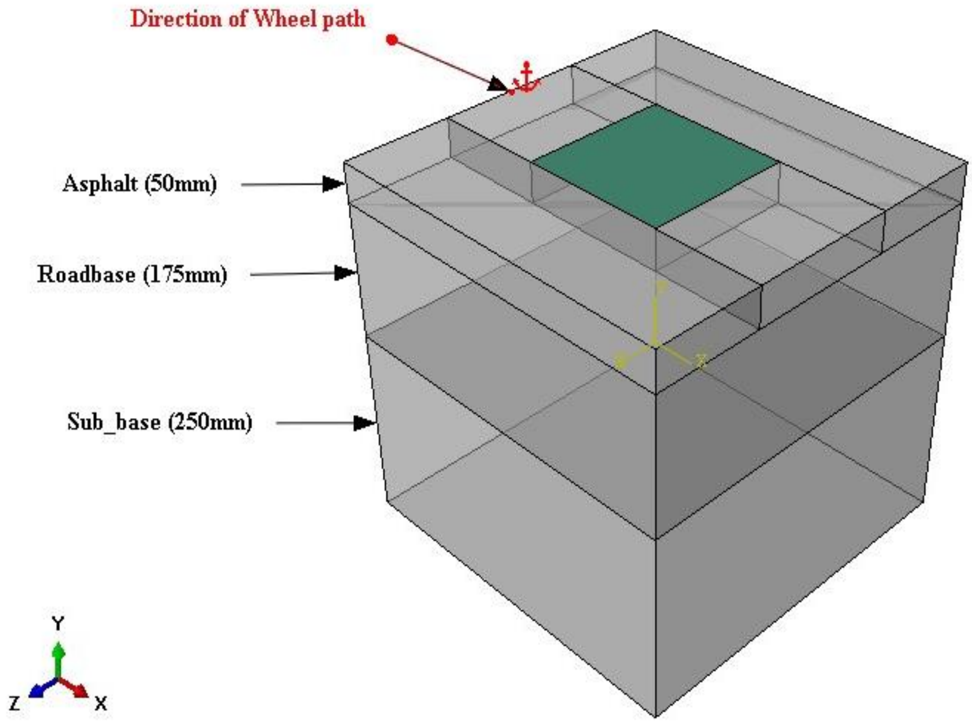


Figure 3.14: Load condition and wheel path direction

E) The job module

Upon completing all tasks related to model definition, including geometry specification, section property assignment, and contact definition, utilize the Job module to analyze the developed model. The Job module facilitates job creation, submission for analysis, and progress monitoring.

F) Visualization module

The Visualization module offers a graphical representation of finite elements and their corresponding results. It includes model data from the current model database or comprehensive model and result data from an output database.

CHAPTER FOUR
RESULT AND DISCUSION

4.1. Introduction

This chapter investigates the impact of incorporating waste marble powder (WMP) additives into hot mix asphalt (HMA) on rutting performance and benchmarks these findings against conventional fillers. It details the mechanical properties of asphalt mixtures with varying percentages of WMP additives. The analysis is structured into three sections.

The first section examines the physical quality properties of HMA components and presents. Marshall test used to determine the optimum binder content of the asphalt mixture. The second section evaluates the effects of WMP additives on the properties of HMA, identifying the optimal percentages of WMP. The third section employs a performance test and a finite element model to conduct a comparative study of the rutting properties between conventional HMA and WMP-modified HMA.

4.2. Engineering Properties of HMA Composition Material

4.2.1. Physical and mechanical properties of aggregates

The quality of materials used in the hot mix asphalt design is essential, as it must meet the minimum requirements of the standards. To evaluate the aggregate properties, different quality tests are used. The aggregate sieve analysis (Figure 4.1) is a crucial test that ensures a well-graded aggregate, which is essential for providing structural stability by promoting interlocking between particles and enhancing the load-bearing capacity of the asphalt mix.

Table 4.1 and Appendix A (Table A2.1) illustrates that the aggregate crushing value (ACV) is 10.46% which is less than 25% as per BS. The obtained result indicating the aggregate has high resistance to crushing, which enhances the durability and longevity of the asphalt mix by reducing the risk of premature deterioration. Similarly, the aggregate impact value (AIV) is a measure of the aggregate's resistance to impact or sudden loads, and a low value of 5.79% indicates high toughness, which improves the performance of the asphalt mix under different load conditions by reducing the risk of cracking or failure (Refer Table 4.1 and Appendix A, Table A2.2 for details).

The Los Angeles Abrasion Test (LAAV) evaluates the aggregate's resistance to abrasion and degradation. The value of LAA obtained from the test is 9.10% (Table 4.1 and Appendix A, Table A 2.3). The result indicates that the aggregate has high resistance to abrasion and degradation, which enhancing the durability and longevity of the asphalt mix by minimizing wear and maintaining structural integrity. Furthermore, (Table 4.1 and Appendix A, Table A3.2) shows that the specific gravity and water absorption rate of both coarse and fine aggregate. The combined bulk specific gravity and water absorption of aggregate were 2.587, 0.987% respectively. This indicates increased density, leading to the potential for higher-density asphalt mixes that offer improved durability and resistance to rutting. The water absorption rate indicates the aggregate's ability to absorb water, and a low rate of 0.987% indicates low porosity and resistance to moisture-induced distress, improving the durability and performance of the asphalt mix in various environmental conditions by reducing the risk of moisture-related damage and preserving the mix's integrity.

Overall, these aggregate properties indicate high quality and suitability for use in asphalt mix design, ensuring the production of durable and resilient HMA.

Table 4.1. Physical and mechanical properties of aggregates

Tests	Test Results		Specification requirement	Test Method
Aggregate Crushing Value (ACV), %	10.46		<25	BS 812: PART 110:1990
Aggregate Impact value (AIV), %	5.79		<25	BS: 812 PART 112:1990
Los Angeles Abrasion (LAAV), %	9.10		<30	ASTM C-131
Flakiness Index (FI), %	12.43		<45	BS 812 Part 105
Specific gravity and water absorption	CA	FA		
Bulk dry S.G, G_{sb}	2.648	2.563	2.5-3	AASHTO T84-85/ ASTM C127-128
Bulk SSD S.G, $G_{sb\ SSD}$	2.698	2.585		
Apparent SG, G_a	2.787	2.619		
Water absorption, W_{abs}%	1.881	0.827	<2	
Combined bulk dry SG, Gsb	2.587		Note: CA=	Coarse aggregate
Combined water absorption, W_{abs}%	0.987		FA=	Fine aggregate

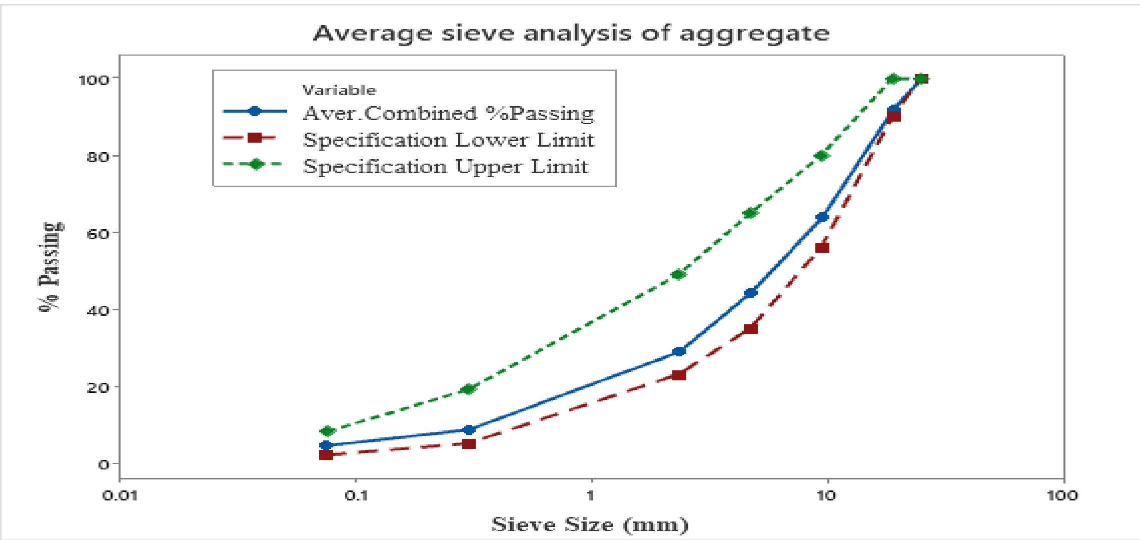


Figure 4.1. Aggregate particle size distribution

4.2.2. Chemical properties of waste marble powder (WMP)

The comprehensive silicate analysis of waste marble powder was conducted at the geochemical laboratory of the Geological Survey of Ethiopia in Addis Ababa. The combined percentage of Al_2O_3, SiO_2, and Fe_2O_3 was found to 2.17% which is less than 70%, which does not meet the ASTM C618 standard requirements for pozzolanic materials suitable for use as a filler. This analysis indicates that waste marble powder is a cementitious material.

The waste marble powder contains a low percentage of SiO_2 at 2.02%, with other oxide components, except for Al_2O_3 and TiO_2, present at less than 0.01%. Laboratory results reveal that the chemical composition of the waste marble powder is predominantly calcite (CaO), which blends well with asphalt to form a homogeneous mixture. Consequently, waste marble powder can be effectively used for asphalt modification. Table 4.2 details the composition properties of the waste marble powder.

Table 4.2: Chemical composition of waste marble powder

Material: Waste marble powder (WMP)								
Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	TiO_2	LOI
% Content	2.02	<0.01	0.14	51.18	4.6	0.74	<0.01	41.4

4.2.3. Asphalt binder properties

Bitumen is a dark, viscous, and sticky material that is primarily used in the construction and maintenance of roads, pavements, and other infrastructure [1, 90]. A bitumen grade of 60/70 was selected for this study area. Key properties such as penetration, softening point, ductility, specific gravity, and flammability are crucial in determining its suitability for various applications as shown in Table 4.3 and Appendix B provide detailed results of asphalt binder quality tests as follows:

1) Penetration test: The penetration value of bitumen is a measure of its hardness or consistency [1]. The penetration value obtained from the test is 6.593mm in five seconds, indicating a bitumen with very high hardness. To convert the penetration to bitumen grade, divide the penetration value by 0.1 mm, and the grade of bitumen is 65.93, which lies between 60-70. Therefore, the grade of this bitumen was 60/70 (Refer Appendix B, Table B1.1 for details).

2) Softening point: the softening point of bitumen is the temperature at which the material transitions from a solid to a semi-solid state [85]. The softening point value was 52.74°C, indicating that the bitumen has a high resistance to softening and maintains its structure well at elevated temperatures. Bitumen with a high softening point is less susceptible to softening and deformation at high temperatures, making it suitable for use in hot climates or in applications where the material is exposed to high temperatures [1] (Refer Appendix B, Table B1.3 for test detail).

3) Ductility: Ductility is a measure of the ability of bitumen to undergo deformation without breaking or cracking [61]. The ductility value was 132 mm, showing that the bitumen can deform without breaking, making it suitable for applications requiring flexibility and crack resistance. Bitumen with high ductility is desirable in applications where flexibility and resistance to cracking are important, such as in the construction of flexible pavements [1] (Refer Appendix B, Table B1.2 for test detail).

4) Specific Gravity: The specific gravity of bitumen is a measure of its density relative to water. The specific gravity value was 1.02, indicating the density of the bitumen relative to water, which is a critical factor in asphalt mixture design and production. The specific gravity of bitumen is an important parameter in the design and production of asphalt mixtures, as it affects the volumetric properties of the mixture (Refer Appendix B, Table B1.4 for test detail).

5) Flash Point and Fire Point: These values measure the temperature at which bitumen can ignite and sustain combustion [85]. The flash point was 296°C, and the fire point was 355°C, indicating low flammability and safe handling and storage due to high ignition and combustion temperature thresholds (Refer to Appendix B, Table B1.5).

In summary, the bitumen used in this research exhibits very low penetration, a high softening point, high ductility, and a specific gravity within the typical range, indicating its suitability for applications requiring stiffness, deformation resistance, and flexibility.

Table 4.3. Quality tests of asphalt binder

Property	Results	Specification requirements	Test Method
Penetration tes tof Bitumen binder @25°C, 100g//5s,0.1mm	65.93	60-70	ASTM D5-86
Softening point temperature in °C	52.74	46-56	ASTM D36
Ductility of bitumen binder, mm, minimum	132	Min 50	ASTM D5-86
Specific gravity @25°C	1.020	0.97-1.02	ASTM D70
Flash point, °C, minimum	296	Min 232	ASTM D92-90
Fire point, °C, minimum	355	Min 280	

4.3. Aggregate Gradation, Blending and Batch for Hot Mix Asphalt Design

When preparing hot mix asphalt (HMA) mixes, the most crucial factors are aggregate gradation, blending, and lab batching of the Marshall mix specimens. "Aggregate gradation" refers to the distribution of different particle sizes within an aggregate sample, typically expressed as the percentage passing through each sieve [1, 85] (See Appendix A, Tables A1.1-A1.3 for details).

Table 4.4 presents the blending proportions of various aggregate sizes necessary to achieve the required gradation for different filler contents in the asphalt binder course, which is essential for preparing optimal asphalt mix specimens. The adopted aggregate blending proportions for four grades of aggregate sizes are detailed in Table 4.5, showing the percentage passing each sieve size for four different aggregate grades with filler contents of 4.25%, 4.75%, 5.25%, and 5.75% for the bituminous paving wearing course.

Using the Job Mix Formula (JMF), aggregates in this study—categorized as coarse (25-9.5mm), intermediate (9.5-2.36mm), fine (2.36-0.075mm), and filler (<0.075mm) were blended to achieve the proper gradation in accordance with ERA guidelines. The results meet the Ethiopian Roads Authority 2014 [84] specification requirements, confirming a well-graded mix (Refer to Appendix C1 and C2 for detailed analysis and insights that enhance the understanding of this study).

Table 4.4. Aggregate blending percent proportion

Filler content (<0.075 mm), %	4.25	4.75	5.25	5.75
Bin #1 (25-9.5 mm), %	41	33	18	26
Bin #2 (9.5-2.36 mm), %	22	28	55	8
Bin #3 (2.36-0.075 mm), %	38	40	26	66
Total, %	100	100	100	100

Table 4.5 Aggregate gradation of asphalt mix design for 19mm nominal sieve size

Sieve Size (mm)	% Passing for four gradations				Specification requirement (ERA 2014)	
	4.25%	4.75%	5.25%	5.75%		
25	100.00	100.0	100.0	100.0	100	100
19	90.21	92.1	95.6	93.7	90	100
9.5	64.20	66.1	63.8	76.2	56	80
4.75	44.81	47.2	44.4	59.6	35	65
2.36	29.17	31.4	29.3	42.4	23	49
0.3	8.26	9.2	9.6	11.6	5	19
0.075	4.25	4.75	5.25	5.75	2	8

Figures 4.2 to 4.5 present the graphical visualization of aggregate gradations based on four varying percentages of conventional CSD filler content, ranging from 4.25% to 5.75% in 0.5% increments, with a maximum nominal aggregate size of 19 mm. For a detailed analysis, refer to Appendix C (Tables C1.1-C1.4).

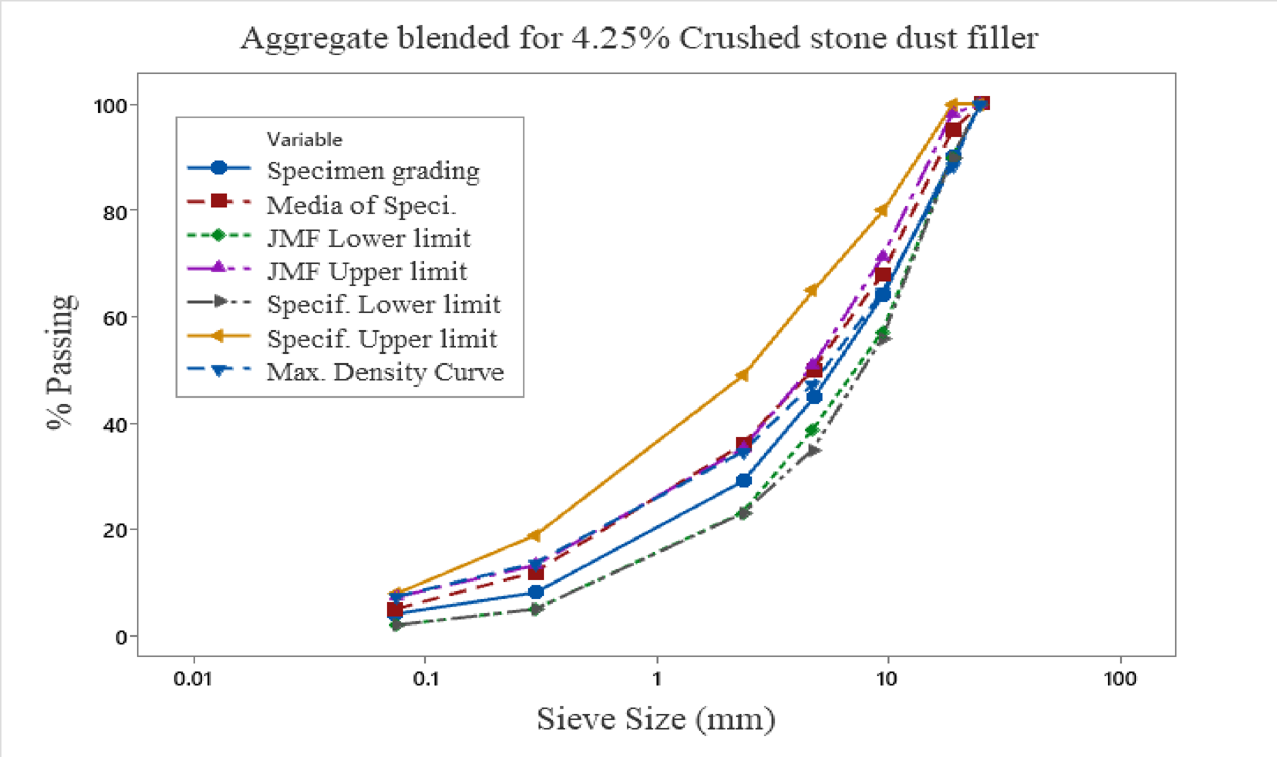


Figure 4.2. Aggregate particle distribution blended for 4.25% CSD filler curve

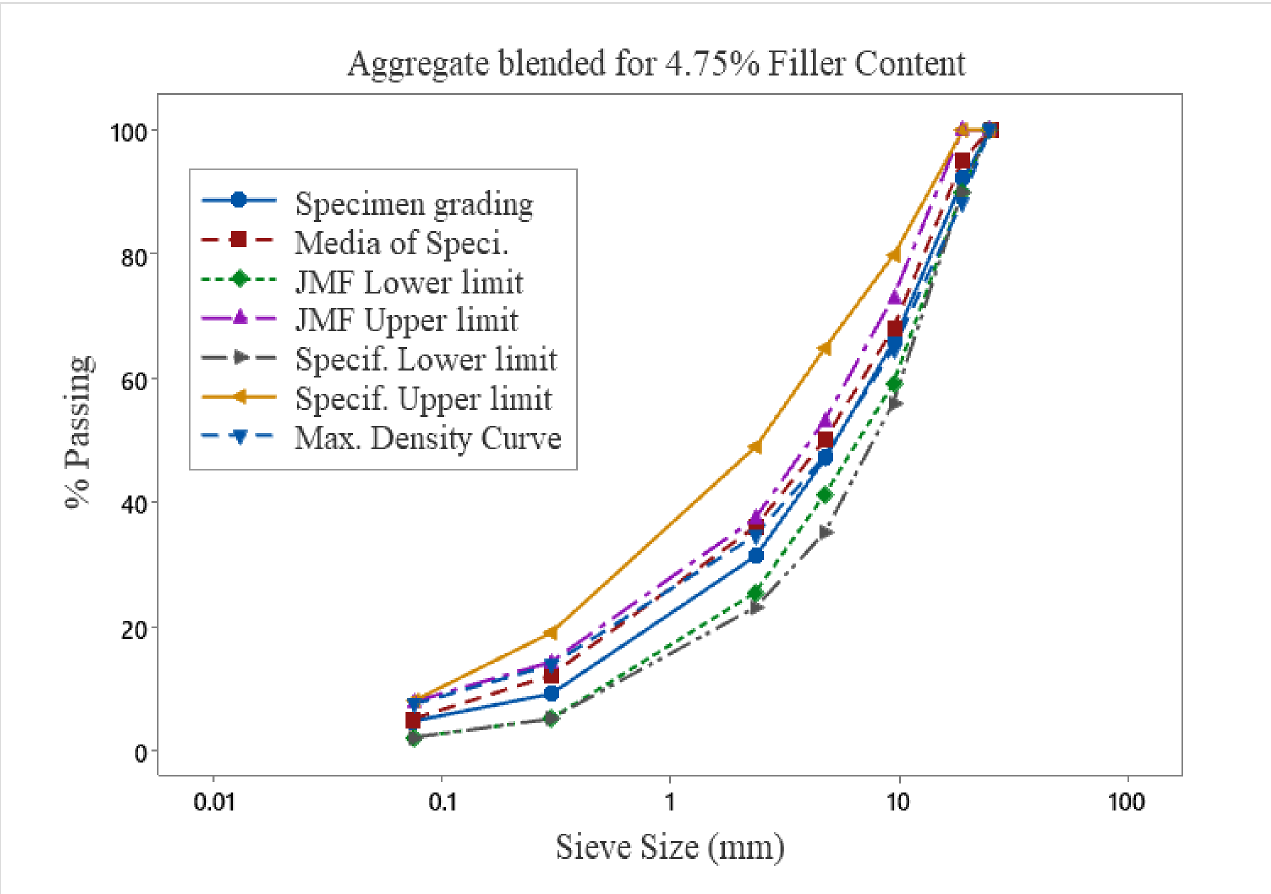


Figure 4.3. Aggregate particle distribution blended for 4.75% CSD filler curve

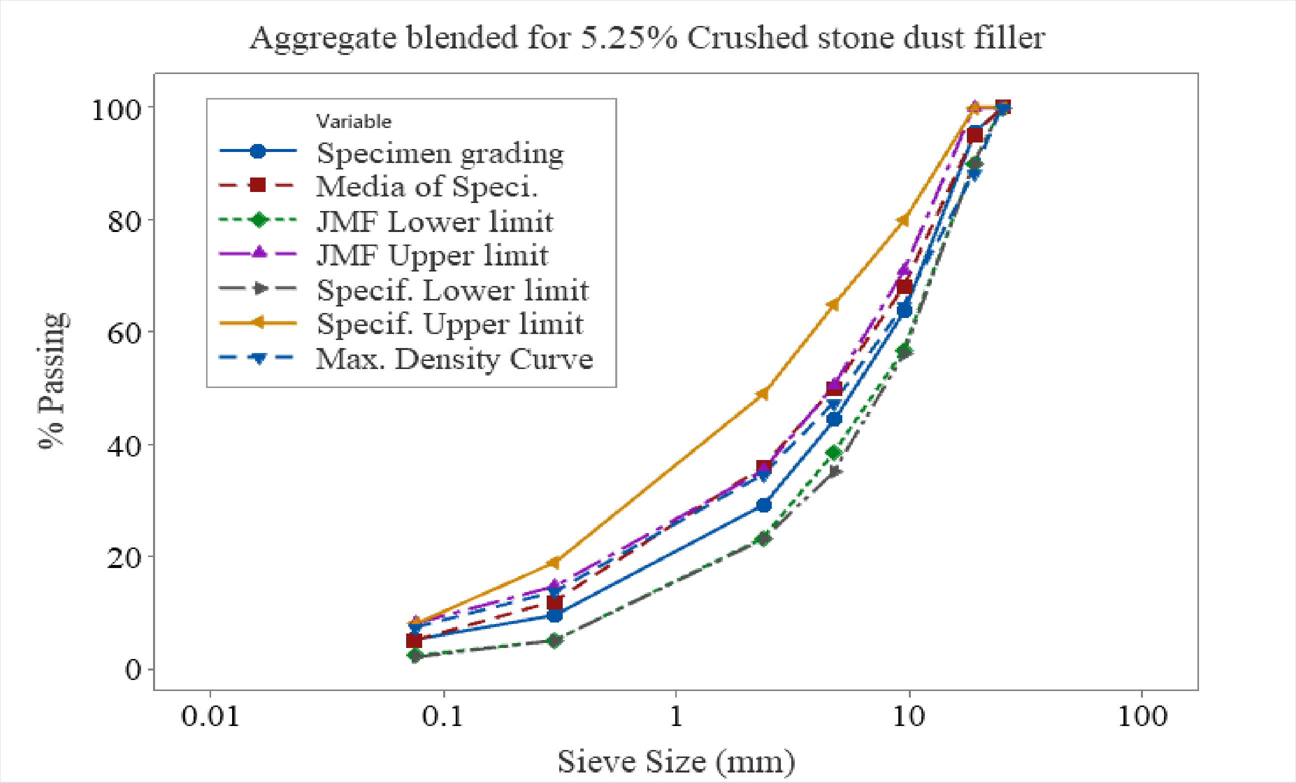


Figure 4.4. Aggregate particle distribution blended for 5.25% CSD filler curve

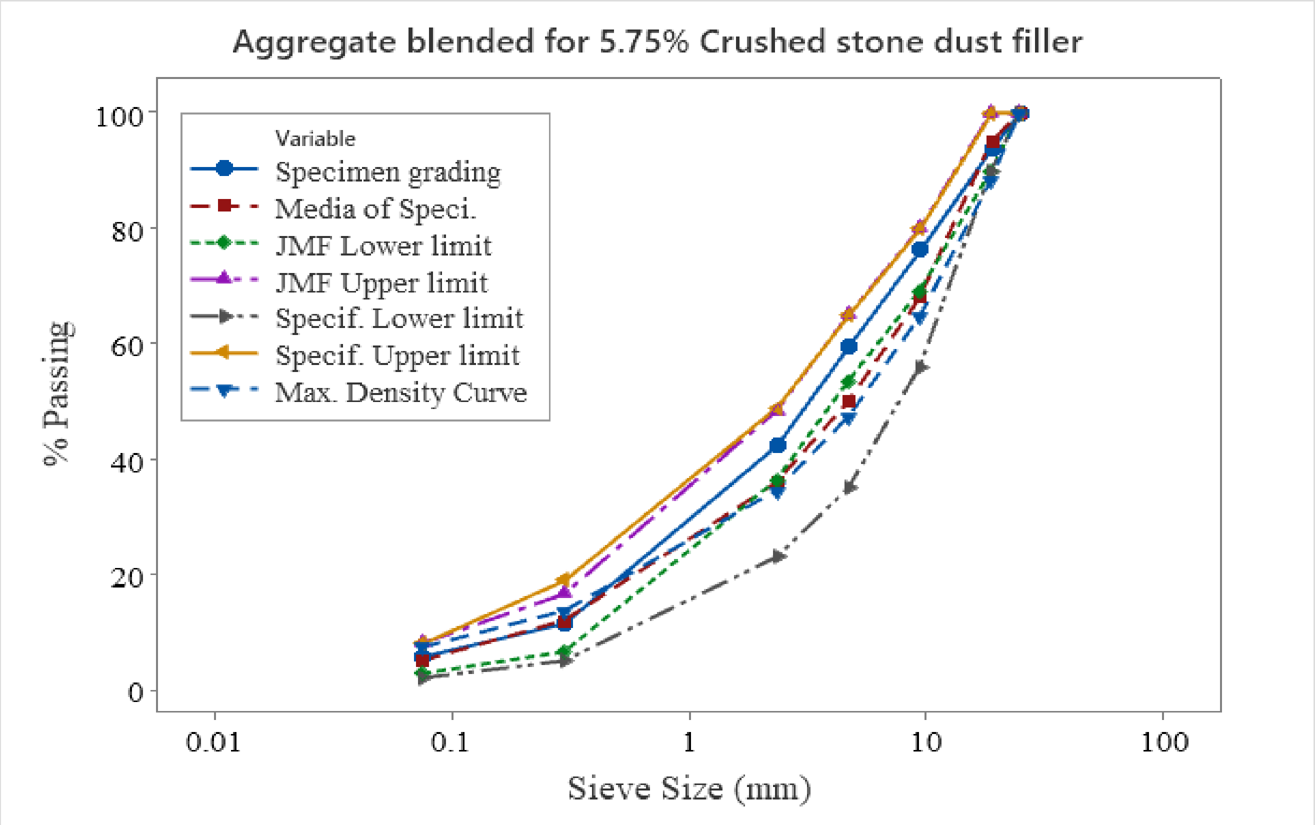


Figure 4.5. Aggregate particle distribution blended for 5.75% CSD filler curve

4.4. Analysis of Hot Mix Asphalt Properties (Control Mix)

The Marshall Mix Design method was employed in the laboratory to determine the optimal asphalt content and evaluate the stability of the mixes. Specimens were created using varying amounts of conventional filler, specifically crushed stone dust, ranging from 4.25% to 5.75% in 0.5% increments by weight of total aggregate. Bitumen contents ranged from 4.5% to 6% in 0.5% increments. A total of 48 samples, each weighing 1150 grams, were produced. The detailed analysis for each filler percentage in the Marshall mix design is summarized in Appendix C (Tables C2.1-C3.1).

4.4.1. Marshall mix properties of 4.25% CSD

Table 4.6 demonstrates that as the bitumen percentage increased, the bulk specific gravity in the mix first rose and then slightly decreased. This indicates that as the bitumen content increases, the hot bitumen helps the aggregates move closer together, reducing air voids and increasing density. The air voids decreased and the void in mineral aggregate decreased to its lowest point and then increased. In contrast, the void filled with asphalt increased as the bitumen content increased. Stability peaked before decreasing, while flow increased as the bitumen concentration increased.

Table 4.6. Marshall mix design output of 4.25% CSD filler

Specimen No	BC (%)	Bulk SG mix (Gmb)	Air void, Pa %	VMA %	VFA %	Marshall Stability, KN	Flow (0.25 mm)
1	4.5	2.241	9.31	17.27	46.08	7.74	2.00
2		2.242	9.27	17.23	46.21	7.70	2.57
3		2.254	8.81	16.81	47.62	7.99	2.34
Average		**2.246**	**9.13**	**17.11**	**46.64**	**7.81**	**2.30**
1	5	2.269	6.34	16.67	61.94	7.18	2.96
2		2.279	5.94	16.31	63.58	9.19	2.92
3		2.265	6.51	16.82	61.28	8.08	2.07
Average		**2.271**	**6.27**	**16.60**	**62.27**	**8.15**	**2.65**
1	5.5	2.302	4.54	15.93	71.49	7.92	3.02
2		2.284	5.29	16.59	68.13	8.85	2.80
3		2.301	4.55	15.94	71.45	7.94	2.67
Average		**2.296**	**4.79**	**16.15**	**70.35**	**8.24**	**2.83**
1	6	2.296	3.10	16.15	80.81	8.15	3.02
2		2.299	2.96	16.03	81.55	8.67	2.96
3		2.286	3.50	16.50	78.77	7.69	3.00
Average		**2.294**	**3.19**	**16.22**	**80.38**	**8.17**	**2.99**

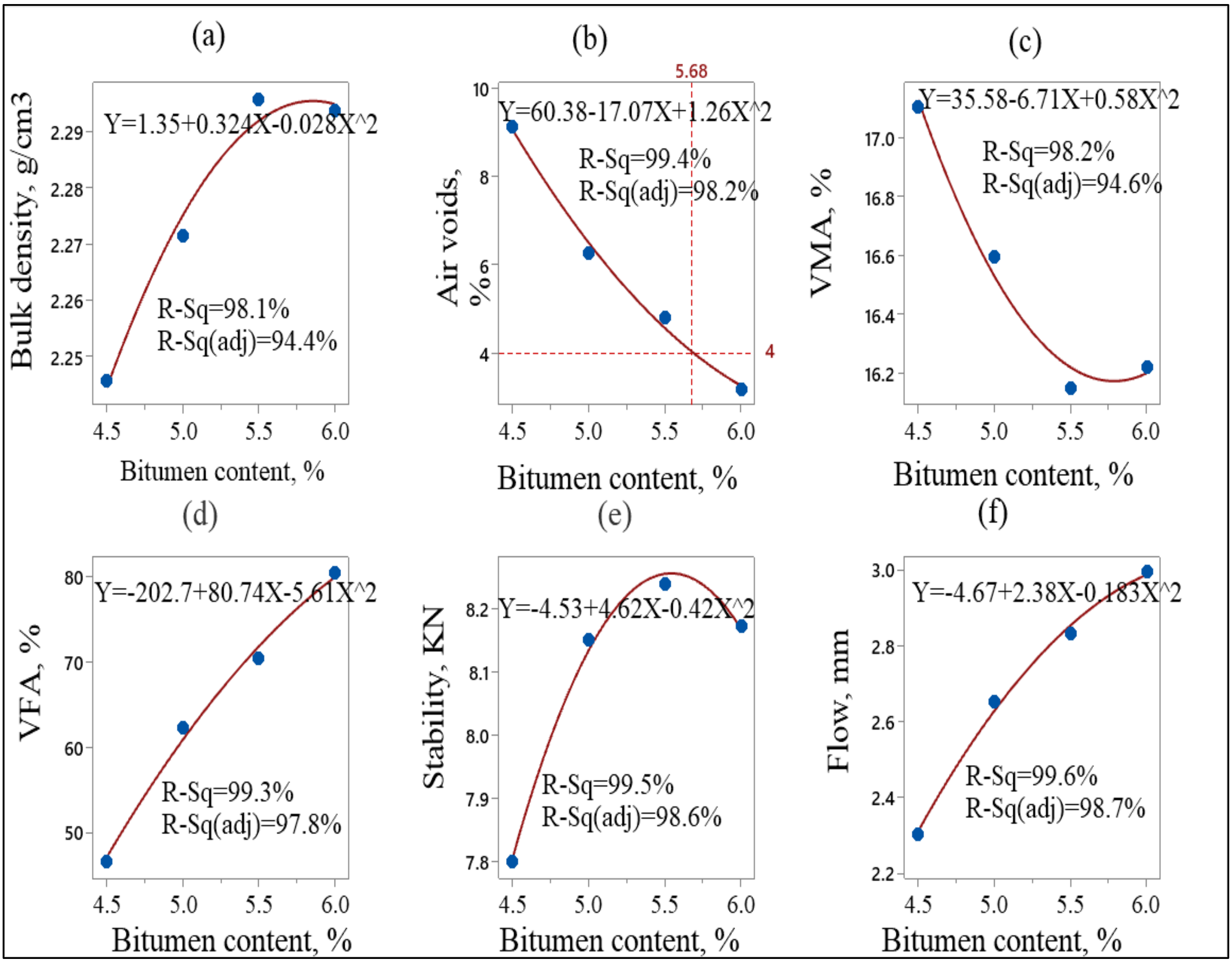


Figure 4.6: Relationship of Marshall properties of HMA design with 4.25% CSD filler

A) Relationship between bulk density and bitumen content

Bulk density is a key property in asphalt mixtures as it influences the mixture's durability, stability, and void content [1]. Table 4.6 and Figure 4.6 (a) illustrates the findings for varied bitumen contents. The density increases as the bitumen percentage increases until it reaches a high (2.296 g/cm^3) at 5.5% bitumen content, after which point it gradually decreases with rising bitumen content. This value is closer to what might be considered an optimal bulk density, providing a balance between durability and workability. It indicates a well-compacted mixture with adequate voids for the asphalt binder, which can result in good long-term performance.

Bulk Density of 2.246 g/cm^3: this is the lowest bulk density among the given values. A lower bulk density can indicate higher air voids within the mixture, which may lead to reduced durability and potential moisture damage. However, it can also mean easier compaction during construction.

B) Relationship between air voids and bitumen content

Air voids in an asphalt mixture are crucial for pavement durability and performance, with the optimal range being 3-5% [1, 84]. Table 4.6 and Figure 4.6 (b) shows that air voids decrease as bitumen content increases:

At 4.5 and 5% bitumen content, the air voids are significantly higher than the optimal range, leading to rapid oxidation, increased moisture damage, and reduced durability. At 5.5% bitumen content, the air voids are 4.79%, within the optimal range, providing a balance between durability and flexibility, with sufficient void space for expansion and good resistance to moisture penetration. At 6% bitumen content, the air voids are 3.19%, at the lower end of the optimal range, which minimizes moisture damage risk but may lead to rutting in hot conditions due to insufficient expansion space. In summary, the mixture with 4.79% air voids at 5.5% bitumen content is likely to perform the best, balancing durability and flexibility. The target optimum bitumen content at 4% air void is 5.68%.

C) Relationship between the percentage of VMA and bitumen content

Voids in mineral aggregate (VMA) are crucial for the durability and crack resistance of asphalt mixtures [1, 33]. Table 4.6 and Figure 4.6 (c) shows the relationship between bitumen content and VMA:

At 4.5% bitumen content, VMA is 17.11%, indicating a high volume of voids within the aggregate. This can allow for more asphalt binder, enhancing durability but potentially compromising stability if not properly balanced. At 5% bitumen content, VMA is 16.6%, slightly lower but still providing ample space for binder, contributing to good durability. At 5.5% bitumen content, VMA is 16.15%, closer to the typical target range for many asphalt mixtures, balancing durability and stability and at 6% bitumen content, VMA is 16.22%, similar to 16.15%, with comparable effects on the mixture. In summary. VMAs of 16.15% and 16.22% are likely to result in a well-balanced mixture with good durability and stability.

D) Relationship between the percentage of VFA and bitumen content

Voids Filled with Asphalt (VFA) is the percentage of the Voids in Mineral Aggregate (VMA) that is filled with asphalt binder [1, 33]. It is a critical factor in determining the durability and rut resistance of an asphalt mixture. Table 4.6 and Figure 4.6 (d) illustrates the relationship between bitumen content and voids filled with asphalt. The graph demonstrated that increasing bitumen content led to a higher void filled with asphalt.

At 4.5% BC the value of VFA is 46.64%. This value is quite low, which indicates that a smaller proportion of the available void space in the aggregate is filled with asphalt binder. This could lead to a dry and potentially brittle mix that may have issues with durability and resistance to moisture damage.

At 5% BC the value of VFA is 62.27% which is closer to the typical target range for VFA, which is generally between 65-75% [1]. At this level, the mix is expected to have a good balance between durability and flexibility. However, being slightly below the target range may pose a risk of insufficient binder to effectively coat the aggregates, potentially leading to durability concerns. VFA at 5.5% BC 70.35% within this range is considered optimal for most asphalt mixtures. It implies that the binder is sufficient to coat aggregates effectively, ensuring durability and moisture resistance, while leaving sufficient voids to prevent excessive deformation under load and 80.38% VFA at 6% BC is above the typical target range and indicates a high proportion of the VMA is filled with asphalt binder. In summary, a VFA of 70.35% is likely to result in the best balance between durability and deformation resistance.

E) Relationship between stability and bitumen content

The maximum load required to make the specimen fail when applied at a constant rate of 50 mm/min at 60°C is known as the stability [1, 33]. The stability results for various bitumen contents are shown in Table 4.6 and Figure 4.6 (e). The stability of the asphalt mix increases as the bitumen percentage goes up, reaching a peak (8.24KN) at 5.5% bitumen content. After that point, it starts to decrease as the bitumen concentration increases further. This shows that the load resistance on the specimen increased with the rise in bitumen content up to 5.5%. Beyond this point, the specimen's plasticity increased, resulting in lower stiffness.

F) Relationship between flow and bitumen content

The total amount of deformation that happens at maximum load is referred to as flow (measured from the start of loading to the point at which stability begins to decrease by 0.25mm) [1, 33].

Table 4.6 and Figure 4.6 (f) illustrates that the flow of 2.3mm at 4.5% bitumen content indicates a stiffer mixture with lower workability. It suggests good stability but may require more effort to compact during construction. Such a mixture is less likely to deform under traffic loads but might be more susceptible to cracking if not compacted adequately.

A flow of 2.65mm at 5% BC represents a balance between workability and stability. The mixture is easier to work with during construction and provides sufficient stability for most traffic conditions. It’s a good middle ground for achieving durable pavement. As the flow value increases to 2.83mm at 5.5% BC, the mixture becomes more workable and flexible. This can facilitate compaction and result in a smooth surface finish. A flow of 2.99mm at 6% BC is the highest flow value among the given numbers, suggesting the most workable and flexible mixture. Pavements with such high flow values might experience more permanent deformation, especially in high-temperature conditions or under heavy loads. In summary, lower flow values generally indicate mixtures that are stiffer and more stable but harder to compact, while higher flow values suggest mixtures that are more workable and easier to compact but may have reduced stability [1].

4.4.2. Marshall mix properties of 4.75% CSD

Table 4.7 illustrates the relationship between bitumen percentage and bulk specific gravity, air voids, void in mineral aggregate, void filled with asphalt, Stability and flow

Table 4.7. Marshall mix design output of 4.75% CSD filler

Specimen No	BC (%)	Bulk SG mix (Gmb)	Air void %	VMA %	VFB %	Marshall Stability, KN	Flow, mm
1	4.5	2.257	8.56	16.69	48.70	7.63	3.04
2		2.258	8.53	16.66	48.78	8.74	1.84
3		2.263	8.32	16.46	49.49	9.49	2.39
Average		**2.259**	**8.47**	**16.60**	**48.99**	8.62	2.42
1	5	2.282	5.48	16.20	66.18	**9.21**	**2.56**
2		2.286	5.30	16.05	66.96	9.61	2.55
3		2.262	6.32	16.95	62.72	8.18	2.63
Average		**2.277**	**5.70**	**16.40**	**65.28**	9.00	2.58
1	5.5	2.328	3.10	14.96	79.26	**10.41**	**2.40**
2		2.283	4.99	16.62	69.99	8.52	3.30
3		2.285	4.89	16.54	70.41	8.61	2.36
Average		**2.299**	**4.33**	**16.04**	**73.22**	9.18	2.69
1	6	2.284	3.54	16.59	78.65	**9.78**	**2.56**
2		2.327	1.72	15.02	88.51	8.63	2.85
3		2.282	3.59	16.63	78.41	8.52	3.00
Average		**2.298**	**2.95**	**16.08**	**81.86**	8.98	2.80

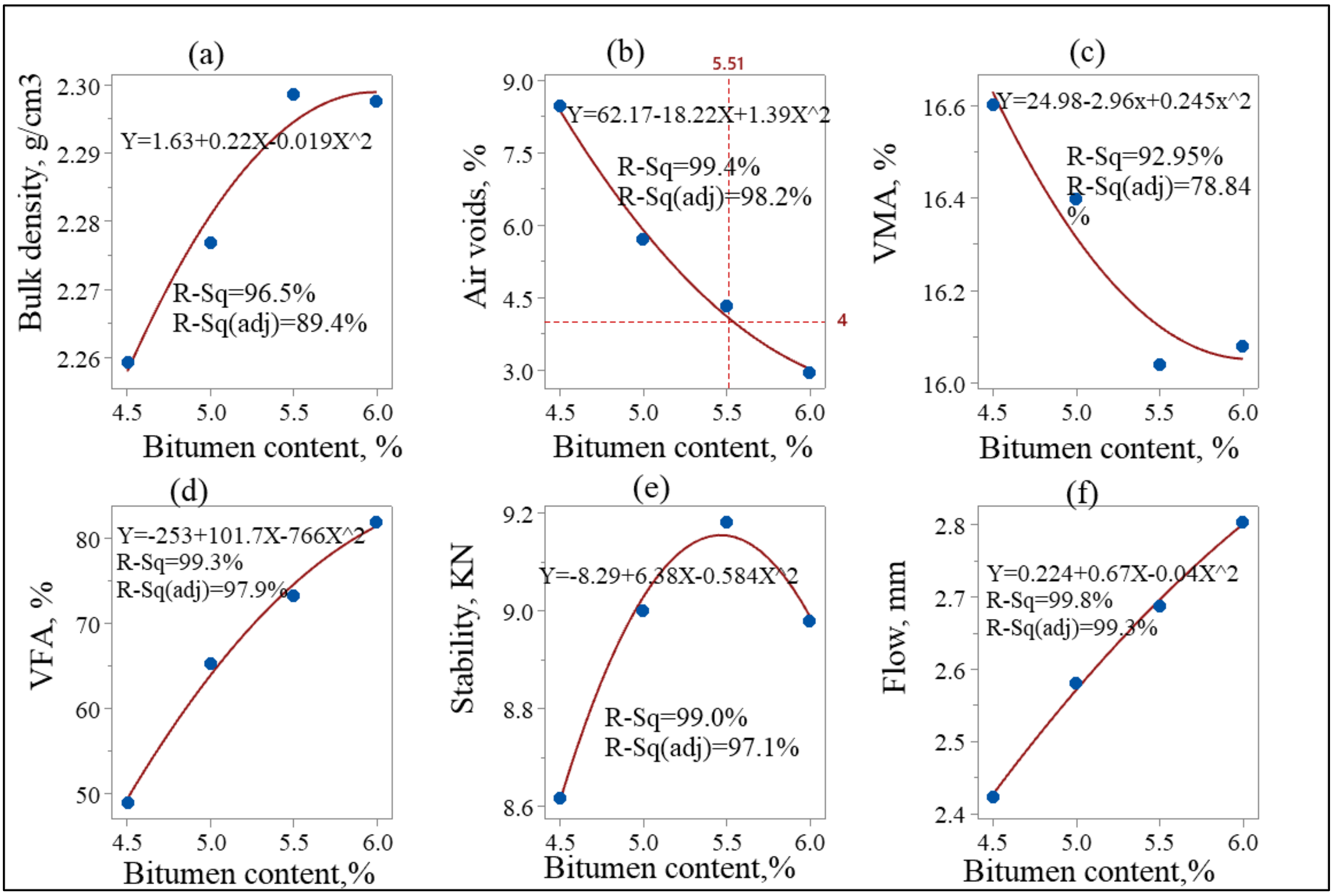


Figure 4.7: Relationship of Marshall properties of HMA design data with 4.75% CSD filler

A) Relationship between bulk density and bitumen content

Table 4.7 and Figure 4.7 (a) presents the findings for various bitumen contents. At 4.5% bitumen content, the lowest bulk density recorded is 2.259 g/cm^3. A lower bulk density suggests higher air voids, potentially reducing durability and susceptibility to moisture damage. Subsequently, at 5% bitumen content, the bulk density slightly increases to 2.277 g/cm^3, indicating a denser mixture with potentially fewer air voids. The bulk density of 2.299 g/cm^3 at 5.5% bitumen content appears to approach an optimal value, offering a balance between durability and ease of compaction. This density indicates a well-compacted mixture with sufficient voids for the asphalt binder, promising good long-term performance. Remarkably, at 6% bitumen content, the bulk density of 2.298 g/cm^3 closely resembles the optimal density observed at 5.5% bitumen content, suggesting similar characteristics and performance.

B) Relationship between air voids and bitumen content

Air voids in asphalt mixtures significantly impact pavement durability and performance, as depicted in Table 4.7 and Figure 4.7 (b). Increasing bitumen content correlates with a decrease in air voids. At 4.5% bitumen content, a high air void percentage of 8.47% can weaken pavement strength, increase vulnerability to moisture damage, and shorten fatigue life. Pavements with elevated air void content are prone to raveling and rutting, compromising surface integrity.

At 5.5% bitumen content, air voids of 4.33% fall within the optimal range 3-5% [1], indicating a well-compacted mixture with adequate space for asphalt binder expansion. Air voids of 2.95% at 6% bitumen content signify a very dense mixture, below the lower end of the optimal range, ensuring pavement stability and longevity. The target optimum bitumen content at 4% air void is 5.51%.

C) Relationship between the percentage of VMA and bitumen content

Table 4.7 and Figure 4.7 (c) shows the relationship between bitumen content and void in mineral aggregates.

At 4.5% bitumen content, the highest VMA recorded is 16.6%, providing ample space for the asphalt binder and enhancing mixture durability by accommodating thermal movements and loading stresses.

Although slightly lower, the VMA value of 16.4% at 5% bitumen content still offers sufficient space for the binder, further enhancing durability. At 5.5% bitumen content, a VMA of 16.04% approaches the lower limit of 13% [84] commonly used in mix designs, indicating optimal performance range. This suggests a denser aggregate structure, potentially leading to a stronger mix with less flexibility due to the compact nature of the aggregates. At 6% bitumen content, a VMA of 16.08% yields nearly identical effects on the asphalt mixture as observed at 5.5% bitumen content.

Higher VMA levels usually allow for more binder, boosting durability, but excessively high levels may cause bleeding issues. Conversely, lower VMA can result in a stronger, stiffer mix less prone to rutting but potentially more susceptible to cracking under certain conditions.

D) Relationship between the percentage of VFA and bitumen content

Table 4.7 and Figure 4.7 (d) illustrates the relationship between bitumen content and VFA. The graph shows that as the amount of bitumen increases, more space in the mixture is filled with asphalt. A VFA of 48.99% at 4.5% bitumen content indicates that less than half of the space is filled with asphalt binder, which is relatively low. This can lead to a mixture that is prone to moisture damage and may not be sufficiently durable against traffic loads. A VFA of 65.28% at 5% bitumen content is near the usual VFA range of 65% to 75%. A VFA of 73.22% at 5.5% BC is within the optimal range for VFA, indicating a good proportion of binder in the void space. While a VFA of 81.86% at 6% bitumen content shows a high level of asphalt binder filling a significant portion of the void space. Although this can lead to highly durable and impermeable pavement, excessive binder content poses a risk of flushing or bleeding.

E) Relationship between stability and bitumen content

As shown in Table 4.7 and Figure 4.7 (e) stability of 8.62 KN at 4.5% BC is the lowest stability value among the given numbers. This indicates that the mixture can moderately resist deformation under load. Although it may work well in low-traffic areas, it may not be ideal for high-traffic or heavy-load zones. The stability of 9 KN at 5% BC shows better resistance to deformation compared to the 8.62 kN value. It is expected to perform well under regular traffic conditions and can be relied upon for typical pavement applications. The stability of 9.18 KN at 5.5% BC suggests an even better resistance to deformation. This mixture would be expected to hold up well under heavy traffic and could be suitable for highways and major roads. Finally, a stability of 8.98 KN at 6% BC is almost the same as 9 KN, showing a similar resistance to deformation.

F) Relationship between flow and bitumen content

The flow results for various bitumen contents are visually presented in Table 4.7 and Figure 4.7 (f), showing the relationship between bitumen content and deformation.

A flow value of 2.42mm at 4.5% BC suggests that the mixture has moderate workability and plasticity. As the flow value increases to 2.69mm at 5.5% BC, the workability of the mixture also increases. A flow of 2.69mm suggests a mixture that is quite workable and flexible, which is beneficial for compaction. Finally, a flow value of 2.8mm at 6% BC, the highest among the provided data points, signifies the most workable and flexible mixture. The higher flow values result in an asphalt mixture that is more workable and flexible, offering advantages during the construction process. However, higher flow values can also result in decreased stability, making the pavement more susceptible to deformation under traffic. Ultimately, the ideal flow value for the asphalt mixture in this study is in the boundary of 2-3.5% recommended by [84].

4.4.3. Marshall mix properties of 5.25% CSD

Table 4.8 illustrates that as the bitumen percentage increased, the bulk specific gravity in the mix first rose and then slightly decreased. As the air voids, and the void in mineral aggregate decreased to its lowest point, the void filled with asphalt increased as the bitumen content increased. Stability peaked before decreasing, while flow increased as the bitumen concentration increased.

Table 4.8. Marshall mix design output of 5.25% CSD filler

Specimen No	BC (%)	Bulk SG mix (G_{mb})	Air void %	VMA %	VFB %	Marshal Stability, KN	Flow (0.25 mm)
1	4.5	2.291	5.88	15.44	61.94	10.61	2.41
2		2.255	7.34	16.76	56.19	10.43	2.29
3		2.259	7.18	16.62	56.76	10.11	2.38
Average		**2.268**	**6.80**	**16.27**	**58.30**	**10.38**	**2.36**
1	5	2.298	4.48	15.62	71.30	11.13	2.50
2		2.295	4.61	15.73	70.72	11.51	3.15
3		2.299	4.43	15.57	71.55	9.97	2.62
Average		**2.298**	**4.51**	**15.64**	**71.19**	**10.87**	**2.76**
1	5.5	2.305	3.58	15.81	77.32	10.42	3.17
2		2.308	3.45	15.69	77.99	11.24	2.96
3		2.298	3.89	16.07	75.82	10.37	3.40
Average		**2.304**	**3.64**	**15.86**	**77.04**	**10.68**	**3.18**
1	6	2.278	3.51	16.79	79.09	10.42	3.85
2		2.305	2.38	15.81	84.96	9.77	3.25
3		2.285	3.22	16.54	80.54	9.78	3.65
Average		**2.289**	**3.04**	**16.38**	**81.53**	**9.99**	**3.58**

A) Relationship between bulk density and bitumen content

From Table 4.8 and Figure 4.8 (a), the finding of density for varied bitumen is summarized as follows: A bulk density of 2.268 g/cm^3 at 4.5% BC suggests a less compact mix, potentially with a higher air void content. Such a mix might offer better workability and compaction at cooler temperatures but could be susceptible to moisture ingress and associated damage due to the higher air voids. When the bulk density increases to 2.298 g/cm^3 at 5% BC, it means the mix is more tightly packed with fewer air spaces. This mix would have improved load-bearing capacity and resistance to water damage, making it suitable for moderate-to-heavy traffic conditions. At 2.304 g/cm^3 with 5.5% BC, the mix is densely packed with minimal air gaps, indicating a higher density. It would provide excellent load support and durability, with reduced potential for rutting and moisture damage. With a bulk density of 2.289 g/cm^3 at 6% BC, there is a small decrease in compaction compared to the previous point. The mix would still maintain good load-bearing characteristics but might offer a bit more flexibility, which could be beneficial in preventing cracking.

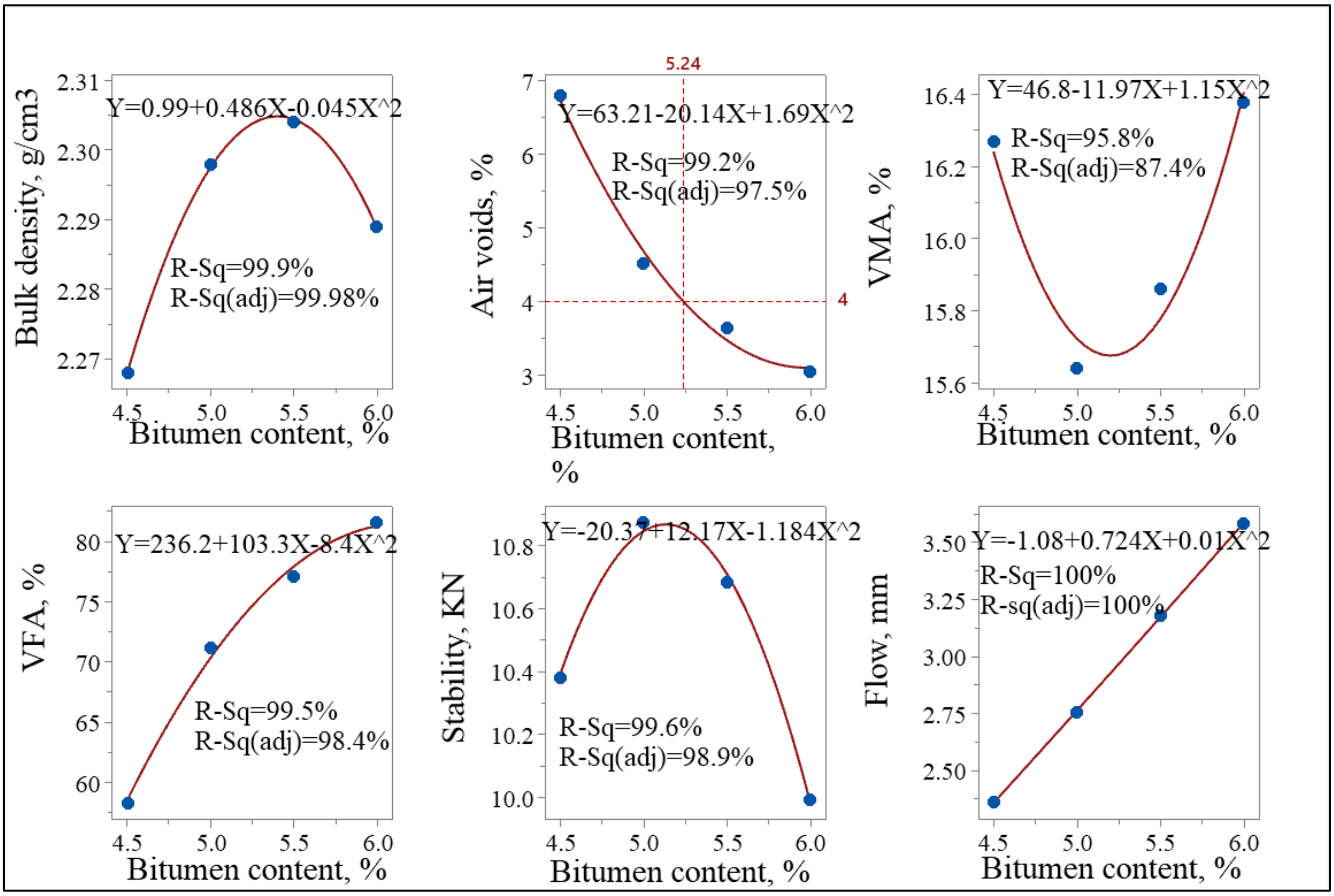


Figure 4.8: Relationship of Marshall properties of HMA design data with 5.25% CSD filler

B) Relationship between air voids and bitumen content

The analysis in Table 4.8 and Figure 4.8 (b) provides a summary of air voids with different bitumen variations: With 6.80% air voids at 4.5% BC, it exceeds the standard 3-5% air void range. This level of air voids in a mix can result in reduced density, which may increase permeability and the risk of moisture damage. An air void of 4.51% at 5% BC is slightly above the ideal range. Air voids of 3.64% at 5.5% BC are within the optimal range for air voids, suggesting a well-compacted mix that should perform well under traffic loads. Air Voids of 3.04% at 6% BC are equal to the recommended minimum of 3%, indicating a very dense mix. Here, the target optimum bitumen content at 4% air void is 5.24%.

C) Relationship between the percentage of VMA and bitumen content

A high VMA value at 4.5% BC indicates good durability, as it allows for more asphalt binder. However, too high a VMA can lead to bleeding and rutting if not balanced with binder content. A VMA of 15.64% at 5% BC is slightly lower, indicating good workability and resistance to compaction-related issues. A VMA of 15.86% at 5.5% BC is closer to the typical VMA range for dense-graded mixes, suggesting a mix with less void space, potentially reducing binder content. A VMA of 16.38% at 6% BC is suggests a good balance of void space and binder content, providing durability and resistance to distresses as shown in Table 4.8 and Figure 4.8 (c).

D) Relationship between the percentage of VFA and bitumen content

Table 4.8 and Figure 4.8 (d) visually shows how the amount of bitumen in the mix impacts the percentage of voids filled with asphalt. The graph indicates that higher bitumen content results in a greater percentage of voids being filled with asphalt. A VFA of 58.3% at 4.5% bitumen content indicates that a notable amount of the void space remains unfilled by asphalt binder. As a result, the mix may become more permeable and prone to damage from moisture. A VFA of 71.19% at 5% bitumen content represents a balanced value often aimed for in designing asphalt mixes. A VFA of 77.04% at 5.5% bitumen content shows better asphalt filling in the voids, decreasing permeability and enhancing resistance to moisture damage. With a VFA of 81.53% at 6% bitumen content, the mix has minimal air voids and a substantial amount of asphalt binder, indicating a dense and well-protected asphalt structure.

E) Relationship between stability and bitumen content

Table 4.8 and Figure 4.10 8 (e) indicates that the stability of the asphalt mix increases as the bitumen percentage goes up to its maximum value (10.87 KN). A stability of 10.38 KN at 4.5% BC indicates a mix with good load-bearing capacity, meaning it can withstand significant traffic loads without excessive deformation. It is expected to perform well under normal traffic conditions, ensuring a durable pavement structure. Stability of 10.87 KN at 5% BC A higher stability value like this one suggests an even stronger mix that can resist higher traffic loads. This mix is ideal for roadways with heavy traffic, offering exceptional resistance to rutting and other pavement distress. While slightly lower at 10.68 KN, the stability at 5.5% BC still signifies a mix with high resistance to deformation. This indicates that the mix is robust, capable of managing substantial traffic loads, and preserving pavement integrity over time. Although the lowest among those listed, the stability of 9.99 KN at 6% still signifies a mix with sufficient stability. It should be able to support moderate traffic loads effectively but may not be as resilient as mixes with higher stability values under extreme conditions.

F) Relationship between flow and bitumen content

Table 4.8 and Figure 4.8 (f) describe the detail properties of flow and bitumen content relationship. Such as: A flow of 2.36mm at 4.5% BC is on the lower end of the flow values and suggests a stiffer mixture. Such a mixture may require more effort to mix and compact but could result in higher stability. A flow of 2.76mm at 5% BC a slightly higher flow value indicates better workability than the 2.36mm flow, making the mixture easier to handle during construction without significantly compromising stability. Flow of 3.18mm at 5.5% BC is moving towards the higher end, which means the mixture is more workable and easier to compact. However, there might be a trade-off with stability, as too much flow can lead to less stable mixtures. The flow of 3.58mm at 6% BC is the highest flow value among the given numbers suggests a very workable mixture that is easy to mix and place. However, it may also indicate a potential for lower stability and strength, as the mixture may be too soft.

4.4.4. Marshall mix properties of 5.75% CSD

Table 4.9 illustrates that as the bitumen percentage increased, the bulk specific gravity increases. As the air voids, and the void in mineral aggregate decreased to its lowest point, the void filled with asphalt increased as the bitumen content increased. Stability peaked before decreasing, while flow increased as the bitumen concentration increased.

Table 4.9. Marshall mix design output of 5.75% CSD filler

Specimen No	BC (%)	Bulk SG mix (Gmb)	Air void %	VMA %	VFB %	Marshal Stability, KN	Flow (0.25 mm)
1	4.5	2.276	6.8	15.98	57.34	9.50	3.04
2		2.244	8.1	17.17	52.64	10.00	1.84
3		2.239	8.3	17.35	51.96	9.93	2.39
Average		**2.253**	**7.8**	**16.84**	**53.98**	**9.81**	**2.42**
1	5	2.259	6.0	17.06	64.99	9.34	2.56
2		2.283	4.9	16.15	69.38	10.35	3.25
3		2.279	5.2	16.34	68.46	10.18	3.23
Average		**2.274**	**5.4**	**16.52**	**67.61**	**9.96**	**3.01**
1	5.5	2.300	3.9	16.01	75.83	9.94	3.24
2		2.300	3.9	16.00	75.85	9.85	3.43
3		2.269	5.2	17.13	69.92	10.19	3.46
Average		**2.289**	**4.3**	**16.38**	**73.87**	**10.00**	**3.38**
1	6	2.306	2.5	16.21	84.52	10.27	3.65
2		2.308	2.5	16.16	84.83	10.26	3.89
3		2.288	3.3	16.87	80.57	9.34	3.35
Average		**2.301**	**2.7**	**16.42**	**83.30**	**9.96**	**3.63**

A) Relationship between bulk density and bitumen content

Table 4.9 and Figure 4.9 (a) illustrates the density increases as the bitumen percentage increases until it reaches a high (2.301 g/cm3) at 6% bitumen content.

In general, a bulk density of 2.253 g/cm³ at 4.5% BC is a relatively low bulk density for an asphalt mix, which may indicate a mix with higher air voids. While the bulk density of 2.274 g/cm³ at 5% BC slight increase in bulk density suggests a better-compacted mix with fewer air voids. This density is likely to provide a good balance between flexibility and load-bearing capacity, making it suitable for most traffic conditions. As the bulk density increases, the mix becomes more compact with even fewer air voids.

This level of density indicates a mix that is well-compacted, offering increased resistance to deformation and potentially longer pavement life [1]. The higher bulk density of 2.301 g/cm³ is at 6% BC indicating a very compact mix with low air voids.

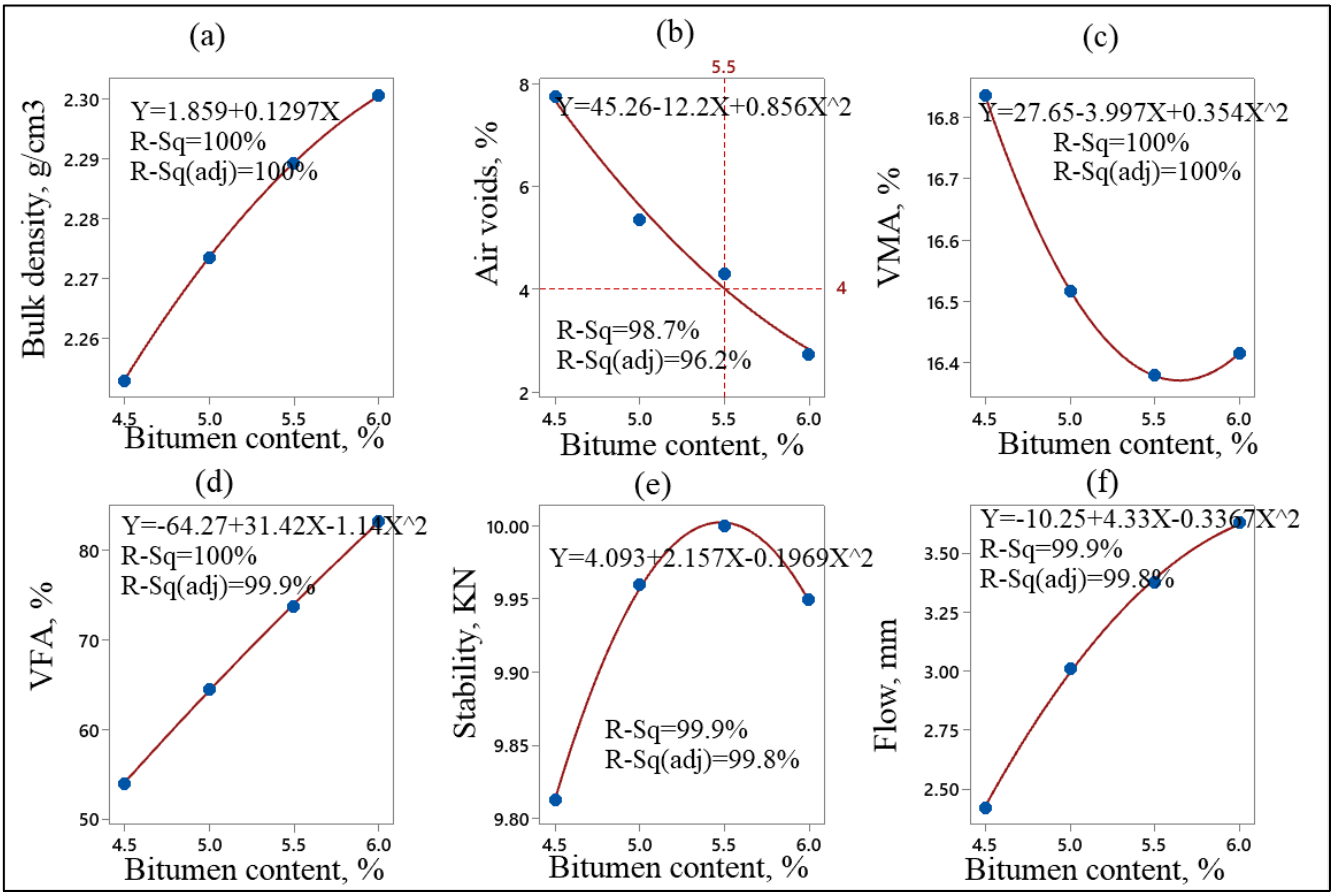


Figure 4.9: Relationship of Marshall properties of HMA design data with 5.75% CSD filler

B) Relationship between air voids and bitumen content

Table 4.9 and Figure 4.9 (b) illustrates how the air void decreases as the bitumen content increases. Here's a discussion of the finding of different air void percentages on asphalt mix design:

Air Voids 7.8% at 4.5% BC is higher than the typical target range of 3-5% for air voids. High air void content can lead to increased oxidation of the asphalt binder, moisture damage, and reduced pavement life. An air voids of 5.4% at 5% BC is within the ideal range for air voids in an asphalt mix. It suggests a good balance between density and space for the asphalt binder to expand in hot weather. Air Voids 4.3% at 5.5% slightly lower than the typical target, this value indicates a well-compacted mix that could provide good pavement performance. Air Voids of 2.7% at 6% BC is below the recommended minimum of 3%. At such a low percentage, the mix may become too dense, leading to issues like reduced permeability and potential rutting due to the mix becoming plastic and unstable in hot weather. The design air void is 4% as according Asphalt Institute criteria [1] and the target optimum bitumen content is 5.5%.

C) Relationship between the percentage of VMA and bitumen content

The Voids in Mineral Aggregate (VMA) of the asphalt mixes, as detailed in the Table 4.9 and Figure 4.9 (c), play a pivotal role in determining their design and performance characteristics.

Starting with the asphalt mix featuring 16.84% VMA at 4.5% bitumen content, it indicates a relatively high void content within the aggregate. This mix may offer good workability and compaction properties, potentially leading to higher density. However, excessive voids could pose challenges such as reduced stability and increased susceptibility to moisture damage.

Moving to the mix with 16.52% VMA at 5% bitumen content, it suggests a slightly denser aggregate structure compared to the previous mix. This could result in improved stability and resistance to rutting while still accommodating sufficient binder for adequate durability.

The mix with 16.38% VMA at 5.5% bitumen content further densifies the aggregate structure, potentially enhancing strength and stability. However, it may also lead to reduced flexibility, particularly in regions with significant temperature variations.

Lastly, the mix featuring 16.42% VMA at 6% bitumen content falls within a similar range as the previous mixes, indicating comparable characteristics. This suggests a well-balanced mix design with attributes such as durability, stability, and flexibility.

Among the provided options, the VMA value of 16.52% at 5% bitumen content appears to strike a good balance. It suggests a suitable void space within the mineral aggregate while accommodating sufficient asphalt binder to ensure adequate durability, stability, and flexibility.

D) Relationship between the percentage of VFA and bitumen content

Table 4.9 and Figure 4.9 (d) illustrates the relationship between bitumen content and voids filled with asphalt. The graph shows that higher bitumen content results in more voids filled with asphalt.

Starting with the asphalt mix featuring 53.98% VFA at 4.5% bitumen content, it suggests a relatively low void space within the asphalt binder. While this may indicate a dense and well-filled mixture, excessively low VFA levels could lead to challenges during compaction and insufficient flexibility, potentially impacting long-term durability.

Moving to the mix with 67.61% VFA at 5% bitumen content, it indicates a higher void space filled with asphalt binder. The mix with 73.87% VFA at 5.5% bitumen content further increases the void space filled with asphalt binder. This could result in improved flexibility and resistance to thermal stresses, making it suitable for applications in regions with significant temperature variations.

Lastly, the mix featuring 83.3% VFA at 6% bitumen content exhibits the highest level of void space filled with asphalt binder. While this may offer excellent flexibility and resistance to cracking, excessively high VFA levels could also lead to reduced stability and durability, particularly under heavy traffic loads.

Among these options, a higher VFA typically indicates better flexibility and resistance to cracking. However, excessively high VFA levels could lead to reduced stability and durability. Considering this, the VFA value of 73.87% at 5.5% bitumen content appears to offer a good balance between void space and asphalt binder content.

E) Relationship between stability and bitumen content

Here, the stability results for bitumen contents ranging from 4.5% to 6% are shown in Table 4.9 and Figure 4.9 (e). At 4.5% bitumen content, a stability of 9.81 KN suggests a moderate level of stability. While indicating fair resistance to deformation under traffic loads, it approaches the lower threshold for heavy traffic conditions, indicating potential limitations in load-bearing capacity.

Increasing the bitumen content to 5% results in a slightly higher stability of 9.96 KN. This indicates improved resistance to deformation, offering a better balance between flexibility and rigidity. Moving further to 5.5% bitumen content, the stability increases to 10 KN, considered good. This suggests a higher resistance to deformation, particularly under heavy traffic conditions. The mix is anticipated to perform excellently, providing a durable and resilient pavement structure.

Comparing these stability values, the mix at 5.5% bitumen content demonstrates the highest stability and is expected to offer the best performance under heavy traffic conditions.

F) Relationship between flow and bitumen content

Table 4.9 and Figure 4.9 (f) provided information highlights the relationship between asphalt mix flow and bitumen content. At 4.5% bitumen content, the flow value of 2.42 mm suggests higher resistance to deformation but may pose challenges during construction due to reduced workability. Increasing the bitumen content to 5% results in a flow of 3.01 mm, indicating a balance between deformation resistance and workability. This suggests a more manageable mix for construction purposes while maintaining adequate resistance to deformation.

Further increasing the bitumen content to 5.5% leads to a flow of 3.38 mm, indicating increased flexibility but also raising concerns about potential rutting issues. The mix becomes more susceptible to deformation under heavy traffic loads. Finally, at 6% bitumen content, the flow value increases to 3.63 mm, indicating excessive plasticity and posing risks of rutting and shoving in the pavement. This mix may be challenging to work with during construction and may exhibit poor performance under traffic loads.

Considering these factors, the asphalt mix with a flow value of 3.01 mm at 5% bitumen content appears to offer the best balance between deformation resistance and workability

4.5. Optimum Bitumen Content Determination

According to the specification [1], to determine the optimum binder content, all Marshall mix properties must meet the criteria. This includes ensuring that air voids are 4% or close in relation to both bitumen content and all mix design parameters. The optimal bitumen contents for all four proposed grades with varying filler proportions were determined based on the recommendations from MS-2 and the ERA 2013 specification procedure methods.

To set a baseline, it is recommended to choose the bitumen content with 4% air voids as the design content. extrapolation from the Figure 4.6 to Figure 4.9 presented was used to calculate and measure all mix properties at this bitumen content. This method includes finding the binder content (BC) values by plotting the bitumen content graph against mix design parameters for each property.

Table 4.10 to 4.13 depicts the extrapolated value at 4% air voids, percent range of bitumen compliance and MS-2 specification limit of various asphalt properties including Marshall stability, flow, VMA, VFA, VIM, and Gmb for different asphalt mix with varying filler contents. The results indicate that all Marshall mix properties, ranging from 4.25% to 5.75% of CSD filler in 0.5% increments, meet the criteria outlined in the Asphalt Institute method (MS-2) mix design standards, particularly at 4% air voids [1].

Furthermore, acceptable optimum bitumen contents for different filler contents, which were found to be 5.68%, 5.51%, 5.24%, and 5.5% for filler contents of 4.25%, 4.75%, 5.25%, and 5.75%, respectively are identified (Refer Figures 4.10 to 4.13 for detailed).

Table 4.10: Details the mix properties of 4.25% CSD with a 4% air void and a bitumen percentage

Mix parameter Properties	Percent range of bitumen giving compliance	Values extrapolated from graph at 4% air void	Specification Limit (MS-2 criteria)	CSD Filler
Bitumen Content, %	4.5-6	5.68	4-10	4.25%
VIM, %	5.37-6	4.00	3-5	
VMA, %	4.5-6	16.17	13 min	
VFA, %	5.18-5.69	75.00	65-75	
Stability, KN	4.5-6	8.25	7 min	
Flow $_{0.25}$, mm	4.5-6	2.92	2-3.5	
G_{mb}, g/cm3	4.5-6	2.295	-	

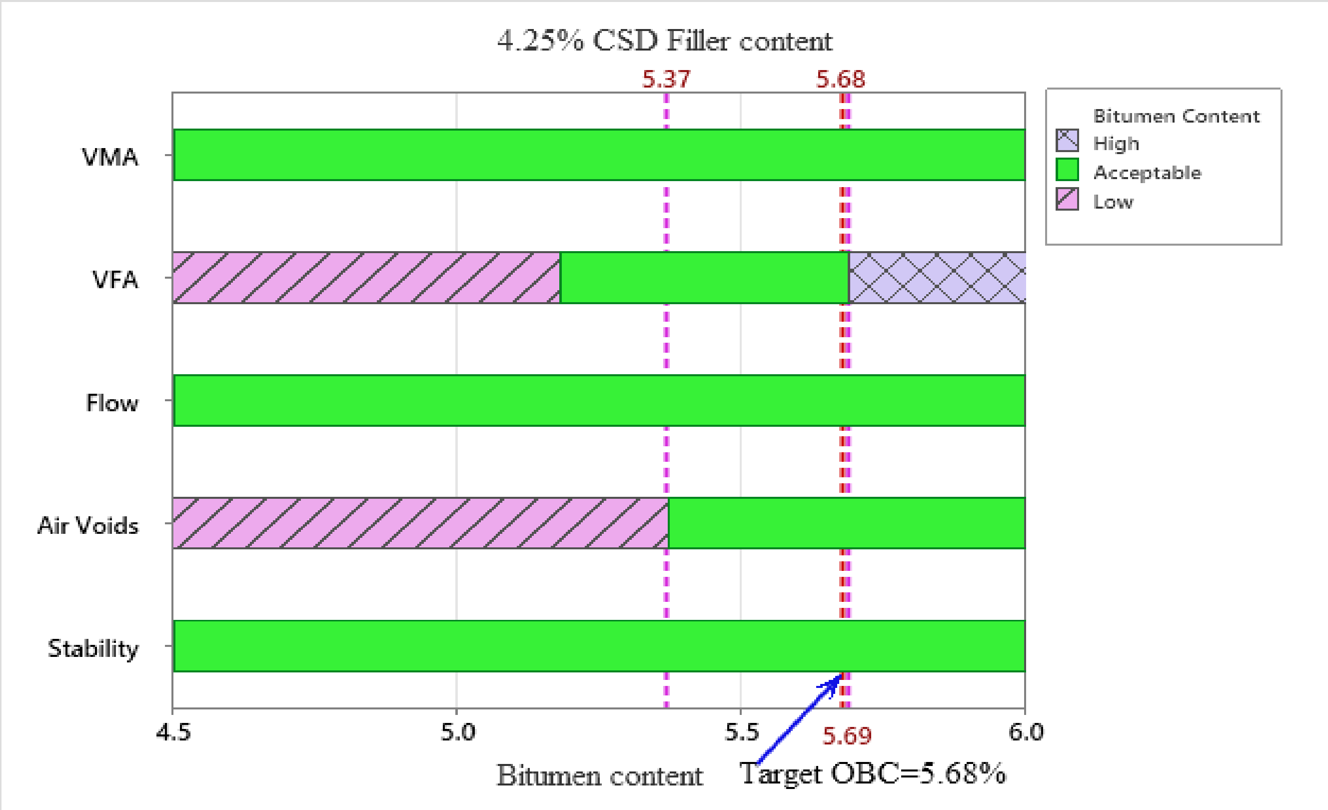


Figure 4.10: Acceptable bitumen range with MS-2 design criteria

Table 4.11: Details the mix properties of 4.75% CSD with a 4% air void and a bitumen percentage

Mix parameter Properties	Percent range of bitumen giving compliance	Values extrapolated from graph at 4% air void	Specification Limit (MS-2 criteria)	CSD Filler
Bitumen Content, %	4.5-6	5.51	4-10	4.75%
VIM, %	5.22-6	4	3-5	
VMA, %	4.5-6	16.11	13 min	
VFA, %	5.02-5.54	74.88	65-75	
Stability, KN	4.5-6	9.16	7min	
Flow $_{0.25}$, mm	4.5-6	2.70	2-3.5	
G_{mb}, g/cm3	4.5-6	2.295	-	

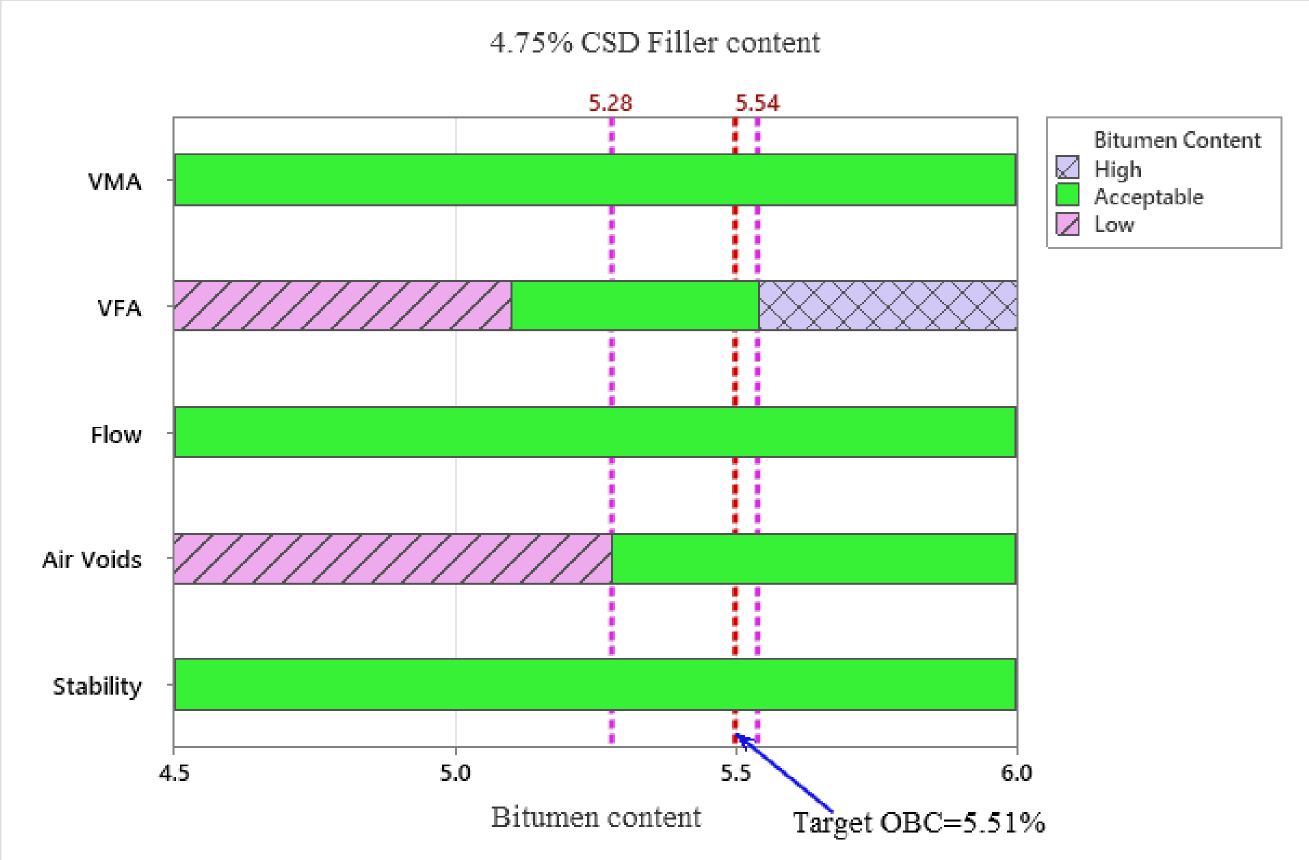


Figure 4.11: Acceptable bitumen range with MS-2 design criteria

Table 4.12: Details the mix properties of 5.25% CSD with a 4% air void and a bitumen percentage

Mix parameter Properties	Percent range of bitumen giving compliance	Values extrapolated from graph at 4% air void	Specification Limit (MS-2 criteria)	CSD Filler
Bitumen Content, %	4.5-6	5.24	4-10	5.25%
VIM, %	4.89-6.	4	3-5	
VMA, %	4.5-6	15.69	13 min	
VFA, %	4.7-5.29	74.64	65-75	
Stability, KN	4.5-6	10.87	7min	
Flow $_{0.25}$, mm	5.89-6	2.959	2-3.5	
G_{mb}, g/cm3	4.5-6	2.304	-	

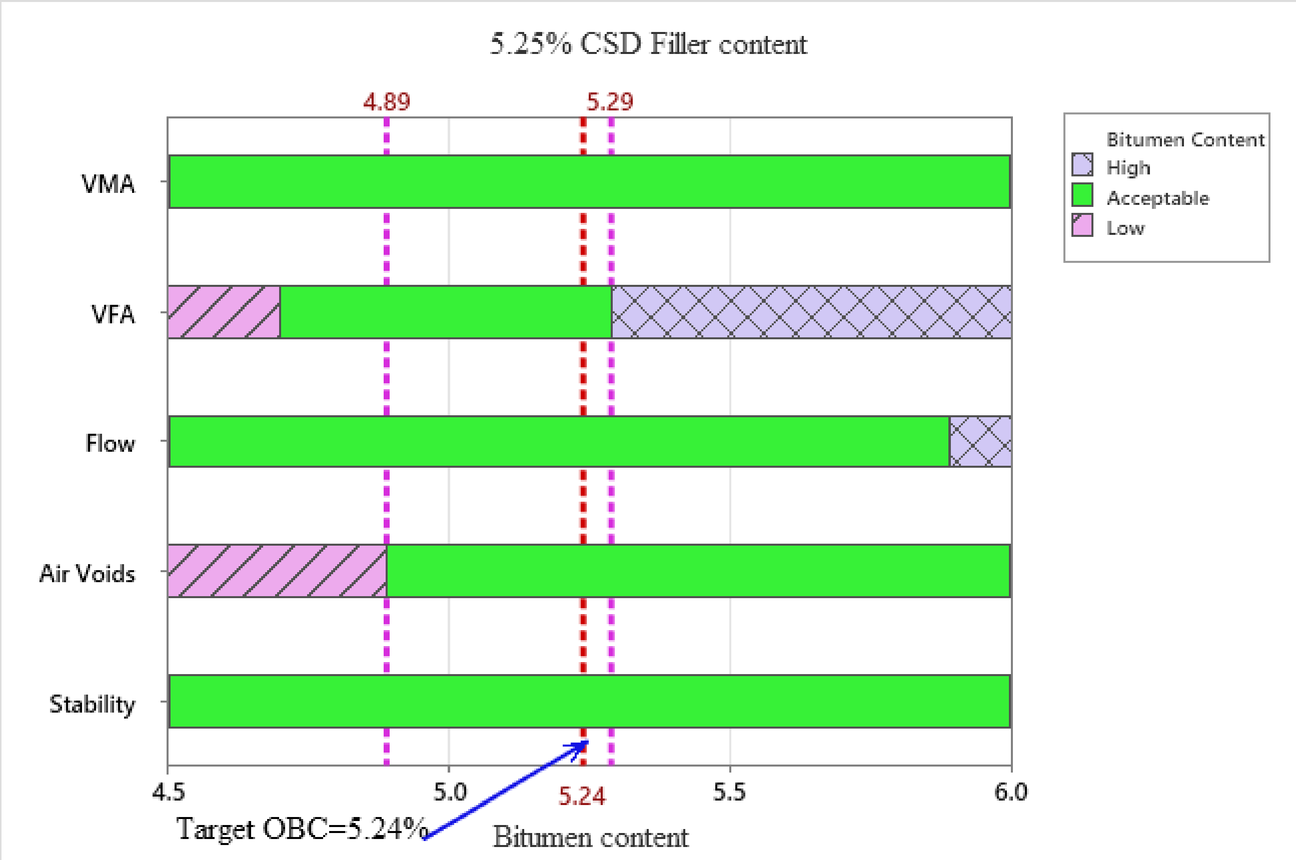


Figure 4.12: Acceptable bitumen range with MS-2 design criteria

Table 4.13: Details the mix properties of 5.75% CSD with a 4% air void and a bitumen percentage

Mix parameter Properties	Percent range of bitumen giving compliance	Values extrapolated from graph at 4% air void	Specification Limit (MS-2 criteria)	CSD Filler
Bitumen Content, %	4.5-6	5.50	4-10	5.75%
VIM, %	5.18-5.91	4.00	3-5	
VMA, %	4.5-6	16.38	13 min	
VFA, %	5.04-5.56	74.56	65-75	
Stability, KN	4.5-6	10.00	7 min	
Flow $_{0.25}$, mm	4.5-5.68	3.38	2-3.5	
G_{mb}, g/cm3	4.5-6	2.289	-	

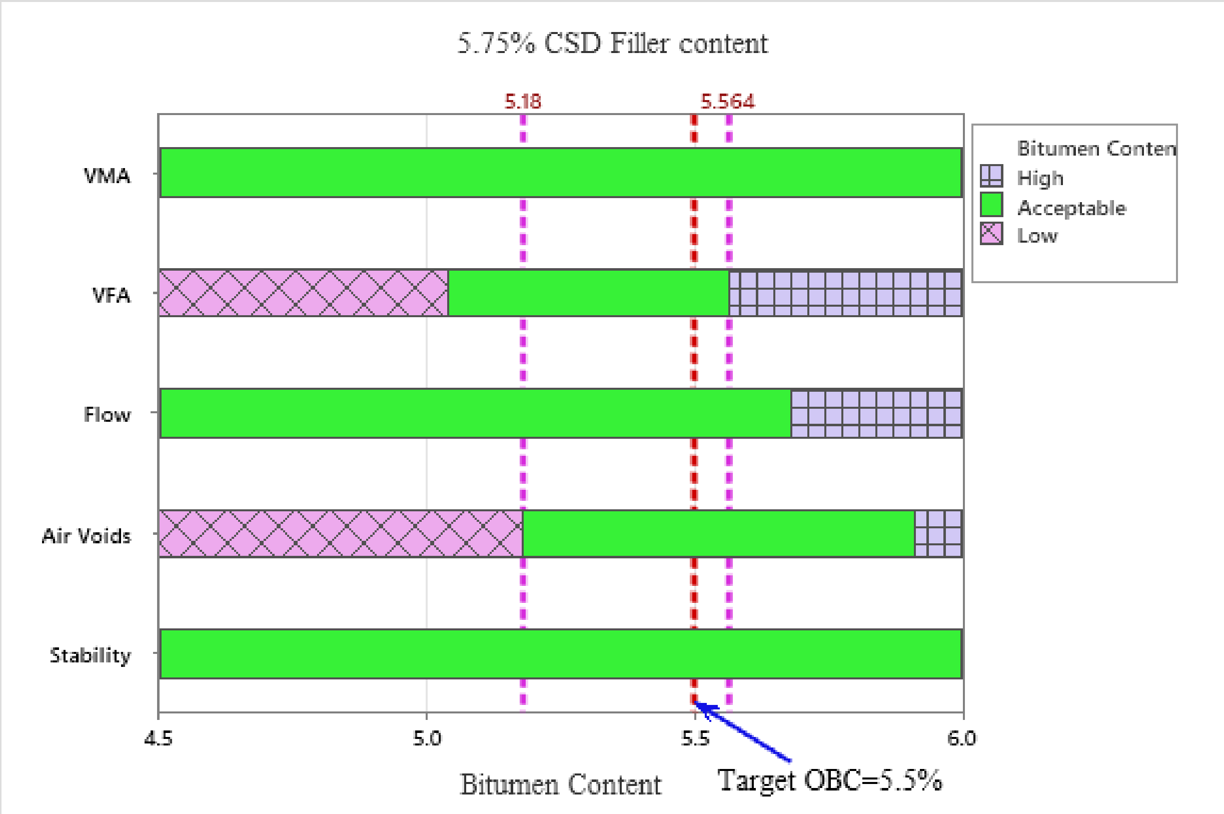


Figure 4.13: Acceptable bitumen range with MS-2 design criteria

Table 4.14: Summary of Marshall mix properties at corresponding OBC

Mixture properties	% Of CSD filler content				Specifications		Remark
	4.25	4.75	5.25	5.75	AI (MS-2)	ERA 2013	
OBC (%)	5.68	5.51	5.24	5.5	4-10	4-10	OK!
VIM (%)	4	4	4	4	3-5	3-5	OK!
VFA (%)	75	74.88	74.64	74.56	65-75	65-75	OK!
VMA (%)	16.17	16.11	15.69	16.38	Min 13	Min 13	OK!
Stability (KN)	8.25	9.16	10.87	10	Min 7	Min 8	OK!
Flow (mm)	2.92	2.70	2.959	3.38	2-3.5	2-3.5	OK!
G_{mb} (g/cm^3)	2.295	2.290	2.304	2.289	-	-	OK!

Selecting the optimum bitumen content (OBC) for asphalt mix design requires a careful balance of various properties, especially when prioritizing resistance to rutting and considering traffic conditions. Let's dissect the provided data from Table 4.14 to ascertain the optimum bitumen content:

1) Marshall Stability: This is a measure of the mix's resistance to deformation under load. The mix with 5.25% filler content has the highest stability at 10.87 KN, which is preferable for high-traffic areas where rutting resistance is critical.

2) Marshall Flow: Lower flow values indicate a stiffer mix, which is beneficial for rutting resistance. The mix with 4.75% filler content has the lowest flow at 2.70 mm, suggesting it is less prone to deformation. However, the mix with 5.25% filler content also has a reasonable flow value of 2.959 mm, which is within the acceptable range.

3) Bulk Density: A higher bulk density indicates better compaction, which can contribute to rutting resistance. The mix with 5.25% filler content has the highest bulk density at 2.304 g/cm^3. But it is not the primary factor in rutting resistance.

4) Voids in Mineral Aggregate (VMA): Adequate VMA ensures enough space for bitumen, which affects the mix's durability and flexibility. The mix with 5.75% filler content has the highest VMA at 16.38%. But it is less directly related to rutting resistance.

5) Voids Filled with Asphalt (VFA): Higher VFA values suggest a denser mix with fewer air voids, which can resist rutting. The mix with 5.75% filler content has the highest VFA at 74.56%. Considering the need to resist rutting under heavy traffic conditions, the mix with 5.25% filler content stands out due to its superior stability. Although the mix with 4.25% filler content has the highest VFA, its stability is slightly lower than the 5.25% filler content mix. Therefore, the 5.25% filler content mix is likely the best choice for areas with heavy traffic, as it provides the best combination of high stability and adequate flow, indicating a strong resistance to rutting. The 5.25% filler content mix is used based on the following properties (Table 4.15).

Table 4.15: Overview of Marshall mix characteristics for control mix at OBC

Marshall Mix Parameter	OBC (%)	VIM (%)	VFA (%)	VMA (%)	Stability (KN)	Flow (mm)	G_{mb} (g/cm^3)	CSD
Optimum design value	5.24	4	74.64	15.69	10.87	2.959	2.304	5.25%
Specification (AI)	4-10	3-5	65-75	Min 13	Min 7	2-3.5	-	

Note: AI is stand for Asphalt Institute

4.6. Waste Marble Powder Modified HMA

The impact of waste marble powder (WMP) on the Hot Mix Asphalt (HMA) blend underwent evaluation via the Marshall mix design. Key performance indicators such as bulk specific gravity, Marshall stability, flow, volume, moisture sensitivity, and rut depth were the focal points of this study. Optimal levels of bitumen (5.24%) and filler (5.25%) were determined, after which systematic replacement of stone dust filler with WMP filler was carried out. This replacement occurred in 10% increments, spanning from 0% to 50% of the total conventional filler mass. This substitution strategy was informed by a thorough examination of existing data, literature, and material availability.

For example, Khan, Khan [4] used 2-6 percent of marble dust by the weight of total aggregate and find the optimum value of marble at 4%. Ma, Wang [118] used 10-30% marble powder as partial replacement of cement in their study.

For each proportion of WMP, three specimens were manufactured, and their average bulk specific gravity, Marshall stability, flow, volume properties, moisture sensitivity, and rut depth were measured. These values were then compared against those of a control mix lacking WMP, which served as the baseline for comparison. The findings unveiled significant alterations in the mix's bulk specific gravity, Marshall stability, flow, volume properties, moisture sensitivity, and rut depth due to the inclusion of WMP (Refer to Table 4.16 for details).

Table 4.16: Marshall test outcomes for mixtures with WMP filler at 5.24% OBC and 5.25% CSD.

Specimen No.	WMP, %	Bulk SG mix (G_{mb}), g/cm3	Max.T.SG (G_{mm})	Air void, %	VMA %	VFA %	Marshal Stability, KN	Flow (mm)
1	10	2.288	2.421	5.48	16.20	66.15	10.34	4.51
2		2.294		5.25	15.99	67.20	10.31	3.33
3		2.303		4.86	15.65	68.94	11.50	2.86
Average		**2.295**		**5.20**	**15.95**	**67.43**	**10.72**	**3.57**
1	20	2.341	2.416	3.07	14.25	78.43	11.62	3.05
2		2.298		4.86	15.83	69.28	11.09	3.00
3		2.284		5.44	16.34	66.71	11.28	4.32
Average		**2.308**		**4.46**	**15.47**	**71.47**	**11.33**	**3.46**
1	30	2.327	2.410	3.46	14.78	76.58	12.89	2.89
2		2.310		4.15	15.39	73.06	11.64	3.04
3		2.299		4.63	15.81	70.74	11.80	2.73
Average		**2.312**		**4.08**	**15.33**	**73.46**	**12.11**	**2.89**
1	40	2.313	2.391	3.28	15.29	78.53	11.88	2.90
2		2.294		4.07	15.98	74.53	12.17	3.89
3		2.305		3.63	15.59	76.70	11.31	2.62
Average		**2.304**		**3.66**	**15.62**	**76.59**	**11.79**	**3.14**
1	50	2.296	2.349	2.26	15.91	85.79	10.32	2.65
2		2.299		3.88	15.81	75.44	11.06	3.36
3		2.304		3.68	15.63	76.49	11.91	2.75
Average		**2.299**		**3.27**	**15.8**	**79.2**	**11.10**	**2.92**

Table 4.17: The Marshall mix properties for varying ratios of WMP and CSD at the specified OBC

Percent of Waste marble powder partially replaced CSD	Bulk SG mix (G_{mb}), g/cm3	Air void, %	VMA, %	VFA, %	Marshal Stability, KN	Flow, mm
Conventional	2.304	4	15.69	74.64	10.87	2.959
10% WMP	2.295	5.20	15.95	67.43	10.72	3.57
20% WMP	2.308	4.46	15.47	71.47	11.33	3.46
30% WMP	2.312	4.08	15.33	73.46	12.11	2.89
40% WMP	2.304	3.66	15.62	76.59	11.79	3.14
50% WMP	2.299	3.27	15.78	79.2	11.10	2.92

4.6.1. Effect of partial replacement of waste marble powder on bulk density

Bulk specific gravity (Gmb) is directly related to bulk density, as it represents the ratio of the density of the asphalt mix to the density of water [1]. Table 4.17 and Figure 4.14 (a) shows that the bulk specific gravity tends to increase with increasing percentages of waste marble powder up to 30%, where it reaches its peak value of 2.312 g/cm³. Beyond 30% waste marble powder, there is a slight decrease in bulk specific gravity, with the value dropping to 2.299 g/cm³ at 50% waste marble powder. This suggests that WMP contributes to a denser mix, which could imply better compaction and potentially improved durability. An increase in bulk specific gravity indicates higher asphalt mix density, which can enhance pavement stability and resistance to rutting.

4.6.2. Effect of partial replacement of waste marble powder on air voids

Table 4.17 and Figure 4.14 (b) illustrate that, the percentage of air voids initially increases with 10% WMP but then decreases as more WMP is added, reaching the lowest value at 50% replacement. Lower air voids can indicate a denser mix, which is less susceptible to water damage and can provide better load-bearing capacity. slight increase in air voids suggests improved asphalt mix workability and compaction, which can facilitate better bonding between aggregate particles and asphalt binder. But excessive air voids may compromise mix durability and lead to increased susceptibility to moisture damage and aging [61]. The 4.08% air void at 30% WMP replacement is close to design air void recommended by Asphalt Institute [1].

4.6.3. Effect of partial replacement of waste marble powder on VMA

As observed from Table 4.17 and Figure 4.14 (c) VMA shows slight fluctuations, with a decrease observed initially and then an increase at higher replacement percentages. The VMA at 30% WMP decreased by 2.29% from 15.69% control mix to 15.33% modified asphalt mix. A decrease in VMA indicates improved aggregate interlock and binder coating, enhancing mix cohesion and resistance to rutting [1].

4.6.4. Effect of partial replacement of waste marble powder on VFA

The VFA increases with the addition of WMP, indicating that the mix becomes denser and has fewer voids. Higher VFA values are generally desirable as they can lead to a more durable pavement with less susceptibility to rutting (refer Table 4.17 and Figure 4.14 (d) for details). The value of VFA decreased from 74.64% of control mix to 73.46% of waste marble powder modified mix by 1.58%. A decrease in VFA suggests improved asphalt binder coating and filling of voids between aggregate particles, contributing to enhanced mix durability and resistance to moisture damage.

4.6.5. Effect of partial replacement of waste marble powder on Marshall stability

As Table 4.17 and Figure 4.14 (e) indicates the stability generally increases by 11.41% with the addition of WMP, with the highest value of 12.11KN observed at 30% replacement. A significant increase in Marshall stability indicates improved resistance to deformation and rutting under traffic loading, resulting in enhanced pavement performance and longevity [1].

4.6.6. Effect of partial replacement of waste marble powder on flow

The flow values fluctuate with the addition of WMP, with the lowest value of 2.89mm at 30% replacement. The flow value of control mix is decreased by 2.36% at 30% waste marble powder modified mix. Lower flow values can indicate a stiffer mix, which is beneficial for resisting deformation under load (Table 4.17 and Figure 4.14 (f).

In summary, the WMP modified HMA shows improvements in several key properties compared to the control mix. The mix with 30% WMP replacement improved the bulk specific gravity, Marshall stability, and VFA of the mix, by 0.355%, 11.41% and 1.58% respectively, which are indicators of a denser and potentially more durable HMA mix. The flow value improved in terms of reduction (2.36%), which is beneficial for the mix’s stiffness and resistance to rutting. The slight increase in air voids and decrease in VMA are within acceptable ranges and do not necessarily indicate a decrease in quality. The data indicates that the optimum dosage of WMP is 30% and it can be a viable alternative to traditional fillers, potentially enhancing the performance of HMA mixes.

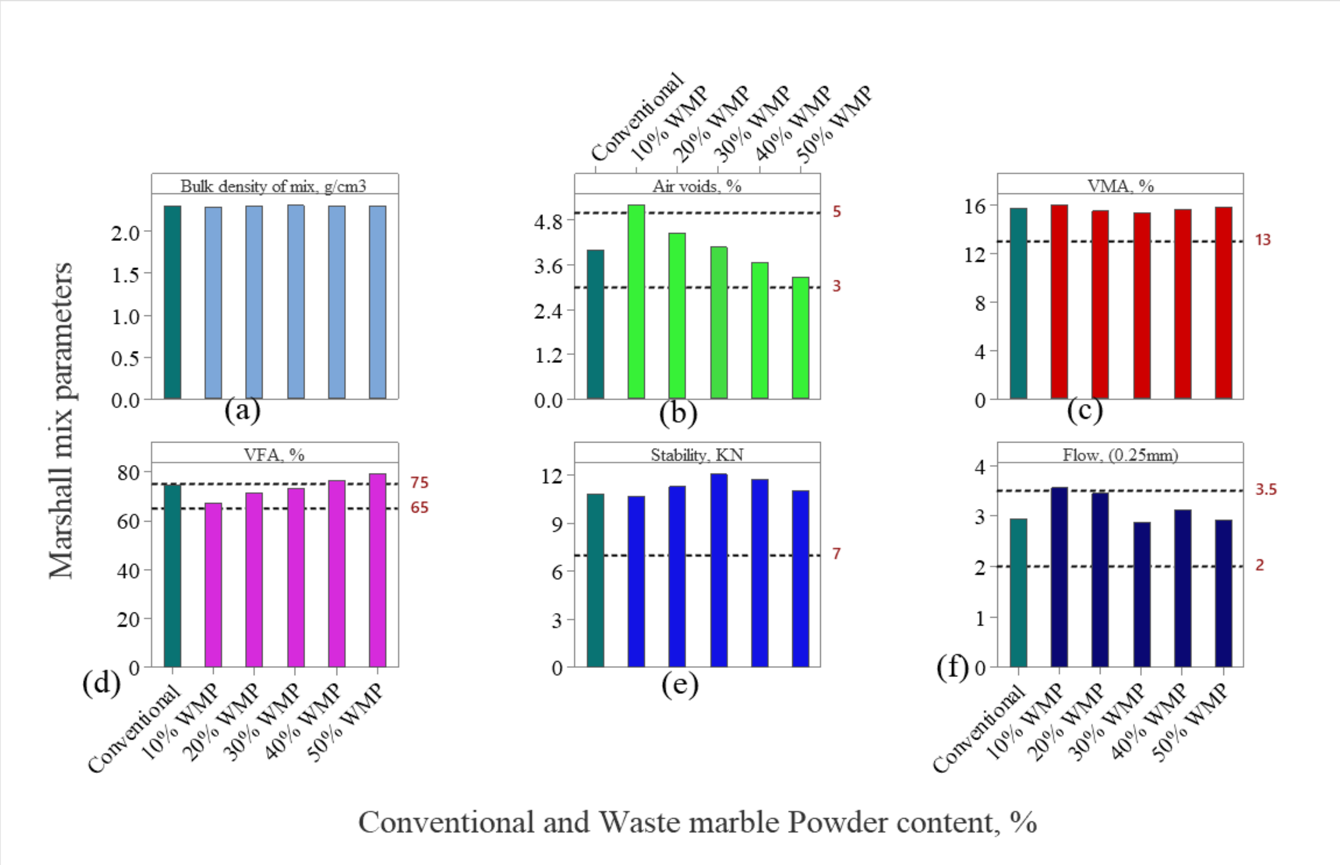


Figure 4.14: The effect of waste marble powder on Marshall mixes properties

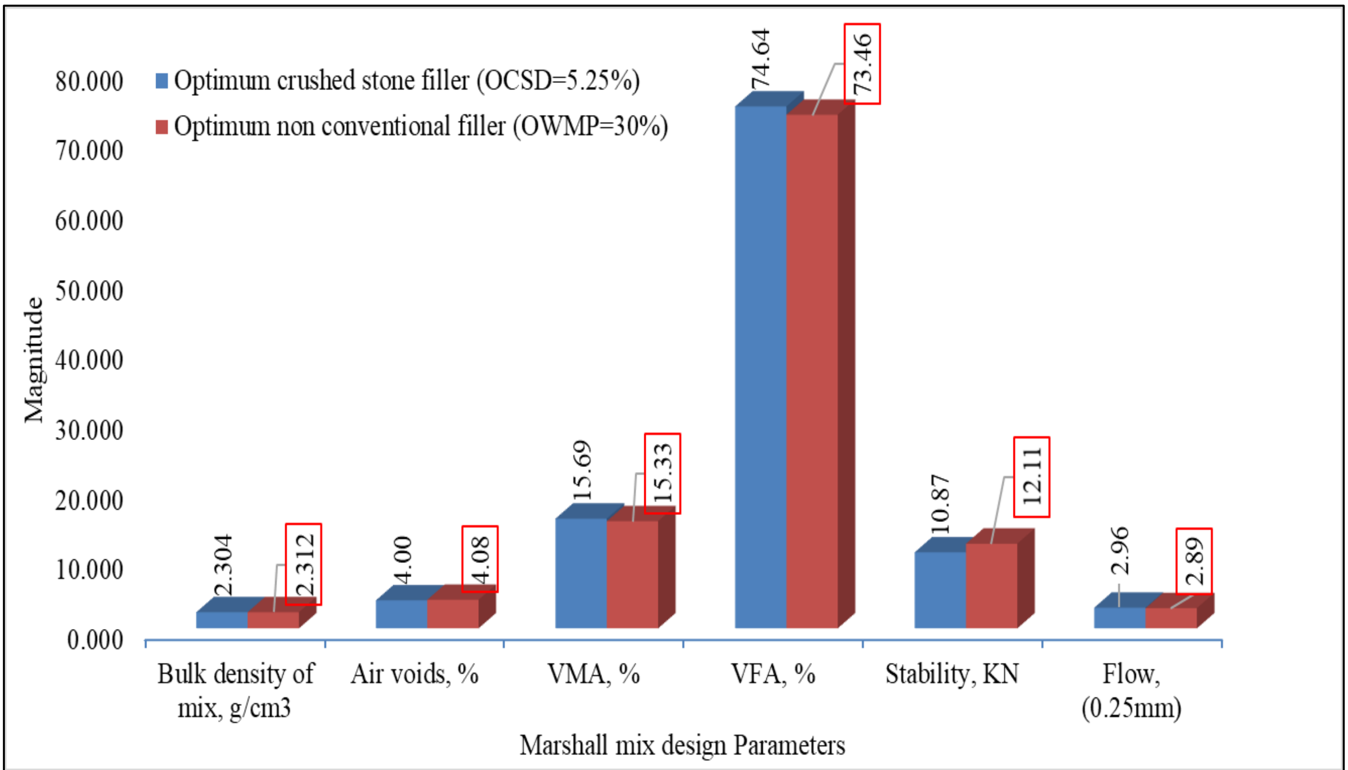


Figure 4.15: Marshall mixes parameter of control and WMP modified at optimum value

4.7. Moisture Induced Damage of HMA Test Results

4.7.1. Indirect tensile strength test results (Control mix)

Moisture induced damage describes how asphalt mixtures deteriorate when exposed to water, which is a crucial factor for the durability and lifespan of asphalt pavements. The tensile strength ratio (TSR) is a key metric for evaluating moisture susceptibility; higher TSR values signify better resistance to water damage [1, 119].

The experiment involved the preparation of Marshall specimens for each mix, incorporating various replacement rates while maintaining optimum asphalt content. Six specimens were prepared for each mix variant, with three designated as condition and three as unconditioned samples. The unconditioned (dry) specimens were stored at room temperature for 24 hours to simulate normal curing conditions before undergoing compressive strength testing. This step establishes a baseline for comparison with the wet group.

The conditioned (wet) specimens were subjected to an accelerated moisture conditioning process. Initially, they were immersed in water at 60℃ for 24 hours to simulate high-temperature soaking, replicating conditions akin to prolonged exposure to moisture. Subsequently, the specimens were transferred to a water bath at 25℃ for two hours to mimic cooling and stabilize the temperature before conducting the tensile strength test. Both unconditioned (dry) and conditioned (wet) specimens underwent indirect tensile strength (ITS) testing to assess their mechanical properties.

The TSR value, representing the ratio of conditioned (wet) to unconditioned (dry) ITS values, was calculated for each sample [114]. ITS and TSR are calculated from Eqn. 3.9 and Eqn.3.10 respectively. The TSR values obtained provide insights into the moisture susceptibility of the asphalt mixes. It offers a systematic approach to evaluate the moisture susceptibility of asphalt mixes. A higher TSR percentage indicates increased susceptibility to moisture damage, signifying a reduction in tensile strength following conditioning. Understanding moisture susceptibility is crucial for designing resilient asphalt pavements capable of withstanding environmental challenges and prolonging service life.

4.7.2. Effect of waste marble powder on moisture susceptibility

The effects of waste marble powder (WMP) filler on the moisture susceptibility of the bituminous paving mixture are demonstrated in Table 4.18. Based on the laboratory results the tensile strength is meet the standard requirement at 30% waste marble powder. The indirect tensile strength test was conducted for control mix and waste marble modified mix at the optimum value of bitumen content, conventional filler content (CSD) and non-conventional filler content (waste marble powder).

Table 4.18: Indirect tensile strength test result at the optimum bitumen content and CSD

Test type: Indirect Tensile Strenght of Asphalt Mixture — Specific Gravity of AC (Gb): **1.020**
Test Method: AASHTO T-283 and NPRA 014 test14.554 — Bulk S.G. Aggregate: **2.587** — Compacted Date: 2-Jan-2024
Compaction : 75 Blows — Grade of AC: 60/70 — Tested Date: dry 3-Jan-2024; wet 4-Jan-2024
Composition: 5.25% OCSD+5.24% OBC

Sample No.	Specimen thickness(mm)		Specimen Dia (mm)	Measured Max. Load (KN)		Indirect Tensile strength S, S_t (Kpa)		E-modulus, Mpa		Tensile strength ratio (TSR), %
	Dry	Wet		Dry	Wet	Dry	Wet	Dry	Wet	
1	65	65	101.6	6.90	5.92	665.06	573.43	4156.85	3597.93	86.22
2	65	65	101.6	8.81	6.89	849.28	668.00	5280.59	4174.81	78.66
3	65	64	101.6	7.86	6.14	757.79	594.84	4722.54	3728.55	78.50
Average	65.00	64.67	101.60	7.86	6.32	757.38	612.09	4719.99	3833.76	81.13
								4276.88		

Note: 5.25% OCSD= 5.25% optimum crushed stone at optimum bitumen content
5.24% OBC= 5.24% optimum bitumen content at 4% air void

Table 4.19: Indirect tensile strength test result at the OBC, OWMP and OCSD

Test type: Indirect Tensile Strenght of Asphalt Mixture — Specific Gravity of AC (Gb): **1.020**
Test Method: AASHTO T-283 and NPRA 014 test14.554 — Bulk S.G. Aggregate: **2.587** — Compacted Date: 2-Feb-2024
Compaction : 75 Blows — Grade of AC: 60/70 — Tested Date: dry 3-Feb-2024; wet 4-Feb-2024
Composition: 5.25% OCSD+5.24% OBC+30% OWMP

Sample No.	Specimen thickness(mm)		Specimen Dia (mm)	Measured Max. Load (KN)		Indirect Tensile strength S, S_t (Kpa)		E-modulus, Mpa		Tensile strength ratio (TSR), %
	Dry	Wet		Dry	Wet	Dry	Wet	Dry	Wet	
1	64.5	63.5	101.6	8.64	7.92	826.63	765.25	5142.42	4768.03	92.58
2	67.0	66.0	101.6	9.07	8.94	867.57	864.02	5392.18	5370.55	99.59
3	65.0	65.0	101.6	9.41	8.96	900.38	866.05	5592.34	5382.93	96.19
Average	65.5	64.8	101.6	9.04	8.61	864.86	831.78	5375.64	5173.83	96.12
								5274.74		

Note: 5.25% OCSD= 5.25% optimum crushed stone at optimum bitumen content
5.24% OBC= 5.24% optimum bitumen content at 4% air void
30% OWMP= 30% Optimum waste marble powder

a) Tensile strength ratio (TSR)

Table 4.18 shows that the control mix has a TSR of 81.13%, indicating a moderate resistance to moisture damage. While acceptable for conventional asphalt, there is potential for improvement. The control mix can withstand moisture to some extent, but prolonged exposure could lead to issues like stripping, where the binder separates from the aggregates, weakening the pavement structure. While the modified mix with waste marble powder has a higher TSR of 96.12% as indicated in Table 4.19. This indicates that the addition of waste marble powder improves the mixture's resistance to moisture by 18.48%.

The higher TSR suggests that the modified asphalt is less prone to moisture-induced stripping and other water-related damage, making it a more durable option, especially in wet environments.

b) Elastic Modulus

The elastic modulus, or modulus of elasticity, measures the stiffness of an asphalt mixture. A higher elastic modulus means a stiffer mixture, which is more resistant to deformation under load. This property is essential for the structural performance of pavements, as stiffer mixtures better distribute loads and prevent rutting. Table 4.18 illustrates that the control mix has an elastic modulus of 4276.88 MPa, indicating a reasonable level of stiffness, which provides adequate load-bearing capacity and resistance to deformation under traffic loads. However, this stiffness might not be sufficient in heavy traffic or high-stress environments to prevent long-term deformation.

However, waste marble powder modified mix shows a significantly higher elastic modulus of 5274.74 MPa as indicated in Table 4.19. This increased stiffness is a direct result of incorporating waste marble powder, which enhances the structural integrity of the asphalt. The higher modulus means the modified mixture is more resistant to deformation, making it better suited for heavy traffic and high-stress conditions. This improved stiffness also contributes to the overall durability and longevity of the pavement. DeMedeiros Melo Neto [120] investigated that the mixture containing 50% of waste marble showed an increase of 16.14% compared to the asphalt mixture 0%.

Comparing the control mix with the waste marble powder modified mix highlights the advantages of using waste marble as an additive in asphalt mixtures. The modified mix shows a significant improvement in TSR, increasing from 81.13% in the control mix to 96.12%. This indicates better resistance to moisture damage, which is critical for maintaining pavement integrity in wet conditions. The elastic modulus of the modified mix is 997.86 MPa (23.33%) higher than that of the control mix. This increase in stiffness translates to better load distribution and resistance to deformation, which are essential for high-performance pavement structures.

In general, adding waste marble powder to asphalt mixtures significantly improves both moisture susceptibility and elastic modulus. The higher TSR and elastic modulus values of the modified mix suggest superior performance in terms of durability and structural integrity. These enhancements make waste marble powder a viable and sustainable additive for improving asphalt pavement performance. This data and comparative analysis highlight the potential benefits of incorporating waste marble powder in asphalt mix design, promoting both environmental sustainability and enhanced pavement performance.

4.8. Effect of Waste Marble Powder on Permanent Deformation

Rutting, also known as permanent deformation, occurs when the asphalt mixture undergoes excessive deformation under repeated loading, leading to pavement distress and reduced service life [1]. Procedure B of the BS EN 12697-22:2020 standard was employed to determine the rut depth of the Hot Mix

Asphalt (HMA) specimens. The rutting resistance of the control mix (0% waste marble powder) was compared to that of a mix containing the optimum amount of WMP (30%).

Table 4.20 and Figure 4.16 shows that the results of the wheel-tracking test met the limit values specified in the UNE-EN requirements. The sample with 100% crushed stone dust (CSD) exhibited a mean rut depth of 0.394 mm, while the sample with 30% WMP filler achieved a slightly lower mean rut depth of 0.378 mm, which is a reduction of 4.06%. This indicates that the mix with 30% WMP has a better rutting resistance compared to the 100% CSD mix.

Additionally, the wheel tracking slope (WTS) per 1,000 load cycles was investigated for each test specimen. The WTS for the control mix was 0.019, whereas for the 30% WMP mix, it was 0.015. The proportional rut depth at different cycles, expressed as a percentage, was also examined. The mean proportional rut depth for the control mix was 0.780%, and for the 30% WMP mix, was 0.756%. These results demonstrate that incorporating 30% WMP in the asphalt mix can enhance rutting resistance compared to a mix with 100% CSD

Table 4.20: Overview of Wheel Truck Test (WTT) result of control mixture and OWMP

Results of UNE-EN 12697 :2020, Part 22 Single wheel Tracking (SWTT)									
	Control mix (0% WMP)			30% WMP Replacement			EN 13108 Requirement		
Trials	WTS_{AIR} (µmm/10^3 Load cycle)	PRD_{AIR} (%)	Mean Rut Depth (mm)	WTS_{AIR} (µmm/10^3 Load cycle)	PRD_{AIR} (%)	Mean Rut Depth (mm)	Rate (µmm/cycle)	PRD_{AIR} (%)	Rut depth (mm)
1	0.020	0.780	0.394	0.016	0.761	0.381	<0.02	<1	<1
2	0.019	0.780	0.394	0.015	0.751	0.375	<0.02	<1	<1
Average	0.019	0.780	0.394	0.015	0.756	0.378	<0.02	<1	<1

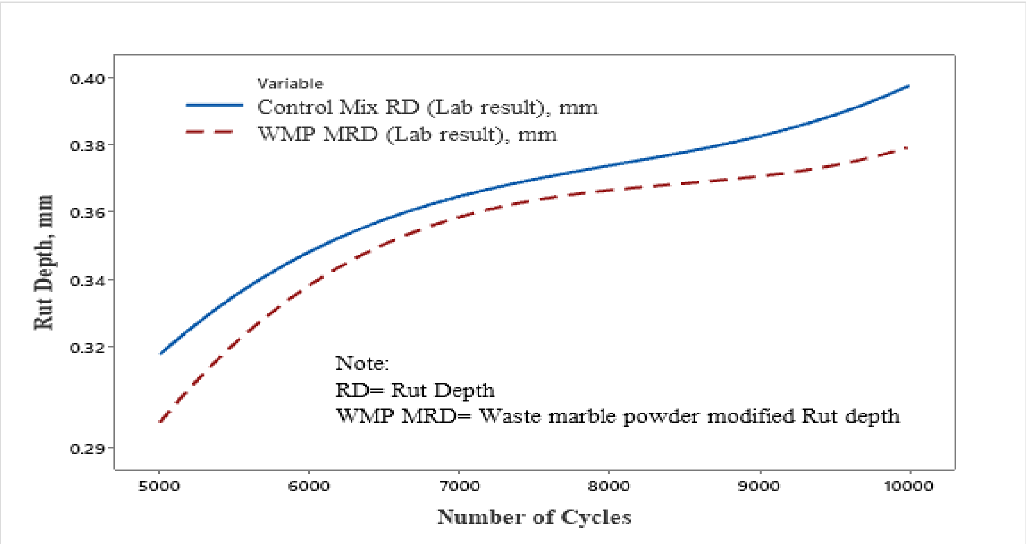
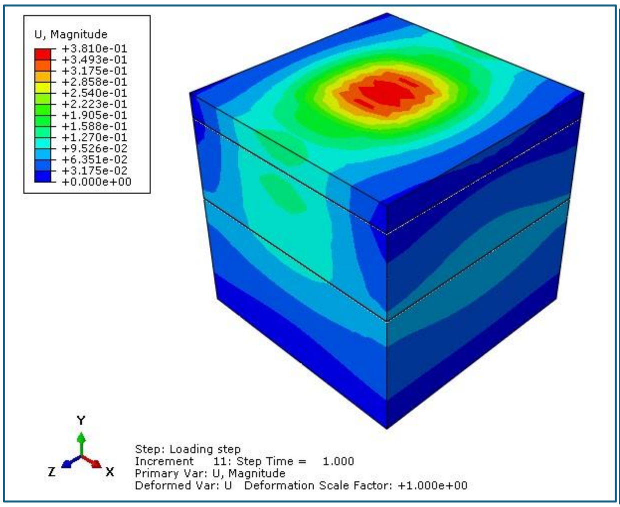


Figure 4.16: Graph of rut depth

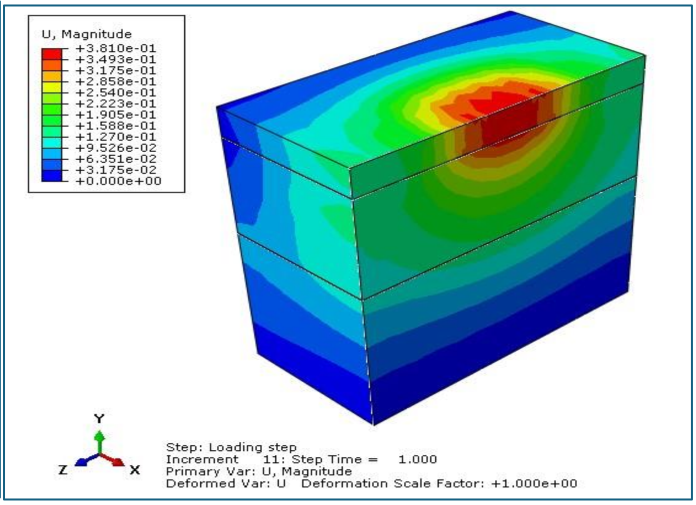
4. 9. Finite Element Simulation Analysis

4.9.1. Rutting depth of control asphalt mix design

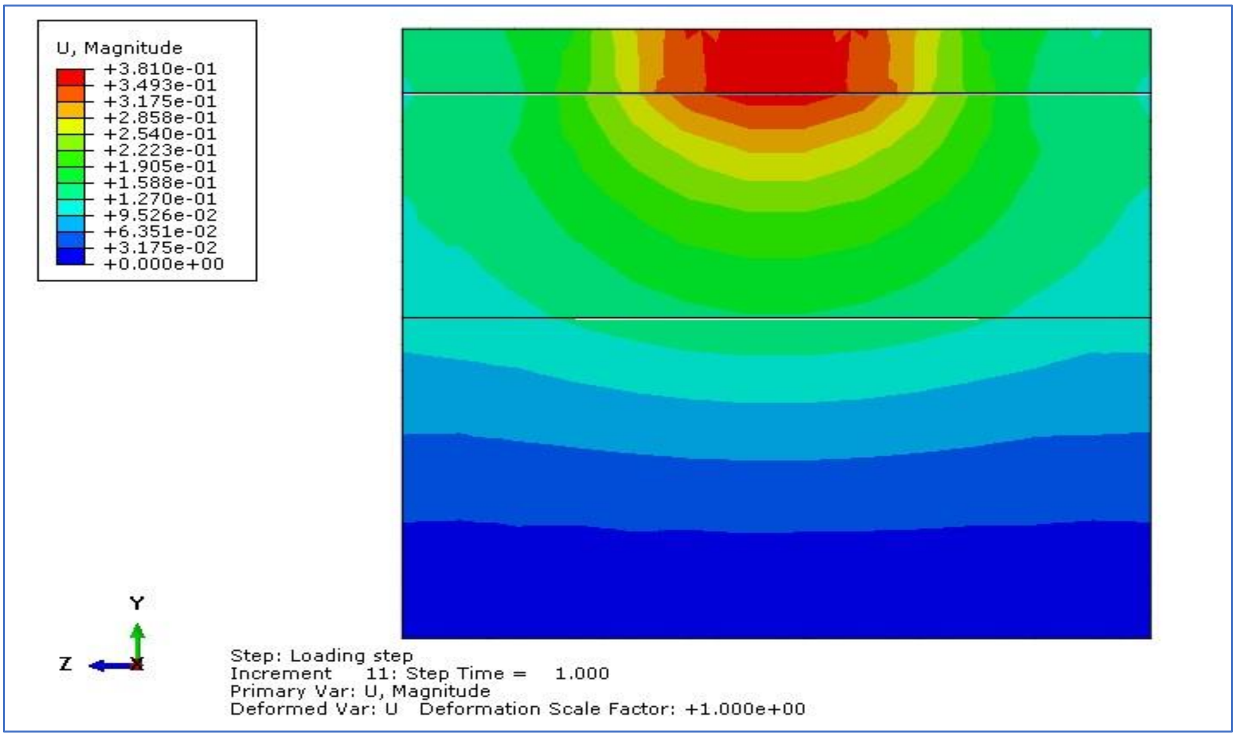
Rutting is a form of pavement deformation that occurs due to repeated application of traffic loads, causing depression in the wheel path. Assessing the rutting depth in asphalt mix design is critical for ensuring long lasting pavement performance [77]. Abaqus software was used to model both control asphalt mix (without waste marble powder) and modified asphalt mix as shown in Figure 4.17 and Figure 4.18 respectively.



(a) Representative 3D View of Deformation



(b) Typical 3D section views of deformation



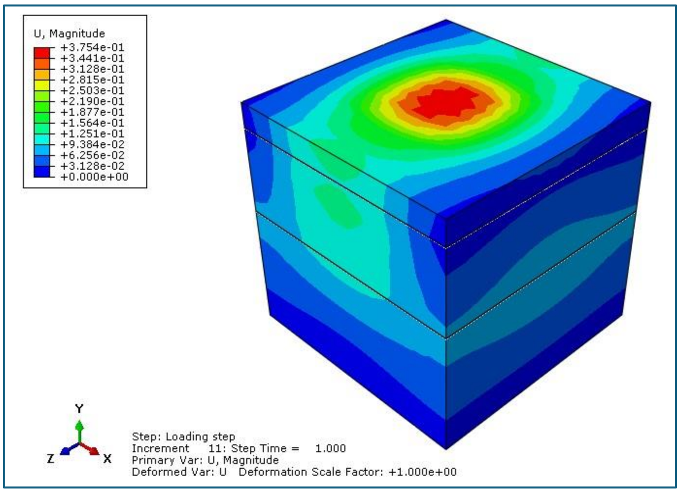
(c) Sectional 2D view of deformation

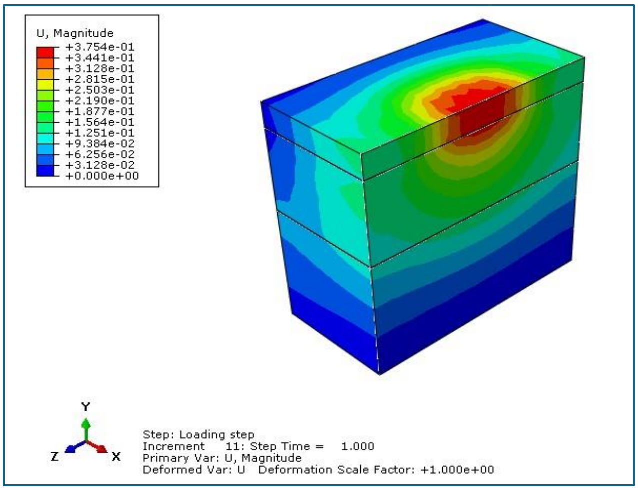
Figure 4.17: Representative deformation (Rutting) of flexible pavement (control asphalt mix)

Figure 4.17(a)-(c) presents both 2D and 3D Abaqus output contour visualization. The accompanying legend delineates the rutting depth characteristics at various nodes, with red indicating the maximum rutting depth and blue the minimum, measured in millimeters. Intermediate colors represent the gradation of rutting depths between these extremes. From the contour visualization graph, the minimum rutting depth is identified as 0 mm, while the maximum rutting depth is 0.381 mm, occurring within the asphalt layer.

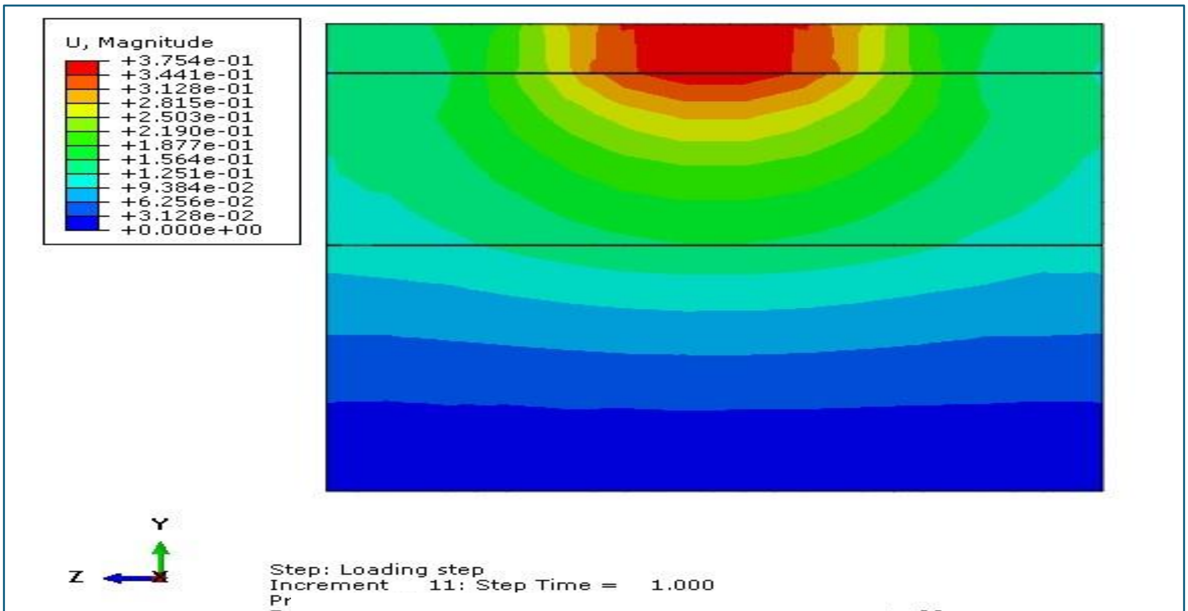
4.9.2 Rutting depth of waste marble powder modified asphalt mix

In Figure 4.18(a)-(c) presents both 2D and 3D Abaqus output contour visualization for modified asphalt mix. From the contour visualization graph, the minimum rutting depth is identified as 0 mm, while the maximum rutting depth is 0.375 mm, occurring within the asphalt layer.





Typical 3D views of vertical deformation (U2)   Typical 3D section views of vertical deformation (U2)



(c) Sectional 2D view of deformation

Figure 4.18: Representative deformation (Rutting) of flexible pavement (modified asphalt mix)

The reduction in rut depth from the control mix (0.381 mm) to the waste marble modified asphalt mix (0.375 mm) indicates an improvement in pavement performance as shown in Figure 4.18. The decrease in rut depth suggests that the modified asphalt mix offers better resistance to rutting, potentially resulting in a smoother and more durable pavement surface. This verify that the use of waste marble powder as a modifier in asphalt binder enhances the mechanical properties and performance characteristics of the pavement mix. The modification process alters the rheological properties of the asphalt binder, leading to improved rut resistance and overall pavement stability.

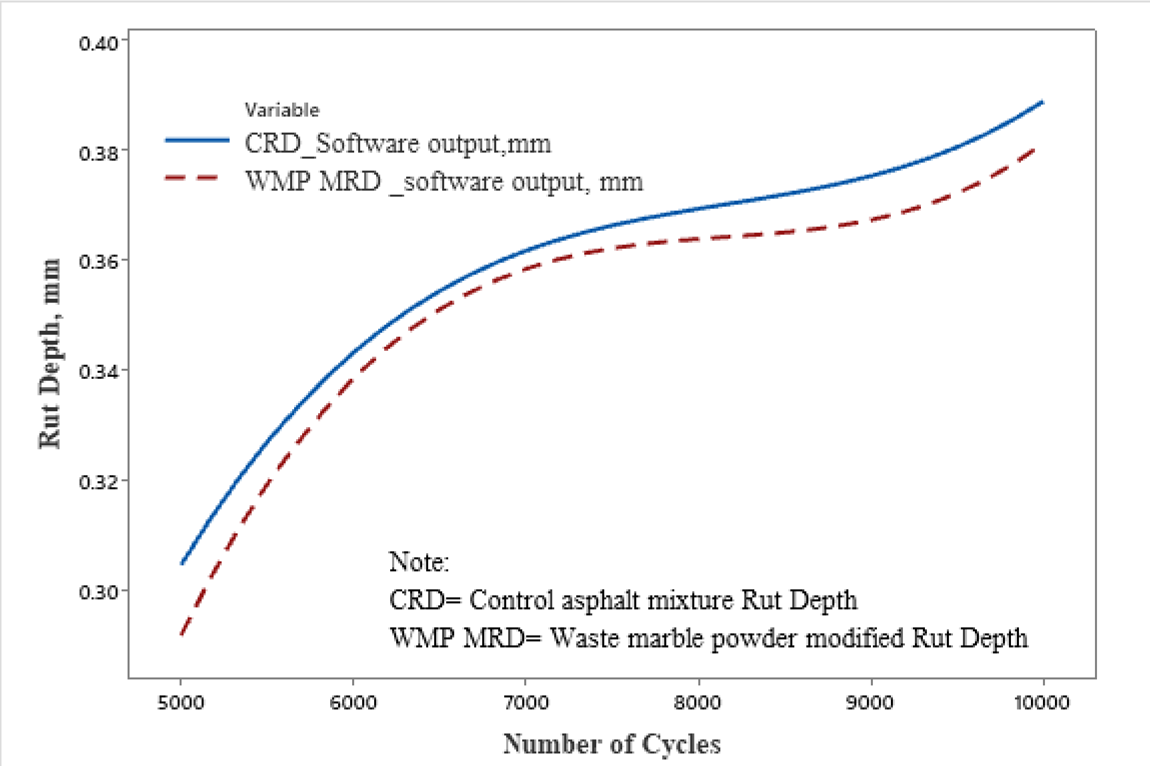


Figure 4.19: Comparing of CRD and WMP MRD asphalt mixture (Abaqus Software output)

Figure 4.19 reveals that the waste marble modified asphalt mix exhibits a slightly lower rut depth (0.375mm) compared to the control mix (0.381mm), indicating an improvement in pavement performance. The calculated percentage of improvement of 1.57%, underscores the effectiveness of the modification in reducing rutting and enhancing the durability of the pavement. This highlights the potential benefits of incorporating waste marble powder into asphalt mixes for sustainable and resilient pavement solutions.

Overall, the findings underscore the potential of waste marble powder as an effective material for improving the structural characteristics of asphalt mixes. This approach not only fosters sustainability through the utilization of industrial waste but also elevates pavement performance.

4.9.3 Abaqus Software rut depth modeling validation by laboratory experimental results

The validation of rut depth results presented in the Table 4.21 and Figure 4.20 is crucial for understanding the effectiveness of using waste marble powder (WMP) as a filler in asphalt mixtures. Let's delve into a detailed discussion on the implications and significance of these findings.

1. Consistency and Reliability

The close agreement between experimental lab results and software output for both the control asphalt mixture and the WMP modified mixture underscores the reliability of the testing methodologies and the accuracy of the predictive software used. Specifically:

Control asphalt mixture (0% WMP): Experimental results showed a rut depth of 0.394 mm, while the software predicted 0.381 mm.

WMP Modified mixture (30% WMP): Experimental results showed a rut depth of 0.378 mm, with the software predicting 0.375 mm.

This consistency is crucial because it validates the software as a reliable tool for predicting rutting performance, which can save time and resources in future testing.

2. Impact of WMP on Rutting Resistance

The data indicates that the inclusion of 30% WMP as a filler improves the rutting resistance of the asphalt mixture compared to the control mixture. This is evidenced by the lower mean rut depth observed in both the experimental results and software predictions for the WMP modified mixture. Specifically:

The reduction in rut depth, although marginal, suggests that WMP can enhance the structural integrity of the asphalt mix, potentially leading to longer-lasting pavements.

3. Compliance with Specifications

Furthermore, these results demonstrate compliance with the EN 13108 specification. Table 4.21 show that the average rut depths, combining experimental and simulated data, were 0.388 mm for the control mix and 0.377 mm for the modified mix. Notably, the asphalt mixture incorporating 30% waste marble powder achieved a rut depth of 0.377 mm, highlighting its efficacy in enhancing performance and sustainability.

Overall, this validation confirms that both mixtures meet the required standards for rut depth, and the results from the experimental lab and software output are in close agreement, further ensuring the reliability of the data. The consistency between experimental and software results further bolsters confidence in using predictive modeling for future asphalt mix designs.

Table 4.21: Summary of rut depth experimental lab results and Abaqus software output

Mix properties	Rut depth (mm)		Average Rut depth (mm)	Specification (EN 13108)	
	Experimental lab results	Software output		Rut Depth (mm)	Remark
Control asphalt mixture (0%WMP)	0.394	0.381	0.388	<1	Pass
WMP Modified mixture (30% WMP)	0.378	0.375	0.377	<1	Pass

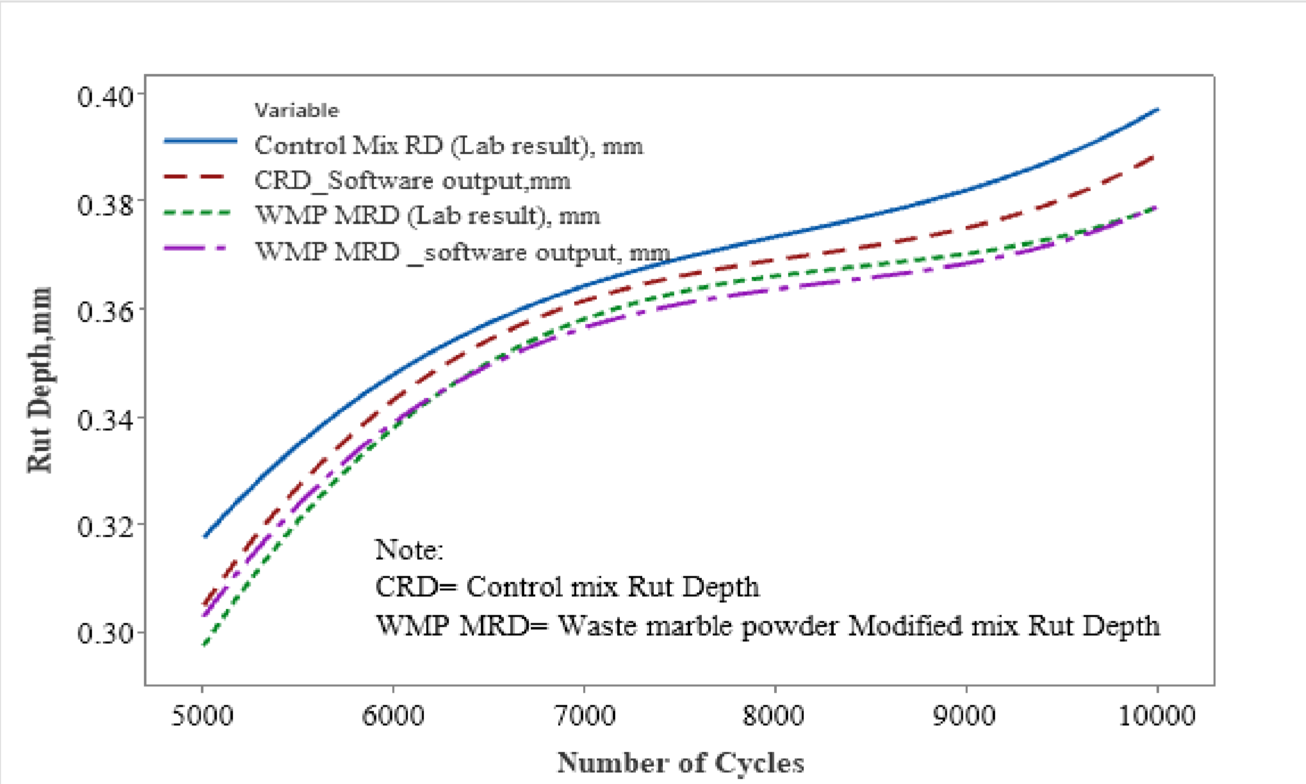


Figure 4.20: Overview of experimental and software output rut depth

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study focuses on evaluating the rutting performance of asphalt mixtures modified with waste marble powder through both experimental and numerical analyses. The research involves laboratory testing of asphalt mixtures with varying percentages of waste marble powder to determine their rutting resistance properties, complemented by finite element modeling using Abaqus software to simulate deformation behavior under a 0.7 MPa tire contact pressure.

Key Findings:

1. Laboratory Experiments:

- ❖ **Material Suitability**: All components (aggregate, bitumen, and waste marble powder) passed physical quality tests, confirming their suitability for asphalt mixes.
- ❖ **Optimum Content:** The optimal bitumen content, crushed stone dust (CSD) and waste marble powder filler were identified as 5.24%, 5.25% and 30% respectively.
- ❖ **Performance Metrics:** At these optimum levels, the control mix exhibited a maximum Marshall stability of 10.87 KN, flow of 2.959 mm, VMA of 15.69%, VFA of 74.64%, bulk density of 2.304 g/cm³, TSR of 81.3%, E_{mod} of 4276.88MPa and rut depth of 0.394 mm.
- ❖ **Waste Marble Powder Integration:** Waste marble powder replaced conventional filler in increments of 10% from 0 to 50%, with 30% replacement optimizing the mix properties, yielding improvements in stability, flow, VMA, VFA, bulk density, TSR, stiffness and rut depth by (11.41, 2.33, 2.29, 1.58, 0.35, 18.23, 23.33 and 4.06) % respectively. This indicates that, the marble enhances the mechanical properties, stiffness, strength, resistance to rutting and moisture susceptibility of the asphalt mixture.

2. Software Simulation:

- ❖ Rutting Resistance: Using Abaqus 6.14v, the simulated rut depths for the control mix (0% WMP) and the optimized mix (30% WMP) were 0.381 mm and 0.375 mm, respectively. The rut depth enhanced by 1.57%.

3. Validation

Consistency and reliability: The experimental results for rut depth closely matched the software predictions, with the control mix showing 0.394 mm (experiment) versus 0.381 mm (simulation) and the modified mix showing 0.378 mm (experiment) versus 0.375 mm (simulation). This alignment confirms the reliability of both the experimental and simulation methodologies.

Furthermore, these results demonstrate compliance with the EN 13108 specification. The average rut depths, combining experimental and simulated data, were 0.388 mm for the control mix and 0.377 mm for the modified mix. Notably, the rut depth of the asphalt mixture in this research, derived from 30% waste marble powder content, was determined to be 0.377 mm. This finding substantiates the effectiveness of incorporating waste marble powder in enhancing the asphalt mixture's performance.

Implications and Contributions:

The study shows that incorporating 30% waste marble powder in asphalt mixtures enhances rutting resistance and promotes sustainability. These findings contribute to advancing sustainable asphalt mix design and provide valuable insights for future research and practice in asphalt engineering. Overall, incorporating waste marble powder not only improves the structural characteristics of asphalt mixes but also promotes sustainability by repurposing industrial waste, thereby enhancing pavement performance.

5.2. Recommendation

1. Adoption of Waste Marble Powder in Asphalt Mixes:

Given the demonstrated benefits of waste marble powder in enhancing the rutting resistance of asphalt mixtures, it is recommended to incorporate this material in standard asphalt mix designs. Specifically, a 30% replacement of conventional filler with waste marble powder is suggested to achieve optimal performance.

2. Quality Testing and Validation:

Regular physical quality tests should be conducted on all asphalt mix components, including aggregates, bitumen, and waste marble powder, to ensure they meet the required standards. This practice will help maintain consistency and reliability in the performance of asphalt pavements.

3. Optimization of Bitumen and Filler Content:

The study identified optimal bitumen and crushed stone dust (CSD) filler contents as 5.24% and 5.25%, respectively. It is recommended that these proportions be used as benchmarks for future asphalt mix designs to achieve maximum stability and durability.

4. Utilization of Finite Element Modeling:

The close agreement between experimental and simulation results underscores the value of using finite element modeling (Abaqus software) for predicting asphalt mix performance. It is recommended that this simulation method be adopted as a standard practice for evaluating new mix designs, which can save time and resources in the testing phase and in addition the static loads used in this investigation are included in the modelling. Future research should include dynamic loads with a complex modulus and Microstructure study of waste marble powder.

5. Sustainable Practices:

Incorporating waste materials like marble powder in asphalt mixes supports sustainable construction practices. The industry should prioritize the use of such alternative materials to reduce environmental impact and conserve natural resources.

6. Further Research and Development:

Continued research is necessary to explore the use of other industrial by-products as alternative fillers in asphalt mixtures. Additionally, long-term field studies and economic feasibility should be conducted to validate the laboratory and simulation findings in real-world conditions.

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APPENDIX

APPENDIX A: AGGREGATE QUALITY TEST AND THEIR PROPERTIES

Table A1.1: Sieve analysis of coarse aggregate

Test type: Sieve Analysis of coarse aggregate — Test Method AASHTO T- 27/ ERA- 2013
Material description: Crushed Aggregate (Basalt) — Bin #1 (19-9.5 mm)
Material for: Asphalt Wearing course — Testing Date: 23-Nov-2023

Sieve Size (mm)	Trial #1			Trial #2			Trial #3			Dry Sieve
	Masst of retained (g)	%Retained mass	%Passing	Mass of retained (g)	%Retained mass	%Passing	Weight of retained (g)	% Retained	% Passing	Average % Passing
25	0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0
19	1087.5	24.9	75.1	915.5	20.3	79.7	1166.0	26.8	73.2	76.0
9.5	1544	35.3	39.8	1620.0	35.9	43.7	1339.0	30.8	42.3	42.0
4.75	1059	24.2	15.5	1172.0	26.0	17.7	1026.0	23.6	18.7	17.3
2.36	555	12.7	2.8	664.0	14.7	3.0	548.5	12.6	6.1	4.0
0.3	123	2.8	0.0	136.0	3.0	0.0	265.0	6.1	0.0	0.0
0.075	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pan	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	4368.5			4507.5			4344.5			

Table A1.2: Sieve analysis of intermediate aggregate

Test type: Sieve Analysis of coarse aggregate — Test Method AASHTO T- 27/ ERA- 2013
Material description: Crushed Aggregate (Basalt) — Bin #2 (9.5-2.36 mm)
Material for: Asphalt Wearing course — Testing Date: 24-Nov-2023

Sieve Size (mm)	Trial #1			Trial #2			Trial #3			Dry Sieve
	Masst of retained (g)	%Retained mass	%Passing	Mass of retained (g)	%Retained mass	%Passing	Weight of retained (g)	% Retained	% Passing	Average % Passing
25	0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0
19	0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0
9.5	1365.5	45.9	54.1	1329.5	45.3	54.7	1046.0	36.3	63.7	57.5
4.75	643	21.6	32.5	597.0	20.4	34.3	582.5	20.2	43.5	36.8
2.36	388	13.0	19.5	398.5	13.6	20.7	426.5	14.8	28.6	23.0
0.3	360	12.1	7.4	342.0	11.7	9.0	469.5	16.3	12.3	9.6
0.075	109.5	3.7	3.7	107.0	3.6	5.4	128.5	4.5	7.9	5.7
Pan	111.5	3.7	0.0	158.0	5.4	0.0	227.0	7.9	0.0	0.0
Sum	2977.5	100		2932	100		2880			

Table A1.3: Sieve analysis of fine aggregate

Test type: Sieve Analysis of fine aggregate — Test Method AASHTO T- 27/ ERA- 2013
Material description: Crushed Aggregate (Basalt) — Bin #3 (2.36-0.075 mm)
Material for: Asphalt Wearing course — Testing Date: 24-Nov-2023

Sieve Size (mm)	Trial #1			Trial #2			Trial #3			Dry Sieve
	Masst of retained (g)	%Retained mass	%Passing	Mass of retained (g)	%Retained mass	%Passing	Weight of retained (g)	% Retained	% Passing	Average % Passing
25	0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0
19	0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	100.0
9.5	335	11.2	88.8	310.0	12.5	87.5	0.0	0.0	100.0	92.1
4.75	500	16.7	72.1	550.5	22.2	65.3	0.0	0.0	100.0	79.1
2.36	880	29.4	42.7	696.0	28.1	37.2	0.0	0.0	100.0	60.0
0.3	883.5	29.5	13.2	548.5	22.1	15.1	1961.5	79.0	21.0	16.4
0.075	211.5	7.1	6.1	225.0	9.1	6.0	224.0	9.0	12.0	8.0
Pan	184	6.1	0.0	148.5	6.0	0.0	297.0	12.0	0.0	0.0
Sum	2994	100.0		2478.5	100.0		2482.5			

Table A2: Mechanical properties of aggregate

Table A2.1: Aggregate crushing value (ACV)

Test type: Aggregate Crushing Value (ACV) Test Method: BS 812: PART 110: 1990	Tested date 23-Nov-23		
Trials	1	2	3
Mass of mould with base plate (w_1), g	13566.6	13566.6	13567
Mass of mould with base plate+sample (w_2), g	16569.1	16570.3	16568
Mass of sample (A)= (w_2-w_1), g	3002.5	3003.7	3001
Mass of portion passing BS 2.36mm sieve after test (B), g	297.5	271.9	373
Aggregate Crushing Value (ACV), %= B/A *100	9.91	9.05	12.43
Average ACV, %	10.46		

Table A2.2: Aggregate Impact value (AIV)

Test type: Aggregate Impact Value (AIV) Test Method: BS: 812 PART 112: 1990	Tested date 23-Nov-23		
Trials	1	2	3
Weight of mould, g	2749.6	2749.6	2749.6
Weight of mould+Sample, g	3489.3	3485	3487
Weight of Sample (w_1), g	739.7	735.4	737.4
Weight of aggregate retained 2.36mm sieve after the test (w_2)	701	693.3	690
w_3= w_1-w_2	38.7	42.1	47.4
Aggregate Impact Value (AIV), %= w_3/w_1 *100	5.23	5.72	6.43
Average AIV (%)	5.79		

Table A2.3: Aggregate Los Angeles Abrasion Value (LAAV)

Test type: Los Angeles Abrasion Value (LAAV) Test Method: ASTM C-131	Tested date 23-Nov-23	
Trials	1	2
Sample description	Coarse aggregate	Coarse aggregate
Grading used	B	B
Number of Sphere ball	11	11
Weight of specimen (w_1), g	5000	5000
Weight of specimen retained on sieve size 1.7mm (w_2), g	4547.3	4543.2
Weight of specimen passing sieve size 1.7mm, (w_1-w_2), g	452.7	456.8
LAAV = (w_1-w_2)/w_1 *100, %	9.05	9.14
LAAV average, %	9.10	

Table A3: Specific gravity and water absorption of aggregate

Table A3.1. Specific gravity and water absorption of coarse aggregate

Sample Description: Coarse Aggregate (2.36mm-25mm) Test type: Specific gravity and water absorption Test Method: AASHTO T-85/ASTM C127	Tested date 17-Nov-2023		
Trials	1	2	3
Mass of sample, g	3000	3000	3000
Mass of wire basket+Sample in water (A), g	2958.5	2959	2955
Mass of wire basket in water (B), g	1058	1058	1062.5
Mass of saturated surface dry sample in air (SSD) (C), g	3017.5	3014.5	3016
Mass of oven dry sample (D), g	2962.5	2952.5	2966
Bulk (dry) specific gravity (G_{sb})= (D/(C-(A-B))	2.652	2.652	2.640
Average G_{sb}	2.648		
Bulk SSD specific gravity, $G_{sb\ SSD}$=C/(C-(A-B))	2.701	2.707	2.684
Average $G_{sb\ SSD}$	2.698		
Apparent specific gravity (G_{sa}) = D/(D-(A-B))	2.790	2.808	2.763
Average G_{sa}	2.787		
Water absorption=(C-D)/D *100, %	1.86	2.10	1.69
Average water absorption, %	1.88		

Table A3.2. Specific gravity and water absorption of fine aggregate

Sample Description: Fine Aggregate (0.075-2.36mm) Test type: Specific gravity and water absorption Test Method: AASHTO T -84/ASTM C128	Tested date 20-Nov-23		
Trials	1	2	3
Mass of air-dried sample, g	1000	1000	1000
Mass of vessel+Sample filled with water (A), g	8693	8678.56	8688
Mass of vessel filled with water only (B), g	8075	8075	8075
Mass of saturated surface dry sample in air (SSD) (C), g	999.56	996.58	996.56
Mass of oven dry aggregate (D), g	990.5	990.65	987
Bulk (dry) specific gravity (G_{sb}) = (D/(C-(A-B))	2.60	2.52	2.57
Average G_{sb}	2.563		
Bulk SSD specific gravity, $G_{sb\ SSD}$=C/(C-(A-B))	2.620	2.536	2.598
Average $G_{sb\ SSD}$	2.585		
Apparent specific gravity (G_{sa}) = D/(D-(A-B))	2.66	2.56	2.64
Average G_{sa}	2.619		
Water absorption=(C-D)/D *100, %	0.91	0.60	0.97
Average water absorption, %	0.83		

Combined specific gravity of aggregate

$$Gsb = \frac{29+71}{\frac{29}{2.648}+\frac{71}{2.563}} = 2.587$$

Combined water absorption, W_{abs} 0.99

Table A4: Specific gravity of crush stone dust (CSD) filler and waste marble powder

Table A4.1: Specific gravity of crush stone dust (CSD) filler

Sample Description: Crushed stone dust (CSD) Test type: Specific gravity Test Method: AASHTO T -84/ASTM C128	Tested date 5-Feb-2024		
Pycnometer code	O	3	G
Trials No.	1	2	3
M_p= Mass of empty, clean Pycnometer, g	30.1	31.1	32
M_{pw}= Mass of Pycnometer filled with Water, g	123.5	125.5	123
M_{pCSD}=Masst of Pycnometer +Crushed stone dust, g	72	75	78
M_{pCSDw}= Mass of Pycnometer + Crushed stone dust + water, g	138	140.4	137.8
Temperature, ^{0}C	22	22	22
M_{dryCSD}= Mass of dry Crushed stone dust, g =M_{pCSD} -M_p	41.9	43.9	46
Specific Gravity =$M_{dryCSD}/(M_p+(M_{pw}-M_{pCSDw})$	2.686	2.710	2.674
Average Specific Gravity CSD	2.690		

Table A4.2: Specific gravity of waste marble powder

Sample Description: Waste Marble Powder (WMP) Test type: Specific gravity Test Method: AASHTO T -84/ASTM C128	Tested date 5-Feb-2024		
Pycnometer code	T	C	R
Trials No.	1	2	3
M_p= Mass of empty, clean Pycnometer, g	27.6	26.5	27
M_{pw}= Mass of Pycnometer filled with Water, g	79	77.2	78.5
M_{pm}=Masst of Pycnometer +Marble, g	60.5	55.3	58.5
M_{pmw}= Mass of Pycnometer + Marble + water, g	94.5	92.7	93.6
Temperature, ^{0}C	21	21	21
M_{drym}= Mass of dry Marble, g =M_{pm} -M_p	32.9	28.8	31.5
Specific Gravity =$M_{drym}/(M_p+(M_{pw}-M_{pmw})$	2.719	2.618	2.6471
Average Specific Gravity of Marble powder	2.661		

APPENDIX B: BITUMEN QUALITY TEST RESULTS

Table B1.1: Bitumen penetration test

Sample Description: Bitumen binder Test type: Penetration test of Bitumen binder @25 °C, 0.1mm/5sec Test Method: ASTM D5-86	Tested date 20-Nov-2023		
Trial No.	1	2	3
Penetration (mm)	5.98	6.85	6.95
Average penetration (mm)	6.59		
Bitumen Grade= Aver. Penetration/0.1mm	65.93		

Table B1.2: Bitumen ductility test

Sample Description: Bitumen binder Test type: Ductility test of bitumen binder Test Method: ASTM D5-86	Tested date 20-Nov-2023		
Trial No.	1	2	3
Initial Reading (mm), A	0	0	0
Final Reading (mm), B	120	135	140
Ductility (mm)=B-A	120	135	140
Average Ductility (mm)	132		

Table B1.3: Bitumen Softening Point test

Sample Description: Bitumen binder Test type: Softening Point Test Method: ASTM D36-70	Tested date 20-Nov-2023		
Trial No.	1	2	3
Temperature in °C at which 1st ball touch the bottom plate	53.29	52.39	52.5
Temperature in °C at which 2st ball touch the bottom plate	53.39	53.45	51.4
Average temperature	53.34	52.92	51.95
Average Final Softening point temperature in °C	52.74		

Table B1.4: Bitumen Specific Gravity

Sample Description: Bitumen binder Test type: Specific gravity Test Method: ASTM D70/AASHTO T-228	Tested date 22-Nov-2023		
Trials No.	1	2	3
A= Mass of Pycnometer, g	38.1	38.12	39.01
B= Mass of Pycnometer filled with Water, g @ 25 ± 0.10C	64.235	63.056	65.015
C= Mass of Pycnometer partially filled With Sample,g	59.104	58.543	60.235
D= Mass of Pycnometer + sample + water, g @ 25± 0.10C	64.53	63.451	65.559
E= Mass of water replaced by sample, g (C-A) +B} – D	20.709	20.028	20.681
Specific Gravity, (C-A)/E	1.014	1.020	1.026
Average Specific Gravity	1.020		

Table B1.5: Bitumen Fire and Flash point

Sample Description: Bitumen binder Test type: Fire and Flash point, °C Test Method: ASTM D92-90				Tested date 20-Nov-2023
Trial No.	1	2	3	Average
Measured Flash point (°C)	292	299	296	296
Measured Fire point (°C)	355	357	354	355

APPENDIX C: MARSHALL DESIGN METHODS FOR HMA

C.1. Design Aggregate Grading

Table C1.1: Aggregate blending proportion for 4.25% crushed stone dust filler

Test Type: Sieve Analysis of Fine and Coarse Aggregate							Test Method AASHTO T- 27, ERA Technical Specification 2013						
Material description: Crushed Aggregate (Basalt)							Proportion %		0.41	0.22	0.38	1.00	
Material for: Asphalt concrete							Tested Date: Nov (23/2023-25/2023)						
Sieve Size (mm)	Bin #1	Pro. %	Bin #2	Pro. %	Bin #3	Pro. %	Combined Grading	Media of Speci.	JMF Tolerance Limit		Specification Limit		Max. Density Curve
	19-9.5mm	41	9.5-2.36mm	22	2.36-0.075mm	38			Lower	Upper	Lower	Upper	
25	100.0	40.8	100.0	21.6	100.0	37.7	100.0	100	100	100	100	100	100
19	76.0	31.0	100.0	21.6	100.0	37.7	90.2	95	90	98	90	100	88
9.5	42.0	17.1	57.5	12.4	92.1	34.7	64.2	68	57	71	56	80	65
4.75	17.3	7.1	36.8	7.9	79.1	29.8	44.8	50	39	51	35	65	47
2.36	4.0	1.6	23.0	4.9	60.0	22.6	29.2	36	23	35	23	49	35
0.3	0.0	0.0	9.6	2.1	16.4	6.2	8.3	12	5	13	5	19	14
0.075	0.0	0.0	5.7	1.2	8.0	3.0	4.25	5	2	7	2	8	7

Table C1.2: Aggregate blending proportion for 4.75% crushed stone dust filler

Test Type: Sieve Analysis of Fine and Coarse Aggregate							Test Method AASHTO T- 27, ERA Technical Specification 2013						
Material description: Crushed Aggregate (Basalt)							Proportion %		0.33	0.28	0.40	1.00	
Material for: Asphalt concrete							Testing Date: Nov (23/2023-25/2023)						
Sieve Size (mm)	Bin #1	Pro. %	Bin #2	Pro. %	Bin #3	Pro. %	Combined Grading	Media of Speci.	JMF Tolerance Limit		Specification Limit		Max. Density Curve
	19-9.5mm	33	9.5-2.36mm	28	2.36-0.075mm	40			Lower	Upper	Lower	Upper	
25	100.0	32.7	100.0	27.7	100.0	39.5	100.0	100	100	100	100	100	100
19	76.0	24.9	100.0	27.7	100.0	39.5	92.1	95	90	100	90	100	88
9.5	42.0	13.7	57.5	15.9	92.1	36.4	66.1	68	59	73	56	80	65
4.75	17.3	5.7	36.8	10.2	79.1	31.3	47.2	50	41	53	35	65	47
2.36	4.0	1.3	23.0	6.4	60.0	23.7	31.4	36	25	37	23	49	35
0.3	0.0	0.0	9.6	2.7	16.4	6.5	9.2	12	5	14	5	19	14
0.075	0.0	0.0	5.7	1.6	8.0	3.2	4.75	5	2	8	2	8	7

Table C1.3: Aggregate blending proportion for 5.25% crushed stone dust filler

Test Type: Sieve Analysis of Fine and Coarse Aggregate							Test Method AASHTO T- 27, ERA Technical Specification 2013						
Material description: Crushed Aggregate (Basalt)							Proportion %		0.18	0.55	0.26	1.00	
Material for: Asphalt concrete							Testing Date: Nov (23/2023-25/2023)						
Sieve Size	Bin #1	Pro. %	Bin #2	Pro. %	Bin #3	Pro. %	Combined	Media of	JMF Tolerance Limit		Specification Limit		Max. Density
(mm)	19-9.5mm	18	9.5-2.36mm	55	2.36-0.075mm	26	Grading	Speci.	Lower	Upper	Lower	Upper	Curve
25	100.0	18.5	100.0	55.1	100.0	26.5	100.0	100	100	100	100	100	100
19	76.0	14.0	100.0	55.1	100.0	26.5	95.6	95	90	100	90	100	88
9.5	42.0	7.7	57.5	31.7	92.1	24.4	63.8	68	57	71	56	80	65
4.75	17.3	3.2	36.8	20.2	79.1	21.0	44.4	50	38	50	35	65	47
2.36	4.0	0.7	23.0	12.6	60.0	15.9	29.3	36	23	35	23	49	35
0.3	0.0	0.0	9.6	5.3	16.4	4.3	9.6	12	5	15	5	19	14
0.075	0.0	0.0	5.7	3.1	8.0	2.1	5.25	5	2	8	2	8	7

Table C1.4: Aggregate blending proportion for 5.75% crushed stone dust filler

Test Type: Sieve Analysis of Fine and Coarse Aggregate							Test Method AASHTO T- 27, ERA Technical Specification 2013						
Material description: Crushed Aggregate (Basalt)							Proportion %		0.26	0.08	0.66	1.00	
Material for: Asphalt concrete							Testing Date: Nov (23/2023-25/2023)						
Sieve Size	Bin #1	Pro. %	Bin #2	Pro. %	Bin #3	Pro. %	Combined	Media of	JMF Tolerance Limit		Specification Limit		Max. Density
(mm)	19-9.5mm	26	9.5-2.36mm	8	2.36-0.075mm	66	Grading	Speci.	Lower	Upper	Lower	Upper	Curve
25	100.0	26.0	100.0	8.1	100.0	65.8	100.0	100	100	100	100	100	100
19	76.0	19.8	100.0	8.1	100.0	65.8	93.7	95	90	100	90	100	88
9.5	42.0	10.9	57.5	4.7	92.1	60.6	76.2	68	69	80	56	80	65
4.75	17.3	4.5	36.8	3.0	79.1	52.1	59.6	50	54	65	35	65	47
2.36	4.0	1.0	23.0	1.9	60.0	39.5	42.4	36	36	48	23	49	35
0.3	0.0	0.0	9.6	0.8	16.4	10.8	11.6	12	7	17	5	19	14
0.075	0.0	0.0	5.7	0.5	8.0	5.3	5.75	5	3	8	2	8	7

C 2. Marshall mix design laboratory specimen batch (mass of aggregate required)

Table C2.1. Marshal mix design laboratory specimen batch for 4.25% crushed stone dust filler

Laboratory specimen batch for 4.25% filler					Proportion	0.41	0.22	0.38	1.0	Combined Grading
Sieve Size (mm)	Bin #1 (19-9.5)	%Retain	Pro.Weight 41	Bin #2 (9.5-2.36)	%Retain	Pro.Weight 22	Bin #3 (2.36-0.075)	%Retain	Pro.Weight 38	
25	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0
19	76.0	24.0	112.6	100.0	0.0	0.0	100.0	0.0	0.0	112.6
9.5	42.0	34.0	159.5	57.5	42.5	105.4	92.1	7.9	34.2	299.2
4.75	17.3	24.6	115.4	36.8	20.7	51.4	79.1	13.0	56.2	223.0
2.36	4.0	13.4	62.6	23.0	13.8	34.2	60.0	19.2	83.0	179.9
0.3	0.0	4.0	18.6	9.6	13.4	33.1	16.4	43.6	188.7	240.5
0.075	0.0	0.0	0.0	5.7	3.9	9.7	8.0	8.4	36.4	46.1
Pan	0.0	0.0	0.0	0.0	5.7	14.1	0.0	8.0	34.8	48.9
Total			468.7			247.9			433.3	1150

Table C2.2. Marshal mix design laboratory specimen batch for 4.75% crushed stone dust filler

Laboratory specimen batch for 4.75% filler					Proportion	0.33	0.28	0.40	1.0	Combined Grading
Sieve Size (mm)	Bin #1 (19-9.5)	%Retain	Pro.Weight 33	Bin #1 (9.5-2.36)	%Retain	Pro.Weight 28	Bin #1 (2.36-0.075)	%Retain	Pro.Weight 40	
25	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0
19	76.0	24.0	90.4	100.0	0.0	0.0	100.0	0.0	0.0	90.4
9.5	42.0	34.0	128.1	57.5	42.5	135.6	92.1	7.9	35.9	299.6
4.75	17.3	24.6	92.6	36.8	20.7	66.1	79.1	13.0	59.0	217.7
2.36	4.0	13.4	50.2	23.0	13.8	44.0	60.0	19.2	87.1	181.4
0.3	0.0	4.0	15.0	9.6	13.4	42.6	16.4	43.6	198.1	255.6
0.075	0.0	0.0	0.0	5.7	3.9	12.5	8.0	8.4	38.2	50.7
Pan	0.0	0.0	0.0	0.0	5.7	18.1	0.0	8.0	36.5	54.6
Total			376.3			318.9			454.8	1150

Table C2.3. Marshal mix design laboratory specimen batch for 5.25% crushed stone dust filler

Laboratory specimen batch for 5.25% filler					Proportion	0.18	0.55	0.26	1.0	Combined Grading
Sieve Size (mm)	Bin #1 (19-9.5)	%Retain	Pro.Weight 18	Bin #1 (9.5-2.36)	%Retain	Pro.Weight 55	Bin #1 (2.36-0.075)	%Retain	Pro.Weight 26	
25	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0
19	76.0	24.0	51.0	100.0	0.0	0.0	100.0	0.0	0.0	51.0
9.5	42.0	34.0	72.3	57.5	42.5	269.2	92.1	7.9	24.1	365.5
4.75	17.3	24.6	52.3	36.8	20.7	131.2	79.1	13.0	39.5	223.0
2.36	4.0	13.4	28.4	23.0	13.8	87.4	60.0	19.2	58.3	174.1
0.3	0.0	4.0	8.4	9.6	13.4	84.5	16.4	43.6	132.6	225.6
0.075	0.0	0.0	0.0	5.7	3.9	24.9	8.0	8.4	25.5	50.4
Pan	0.0	0.0	0.0	0.0	5.7	35.9	0.0	8.0	24.5	60.4
Total			212.3			633.2			304.5	1150

Table C2.4. Marshal mix design laboratory specimen batch for 5.75% crushed stone dust filler

Laboratory specimen batch for 5.75% filler					Proportion	0.26	0.08	0.66	1.0	Combined Grading
Sieve Size (mm)	Bin #1 (19-9.5)	%Retain	Pro.Weight 26	Bin #1 (9.5-2.36)	%Retain	Pro.Weight 8	Bin #1 (2.36-0.075)	%Retain	Pro.Weight 66	
25	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0
19	76.0	24.0	71.9	100.0	0.0	0.0	100.0	0.0	0.0	71.9
9.5	42.0	34.0	101.9	57.5	42.5	39.7	92.1	7.9	59.8	201.4
4.75	17.3	24.6	73.7	36.8	20.7	19.4	79.1	13.0	98.2	191.3
2.36	4.0	13.4	40.0	23.0	13.8	12.9	60.0	19.2	145.1	197.9
0.3	0.0	4.0	11.9	9.6	13.4	12.5	16.4	43.6	329.7	354.1
0.075	0.0	0.0	0.0	5.7	3.9	3.7	8.0	8.4	63.5	67.2
Pan	0.0	0.0	0.0	0.0	5.67	5.3	0.0	8.0	60.8	66.1
Total			299.4			93.4			757.1	1150

C 3. Mixing and compaction

Table C3.1. Total Marshal mix design laboratory specimen batch weight with Bitumen for all crushed stone dust filler

Bitumen % by Wt of Total Mix	4.5	5	5.5	6
Bitumen Content in (g)	54.2	60.5	66.9	73.4
Total Batch Weight (g)	1204.2	1210.5	1216.9	1223.4

The pre-heated mould, base plate, filling collar and an inserted paper disc should be preassembled so that the sample can be compacted immediately after mixing is completed. The mould is filled with the mixed material and the contents spaded vigorously with a heated spatula or trowel, 15 times around the perimeter and 10 times over the interior. The surface of the material is then smoothed to a slightly rounded shape onto which another paper disc is placed. The temperature of the mix prior to compaction 155°C and 135°C respectively. The mould, base plate and filling collar are transferred to the Marshall compaction apparatus and the sample compacted by the specified number of blows (75) of the Marshall hammer both sides. The mould assembly is then placed on a bench where the base plate, filling collar and paper discs are removed. The mould and the specimen are allowed to cool in air to a temperature at which there will be no deformation of the specimen during extraction from the mould using an extrusion jack. The whole procedure is then repeated on the remaining prepared samples.

C 4. Testing Marshall stability-flow and Volumetric characteristics

Here, the combined bulk density and effective specific gravity of aggregate, mixture bulk density and asphalt Volumetric characteristic formula used in Table C4.1-C4.5

NOTE:

$$Gsb = \frac{P_{coarse} + Pfine}{\frac{P_{coarse}}{G_{coarse}} + \frac{P_{fine}}{G_{fine}}}$$

G_{sb}= Combine bulk (dry) specific gravity of the aggregate

P_{coarse}= Percentage by weight retained on the 2.36mm Sieve

P_{fine}= Percentage by weight passed on the 2.36mm Sieve

G_{coarse}= Bulk (dry) specific gravity of the coarse fraction

G_{fine}= Bulk (dry) specific gravity of the fine fraction

$$Gsb = \frac{29+71}{\frac{29}{2.648} + \frac{71}{2.563}} = 2.587$$

$$Gmb = \frac{A}{\rho_w B}$$

Weight of specimen in air, g

Bulk Volume, cm^3

density of water,1.000 g/cm^3

$$VFA = 100 * \frac{VMA-Pa}{VMA}$$

VFA= Voids filled with asphalt

VMA= Voids in the mineral aggregate

$$P_a = 100 - \frac{100*Gmb}{Gmm}$$

P_a= Air voids in compacted mixture,percentage of total volume

G_{mm} Maximum theoritical specific gravity of paving mixture

$$VMA = (100 - \left(\frac{Gmb}{Gsb}\right) * Ps)$$

VMA= Voids in the Mineral aggregate

G_{mb}= Bulk specific gravity of paving mixture

G_{sb}= Bulk (dry) specific gravity of the aggregate

P_s= Percentage of aggregate by total mix weight

$$Gse = \frac{Ps}{\frac{100}{Gmm} + \frac{P_b}{G_b}}$$

P_b= Percent of bitumen content

G_b= Specific gravity of bitumen

Table C4.1: Marshall mix design test lab output data of mixture with 4.25% CSD filler gradation

Test type: Marshall properties of bituminous mixture	Specific gravity of AC (Gb): 1.020	Water absorbation of aggregate (A)	0.987
Test method: ASTM D1559/AASHTO T 245	Bulk S.G. aggregate: 2.587	Effective S.G. aggregate:	2.617
Compaction : 75 Blows	Grade of AC: 60/70	Compacted date:	11-Dec-2023
Crushed stone dust filler content by weight of total mix: 4.25%		Tested Date:	13-Dec-2023

Specimen No	BC (%)	Height of specimen (mm)	Mass of specimen (gm)			Bulk volume (cc)	Bulk SG mix (Gmb)	Max.T.SG (Gmm)	Air void,P_a %	VMA %	VFA %	Marshal stability KN			Flow (0.25 mm)
			in air	in water	SSD							Load	Coeff factor	Corrected load	
1	4.5	66.0	1201.0	668	1203.9	536	2.241	2.471	9.31	17.27	46.08	8.23	0.94	7.74	2.00
2		66.0	1206.0	670	1207.9	538	2.242		9.27	17.23	46.21	8.19	0.94	7.70	2.57
3		65.5	1199.0	668.12	1200.1	532	2.254		8.81	16.81	47.62	8.41	0.95	7.99	2.34
Average		**65.8**	**1202.0**	**668.7**	**1204.0**	**535**	**2.246**		**9.13**	**17.11**	**46.64**	**8.28**	**0.94**	**7.81**	**2.30**
1	5	65.0	1206.5	680.39	1212.0	532	2.269	2.423	6.34	16.67	61.94	7.48	0.96	7.18	2.96
2		64.0	1205.5	681.12	1210.0	529	2.279		5.94	16.31	63.58	9.28	0.99	9.19	2.92
3		65.0	1206.6	678.89	1211.5	533	2.265		6.51	16.82	61.28	8.42	0.96	8.08	2.07
Average		**64.7**	**1206.2**	**680.1**	**1211.2**	**531**	**2.271**		**6.27**	**16.60**	**62.27**	**8.39**	**0.97**	**8.15**	**2.65**
1	5.5	65.8	1212.2	688	1214.6	527	2.302	2.411	4.54	15.93	71.49	8.52	0.93	7.92	3.02
2		66.0	1212.7	685.64	1216.6	531	2.284		5.29	16.59	68.13	9.42	0.94	8.85	2.80
3		66.5	1215.2	689.55	1217.5	528	2.301		4.55	15.94	71.45	8.54	0.93	7.94	2.67
Average		**66.1**	**1213.3**	**687.7**	**1216.3**	**529**	**2.296**		**4.79**	**16.15**	**70.35**	**8.83**	**0.93**	**8.24**	**2.83**
1	6	66.5	1221.3	692.0	1224.0	532	2.296	2.369	3.10	16.15	80.81	8.76	0.93	8.15	3.02
2		67.0	1222.8	691.6	1223.5	532	2.299		2.96	16.03	81.55	9.42	0.92	8.67	2.96
3		67.5	1225.4	689.6	1225.6	536	2.286		3.50	16.50	78.77	8.54	0.90	7.69	3.00
Average		67.0	1223.2	691.1	1224.4	533	2.294		3.19	16.22	80.38	8.91	0.92	8.17	2.99

Table C4.2: Marshall mix design test lab output data of mixture with 4.75% CSD filler gradation

Test type: Marshall properties of bituminous mixture	Specific gravity of AC (Gb):	1.020	Water absorbation of aggregate (A):	0.987
Test Method: ASTM D1559/AASHTO T 245	Bulk S.G. aggregate:	2.587	Effective S.G. aggregate:	2.610
Compaction : 75 Blows	Grade of AC:	60/70	Compacted date:	14-Dec-2023
Crushed stone dust filler content by weight of total mix: 4.75%			Tested date:	15-Dec-2023

Specimen No	BC (%)	Height of specimen	Wt of specimen (gm)			Bulk volume (cc)	Bulk SG mix (Gmb)	Max.T. SG (Gmm)	Air void %	VMA %	VFB %	Marshal stability KN			Flow (0.25 mm)
			in air	in water	SSD							Load	Coeff	Corrected	
1	4.5	66.7	1201	680	1212	532	2.257	2.468	8.56	16.69	48.70	8.09	0.94	7.63	3.04
2		65.0	1200	677	1209	532	2.258		8.53	16.66	48.78	9.10	0.96	8.74	1.84
3		66.5	1204	678	1210	532	2.263		8.32	16.46	49.49	10.20	0.93	9.49	2.39
Average		**66.1**	**1202**	**678**	**1210**	**532**	**2.259**		**8.47**	**16.60**	**48.99**	**9.13**	**0.94**	**8.62**	**2.42**
1	5	66.0	1211	686	1217	531	2.282	2.414	5.48	16.20	66.18	9.80	0.94	9.21	2.56
2		65.8	1209	686	1215	529	2.286		5.30	16.05	66.96	10.22	0.94	9.61	2.55
3		66.0	1211	685	1220	535	2.262		6.32	16.95	62.72	8.80	0.93	8.18	2.63
Average		**65.9**	**1210**	**686**	**1217**	**531**	**2.277**		**5.70**	**16.40**	**65.28**	**9.61**	**0.94**	**9.00**	**2.58**
1	5.5	64.0	1201	685	1201	516	2.328	2.403	3.10	14.96	79.26	10.52	0.99	10.41	2.40
2		66.0	1221	690	1225	535	2.283		4.99	16.62	69.99	9.03	0.94	8.52	3.30
3		66.5	1222	691	1226	535	2.285		4.89	16.54	70.41	9.26	0.93	8.61	2.36
Average		**65.5**	**1215**	**689**	**1217**	**529**	**2.299**		**4.33**	**16.04**	**73.22**	**9.60**	**0.95**	**9.18**	**2.69**
1	6	66.5	1217	696	1229	533	2.284	2.367	3.54	16.59	78.65	10.52	0.93	9.78	2.56
2		66.0	1226	696	1223	527	2.327		1.72	15.02	88.51	9.15	0.94	8.63	2.85
3		67.0	1223	696	1232	536	2.282		3.59	16.63	78.41	9.26	0.92	8.52	3
Average		**66.5**	**1222**	**696**	**1228**	**532**	**2.298**		**2.95**	**16.08**	**81.86**	**9.64**	**0.93**	**8.98**	**2.80**

Table C4.3: Marshall mix design test lab output data of mixture with 5.25% CSD filler gradation

Test type: Marshall properties of bituminous mixture	Specific Gravity of AC (Gb): 1.020	Water absorbation of aggregate (A):	0.987
Test method: ASTM D1559/AASHTO T 245	Bulk S.G. Aggregate: 2.587	Effective S.G. aggregate:	2.592
Compaction : 75 Blows	Grade of AC: 60/70	Compacted date:	18-Dec-2023
Crushed stone dust filler content by weight of total mix: 5.25%		Tested date:	19-Dec-2023

Specimen No	BC (%)	Height of specimen (mm)	Wt of specimen (gm)			Bulk volume (cc)	Bulk SG mix (G_{mb})	Max.T. SG (G_{mm})	Air void %	VMA %	VFB %	Marshal stability KN			Flow (0.25 mm)
			in air	in water	SSD							Load	Coeff factor	Corrected load	
1	4.5	64.0	1202.1	682	1206.8	525	2.291	2.434	5.88	15.44	61.94	10.72	0.99	10.61	2.41
2		66.0	1202.0	682	1215.0	533	2.255		7.34	16.76	56.19	11.10	0.94	10.43	2.29
3		65.5	1201.8	676	1207.6	532	2.259		7.18	16.62	56.76	10.53	0.96	10.11	2.38
Average		**65.2**	**1202.0**	**680**	**1209.8**	**530**	**2.268**		**6.80**	**16.27**	**58.30**	**10.78**	**0.96**	**10.38**	**2.36**
1	5	65.0	1208.8	690	1216.0	526	2.298	2.406	4.48	15.62	71.30	11.25	0.99	11.13	2.5
2		65.0	1206.2	690	1216.0	526	2.295		4.61	15.73	70.72	11.63	0.99	11.51	3.15
3		65.5	1210.0	689	1215.5	526	2.299		4.43	15.57	71.55	10.67	0.94	9.97	2.62
Average		**65.2**	**1208.3**	**690**	**1215.8**	**526**	**2.298**		**4.51**	**15.64**	**71.19**	**11.18**	**0.93**	**10.87**	**2.76**
1	5.5	65.0	1214.4	695	1222.0	527	2.305	2.391	3.58	15.81	77.32	10.85	0.96	10.42	3.17
2		64.0	1210.7	691	1216.0	525	2.308		3.45	15.69	77.99	11.36	0.99	11.24	2.96
3		65.5	1212.9	692	1220.0	528	2.298		3.89	16.07	75.82	10.91	0.95	10.37	3.40
Average		**64.8**	**1212.7**	**693**	**1219.3**	**526**	**2.304**		**3.64**	**15.86**	**77.04**	**11.04**	**0.97**	**10.68**	**3.18**
1	6	66.0	1222.5	690	1226.6	537	2.278	2.361	3.51	16.79	79.09	10.85	0.96	10.42	3.85
2		65.0	1221.5	692	1222.0	530	2.305		2.38	15.81	84.96	9.86	0.99	9.77	3.25
3		66.0	1218.9	687	1220.4	533	2.285		3.22	16.54	80.54	10.18	0.96	9.78	3.65
Average		**65.7**	**1221.0**	**690**	**1223.0**	**533**	**2.289**		**3.04**	**16.38**	**81.53**	**10.30**	**0.97**	**9.99**	**3.58**

Table C4.4: Marshall mix design test lab output data of mixture with 5.75% CSD filler gradation

Test type: Marshall properties of bituminous mixture	Specific Gravity of AC (Gb): 1.020	Water absorbation of aggregate (A):	0.987
Test method: ASTM D1559/AASHTO T 245	Bulk S.G. aggregate: 2.587	Effective S.G. aggregate:	2.595
Compaction : 75 Blows	Grade of AC: 60/70	Compacted date:	21-Dec-2023
Crushed stone dust filler content by weight of total mix: 5.75%		Tested date:	22-Dec-2023

Specimen No	BC (%)	Height of specimen (mm)	Wt of specimen (gm)			Bulk volume (cc)	Bulk SG mix (Gmb)	Max.T. SG (Gmm)	Air void %	VMA %	VFB %	Marshal stability KN			Flow (0.25 mm)
			in air	in water	SSD							Load	Coeff factor	Corrected load	
1	4.5	65.0	1202.29	678	1206.2	528	2.276	2.443	6.8	15.98	57.34	9.89	0.96	9.50	3.04
2		66.5	1204.56	673	1209.5	537	2.244		8.1	17.17	52.64	10.70	0.94	10.00	1.84
3		66.5	1208.54	675	1214.3	540	2.239		8.3	17.35	51.96	10.62	0.94	9.93	2.39
Average		**66.0**	**1205.1**	**675**	**1210.0**	**535**	**2.253**		**7.8**	**16.84**	**53.98**	**10.41**	**0.94**	**9.81**	**2.42**
1	5	66.5	1210.69	679	1214.9	536	2.259	2.402	6.0	17.06	64.99	9.99	0.94	9.34	2.56
2		65.5	1200.62	679	1204.8	526	2.283		4.9	16.15	69.38	10.95	0.95	10.35	3.25
3		66.0	1210.69	682	1213.4	531	2.279		5.2	16.34	68.46	10.83	0.94	10.18	3.23
Average		**66.0**	**1207.3**	**680**	**1211.0**	**531**	**2.274**		**5.4**	**16.52**	**67.61**	**10.59**	**0.94**	**9.96**	**3.01**
1	5.5	64.5	1213.33	690	1218.1	528	2.300	2.392	3.9	16.01	75.83	10.15	0.98	9.94	3.24
2		66.0	1213.31	690	1218	528	2.300		3.9	16.00	75.85	10.48	0.94	9.85	3.43
3		65.0	1217.36	687	1223.9	537	2.269		5.2	17.13	69.92	10.62	0.96	10.19	3.46
Average		**65.2**	**1214.7**	**689**	**1220.0**	**531**	**2.289**		**4.3**	**16.38**	**73.87**	**10.42**	**0.96**	**10.00**	**3.38**
1	6	65.5	1219.95	691	1220.3	529	2.306	2.366	2.5	16.21	84.52	10.87	0.95	10.27	3.65
2		65.8	1222.98	694	1224.1	530	2.308		2.5	16.16	84.83	10.92	0.94	10.26	3.89
3		66.5	1224.07	691	1225.5	535	2.288		3.3	16.87	80.57	9.99	0.94	9.34	3.35
Average		**65.9**	**1222.33**	**692**	**1223.3**	**531**	**2.301**		**2.7**	**16.42**	**83.30**	**10.59**	**0.94**	**9.96**	**3.63**

Table C4.5: Modified Marshall mix design test lab output data of mixture with partial replacement of waste marble powder as filler

Test type: Marshall properties of bituminous mixture	Specific Gravity of AC (Gb): 1.020	Absorbed AC of aggregate: 0.987	
Test method: ASTM D1559/AASHTO T 245	Bulk S.G. Aggregate: 2.587	Effective S.G. aggregate: 2.595	
Compaction : 75 Blows	Grade of AC: 60/70	Compacted date: 11-Jan-2024	
Optimum conventional filler (CSD)= 5.25 %	OBC= 5.24 %	Tested date: 12-Jan-2024	

Specimen No	WMP (%)	Height of specimen (mm)	Mass of specimen (gm)			Bulk volume (cc)	Bulk SG mix (Gmb)	Max.T.S G (Gmm)	Air void, P_a %	VMA %	VFA %	Marshal stability KN			Flow (0.25 mm)
			in air	in water	SSD							Load	Coeff factor	Corrected load	
1	10.0%	65.0	1216.9	688.0	1219.9	532	2.288	2.421	5.48	16.20	66.15	10.77	0.96	10.34	4.51
2		66.0	1211.8	687.5	1215.8	528	2.294		5.25	15.99	67.20	10.97	0.94	10.31	3.33
3		66.5	1215.9	688.4	1216.3	528	2.303		4.86	15.65	68.94	12.26	0.94	11.50	2.86
Average		**65.8**	**1214.8**	**690.0**	**1217.3**	**529**	**2.295**		**5.20**	**15.95**	**67.43**	**11.33**	**0.95**	**10.72**	**3.57**
1	20.0%	65.0	1208.6	695.0	1211.2	516	2.341	2.416	3.07	14.25	78.43	12.10	0.96	11.62	3.05
2		65.0	1217.9	690.0	1220.0	530	2.298		4.86	15.83	69.28	11.55	0.96	11.09	3.00
3		66.0	1217.1	689.5	1222.3	533	2.284		5.44	16.34	66.71	12.00	0.94	11.28	4.32
Average		**65.3**	**1214.5**	**691.5**	**1217.8**	**526**	**2.308**		**4.46**	**15.47**	**71.47**	**11.88**	**0.95**	**11.33**	**3.46**
1	30.0%	65.5	1210.3	692.0	1212.2	520	2.327	2.410	3.46	14.78	76.58	13.57	0.95	12.89	2.89
2		65.0	1213.5	691.5	1216.8	525	2.310		4.15	15.39	73.06	12.13	0.96	11.64	3.04
3		65.0	1220.7	692.5	1223.6	531	2.299		4.63	15.81	70.74	12.29	0.96	11.80	2.73
Average		**65.2**	**1214.8**	**692.0**	**1217.5**	**526**	**2.312**		**4.08**	**15.33**	**73.46**	**12.66**	**0.96**	**12.11**	**2.89**
1	40.0%	65.0	1211.4	691.7	1215.5	524	2.313	2.391	3.28	15.29	78.53	12.37	0.96	11.88	2.90
2		66.0	1216.6	689.0	1219.3	530	2.294		4.07	15.98	74.53	12.68	0.96	12.17	3.89
3		65.5	1215.5	690.8	1218.2	527	2.305		3.63	15.59	76.70	11.91	0.95	11.31	2.62
Average		**65.5**	**1214.5**	**690.5**	**1217.7**	**527**	**2.304**		**3.66**	**15.62**	**76.59**	**12.32**	**0.96**	**11.79**	**3.14**
1	50.0%	66.0	1211.5	687.0	1214.6	528	2.296	2.349	2.26	15.91	85.79	10.98	0.94	10.32	2.65
2		66.5	1217.5	689.0	1218.7	530	2.299		3.88	15.81	75.44	11.89	0.93	11.06	3.36
3		65.0	1215.5	690.0	1217.7	528	2.304		3.68	15.63	76.49	12.41	0.96	11.91	2.75
Average		**65.8**	**1214.8**	**688.7**	**1217.0**	**528**	**2.299**		**3.27**	**15.8**	**79.2**	**11.8**	**0.94**	**11.10**	**2.92**

C 5. Maximum Theoretical Specific Gravity of HMA Mixtures (G_{mm})

Table C5.1: Maximum Theoretical Specific Gravity of HMA Mixtures with 4.25% crushed stone dust filler

Test type: Maximum theoretical specific gravity of HMA mixture (Gmm) 4.25% CSD Filler												Tested Date
Test Method: ASTM D- 2041-90												14-Dec-24
Bitumen content (%)	4.5			5			5.5			6		
Trial No.	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)
A. Weight of Flask, (g)	689.5	640	690	689.5	640	689.5	689.5	640	689.5	689.5	640	689.5
B. Weight of Flask filled with water, (g)	2165	2152	2165	2165	2152	2165	2165	2152	2165	2165	2152	2165
C. Weight of Flask+ Sample, (g)	1878	1880	1893	1909	1858.5	1879	1879	1855	1864	1889	1886	1891
D. Weight of Flask filled with water+sample	2873	2889	2883	2880	2868.5	2864	2861.5	2849	2865	2865	2863	2862
E. Weight of dry sample in air, (g)=C-A	1189	1240	1204	1220	1218.5	1190	1189.5	1215	1175	1200	1246	1202
Maximum Theoretical specific gravity, Gmm	2.471	2.463	2.480	2.417	2.427	2.425	2.413	2.346	2.475	2.401	2.327	2.379
Average Gmm, (g/cm3)	2.471			2.423			2.411			2.369		

Table C5.2: Maximum Theoretical Specific Gravity of HMA Mixtures with 4.75% crushed stone dust filler

Test type: Maximum theoretical specific gravity of HMA mixture (Gmm) 4.75% CSD Filler												Tested Date
Test Method: ASTM D- 2041-90												16-Dec-24
Bitumen content (%)	4.5			5			5.5			6		
Trial No.	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)
A. Weight of Flask, (g)	689.5	640	690	689.5	640	689.5	689.5	640	689.5	689.5	640	689.5
B. Weight of Flask filled with water, (g)	2165	2152	2165	2165	2152	2165	2165	2152	2165	2165	2152	2165
C. Weight of Flask+ Sample, (g)	1889	1847	1865	1899	1843	1895	1897.5	1849	1887	1895	1878	1899
D. Weight of Flask filled with water+sample	2891	2864	2858	2876	2853.5	2872	2876	2852	2864	2860	2867	2866
E. Mass of dry sample in air, (g)=C-A	1200	1207	1176	1210	1203	1206	1208	1209	1198	1206	1238	1210
Maximum Theoretical specific gravity, Gmm	2.531	2.438	2.436	2.426	2.399	2.418	2.431	2.375	2.402	2.361	2.365	2.376
Average Gmm, (g/cm3)	2.468			2.414			2.403			2.367		

Table C5.3: Maximum Theoretical Specific Gravity of HMA Mixtures with 5.25% crushed stone dust filler

Test type: Maximum theoretical specific gravity of HMA mixture (Gmm) 5.25% CSD Filler										Tested Date		
Test Method: ASTM D- 2041-90										20-Dec-24		
Bitumen content (%)	4.5			5			5.5			6		
Trial No.	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)
A. Weight of Flask, (g)	689.5	640	690	689.5	640	689.5	689.5	640	689.5	689.5	640	689.5
B. Weight of Flask filled with water, (g)	2165	2152	2165	2165	2152	2165	2165	2152	2165	2165	2152	2165
C. Weight of Flask+ Sample, (g)	1886	1832	1874	1885	1841.5	1879	1893	1835	1864	1894	1855	1886
D. Weight of Flask filled with water+sample	2864	2858	2865	2873	2838.5	2866	2858.5	2851	2851	2855	2846	2865
E. Mass of dry sample in air, (g)=C-A	1197	1192	1185	1196	1201.5	1190	1203.5	1195	1175	1205	1215	1197
Maximum Theoretical specific gravity, Gmm	2.403	2.453	2.446	2.450	2.333	2.435	2.360	2.408	2.404	2.341	2.332	2.410
Average Gmm, (g/cm3)	2.434			2.406			2.391			2.361		

Table C5.4: Maximum Theoretical Specific Gravity of HMA Mixtures with 5.75% crushed stone dust filler

Test type: Maximum theoretical specific gravity of HMA mixture (Gmm) 5.75% CSD Filler										Tested Date		
Test Method: ASTM D- 2041-90										25-Dec-24		
Bitumen content (%)	4.5			5			5.5			6		
Trial No.	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)	1(G)	2 (B)	3(G)
A. Weight of Flask, (g)	689.5	640	690	689.5	640	689.5	689.5	640	689.5	689.5	640	689.5
B. Weight of Flask filled with water, (g)	2165	2152	2165	2165	2152	2165	2165	2152	2165	2165	2152	2165
C. Weight of Flask+ Sample, (g)	1894	1894	1894	1896	1858.5	1889	1889	1855	1864	1896	1856	1895
D. Weight of Flask filled with water+sample	2876	2890	2880	2873	2870.5	2854	2864.5	2855	2851	2858	2848	2870
E. Mass of dry sample in air, (g)=C-A	1204	1254	1205	1207	1218.5	1200	1199.5	1215	1175	1207	1216	1206
Maximum Theoretical specific gravity, Gmm	2.439	2.428	2.461	2.420	2.437	2.350	2.399	2.373	2.404	2.350	2.338	2.409
Average Gmm, (g/cm3)	2.443			2.402			2.392			2.366		

Table C5. 5: Maximum Theoretical Specific Gravity of Modified HMA Mixtures by waste marble powder

Maximum theoretical specific gravity (Gmm) of HMA mixture Test Method: ASTM D 2041-90								Optimum conventional filler (CSD)=5.25% Optimum bitumen content (OBC)=5.24%						Tested Date 14-Jan-24	
Waste Marble Powder Content, WMP (%)	10			20			30			40			50		
Trial No.	1(B)	2 (G)	3(B)	1(B)	2 (G)	3(B)	1(B)	2 (G)	3(B)	1(B)	2 (G)	3(B)	1(G)	2 (B)	3(C)
A. Weight of Flask, (g)	640	689	640	640	689	640	640	689	640	640	689	640	689	640	684
B. Weight of Flask filled with water, (g)	2120	2163.3	2120	2120	2163.3	2120	2120	2163.3	2120	2120	2163.3	2120	2163.3	2120	2135
C. Weight of Flask+ Sample, (g)	1861.4	1899.6	1853	1849	1899.8	1879	1845.3	1898	1854	1849.1	1899.1	1855	1865	1886	1889
D. Weight of Flask filled with water+sample	2832.7	2876	2830.3	2828	2870.9	2845	2823.7	2869	2830	2824	2865.3	2825	2830.6	2832	2835
E. Weight of dry sample in air, (g)=C-A	1221.4	1210.6	1213	1209	1210.8	1239	1205.3	1209	1214	1209.1	1210.1	1215	1176	1246	1205
Maximum theoretical specific gravity, G_{mm} (g/cm3)	2.407	2.437	2.419	2.419	2.412	2.416	2.408	2.408	2.414	2.399	2.387	2.388	2.317	2.339	2.392
Average G_{mm}, (g/cm3)	2.421			2.416			2.410			2.391			2.349		

APPENDIX D: WHEEL TRACKING TEST RESULT (ASPHALT RUTTING TEST)

Test Type: Single wheel Tracking (SWTT)										
Test Method: BS EN 122697-22:2020, Part 22 Bituminous mixtures Wheel Tracking Test										
Control mix (0% WMP)						30% WMP Replacement				
Trials	1		2		(1+2)/2	1		2		(1+2)/2
Testing date	June 13-14/2024		June 14-15/2024		Ave. Rut depth (mm)	June 15-16/2024		June 16-17/2024		Ave. Rut depth (mm)
Number of Cycles	Rut Depth (mm)	Rpm	Rut Depth (mm)	Rpm		Rut Depth (mm)	Rpm	Rut Depth (mm)	Rpm	
0	0.000	26.53	0.000	26.50	0.000	0.000	26.50	0.000	26.50	0.000
250	0.070	26.62	0.065	26.62	0.068	0.060	26.67	0.064	26.66	0.062
500	0.100	26.65	0.086	26.65	0.093	0.090	26.67	0.075	26.67	0.083
750	0.120	26.67	0.110	26.66	0.115	0.112	26.66	0.090	26.67	0.101
1000	0.120	26.65	0.140	26.65	0.130	0.114	26.67	0.099	26.67	0.106
1250	0.130	26.68	0.145	26.66	0.138	0.120	26.67	0.115	26.66	0.117
1500	0.140	26.67	0.158	26.66	0.149	0.125	26.66	0.122	26.67	0.123
1750	0.150	26.69	0.165	26.65	0.158	0.125	26.67	0.138	26.65	0.132
2000	0.160	26.67	0.170	26.65	0.165	0.146	26.67	0.147	26.65	0.146
2250	0.170	26.69	0.175	26.65	0.173	0.147	26.67	0.157	26.65	0.152
2500	0.180	26.67	0.184	26.66	0.182	0.147	26.67	0.178	26.66	0.162
2750	0.200	26.67	0.179	26.26	0.190	0.157	26.67	0.188	26.26	0.172
3000	0.200	26.67	0.206	26.65	0.203	0.168	26.68	0.198	26.67	0.183
3250	0.220	26.67	0.216	26.67	0.218	0.199	26.68	0.193	26.67	0.196
3500	0.226	26.67	0.235	26.67	0.231	0.199	26.68	0.221	26.67	0.210
3750	0.235	26.68	0.253	26.65	0.244	0.228	26.67	0.230	26.65	0.229

4000	0.258	26.68	0.255	26.65	0.257	0.244	26.67	0.247	26.65	0.245
4250	0.275	26.67	0.268	26.66	0.272	0.262	26.67	0.260	26.66	0.261
4500	0.285	26.67	0.276	26.66	0.281	0.273	26.68	0.280	26.65	0.276
4750	0.290	26.66	0.295	26.65	0.293	0.291	26.67	0.283	26.65	0.287
5000	0.290	26.66	0.297	26.53	0.310	0.301	26.68	0.300	26.67	0.301
5250	0.310	26.66	0.318	26.66	0.330	0.311	26.68	0.302	26.67	0.306
5500	0.320	26.66	0.328	26.65	0.340	0.321	26.67	0.314	26.66	0.318
5750	0.340	26.65	0.340	26.66	0.345	0.334	26.68	0.333	26.67	0.334
6000	0.340	26.65	0.349	26.66	0.350	0.337	26.67	0.336	26.66	0.337
6250	0.350	26.65	0.359	26.65	0.355	0.345	26.68	0.346	26.67	0.345
6500	0.350	26.66	0.360	26.67	0.356	0.346	26.67	0.355	26.67	0.350
6750	0.350	26.66	0.365	26.67	0.360	0.350	26.68	0.356	26.67	0.353
7000	0.360	26.65	0.369	26.68	0.362	0.361	26.68	0.361	26.65	0.361
7250	0.360	26.65	0.375	26.68	0.365	0.362	26.67	0.364	26.65	0.363
7500	0.360	26.65	0.369	26.66	0.367	0.363	26.68	0.364	26.66	0.364
7750	0.360	26.66	0.369	26.65	0.370	0.364	26.67	0.368	26.68	0.366
8000	0.370	26.65	0.370	26.65	0.373	0.366	26.67	0.365	26.68	0.366
8250	0.370	26.66	0.374	26.66	0.375	0.366	26.67	0.365	26.66	0.366
8500	0.370	26.66	0.379	26.65	0.378	0.366	26.66	0.367	26.66	0.366
8750	0.370	26.65	0.379	26.66	0.383	0.370	26.68	0.369	26.67	0.369
9000	0.370	26.65	0.379	26.67	0.385	0.374	26.67	0.366	26.67	0.370
9250	0.375	26.65	0.375	26.65	0.387	0.376	26.67	0.370	26.67	0.373
9500	0.380	26.66	0.385	26.66	0.390	0.377	26.67	0.372	26.66	0.375
9750	0.390	26.66	0.386	26.65	0.392	0.380	26.67	0.373	26.66	0.377
10000	0.394	26.65	0.394	26.50	0.394	0.381	26.66	0.375	26.66	0.378