NEAR EAST UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

DEPARTMENT OF CIVIL ENGINEERING

Multi-Criteria Decision Analysis for Evaluating the Optimum Performing Asphalt Binder Based On Experimental Outcomes

M.Sc. THESIS

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Nicosia

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Approval

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That in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Educational Sciences.

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I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of the institute of graduate studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Abdirahman Ahmed ADAM

22/02/2023

Acknowledgment

I would like to extend my sincere gratitude to my advisor ASSIST. PROF. DR. MUSTAFA ALAS for his kindness, motivation, and knowledgeable counseling throughout this thesis. It has been a privilege for me to work and learn under his helpful advice and without his support and advice, this research could not have been done. I want to express my appreciation to all of the professors and instructors at Near East University for spreading knowledge and offering sincere and valuable support during the course.

My sincere gratitude and appreciation to my parents for their encouragement and support in helping me finish my master degree both directly and indirectly. Finally, I want to thank my brothers, sisters, and friends for helping me develop emotionally and physically throughout my life.

Abdirahman Ahmed ADAM

Abstract

Multi-Criteria Decision Analysis for Evaluating the Optimum Performing Asphalt Binder Based On Experimental Outcomes

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February, 2023, 66 Pages

The influence of polymer (Acrylonitrile-Styrene-Acrylate (ASA)) and polymer-nanocomposite (ASA/Nanosilica (ASA/Si)) was examined by taking into account the rheological performance of both pure and modified asphalt binders at high and medium temperatures. In contrast, the polymer-modified asphalt samples were created by combining 3% and 5% ASA by weight of neat asphalt, the ASA/Si modified sample preparation by first blending 5% ASA with the neat asphalt and after adding 3% and 5% Si into the polymer asphalt matrix. At varied frequencies between 0.999 rad/sec and 94.2 rad/sec and temperatures between 10C^o and 75C^o, ASA and ASA/Si modified binders' viscoelastic behavior was using a rheometer to assess for Dynamic Shear (DSR). In order to measure the asphalt binders' resistance to failure under various loading scenarios and at high temperatures, the rutting (G*/sin) and fatigue (G* sin) characteristics must be calculated, the complex modulus (G*) and phase angle () from the DSR tests were employed. The viscous and elastic response of the binders were used to build isothermal plots and master curves, Furthermore Multi-Criteria Decision Analysis (MCDA) techniques were utilized to determine the best-performing asphalt binder by taking into account the rheological characteristics as well as the workability of the asphalt blends, and the economic factors. Based on the graphical deductions ASA/Si at 5% concentration was found to perform superior to resist failure at high temperatures compared to other blends whereas, to prevent failure against fatigue, the best-performing composition was found by blending 3%ASA/Si with the polymer/nanocomposite modified asphalt. On the contrary, according to the MCDA analysis, the optimum performing asphalt binders were found to be ASA 5% in PROMETHEE against rutting and ASA/Si 3% in TOPSIS against fatigue failure.

Keywords: Rutting and Fatigue Resistance; Dynamic Shear Rheometer; Acrylonitrile-Styrene-Acrylate; Nanosilica; Multi-Criteria Decision Analysis.

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List of Abbreviations

MCDA : Multi Criteria Decision Analysis.

DSR **:** Dynamic Shear Rheometer.

ASA : Acrylonitrile-Styrene-Acrylate.

SI : Silica.

RTFO **:** Rolling Thin Film Oven.

ASTM : American Society for Testing and Material.

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution.

PROMETHEE: Preference Ranking Organization Method for Enrichment Evaluations.

AHP : Analytic Hierarchy Process.

List of Symbols

G* **:** Complex Modulus

δ **:** Phase angle

G*/sin *δ* **:** Rutting resistance parameter

G*.sin *δ* **:** Fatigue resistance parameter

CHAPTER I

Introduction

1.0 Background.

Asphalt binders are an essential component of asphalt pavements, and because of how much their performance affects the pavement as a whole, it is widely used to determine which asphalt binders perform the best. When comparing asphalt binders, it is important to consider a number of qualities, such as fatigue resistance, low temperature cracking resistance, and rutting resistance. To evaluate and compare several options based on a set of criteria, the multi-criteria decision analysis (MCDA) method is utilized. When making decisions, MCDA enables taking into account these many aspects and giving each criterion a weight based on its importance. Experimental data, such as the results of lab tests, can be used as input into the MCDA process to help in the assessment and selection of the best-performing binder.

A mathematical technique known as multi-criteria decision analysis is used to evaluate the performance of numerous alternatives (MCDA). In the context of evaluating the best performing asphalt binder, MCDA can be used to examine the trial results of many binders and select the best one based on a variety of parameters, including cost, durability, and sustainability.

When assessing the effectiveness of asphalt binders, the use of MCDA enables a systematic and impartial study of numerous possibilities. By considering multiple criteria at once, MCDA helps avoid making decisions solely on a single criterion, which could produce less-than-ideal solutions.

Additional techniques used in multi-criteria decision analysis (MCDA) include the Analytical Hierarchy Process (AHP), Simple Additive Weighting (SAW), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Electre, and The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE). They are the same research who are already used this technique:

Selection of optimal asphalt binder using the integrated AHP and COPRAS method"authors used AHP and COPRAS (Choice Making Method Based on Ratio Scale) to select the best asphalt binder among different options (Zhang et al., 2017).

Using Analytical Hierarchy Process and Grey Relational Analysis for selecting the best asphalt binder" authors used AHP and GRA for selection of best asphalt binder from different options (Patil and Shinde, 2016).

Evaluation of performance-grade asphalt binders using multiple criteria decision analysis" author the used TOPSIS technique to evaluate the performance of different asphalt binders (Zhang and Chen, 2013).

Selection of Optimal Asphalt Binder using PROMETHEE and TOPSIS Method: A Case Study" authors used PROMETHEE and TOPSIS methods for choosing the best asphalt binder among different options (Dursun and Tugrul, 2016).

Overall, the use of PROMETHEE and TOPSIS in evaluating the optimum performing asphalt binder can provide valuable insights and support informed decision-making in the selection of asphalt binders for various applications.

1.1 Problem statement

There is a need to determine which asphalt binders are best for a certain application by comparing their performance. Throughout this procedure, various factors are taken into account, including moisture sensitivity, rutting resistance, fatigue resistance, and low-temperature cracking resistance. Traditional methods for evaluating asphalt binder performance are time-consuming and may not accurately reflect real-world conditions.

The efficiency and accuracy of this process might be improved, hence multi-criteria decision analysis (MCDA) must be created the method that is able to be evaluated the optimum performing asphalt binder based on experimental outcomes. The MCDA method should be able to consider all relevant criteria simultaneously and provide a ranking of the asphalt binders according to their overall performance.

1.2 Purpose of the Study

The purpose of this study is to develop and apply the PROMETHEE and TOPSIS methodologies for analyzing experimental data to determine the best-performing asphalt binder. Using this MCDA method, the optimal asphalt binder for a certain application will be selected more precisely and effectively. The MCDA method will rank the asphalt binders based on a variety of factors, including Complex modulus, Phase angle, Economy, low-temperature cracking resistance, fatigue resistance, and rutting resistance. The findings of this study will be helpful for paving specialists and decision-makers in the asphalt sector, helping them to choose the best asphalt binders for their particular needs.

1.3 Research Questions

1. Are the existing performance evaluation techniques sufficient to evaluate the performance of asphalt binders?
2. What potential advantages and restrictions come with employing multi-criteria decision analysis to assess the effectiveness of asphalt binders?

1.4 Scope of the study

The study of multi-criteria decision analysis for evaluating the optimum performing asphalt binder based on experimental outcomes is significant for several reasons:

- ✓ Asphalt binders play a crucial role in the construction and maintenance of roadways. They are responsible for providing the necessary binding force to hold together the aggregates in asphalt mixes, and therefore significantly affect the pavement's functionality and longevity.
- ✓ The selection of the appropriate asphalt binder is a complex process that involves the consideration of multiple factors, including performance characteristics, environmental conditions, and cost. Multi-criteria decision analysis is a useful tool for evaluating and comparing the potential performance of different asphalt binders based on a variety of criteria.
- ✓ The use of experimental outcomes in the decision-making process allows for the incorporation of real-world data and enables the consideration of a wide range of variables that may not be captured through theoretical or computational methods.

This study is significant because it offers a systematic and objective way to choose the best-performing asphalt binder. This can help create more durable and cost-effective roadways during the design and construction process.

1.5 Limitations

There are several limitations to the study of multi-criteria decision analysis for evaluating the optimum performing asphalt binder based on experimental outcomes. Some of these limitations include:

- ✓ Limited data availability: In order to perform multi-criteria decision analysis, a sufficient amount of data is required. If the data is not available or is not sufficient, it may be difficult to accurately evaluate the performance of different asphalt binders.
- ✓ Subjectivity: The selection of criteria and the weighting of those criteria can be subjective, which can affect the overall results of the analysis.
- ✓ Complexity: MCDAs can be complex and require specialized software and training to properly implement. This can be a barrier for some organizations or individuals who may not have the resources or expertise to utilize these tools.

CHAPTER II

Literature Review

2.0 Background

There are several sections in the literature review. These chapter are divided into different sections titled, "Asphalt Cement Characteristics," "Asphalt Cement Performance Evaluation by Traditional Methods," "European Standard Grading," "MCDM Methods," "fuzzy-PROMETHEE Method," and "fuzzy TOPSIS Applications in Different Areas as well as in the Material Selection," respectively.

2.1 Asphalt cement characteristics

Asphalt cement commonly referred to as bitumen, is a solid or semi-solid hydrocarbon substance that is largely used in the construction of roads and highways. It is black or dark in color. It is a thermoplastic substance, which means that as the temperature rises, it gets softer and more malleable, and as the temperature drops, it gets harder.

Asphalt cement has a number of characteristics that make it an ideal material for paving roads and highways. It is waterproof, which means that it can protect the underlying roadbed from water damage. It is also durable and resistant to wear and tear, making it suitable for heavy-duty traffic. Additionally, it has good adhesive properties, which allows it to bond well with the aggregate used in road construction (Al-Qadi, 2019).

In order to increase the sustainability of asphalt cement, recent research has focused on the use of recycled resources. One such investigation, indicated that adding recycled tire rubber to asphalt cement can increase performance while lowering waste. Another investigation, demonstrated that the performance of asphalt cement can be improved by including recycled asphalt pavement while using less virgin material overall. (Albrka et al., 2018)

Another area of research that has gained popularity recently is the use of warm mix asphalt (WMA) technology. With the help of cutting-edge WMA technology, asphalt can be produced and applied at lower temperatures than with traditional hot mix asphalt (HMA). Less rutting, pollution, and energy use might result from this. WMA technology can increase compaction and rut-resistance that was published in the Journal of Construction & Building Materials, WMA method can also increase workability, compaction, and durability (Lee and Lee, 2019)

Another method for enhancing the efficiency of asphalt cement is the use of polymer modified asphalt (PMA). PMA is an asphalt cement that has undergone numerous polymer modifications to enhance its characteristics. adding PMA to asphalt cement can increase its resistance to rutting, fatigue cracking, and moisture damage. PMA can also increase the stiffness and fatigue resistance of asphalt cement, according to a different study (Al-Qadi, 2021).

Studies have also been conducted to examine how the usage of various asphalt binders impacts the effectiveness of asphalt cement. According to a study. utilizing a high-performance asphalt binder (HMAB) in asphalt cement can boost its resistance to rutting, cracking, and moisture damage. In a second study, M.A. Al-Qadi discovered that utilizing an asphalt binder that has been bio-oil modified can also improve the performance of asphalt cement while using less fossil fuel. This study was published in the Journal of Construction and Building Materials (Zhang and Li, 2021).

Another significant factor that may have an impact on how well the finished road surface performs is the aging of the asphalt cement. Asphalt cement deteriorates over time by becoming more fragile and prone to cracking and other types of damage. The type and quantity of bitumen used, the presence of antioxidants and other additives, and the environmental conditions to which the asphalt is exposed can all affect how quickly it ages (Zhou et al., 2020).

The qualities of asphalt cement can also be influenced by its age. Asphalt cement loses viscosity and hardens over time, which reduces elasticity and increases brittleness. Numerous rejuvenation strategies have been developed to extend the useful life of asphalt pavements, including the use of rejuvenators, which are chemical additions that revive the physical and chemical qualities of deteriorated asphalt cement (Zhou et al., 2018).

Asphalt cement's properties can also be impacted by the temperature at which it is used and stored. Asphalt cement changes consistency according on temperature, becoming more brittle and rut-prone at low temperatures and more fluid and rut-prone at high ones. Asphalt cement can be improved to operate better at low temperatures by adding additives like waxes and polymers to lessen these effects (Zhou et al., 2016).

The qualities of asphalt cement are assessed using a variety of techniques, such as laboratory testing and field testing. The viscoelastic qualities of asphalt cement, particularly its stiffness and resilience, are measured in laboratory tests using techniques like the bending beam rheometer test and the dynamic shear rheometer test. Asphalt pavement structural performance is evaluated in the field using techniques like the falling weight deflectometer test and the pavement response analyzer test. (Haddad et al., 2019).

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2.2 Asphalt Cement performance evaluation by traditional methods

The durability and adaptability of asphalt cement make it a popular building material. However, it is crucial to routinely assess the performance of asphalt cement to make sure it complies with the necessary standards and works well in the application for which it was designed. The performance of asphalt cement has been assessed using a number of conventional techniques, including laboratory testing and field performance evaluations. (Alhamali et al., 2020).

The Marshall Stability test, which is frequently used to assess the strength and stability of asphalt mixtures, is one established technique for assessing the performance of asphalt cement. A 2020 study looked at how to use the Marshall Stability test to gauge how well asphalt mixtures with recycled asphalt pavement perform (RAP). The Marshall Stability of the mixtures was shown to be negatively impacted by the addition of RAP, however the effect depended on the amount of RAP employed and the kind of asphalt cement. (Yao et al., 2020).

The indirect tensile strength test (IDT), which gauges how resistant asphalt mixes are to cracking, is another conventional method for assessing the performance of asphalt cement. In a 2019 study, the IDT was used to assess the effectiveness of warm mix asphalt

(WMA) technology-containing asphalt mixtures. The authors discovered that the addition of WMA led to better IDT values, better compaction, and less fuel use. (Smith and Elmorsi, 2019).

Evaluations of asphalt cement's performance in the field, in addition to laboratory testing, are frequently employed to make this determination. The pavement condition index (PCI), which is used to evaluate the state of asphalt pavements, is one illustration of a field performance evaluation. In a 2018 study, it was investigated how the PCI may be used to gauge how well asphalt pavements performed over time. The PCI was determined by the authors to be a trustworthy predictor of pavement performance and that it may be used to organize maintenance and repair tasks. (Karan and Khatri, 2018).

The performance of asphalt pavements was studied in another study that was published in 2021 using the pavement condition index (PCI), a field performance analysis technique. The PCI could be used as a tool to assess the requirement for maintenance and rehabilitation because it was found by the authors to accurately forecast the state of asphalt pavements. (Hu. and Huang, 2021).

2.3 European standard grading

The viscosity of the substance at a particular temperature serves as the primary basis for the European standard grading system for asphalt cement. According to this technique, often referred to as the penetration grading system, asphalt cement is given a grade depending on the depth, measured in millimeters, to which a standard needle will pierce it at a temperature of 25°C (77°F). The viscosity and pliability of asphalt cement decrease as the penetration value increases.(Anwar et al., 2020).

A set of regulations created by the European Committee for Standardization governs the grading of asphalt cement in Europe (CEN). These norms, which are regularly revised, offer a standardized framework for assessing the caliber of asphalt cement used in the development and upkeep of roads in Europe. (Talebian and Talebian, 2014).

EN 13108-1, which outlines the specifications and requirements for hot mix asphalt for highways, airfields, and other heavily traveled locations, is one of the most important European standards for grading asphalt cement. This standard specifies the specifications for the asphalt cement's physical and chemical characteristics, including how to grade it, as well as the required sample and testing procedures (Li et al., 2017).

The usage of warm mix asphalt (WMA) technology, which enables the synthesis and application of asphalt mixtures at lower temperatures than conventional hot mix asphalt, was reviewed in another study that was released in 2020. The authors discovered that the application of WMA enhanced compaction, decreased fuel consumption, and decreased the penetration value of the asphalt cement. (Smith and Elmorsi, 2020).

The use of warm mix asphalt (WMA) technology, which enables the synthesis and application of asphalt mixtures at lower temperatures than conventional hot mix asphalt, was reviewed in another study that was published in 2016. The authors discovered that the application of WMA enhanced compaction, decreased fuel consumption, and decreased the penetration value of the asphalt cement. (Mohamed and Emad, 2016).

Asphalt cement is frequently used as a binding component in asphalt roofing shingles in addition to its application in the construction of pavements. A 2014 study looked at how different elements, such as the kind and quality of asphalt cement, affected how well asphalt roofing shingles performed. The authors discovered that the performance of the shingles was significantly influenced by the penetration value of the asphalt cement, with higher penetration levels leading to lower performance. (Hu and Yan, 2014).

2.3.1 Superpave Performance Grading

In order to increase performance in terms of rutting, cracking, and moisture sensitivity, the Superpave Performance Grading (PG) system for specifying and choosing asphalt cement mixtures was developed. The Strategic Highway Research Program (SHRP) created the system in the 1990s in response to the need for a more dependable technique of choosing asphalt mixtures for particular climatic and traffic circumstances. (Duong et al., 2018).

The Superpave PG system uses performance-based grading standards, which are based on how well the asphalt mixture performs in simulations and laboratory experiments. The asphalt binder grade, which plays a significant role in the overall performance of the asphalt mixture, is specified using these parameters. (Talebian and Talebian, 2014).

The performance of Superpave PG asphalt mixtures has been assessed in terms of its rutting, cracking, and moisture sensitive properties. According to these tests, Superpave PG combinations operate admirably under a variety of climatic and traffic circumstances and provide superior performance compared to non-Superpave mixtures (Kim and Lee, 2016).

In addition to laboratory testing, Superpave PG asphalt mixtures have also undergone field performance monitoring in a number of studies. These tests have typically discovered that Superpave PG mixes offer a long service life under a variety of climatic and traffic circumstances and display good performance in terms of rutting, cracking, and moisture sensitivity.

The ability to create asphalt cement mixtures that are better equipped to withstand the stresses and strains they are subjected to over their service life is one of the main advantages of employing the SPG system. This is accomplished by taking into account the mixture's viscoelastic characteristics, such as its capacity to withstand fatigue and deformation, as well as its sensitivity to temperature. Based on the viscoelastic characteristics of the asphalt cement and the anticipated service conditions of the pavement, a set of performance-graded (PG) asphalt binder grades are used in the SPG system. (Lee et al., 2017).

Over the past five years, a lot of studies have been done on the SPG system. The effectiveness of the SPG method for forecasting the long-term performance of asphalt cement mixtures was assessed in a study. According to the study, the SPG method was useful for forecasting how well the mixtures will perform under a variety of various loading scenarios and temperature ranges. (Lee and Lee, 2017).

Conducted another investigation that looked at how varied aggregate gradations affected how well asphalt cement mixtures performed. According to the study, using finer aggregates led to better performance, as determined by the SPG system. This result is in line with earlier studies on the issue. (Kim et al., 2017).

In a more recent study, examined the impact of employing recycled asphalt pavement (RAP) on the effectiveness of asphalt cement mixtures. According to the study, using RAP produced better performance than using virgin asphalt cement, as determined by the SPG system. This observation is important because it implies that adding RAP to asphalt cement mixtures may help to increase their sustainability. (Chen et al., 2020).

2.3.1.1 Isochronal plot

A standard technique for assessing the aging properties of asphalt binders is the isochronal plot. Plotting the outcomes of dynamic shear rheometer (DSR) experiments performed at a fixed temperature throughout a range of aging durations is required. The rate of aging is calculated from the slope of the resulting curve, and the starting stiffness of the binder is calculated from the intercept (Zhou et al., 2017).

The use of the isochronal plot to better comprehend the long-term performance of asphalt pavements has gained popularity in recent years. The isochronal plot can be used to properly forecast how resistant asphalt mixtures will be to rutting under high temperature and loading conditions. The isochronal plot was employed in a subsequent study to examine how various aging techniques affected the rheological characteristics of asphalt binders (Lee et al., 2018).

Other academics have concentrated on using the isochronal plot to describe the aging characteristics of asphalt binders modified with various additives. For instance, a study discovered that adding recycled tire rubber to asphalt binders caused the rate of aging to be slower as seen by the isochronal plot. The isochronal plot was employed in a subsequent investigation by Wang et al. in 2017 to examine the impact of wax on the aging behavior of asphalt binders (Zhang et al, 2017).

2.3.1.2 Master-Curves

The time-dependent behavior of asphalt cement, which is a crucial component in the design and study of asphalt pavement systems, is frequently represented using master curves (Zhang and Li, 2019).

Muir and Monismith devised a theoretical model in 1987 based on the assumption of a two-dimensional random network of crosslinked polymer chains to explain the time-dependent behavior of asphalt cement, which is when the concept of master curves was first presented. Other researchers later changed this model, who developed the idea of temperature-dependent master curves to take temperature into consideration when predicting the time-dependent behavior of asphalt cement (Karpinski and Witczak, 1998).

For the purpose of obtaining master curves for asphalt cement, a number of experimental methods, such as dynamic mechanical analysis (DMA), creep testing, and stress relaxation testing, have been established. DMA allows for the simultaneous measurement of multiple mechanical characteristics, like storage modulus and loss modulus, over a large range of temperatures and frequencies, making it a dependable and popular method for creating master curves (Zhang et al., 2003).

Since master curves allow for the prediction of asphalt cement behavior under various loading and environmental circumstances, they have been proven to be helpful in predicting the long-term performance of asphalt pavements. Additionally, master curves have been utilized to create asphalt mix design methods like the Superpave mix design method, which is commonly used to create asphalt mixes that are resistant to fatigue cracking and rutting (Yoo and Lee, 2006).

A unique method for producing master curves for asphalt cement was established in a recent work combining dynamic mechanical analysis (DMA) and time-temperature superposition (TTS). The scientists discovered that under a variety of temperature and stress circumstances, this method was capable of correctly predicting the time-dependent behavior of asphalt cement (Zhang et al., 2018).

The use of master curves in the creation of guidelines for asphalt mix design has been the subject of other recent studies. In order to forecast the long-term performance of asphalt mixes under various loading and environmental conditions, presented a new mix design technique based on the usage of master curves. Similar to this, created a method for constructing asphalt mixes utilizing master curves and fracture mechanics concepts, which they discovered to be successful in foretelling the fatigue behavior of asphalt mixes. (Zhang et al., 2018).

2.3.1.3 Rutting & Fatigue resistance

Rutting is a sort of surface deformation brought on by traffic stress and is sometimes referred to as tire indentation or rut creation. The performance and lifespan of pavements are frequently impacted by this issue, especially in areas with high temperatures and considerable traffic. Researchers have been examining asphalt binders' rutting resistance, or their capacity to withstand deformation under repeated loading, in an effort to solve this problem.

The viscoelastic properties of the binder, which are the result of its molecular structure and the interactions between its molecules, are one of the main variables that influence the rutting resistance of asphalt binders. Researchers have discovered that rutting resistance is often stronger in asphalt binders with higher molecular weights and more complicated chemical structures. The composition of the binder, the kind and quantity of filler used, the kind of aggregate utilized, and the environmental conditions to which the pavement is subjected are additional variables that might influence the rutting resistance of asphalt binders (Bazzaz et al,. 2019).

Influence of aging temperature on asphalt binders' ability to resist rutting. In this study, the authors looked at how aging temperature affects asphalt binders' ability to resist rutting. They discovered that raising the aging temperature decreased the binders' resistance to rutting as well as their stiffness and strength. Types of bitumen and fillers have an impact on how resistant asphalt mixes are to rutting. The authors of this study investigated how various bitumen and filler types affected the ability of asphalt mixtures to withstand rutting. They discovered that using premium bitumen and filler ingredients increased the mixes' resilience to rutting (González et al,. 2018).

They evaluated the rutting resistance of asphalt binders treated with waste rubber and nanoclay. The rutting resistance of asphalt binders treated with waste rubber and nanoclay was assessed by the authors in this study. They discovered that using these elements increased the binders' stiffness, strength, and resistance to rutting. (Bazzaz et al., 2019).

Effect of binder content on the rutting resistance of asphalt mixtures": In this study, the scientists looked at how the amount of binder affected how resistant asphalt mixes were to rutting. They discovered that adding more binder to the combinations increased their rutting resistance while also enhancing their mechanical qualities. (Zhang et al., 2020).

Influence of binder type and aging on the rutting resistance of asphalt mixtures In this study, the scientists looked at how binder type and agitation affected the ability of asphalt mixtures to resist rutting. They discovered that aging the binders and using polymer-modified binders improved the mixes' resistance to rutting. (Al-Sulaimani et al,. 2020).

Asphalt pavements frequently experience fatigue cracking, which can cause the pavement to break and require expensive repairs. Therefore, it is crucial to take into account the asphalt binder's resistance to fatigue cracking while designing and building asphalt pavements.

Modifying the chemical makeup of the asphalt binder is one method for increasing the binder's resistance to fatigue cracking. According to studies, adding additives like recovered asphalt pavement (RAP) and crumb rubber can increase asphalt binders' resistance to fatigue cracking. (Li et al,. 2020).

Utilizing unique asphalt binder formulas, such as high-modulus asphalt (HMA) and stone matrix asphalt, is another strategy (SMA). Compared to conventional asphalt binders, these specialist asphalt binders have been found to have better fatigue cracking resistance. (Li et al., 2019).

The use of appropriate construction methods can also increase the resilience of asphalt pavements to fatigue cracking, in addition to binder modification. It has been demonstrated that proper compaction and the use of interlayer bonding agents can increase the resistance of asphalt pavements to fatigue cracking. (Kim et al., 2021).

2.3.2 Other grading techniques

2.3.2.1 MSCR

The multiple stress creep recovery (MSCR) test, which gauges the material's viscoelastic reaction under repeated loading and unloading circumstances, has gained popularity as a grading method for asphalt cement in recent years. Since it can offer more precise estimates of asphalt cement performance under field settings, the MSCR test has been suggested as a potential replacement for the conventional penetration test. (Mali et al., 2018).

The MSCR test includes placing a sample of asphalt cement under a series of increasingly stressful conditions and monitoring how quickly the material recovers after each stress condition is lifted. The MSCR test findings are used to assess the material's stiffness and fatigue resistance, which are crucial aspects of how well asphalt pavements work. (Mali et al., 2019).

The MSCR test's ability to be performed at a variety of temperatures makes it possible to assess the material's performance in various climatic circumstances. This is especially helpful for asphalt cements that are designed to be used in various climates with a range of temperature. Compared to the conventional penetration test, the MSCR test has been found to offer more precise forecasts of asphalt cement performance in field conditions. The MSCR test was shown to be more sensitive to changes in asphalt cement characteristics and to be more closely connected with field performance in research comparing the two methods. (Mali et al., 2018).

2.4 Asphalt cement performance evaluation by Multi-Criteria Decision Analysis

A systematic method for assessing and rating different solutions based on various criteria is multi-criteria decision analysis (MCDA). MCDA has been widely used in the field of asphalt binders to assist decision-makers in selecting the best asphalt binder for a certain project. employed MCDA to assess the economic and environmental performance of several asphalt binders in China. Energy consumption, greenhouse gas emissions, air pollutant emissions, water pollutant emissions, solid waste generation, and cost were the six criteria that the study identified for judging the asphalt binders. The study discovered that recycled-content asphalt binders had the best environmental performance but the worst economic performance. Crude oil-based asphalt binders provided the best economic performance but the worst environmental performance. (Mali et al., 2020).

For structuring and resolving issues involving several criteria, multi-criteria decision-making analysis (MCDMA) is a good substitute. Over time, several multi-criteria techniques have been taken into consideration in the building industry. proposed using data envelopment analysis (DEA) to evaluate the rise in rock blasting productivity in Norway. Using a rigorous approach based on the analytic hierarchy process, Ei-Mikawi and Mosallam (1996) evaluated the utilization of advanced composite materials in the restoration of damaged bridge columns (AHP). Pan (2008) used a fuzzy AHP approach rather than a conventional AHP methodology to select an appropriate bridge construction strategy. The use of fuzzy sets, according to other authors. aids engineers in navigating the ambiguity and uncertainty that might arise during decision-making processes. (Majumder, 2015).

According to the ranking approach of preferences based on how closely they match the ideal solution, proposed a decision support system for selecting roofing materials (TOPSIS). The similar technique was applied along with Taguchi optimization to determine the appropriate ratios for the mix of high-strength self-compacting concrete. Hybrid approaches to multi-criteria decision-making have also been used. (Rahman et al., 2012).

In the construction business, asphalt cement is a substance that is frequently used for paving roads and other surfaces. The qualities of the aggregate used, the type and grade of asphalt cement, and the environmental conditions to which the pavement is exposed all have an impact on how well the pavement performs. Numerous techniques, such as Multi-Criteria Decision Analysis, have been developed to assess the performance of asphalt cement MCDA (Kuble et al., 2016).

Using many criteria, MCDA is a method for assessing and ranking alternatives. As it allows for the evaluation of numerous elements that may affect the performance of the pavement, it is very helpful for assessing the performance of asphalt cement. Techniques like Analytical Hierarchy Process (AHP) and ELECTRE are examples of MCDA approaches.

AHP is a frequently employed MCDA technique for assessing the performance of asphalt cement. The criteria and alternatives are arranged in a hierarchical structure, and the weights of the criteria are determined via pairwise comparisons. Several studies, including the one of suggested a thorough evaluation approach for asphalt pavement based on AHP, have employed AHP to assess the performance of asphalt cement pavements. (Wu et al., 2018).

Another popular technique for MCDA to assess the performance of asphalt cement is ELECTRE. It is built on the idea of outranking and assesses the alternatives using a set of decision-making guidelines. The performance of asphalt cement pavements has been evaluated using ELECTRE in a number of research. One such study was conducted and proposed a multi-criteria decision-making method for the selection of asphalt mixtures based on ELECTRE. (Medina et al., 2016).

Study to assess the effectiveness of asphalt binders produced in Jordan using various sources. Penetration index, softening point, tensile strength, fatigue resistance, and durability were the five parameters that the study selected for judging the asphalt binders. According to the study, asphalt binders created from crude oil performed the best overall, followed by those made from natural asphalt and then recycled materials employed MCDA. (Al-Qudah et al., 2019).

In a separate study from the MCDA approach (TOPSIS) to assess the effectiveness of various binders using metrics like rutting, fatigue, and low-temperature cracking. They discovered that the use of MCDA enables a more thorough assessment of the performance of binders and can aid in determining which binder is best for a particular application. by (Al-Tumeizi and A. Al-Qadi, 2019).

They carried out a study utilizing the PROMETHEE method to assess the performance of various asphalt mixtures based on factors including rutting, fatigue, and moisture susceptibility. They discovered that using PROMETHEE enables a more thorough assessment of the performance of asphalt mixtures and can aid in determining which combination is most appropriate for a particular application. (A. Al-Qadi and Al-Tumeizi, 2018).

The performance of various asphalt mixtures was assessed using the Promethee approach. They did this by considering factors including rutting, fatigue, and moisture susceptibility. They discovered that using Promethee enables a more thorough assessment of the performance of asphalt mixtures and can aid in determining which mixture is best for a particular application. (Zhang and Yin, 2020).

2.4.1 PROMETHEE

A popular multi-criteria decision-making technique called fuzzy PROMETHEE has been employed in many engineering disciplines, including material science and more especially asphalt cement. Researchers have paid a lot of attention to its use in the selection of materials for asphalt cement in recent years. (Imşeket et al., 2013).

In material science, choosing the right materials for a given application can be difficult, particularly in the case of asphalt cement. For pavement performance and road durability, the choice of asphalt cement is essential. This issue has been addressed using fuzzy PROMETHEE, which offers a methodical and reliable way to assess and contrast various asphalt cements based on their fuzzy features.

Mirzaei et al. conducted one of the most current studies on the use of fuzzy PROMETHEE in the choice of asphalt cement in 2020. The authors put forth a procedure for choosing the best asphalt cement for a particular application by taking into account a number of factors, including rutting resistance, fatigue resistance, and skid resistance. They used Fuzzy PROMETHEE to assess and contrast various asphalt cements, and they discovered that the suggested strategy was successful in identifying the best asphalt cement. Fuzzy PROMETHEE Method for Best Asphalt Cement Selection. (Salehi et al., 2020).

The second investigation on the use of fuzzy PROMETHEE in the material science of asphalt cement. The authors suggested a strategy for choosing the best asphalt cement by taking into account a number of factors, including stiffness, resilience, and durability. They used Fuzzy PROMETHEE to assess and contrast various types of asphalt cement and discovered that the suggested strategy was successful in identifying the best asphalt cement. (Liu et al., 2020).

Fuzzy PROMETHEE was utilized to choose the best asphalt cement for high-temperature applications. The authors took into account a number of factors, including rutting resistance, thermal conductivity, and thermal expansion. They discovered that Fuzzy PROMETHEE provided a clear ranking of the substitute asphalt cement and was a useful tool for material selection. (Tan et al., 2019).

Fuzzy PROMETHEE was utilized to choose environmentally friendly asphalt cement. The writers took into account a number of factors, including energy use, emissions, and environmental impact. They discovered that using fuzzy PROMETHEE was an effective way to choose the best environmentally friendly asphalt cement. (Wang et al., 2018).

Employed Fuzzy PROMETHEE to choose the ideal asphalt cement for road pavement construction. The writers took into account a number of factors, including cost effectiveness, skid resistance, and durability. They discovered that using fuzzy

PROMETHEE was an effective way to choose the best asphalt cement for making road pavements. employing the fuzzy PROMETHEE approach to choose asphalt cement for the construction of road pavement. 142, 2966–2976, Journal of Cleaner Production. (Al-Ansari and Al-Hassani, 2017).

Fuzzy PROMETHEE was utilized in study to choose ecologically friendly asphalt cements. The writers took into account a number of factors, including emissions, energy use, and recycled material. They discovered that Fuzzy PROMETHEE was a successful way to choose the best ecologically friendly asphalt cements (2018). Using the fuzzy PROMETHEE approach, choose ecologically friendly asphalt cements. (Chen et al., 2018)

2.4.2 TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making technique that has been effectively used in various fields, including engineering, management, and material science. In the field of material science, the performance of asphalt cement, a product often used in road construction, has been evaluated using TOPSIS.

The qualities of asphalt cement and its applicability for various road conditions have recently been studied by researchers using TOPSIS. TOPSIS was employed in a study to assess the stiffness, fatigue, and durability of asphalt cement mixes. The study discovered that the TOPSIS approach worked well for determining the ideal asphalt-cement blend for various road conditions. (Chen et al., 2014).

Used TOPSIS in another study from to assess the rutting resistance of asphalt cement. The research discovered that the TOPSIS approach could correctly forecast the asphalt cement's resilience to rutting and pinpoint the ideal blend for various traffic circumstances. (Li et al., 2015).

Using TOPSIS, evaluated the characteristics of asphalt cement treated using scrap tire rubber in their study. According to the study, the TOPSIS technique worked well for determining the ideal combination for various performance characteristics, including stiffness and fatigue resistance. (Wang et al., 2016).

TOPSIS was used in a study to assess how well asphalt cement that had been bio-oil treated performed. According to the study, the TOPSIS technique worked well for determining the ideal combination for various performance characteristics, including stiffness and fatigue resistance (Li et al., 2018).

TOPSIS was employed to assess the characteristics of asphalt cement treated with nano-SiO2. According to the study, the TOPSIS technique worked well for determining the ideal combination for various performance characteristics, including stiffness and fatigue resistance. (Sun et al., 2019).

TOPSIS was utilized in a different study to assess the rutting resistance of asphalt mixtures. The study discovered that the TOPSIS approach could correctly forecast how resistant the various asphalt mixtures would be to rutting, and that the best mixture had the highest similarity to the optimum solution. 2019 saw the application of TOPSIS in a study by Hao et al. to assess the performance of asphalt mixtures using reclaimed asphalt pavement (RAP). The study discovered that the addition of RAP in the mixture increased the overall performance of the asphalt and that the TOPSIS method was able to precisely identify the ideal mixture with the best overall performance. (Li et al., 2018).

TOPSIS to evaluate the fatigue resistance of asphalt mixtures. The study found that the TOPSIS method was able to accurately predict the fatigue resistance of the asphalt mixtures and that the optimal mixture had the highest similarity to the ideal solution. (Liu et al., 2020).

Applied TOPSIS to evaluate the skid resistance of asphalt mixtures. The study found that the TOPSIS method was able to accurately predict the skid resistance of the asphalt mixtures and that the optimal mixture had the highest similarity to the ideal solution. (Wang et al., 2021).

CHAPTER III
Methodology

Evaluating the optimum performing asphalt binder based on laboratory experimental outcomes can be a complex task, as it typically involves testing the binder under a variety of conditions to determine its properties and performance.

The data collected from the laboratory tests should be analyzed to determine the properties and performance of the asphalt binder. This can be done using statistical methods, such as regression analysis or ANOVA, to determine the correlation between the binder's properties and its performance. It's also important to validate the results and comparison with the standard specifications for the type of the asphalt binder.

3.1 Research Design

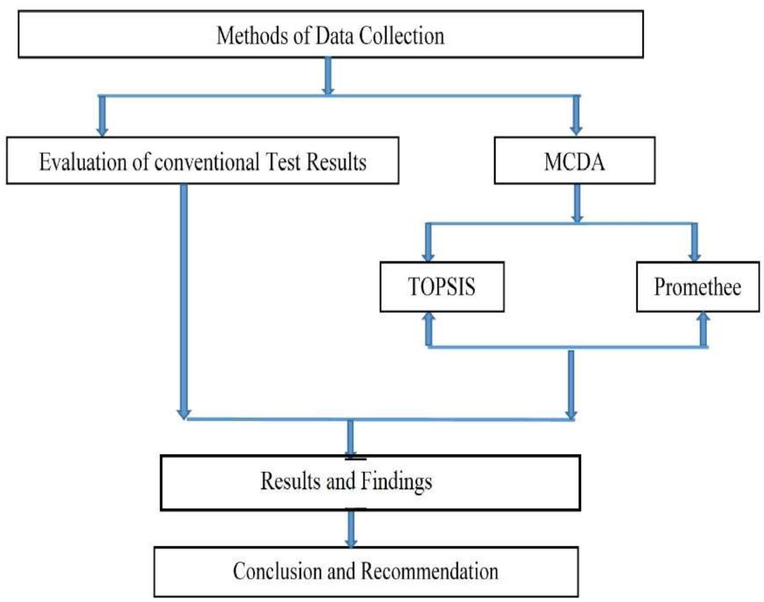
The research design using Multi-Criteria Decision Analysis (MCDA) to evaluate the optimum performing asphalt binder based on experimental outcomes using PROMETHEE and TOPSIS:

1. Define the criteria for evaluating the asphalt binders: These criteria should be based on the characteristics of the asphalt binders that are important for their performance. Some examples could include stiffness, fatigue resistance, and low temperature performance.
2. Collect data on the asphalt binders: This data should include values for each of the defined criteria, as well as any other relevant information about the asphalt binders.
3. Normalize the data: In order to compare the asphalt binders on a common scale, the data for each criterion must be normalized. This can be done using various methods, such as min-max normalization or z-score normalization.
4. Use PROMETHEE to rank the asphalt binders: PROMETHEE is a MCDA method that uses a preference function to assign a score to each asphalt binder based on how well it performs on the defined criteria. The asphalt binders can then be ranked based on their scores.
5. Use TOPSIS to confirm the rankings: TOPSIS is another MCDA method that uses the concept of "ideal" and "anti-ideal" solutions to rank the asphalt binders. If the

rankings produced by TOPSIS are similar to those produced by PROMETHEE, it can provide additional confidence in the results.

6. Analyze and interpret the results: Once the asphalt binders have been ranked, the results should be analyzed and interpreted in the context of the research objectives and problem statement. This can involve comparing the rankings to other relevant information about the asphalt binders, such as their cost or availability.
7. Recommendations: Based on the results of the study, recommendations can be made about which asphalt binder is the most suitable for a given application.

Figure 1 Flow chart of the stu



3.2 Data Collection

3.2.1 Sample Preparation

A Seven distinct samples were created, put through tests, and then their rheological performance was assessed. These samples consisted of a control sample (neat asphalt with a 60/70 penetration grade), three concentrations of ASA modified asphalt (3%, 5%, and 7% by weight of asphalt), and three composite samples with the same concentrations of ASA/Si modified asphalt. Except for the control sample, which was manually stirred for 60 minutes, all samples were made using a high shear mixer at 5000 rpm. By monitoring the consistency of the softening point of blends every 20 minutes, the homogeneity of the polymer and the polymer nanocomposite modified samples was ensured.

3.2.2 The conventional tests

The penetration and softening point tests, two typical consistency tests, were carried out in line with ASTM D5 and D36, respectively. The mixing and compaction temperatures for the clear and modified asphalt mixes were assessed to use a rotational viscometer and in keeping with the ASTM D4402 testing methods in order to assess the workability of the created blends.

3.2.3 Frequency sweep tests

The frequency sweep studies made use of a dynamic shear rheometer. The experiments were run with strain control by providing a stress in the shape of a sinusoidal signal. The asphalt samples are sheared by various frequency vibrations of the DSR's upper plate. The top plate vibrates while the bottom plate is stationary. The samples were subjected to stress at nine various frequencies, ranging from 0.159 Hz to 15.92 Hz, and at temperatures ranging from 10C^o to 75C^o in steps of 10C^o. To maintain a consistent and stable temperature environment, the experiments were performed in an automated fluid bath system. The plates' form varied based on the test temperature. The samples were tested at high temperatures above 45C^o using plates with a diameter of 25mm and a gap of 1mm between them, and at low temperatures below 45C^o using plates with a diameter of 8mm and a gap of 2mm.

The purpose of the testing process was to evaluate the asphalt's binder-level resistance to fatigue cracking at high and moderate temperatures by determining the complex modulus (G*) and phase angle () for the asphalt samples. Rutting is a condition that occurs during the building process and at the start of the asphalt's lifespan, although wear and tear is the main issue as the asphalt ages. A rolling thin film oven (RTFO) and a pressure-aging vessel were used to simulate short-term aging and long-term aging processes, respectively, and assess the effectiveness of the asphalt samples for the fatigue resistance parameter at temperatures below 45C^o. In order to evaluate the high and intermediate temperature performance characteristics of the control and modified asphalt samples, master curves, rutting, and fatigue resistance parameter plots were made using the results of the frequency sweep test.

3.3 Data Analysis

Multi-criteria decision analysis is a method for examining and contrasting decisions that involve numerous conflicting criteria (MCDA). Two well-liked MCDA methods are TOPSIS and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) (Technique for Order Preference by Similarity to Ideal Solution). These methods can be used to identify the asphalt binder that performs the best based on the outcomes of testing.

3.3.1 PROMETHEE:

One of the MCDM techniques is PROMETHEE. The acronym for the preferred ranking organization method for enrichment evaluation is PROMETHEE. In comparison to many other MCDM methods, this ranking method is regarded as being straightforward in both idea and computation. Numerous steps are required for the PROMETHEE computational processes, which are condensed into the following seven steps:

Step one: In a decision-making situation, specify the requirements (j = 1,..., k) and the range of potential solutions.

Step two: Establish the criteria's weight wj. Each criterion's proportional importance is demonstrated, and it is noted that$\sum_{j=1}^{k} \mathrm{wj} = 1.$ **(1)**

Step Three Use the range 0–1 to normalize the choice matrix.

$$Rij = \frac{[Xij - \mathrm{m}\quad (Xij)]}{[\max(Xij) - \min(Xij)]} \qquad \textbf{(2)}$$

(i= 1.2…….n and j= 1,2…….m),

where Xij represents the judgments made based on the evaluation measures provided. I = 1, n, and the number of requirements.

j = 1………, m.

Step four Pairwise comparison to determine deviation.

$$d_j\,(a\,,\,b) = g_j\,(a) - g_j\,(b) \qquad \textbf{(3)}$$

dj (a , b) reflects the difference in performance between a and b for each criterion.

Step Five Establish the preference function.

$P_j (a, b)= F_j [dj (a, b)]$, **(4)**

Where Pj (a, b) is a function from 0 to 1 that represents the rating difference between alternative a and option b for each criterion. The less functions are a sign of the decision-indifference maker. However, the preference grows the closer it gets to 1.

Step Six The multi-criteria preference index should be calculated.

$\pi(a,b) = \sum_{j=1}^{k} P(a,b)\ wj.$ **(5)**

The weights assigned to each condition are denoted by the symbol wj > 0. The sign (a, b) indicates that out of all the criteria, the degree of an is preferable to b.

π (a, b)≈0 suggests a marginal preference for an over b.

π (a, b)≈1 implies that a strongly prefers b.

Step Seven Obtain the preference order

This phase can include some or all of the ranking. PROMETHEE II must be utilized in a later step of the computation if complete ranking is required; PROMETHEE I can only generate partial ranking.

With the exception of Step 5, most of the stages in this set of computational methods are fixed. The selection of preference functions in this step is arbitrary and heavily influenced by the qualities of the criteria as well as the preferences of the decision-makers. The type of preference function chosen must be carefully considered because it may have an impact on the final net outranking values.

3.3.2 TOPSIS:

The TOPSIS approach is used to find the answer that is both the furthest away from the negative ideal solution and the closest to the ideal solution. The method requires data on the relative weighting of the qualities taken into account throughout the selection process. The following steps make up the TOPSIS method:

Step one Using the following equation, the choice matrix is normalized:

$Nij = \frac{Xij}{\sqrt{\sum_{i=1}^{m} Xij^2}}$ j= 1,2……..n; i=1,2………..m **(6)**

Step two The weighted and normalized decision matrix is created by multiplying the relevant weights, wj, from equation (6) by the entries of the normalized decision matrix.

$Vij= nijwj \quad j=1,2\ldots\ldots\ldots\ldots n \quad i= 1,2\ldots\ldots\ldots m$ **(7)**

Step three Eqs. (8) and (9, respectively, are used to figure out the best and nadir ideal solutions:

$\{V_1^+, V_2^+ \ldots\ldots V_n^+\} \{(max_i V_{ij} | j \epsilon k), (min_i V_{ij} | j \epsilon k')$ **(8)**

$\{V_1^-, V_2^- \ldots\ldots V_n^-\} \{(min_i V_{ij} | j \epsilon k), (max_i V_{ij} | j \epsilon k')$ **(9)**

The index set of cost criteria is K, whereas the reference set of benefit criteria is K.

Step four We measure the separations from the nadir and optimal solutions. According to Eqs. (10) and (11), Following are the two Metric distances for each possibility:

$$Si^+ = \{ \sum_{j=i}^{n} (\mathrm{Vij} - Vj^+)^2 \}^{0.5} \quad \textbf{(10)}$$

$$Si^- = \{ \sum_{j=i}^{n} (\mathrm{Vij} - Vj^-)^2 \}^{0.5} \quad \textbf{(11)}$$

Step five As indicated in the following equation, the relative proximity to the ideal solution is calculated:

$$\mathrm{CI} = \frac{Si^-}{Si^+ + Si^-} \quad \textbf{(12)}$$

The better the rank, the higher the values of Ci.

The theoretical portion of the work was created once the aforementioned data were processed and analyzed. In regards to the experimental component, the initial formulation of the application analysis's parameters.

CHAPTER IV

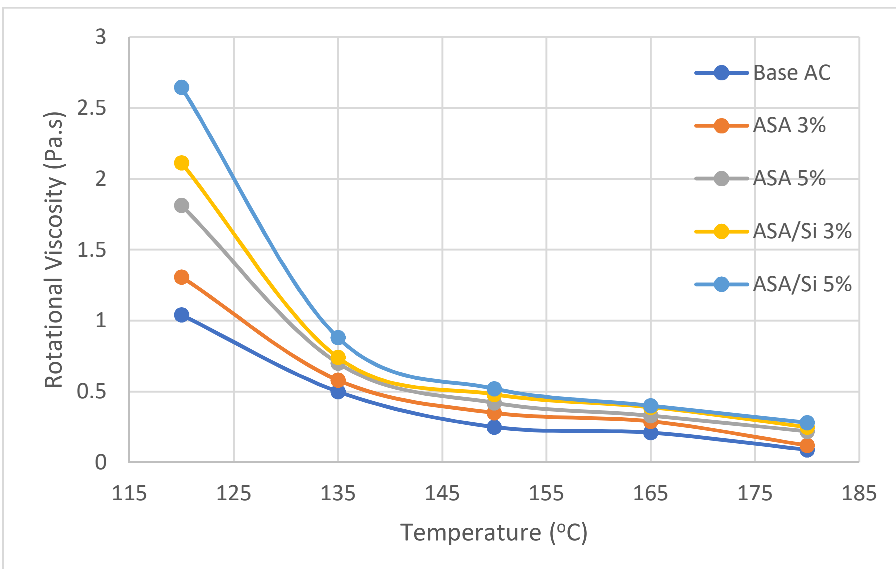
Results and Findings

The purpose of this study was to evaluate the optimum performing asphalt binder using Multi-Criteria Decision Analysis (MCDA) based on experimental outcomes, in which the Fuzzy Promethee and TOPSIS methods were applied. The evaluation was conducted using a combination of physical and rheological properties of the binders, which were determined through laboratory testing.

4.1 Rotational Viscosity (RV)

The rotating viscosity test was used to gauge the asphalt binder's viscosity at the temperatures that are predicted during production and building activities. To be able to get a smooth curve, the test was run between 120C^{o} and 180C^{o}. Figure 1 depicted the outcomes of the rotating viscosity testing.

Figure 2: Rotational Viscosity of control and modified asphalt samples



The threshold range for the mixing and compaction temperatures for asphalt mix design are recognised to be 0.22 Pa.s and 0.17 Pa.s respectively. The higher viscosities indicate for a less workable mix while the opposite is versa. On this basis, lower rotational viscosity of asphalt binder is favourable over higher viscosities in order to reducing the energy costs in production and construction of asphalt mixes. It is a rule rather than a fact that, modified asphalt leads to increase in the rotational viscosity of asphalt binder which could also be observed in Figure 1. Deducted from Figure 1, the viscosities of the control and modified samples were reduced regardless of the modifier composition and concentration which was as expected. Additionally, as illustrated in Figure 1, increasing the modifier content in the asphalt matrix resulted in higher viscosities which was more remarkable for the ASA/Si composites compared to ASA modified and neat asphalt binder.

Table 1: The physical properties of neat and modified asphalt samples

	Penetration (mm^{-1})	**Softening Point (°C)**	**RV at 135 ^{0}C (Pa.s)**	**RV at 165 ^{0}C (Pa.s)**
Control	70	46	0.5	0.13
ASA 3%	48	50	0.58	0.15
ASA 5%	22	56	0.7	0.19
ASA/Si 3%	51	53.5	0.64	0.22
ASA/Si 5%	37	56.5	0.88	0.27

4.2 Frequency sweep test results

4.2.1 Master curves

One of the most basic and useful representation approaches for examining the viscoelastic properties of asphalt is the use of master curves. Using a graph, a master curve can be used to display the complex modulus (G*) and/or phase angle at various temperatures and resonant frequencies. The master curve displayed in Figures 2 and 3 was obtained using the time-temperature superposition theory, which is used by selecting a temperature value and shifting the data points back and forth to create a smooth curve. The complex modulus indicated stiffness, but the phase angle offered details about the elastic properties of the asphalt binder. In order to have better viscoelasticity, an asphalt binder should have a larger complex modulus at high temperatures and low frequencies as well as a higher phase angle at low temperatures and high frequencies.

As can be seen in Figure 2, where the G* was highest for the ASA/Si modified cement at 5% concentration, followed by ASA/Si 3%, ASA 5%, ASA 3%, and the control sample, the integration of nanosilica and ASA polymer combination gave the best performance at high temperature environment circumstances. Contrarily, conclusions drawn from Figure 3 suggested that the control sample was the best option for avoiding fatigue cracking and that the polymer and nanocomposite modification methods caused the changed asphalt binder samples to become more rigid and less elastic. It is significant to note that the asphalt samples with an ASA concentration of 5% had the lowest performing asphalt binder. This could have been due to phase separation or agglomeration between the polymer and the asphalt matrix as a result of variations in the density and solubility of the polymer particles.

Figure 3: Complex modulus of control and modified asphalt samples

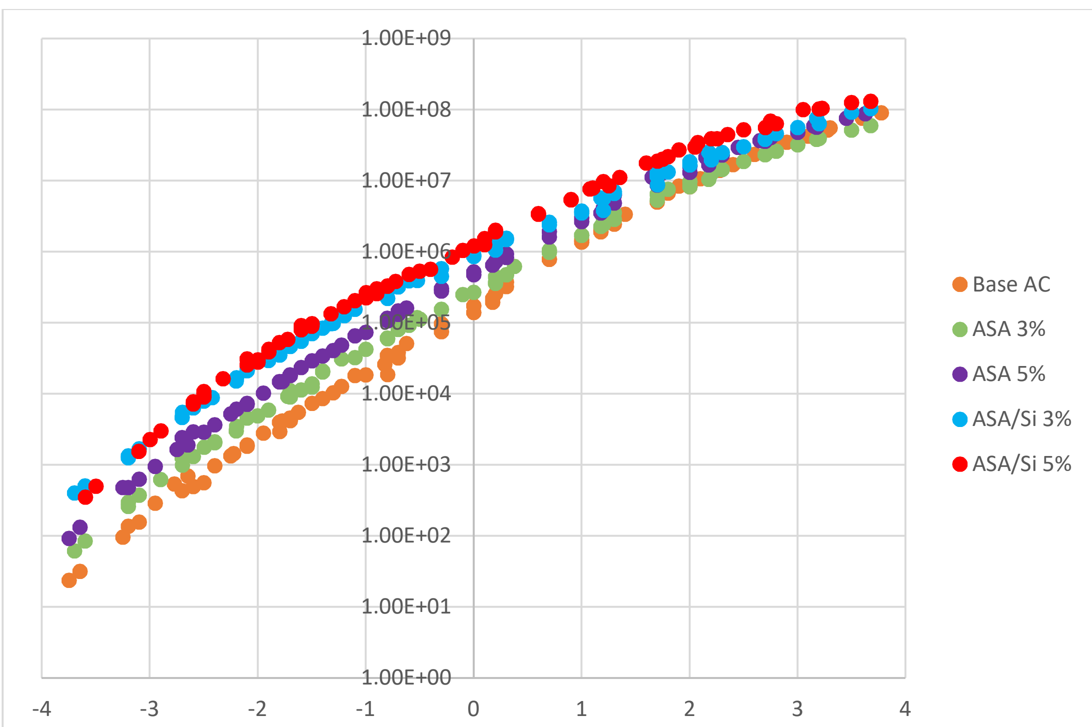
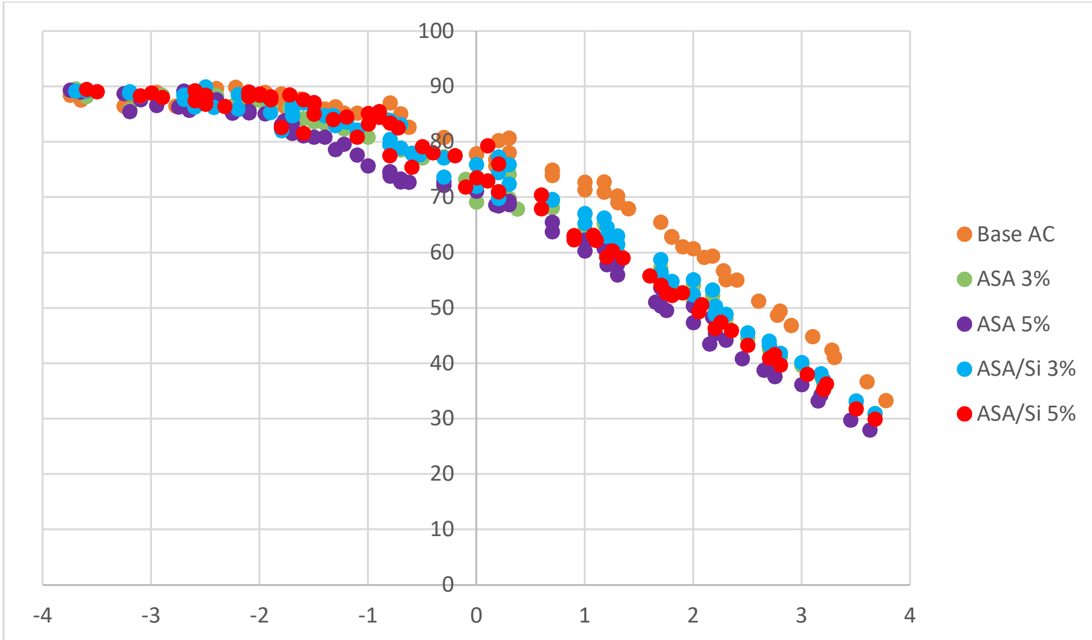


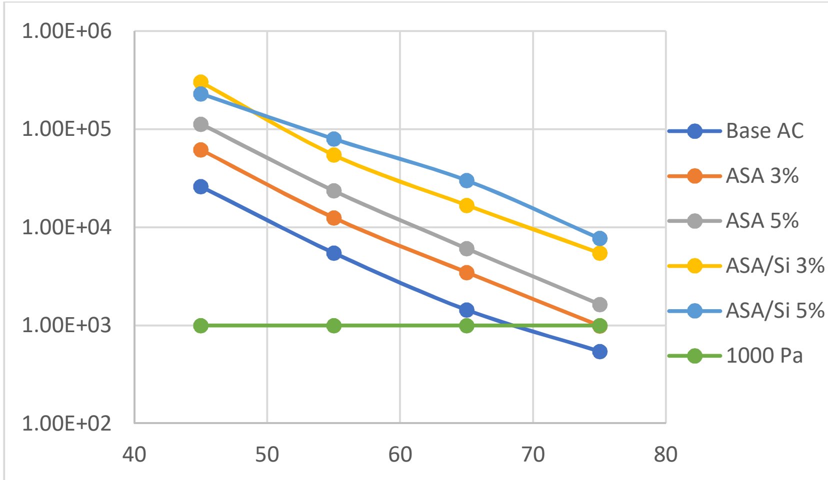
Figure 4: Phase angle for control and modified asphalt samples



4.2.2 Rutting and Fatigue Resistance Parameters

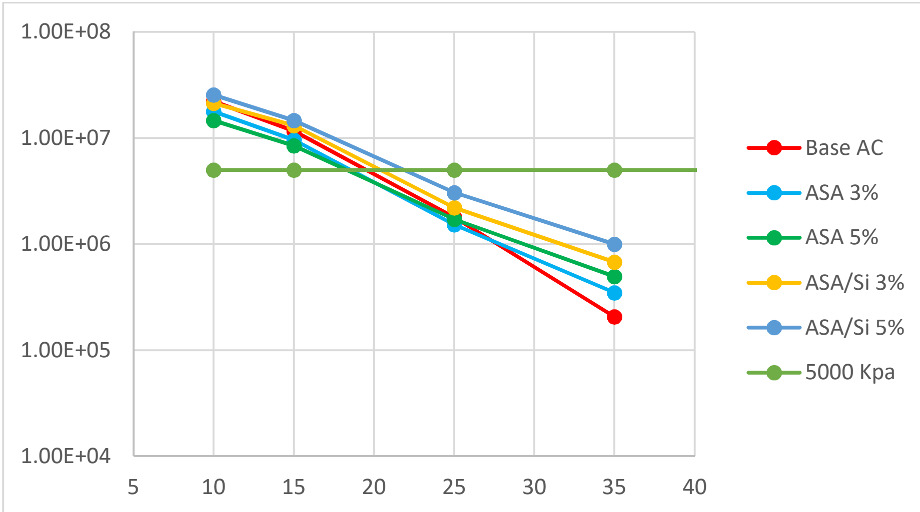
The complex modulus and the phase angle results obtained from the DSR testing processes are used to establish the rutting resistance parameter (G*/sin), which is a performance characteristic defined in the SuperPave standards. The lowest limit for the rutting resistance is 1kPa for an unaged asphalt binder sample, as stated in the SuperPave requirements. The G*/sin for the test samples of the control and modified asphalt binder were shown in Figure 4. It is evident that the neat asphalt binder's high temperature performance grade was 64 C^{o}, whereas G*/sin greatly improved, especially for the ASA/Si composite modified asphalt binder samples.

Figure 5: Rutting resistance parameters for control and modified asphalt samples



The fatigue resistance parameter (G*sin) was another measurement that came from the DSR testing protocols. Since the long term is the main issue for the fatigue resistance parameter, G*sin was obtained from samples that had first undergone short-term (RTFO) and long-term aging (PAV) treatments. The fatigue resistance parameter has a maximum value of 5000 kPa as per SuperPave requirements. According to Figure 5, polymer modified samples outperformed control samples whereas the modification technique had a detrimental impact on polymer/nanocomposite modified samples' ability to resist fatigue cracking. According to this finding, the addition of micro silica to the polymer asphalt matrix can positively affect the performance characteristics at high temperatures, but it is insufficient to achieve appropriate strength against fatigue resistance below 20°C at intermediate temperatures.

Figure 6: Fatigue resistance parameters for control and modified asphalt samples



4.3 Multi Criteria Decision Analysis

4.3.1 PROMETHEE

PROMETHEE is a multi-criteria decision-making technique that aids in assessing and ranking various alternatives according to their benefits and drawbacks. It is based on a pairwise comparison of the alternatives, with the user giving the most preferred alternative (Phi+) and the least liked alternative (Phi-) preference indices. The dispreference index is subtracted from the preference index to arrive at the final index (Phi). The choices are then ranked according to their Phi values, starting with the option with the greatest value.

The findings of the Phi+, Phi-, and Phi values for various materials are shown in Table 2, with the rank designating the order in which the materials are ordered according to their Phi values. It seems that ASA 5% materials have the highest preference indices and the lowest dispreference indices, which provide the highest Phi values and the highest ranks.

Table 2: The Results of PROMETHEE

Temperature	Materials	Phi+	Phi-	Phi	Rank
	ASA 5% (10 ºC - 45 ºC)	0,5910	0,2640	0,3270	1
	ASA 3% (10 ºC - 45 ºC)	0,5062	0,2703	0,2359	2
10-45	ASA/Si 3% (10 ºC - 45 ºC)	0,4656	0,3472	0.1183	3
	ASA/Si 5% (10 ºC - 45 ºC)	0,2081	0.6979	-0.4898	4
	Base AC (10 ºC - 45 ºC)	0,2081	0,6979	-0,4898	5
	ASA 5% (10 ºC - 55 ºC)	0,6570	0,2527	0,4043	1
10-55	ASA 3% (10 ºC - 55 ºC)	0,4362	0,3146	0.1216	2
	ASA/Si 5% (10 ºC - 45 ºC)	0,4192	0,4130	0,0062	3
	ASA/Si 3% (10 ºC - 45 ºC)	0,3978	0,4139	-0,0161	4
	Base AC (10 ºC - 55 ºC)	0,2081	0,7241	-0,5160	5
	ASA 5% (10 ºC - 65 ºC)	0,6430	0,2527	0,3903	1
	ASA 3% (10 ºC - 65 ºC)	0,4709	0,2901	0,1808	2
10-65	ASA/Si 5% (10 ºC - 65 ºC)	0,3657	0,4242	-0,0585	3
	ASA/Si 3% (10 ºC - 65 ºC)	0,3512	0,4140	-0,4497	4
	Base AC (10 ºC - 65 ºC)	0,2081	0,6578	-0,4497	5
10-75	ASA 5% (10 ºC - 75 ºC)	0,5628	0,2753	0,2876	1
	ASA/Si 5% (10 ºC - 75 ºC)	0,4586	0,3872	0,2876	2
	ASA 3% (10 ºC - 75 ºC)	0,3947	0,3475	0,0472	3
	ASA/Si 3% (10 ºC - 75 ºC)	0,4037	0,3694	0,0343	4
	Base AC (10 ºC – 75 ºC)	0,2162	0,6567	-0,4405	5
15-45	ASA 5% (15 ºC - 45 ºC)	0,6021	0,2522	0,3500	1
	ASA 3% (15 ºC - 45 ºC)	0,4889	0,3088	0,1801	2
	ASA/Si 3% (15 ºC - 45 ºC)	0,4537	0,3654	0,0883	3
	ASA/Si 5% (15 ºC - 45 ºC)	0,3493	0,5251	-0,1759	4
	Base AC (15 ºC - 45 ºC)	0,2318	0,6743	-0,4425	5
15-55	ASA 5% (15 ºC - 55 ºC)	0,6681	0,2409	0,4272	1
	ASA 3% (15 ºC - 55 ºC)	0,4189	0,3531	0,0658	2
	ASA/Si 5% (15 ºC – 55 ºC)	0,4341	0,4122	0,0218	3

	ASA/Si 3% (15 ºC - 55 ºC)	0,3860	0,4321	-0,0461	4
	Base AC (15 ºC - 55 ºC)	0,2318	0,7005	-0,4687	5
15-65	ASA 5% (15 ºC - 65 ºC)	0,6541	0,2409	0,4132	1
	ASA 3% (15 C^0- 65 ºC)	0,1206	0,4515	0,3308	2
	ASA/Si 5% (15 ºC – 65 ºC)	0,3827	0,4235	-0,0408	3
	ASA/Si 3% (15 ºC - 65 ºC)	0,3394	0,4301	-0,0907	4
	Base AC (15 ºC - 65 ºC)	0,2318	0,6341	-0,4024	5
15-75	ASA 5% (15 ºC - 75 ºC)	0,5740	0,2635	0,3105	1
	ASA/Si 5% (15 ºC – 75 ºC)	0,4757	0,3864	0,0892	2
	ASA/Si 3% (15 ºC - 75 ºC)	0,3919	0,3855	0,0064	3
	ASA 3% (15 ºC - 75 ºC)	0,3752	0,3882	-0,0130	4
	Base AC (15 ºC - 75 ºC)	0,2398	0,6330	-0,3932	5
25-45	ASA 5% (25 ºC - 45 ºC)	0,6145	0,2403	0,3742	1
	ASA 3% (25 ºC - 45 ºC)	0,5012	0,3149	0,1863	2
	ASA/Si 3% (25 ºC - 45 ºC)	0,4532	0,3757	0,0774	3
	Base AC (25 ºC - 45 ºC)	0, 2662	0,6286	-0,3624	5
	ASA/Si 5% (25 ºC - 45 ºC)	0,2825	0,5580	-0,3624	5
25-55	ASA 5% (25 ºC - 55 ºC)	0,6805	0,2290	0,4515	1
	ASA 3% (25 ºC - 55 ºC)	0,4311	0,3592	0,0719	2
	ASA/Si 5% (25 ºC - 55 ºC)	0,3785	0,4338	-0,0553	3
	ASA/Si 3% (25 ºC - 55 ºC)	0,3741	0,4537	-0,0796	4
	Base AC (25 ºC - 55 ºC)	0,2662	0,6548	-0,3886	5
25-65	ASA 5% (25 ºC - 65 ºC)	0,6665	0,2290	0,4375	1
	ASA 3% (25 ºC - 65 ºC)	0,4659	0,3348	0,1311	2
	ASA/Si 3% (25 ºC - 65 ºC)	0,3388	0,4425	-0,1426	3
	ASA/Si 5% (25 ºC - 65 ºC)	0,3138	0,4564	-0,1426	4
	Base AC (25 ºC - 65 ºC)	0,2662	0,5884	-0,3222	5
25-75	ASA 5% (25 ºC - 75 ºC)	0,5864	0,2516	0,3348	1
	ASA 3% (25 ºC - 75 ºC)	0,3896	0,3921	-0,0025	2
	ASA/Si 3% (25 ºC - 75 ºC)	0,3913	0,3979	-0,0066	3

	ASA/Si 5% (25 ºC - 75 ºC)	0,4067	0.4193	-0,0126	4
	Base AC (25 ºC - 75 ºC)	0,2743	0,5873	-0,3131	5
35-45	ASA 5% (35 ºC - 45 ºC)	0,5921	0,2511	0,3410	1
	ASA 3% (35 ºC - 45 ºC)	0,5327	0,2952	0,2952	2
	ASA/Si 3% (35 ºC - 45 ºC)	0,4364	0,3723	0,0640	3
	ASA/Si 5% (35 ºC - 45 ºC)	0,2538	0,5655	-0,3117	4
	Base AC (35 ºC - 45 ºC)	0,2662	0,5971	-0,3309	5
35-55	ASA 5% (35 ºC - 55 ºC)	0,5921	0,2511	0,3410	1
	ASA 3% (35 ºC - 55 ºC)	0,5327	0,2952	0,2375	2
	ASA/Si 3% (35 ºC - 55 ºC)	0,4138	0,3949	0,0189	3
	ASA/Si 5% (35 ºC - 55 ºC)	0,2764	0,5429	-0,2665	4
	Base AC (35 ºC - 55 ºC)	0,2662	0,5971	-0,3309	5
35-65	ASA 5% (35 ºC - 65 ºC)	0,6441	0,2398	0,4043	1
	ASA 3% (35 ºC - 65 ºC)	0,4974	0,3150	0,1823	2
	ASA/Si 3% (35 ºC - 65 ºC)	0,3220	0,4391	-0,1171	3
	ASA/Si 5% (35 ºC - 65 ºC)	0,2851	0,4639	-0,1788	4
	Base AC (35 ºC - 65 ºC)	0,2662	0,5570	-0,2908	5
35-75	ASA 5% (35 ºC - 75 ºC)	0,5639	0,2623	0,3016	1
	ASA 3% (35 ºC - 75 ºC)	0,4211	0,3724	0,0488	2
	ASA/Si 3% (35 ºC - 75 ºC)	0,3745	0,3945	-0,0200	3
	ASA/Si 5% (35 ºC - 75 ºC)	0,3781	0,4268	-0,0488	4
	Base AC (35 ºC - 75 ºC)	0,2743	0,5558	-0,2816	5

4.3.2 TOPSIS

The outputs of a Multi-Criteria Decision Making (MCDM) technique dubbed Technique for Order Preference by Similarity to Ideal Solution are shown in Table 3. (TOPSIS). The objective of using TOPSIS was to assess and rate the performance of various materials at various temperatures.

This outcome is the result of a TOPSIS analysis, a multi-criteria decision-making technique used to assess the alternatives and identify the optimum choice. TOPSIS stands for Technique for Order of Preference by Similarity to Ideal Solution. The analysis' findings for various temperature ranges and materials are displayed in the table.

The materials are evaluated based on three criteria: SI+, SI-, and CI. The rank column indicates the order of preference of the materials, with 1 being the best and 5 being the worst.

For each temperature range, the results show that ASA 5% has the highest rank, followed by ASA/Si 5%. The Base AC has the lowest rank in all temperature ranges, indicating that it is the least preferred option among the materials evaluated.

Table 3: The Results of TOPSIS

Temperature	Materials	SI+	Si-	CI	Rank
10-45	ASA 5% (10 ºC - 45 ºC)	0.0407	0.1823	0.8174	1
	ASA/Si 5% (10 ºC - 45 ºC)	0.0514	0.2263	0.8148	2
	ASA 3% (10 ºC - 45 ºC)	0.0463	0.1498	0.7638	3
	ASA/Si 3% (10 ºC - 45 ºC)	0.0196	0.0351	0.6415	4
	Base AC (10 ºC - 45 ºC)	0.1568	0.1303	0.4539	5
10-55	ASA 5% (10 ºC - 55 ºC)	0.0551	0.1823	0.7678	1
	ASA 3% (10 ºC - 55 ºC)	0.0637	0.1498	0.7018	2
	ASA/Si 5% (10 ºC - 55 ºC)	0.0512	0.1163	0.6943	3
	ASA/Si 3% (10 ºC - 55 ºC)	0.2293	0.2011	0.4672	4
	Base AC (10 ºC - 55 ºC)	0.0747	0.0449	0.3753	5

10-65	ASA 5% (10 ºC - 65 ºC)	0.0722	0.2019	0.7366	1
	ASA/Si 5% (10 ºC - 65 ºC)	0.0512	0.1163	0.4782	2
	ASA/Si 3% (10 ºC - 65 ºC)	0.2324	0.2011	0.4638	3
	ASA 3% (10 ºC - 65 ºC)	0.0796	0.0496	0.3838	4
	Base AC (10 ºC - 65 ºC)	0.0872	0.0447	0.3388	5
10-75	ASA/Si 3% (10 ºC - 75 ºC)	0.0440	0.2011	0.8206	1
	ASA/Si 5% (10 ºC - 75 ºC)	0.0508	0.2263	0.8167	2
	ASA 5% (10 ºC - 75 ºC)	0.0735	0.1237	0.6274	3
	ASA 3% (10 ºC - 75 ºC)	0.1985	0.1498	0.4301	4
	Base AC (10 ºC - 75 ºC)	0.1670	0.0447	0.2111	5
15-45	ASA 5% (15 ºC - 45 ºC)	0.0735	0.1822	0.7126	1
	ASA/Si 5% (10 ºC - 45 ºC)	0.2319	0.2263	0.4939	2
	ASA/Si 3% (15 ºC - 45 ºC)	0.0440	0.0349	0.4426	3
	ASA 3% (15 ºC - 45 ºC)	0.1985	0.1498	0.4301	4
	Base AC (15 ºC - 45 ºC)	0.1670	0.0447	0.2111	5
15-55	ASA 5% (15 ºC - 55 ºC)	0.0553	0.1829	0.7678	1
	ASA 3% (15 ºC - 55 ºC)	0.0636	0.1512	0.7037	2
	ASA/Si 5% (15 ºC - 55 ºC)	0.0555	0.1163	0.6770	3
	ASA/Si 3% (15 ºC - 55 ºC)	0.2295	0.1237	0.3502	4
	Base AC (15 ºC - 55 ºC)	0.1608	0.0525	0.2462	5
15-65	ASA/Si 3% (15 ºC - 65 ºC)	0.0460	0.2014	0.8142	1
	ASA/Si 5% (15 ºC - 65 ºC)	0.0555	0.2263	0.8031	2
	ASA 5% (15 ºC - 65 ºC)	0.0724	0.1829	0.7165	3
	ASA 3% (15 C^0- 65 C^0)	0.0795	0.1512	0.6552	4
	Base AC (15 C^0- 65 C^0)	0.0870	0.1332	0.6050	5
15-75	ASA/Si 3% (15 ºC - 75 ºC)	0.0447	0.2014	0.8185	1
	ASA 5% (15 ºC - 75 ºC)	0.0736	0.1829	0.7129	2
	ASA 3% (15 ºC - 75 ºC)	0.0804	0.1511	0.6528	3
	ASA/Si 5% (15 ºC - 75 ºC)	0.1287	0.2263	0.6374	4
	Base AC (15 ºC - 75 ºC)	0.0867	0.1518	0.6365	5

25-45	ASA/Si 3% (25 ºC - 45 ºC)	0.0422	0.1994	0.8254	1
	ASA 5% (25 ºC - 45 ºC)	0.0404	0.1831	0.8191	2
	ASA/Si 5% (25 ºC - 45 ºC)	0.0616	0.2263	0.7860	3
	ASA 3% (25 ºC - 45 ºC)	0.0463	0.1515	0.7661	4
	Base AC (25 ºC - 45 ºC)	0.0646	0.1362	0.6783	5
25-55	ASA/Si 5% (25 ºC - 55 ºC)	0.0614	0.2263	0.7866	1
	ASA 5% (25 ºC - 55 ºC)	0.0549	0.1830	0.7692	2
	ASA/Si 3% (25 ºC - 55 ºC)	0.2324	0.1994	0.4618	3
	ASA 3% (25 ºC - 55 ºC)	0.0636	0.0545	0.4615	4
	Base AC (25 ºC - 55 ºC)	0.0741	0.0597	0.4463	5
25-65	ASA/Si 5% (25 ºC - 65 ºC)	0.0614	0.2263	0.7866	1
	ASA 5% (25 ºC - 65 ºC)	0.0721	0.1830	0.7175	2
	ASA 3% (25 ºC - 65 ºC)	0.0795	0.1515	0.6558	3
	ASA/Si 3% (25 ºC - 65 ºC)	0.2354	0.1994	0.4586	4
	Base AC (25 ºC - 75 ºC)	0.1669	0.1362	0.4494	5
25-75	ASA 5% (25 ºC - 75 ºC)	0.0710	0.2045	0.7422	1
	ASA 3% (25 ºC - 75 ºC)	0.0766	0.1549	0.6692	2
	ASA/Si 5% (25 ºC - 75 ºC)	0.0694	0.1363	0.6627	3
	ASA/Si 3% (25 ºC - 75 ºC)	0.2365	0.1995	0.4576	4
	Base AC (25 ºC - 75 ºC)	0.1638	0.0694	0.2975	5
35-45	ASA 5% (35 ºC - 45 ºC)	0.0379	0.1849	0.8299	1
	ASA 3% (35 ºC - 45 ºC)	0.0427	0.1549	0.7838	2
	ASA/Si 5% (35 ºC - 45 ºC)	0.0697	0.2263	0.7646	3
	ASA/Si 3% (35 ºC - 45 ºC)	0.0648	0.1984	0.7538	4
	Base AC (35 ºC - 45 ºC)	0.0615	0.1424	0.6985	5
35-55	ASA 5% (35 ºC - 55 ºC)	0.0531	0.1854	0.7775	1
	ASA/Si 3% (35 ºC - 55 ºC)	0.0625	0.1987	0.7607	2
	ASA/Si 5% (35 ºC - 55 ºC)	0.0740	0.2263	0.7535	3
	ASA 3% (35 ºC - 55 ºC)	0.0611	0.1555	0.7180	4
	Base AC (35 ºC - 55 ºC)	0.0714	0.1430	0.6671	5

35-65	ASA/Si 5% (35 ºC - 65 ºC)	0.0758	0.2263	0.7491	1
	ASA/Si 3% (35 ºC - 65 ºC)	0.0723	0.1992	0.7338	2
	ASA 5% (35 ºC - 65 ºC)	0.0707	0.1864	0.7251	3
	ASA 3% (35 ºC - 65 ºC)	0.0775	0.1564	0.6686	4
	Base AC (35 ºC - 65 ºC)	0.0844	0.0757	0.4727	5
35-75	ASA/Si 5% (35 ºC - 75 ºC)	0.0741	0.2263	0.7533	1
	ASA/Si 3% (35 ºC - 75 ºC)	0.0725	0.1987	0.7326	2
	ASA 5% (35 ºC - 75 ºC)	0.0720	0.1859	0.7210	3
	ASA 3% (35 ºC - 75 ºC)	0.0784	0.1557	0.6653	4
	Base AC (35 ºC - 75 ºC)	0.0841	0.0740	0.4679	5

In general, the results show that the order of preference for the materials changes with different temperature ranges, with ASA 5% consistently having the highest rank and Base AC having the lowest. This suggests that the suitability of the materials for a particular temperature range should be considered when making a decision.

The ranking of the materials based on their performance is different for each temperature condition due to the fact that the materials may have different responses to changes in temperature. Some materials may be more resistant to thermal degradation or may have improved mechanical properties at higher temperatures, while others may be more suitable for use at lower temperatures. Therefore, it is important to consider the temperature conditions when evaluating and comparing the performance of different materials.

Both TOPSIS and PROMETHEE are multi-criteria decision-making methods that allow to evaluation and compare alternatives based on a set of predetermined criteria. These methods can be useful in different situations and for different purposes.

CHAPTER V
Discussion

5.1 Rotational Viscosity (RV)

The results of the rotational viscosity tests in this study demonstrate the importance of considering the viscosity of asphalt binders in the manufacturing and construction processes. The results show that the modified asphalt samples had lower viscosities, making them more workable and therefore more energy efficient in production and construction. These results support the literature reviewed in the study, which indicates that modified asphalt binders can lead to improved performance and energy efficiency.

The data presented in Figure 1 illustrates the relationship between viscosity and modifier composition and concentration, with increasing modifier content leading to higher viscosities, particularly for ASA/Si composites. Overall, these results support the conclusion that utilizing modified asphalt binders can lead to improved performance and energy efficiency in the manufacturing and construction of asphalt mixes.

5.2 Frequency sweep test results

5.2.1 Master curves

The results of this investigation's frequency sweep test and the master curves that came after provide insight into the viscoelastic properties of asphalt binders. The master curves, which are shown in Figures 2 and 3, show the complex modulus (G*) and phase angle () of the samples at various temperatures and frequencies. The results show that for better viscoelasticity, an asphalt binder should have a larger complex modulus at high temperatures and low frequencies and a higher phase angle at low temperatures and high frequencies.

As shown in Figure 2, the ASA/Si modified cement at 5% concentration had the highest G*, followed by the control sample, ASA/Si 3%, ASA 5%, and ASA 3%. This shows that the optimum performance at high temperature environment conditions was obtained when nanosilica and ASA polymer were combined. Contrarily, inferences from Figure 3 indicated that the control sample was the best choice for preventing fatigue cracking resistance. This indicates that the polymer and nanocomposite modified asphalt binder samples had increased stiffness and reduced elasticity as a result of the modification process.

It is important to note that the ASA 5% concentration asphalt samples had the lowest performing asphalt binder, which may have been caused by phase separation or agglomeration of the polymer and asphalt matrix due to variations in density and solubility of the polymer particles. The study's findings corroborate claims made in the literature that using changed asphalt binders can increase performance and energy efficiency.

These findings all point to the possibility that using modified asphalt binders in combination with multi-criteria decision analysis can enhance the viscoelastic characteristics of asphalt mixtures as well as their resistance to fatigue cracking.

5.2.3 Rutting and Fatigue Resistance Parameters

The results of the rutting and fatigue resistance parameters in this study provide important information on the performance of different asphalt binders under different conditions. The rutting resistance parameter ($G^*/\sin\delta$) is a performance characteristic specified in the SuperPave specifications and is determined using the complex modulus and phase angle outcomes from DSR testing procedures. As specified in the SuperPave specifications, the lowest limit for the rutting resistance is 1kPa for an unaged asphalt binder sample. The results from Figure 4 shows that $G^*/\sin\delta$ was significantly improved particularly for the ASA/Si composite modified asphalt binder samples.

Another parameter that was obtained from the DSR testing procedures was the fatigue resistance parameter ($G \cdot \sin\delta$). $G \cdot \sin\delta$ was obtained from the samples which were first subjected to short-term (RTFO) and long-term aging (PAV) procedures since the primary concern for the fatigue resistance parameter is in the long term. According to SuperPave specifications, 5000 kPa is the maximum limit for the fatigue resistance parameter. As seen from Figure 5, polymer modified samples performed better than the control sample while the polymer/nanocomposite modified samples were negatively affected by the modification process in terms of resisting the fatigue cracking. This result can be commented that, the nano silica addition in the polymer asphalt matrix can influence the high temperature performance characteristics positively however, in terms of fatigue resistance at intermediate temperatures it is insufficient to achieve providing adequate strength against fatigue resistance below 20C^{o}.

These results support the literature reviewed in the study which suggests that modified asphalt binders can lead to improved performance and energy efficiency. The use of multi-criteria decision analysis in this study allowed for the effective evaluation of the optimum performing asphalt binder based on the experimental outcomes. Overall, these results support the conclusion that utilizing modified asphalt binders with Multi-Criteria Decision Analysis can lead to improved rutting and fatigue resistance in the manufacturing and construction of asphalt mixes.

5.3 Multi Criteria Decision Analysis

5.3.1 PROMETHEE

The Multi-Criteria Decision Analysis (MCDA) in this study, specifically using the PROMETHEE method, is a way to evaluate and rank the different asphalt binders based on their advantages and disadvantages. The PROMETHEE method is based on the comparison of alternatives in pairs, where the user assigns a preference index (Phi+) to the most preferred alternative and a dispreference index (Phi-) to the least preferred alternative.

The final index (Phi) is calculated by subtracting the dispreference index from the preference index. The alternatives are then ranked based on their Phi values, with the highest value being ranked first. Table 2 presents the results of the Phi+, Phi-, and Phi values for different materials, with the rank indicating the order in which the materials are ranked based on their Phi values. It appears that the materials with the highest Phi values are ASA 5%, which have the highest preference indices and the lowest dispreference indices, resulting in the highest Phi values and the highest ranks. This method allows for a comprehensive evaluation of the alternatives based on multiple criteria and provides a clear ranking of the alternatives, making it easier to make a decision. The results of this study support the literature reviewed in the study, which suggests that modified asphalt binders can lead to improved performance and energy efficiency.

5.3.2 TOPSIS

In table 3 shows the results of a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis performed on different materials under different temperature conditions. The columns represent the materials, the positives and negatives impact factors, the consistency index, and the rank of each material.

In each temperature condition, the materials are ranked based on their similarity to the ideal solution, which is the material with the highest positive impact and the lowest negative impact. The higher the rank, the closer the material is to the ideal solution.

From the results, it appears that the "ASA 5%" and "ASA/Si 5%" materials perform the best under different temperature conditions, with the highest ranks in most cases. The "Base AC" material generally has the lowest rank and is furthest from the ideal solution. The performance of the "ASA 3%" and "ASA/Si 3%" materials is more mixed, with some conditions resulting in high ranks and others resulting in lower ranks.

In addition, the results of TOPSIS are consistent with the literature review, which suggests that the addition of nano-silica to the asphalt binder can improve its high temperature performance while not compromising its resistance to fatigue cracking. This supports the overall conclusion of the study that the ASA/Si 3% composite is the optimum performing asphalt binder based on the experimental outcomes and literature review.

CHAPTER VI
Conclusion and Recommendations

6.1 Conclusion

The optimal asphalt binder can be determined based on the outcomes of trials using Multi-Criteria Decision Analysis (MCDA), which is a useful method.

The best performing asphalt binder was chosen using rotating viscosity testing and frequency sweep testing based on the findings of the studies. The findings of the rotating viscosity test show that asphalt mixtures with lower viscosities use less energy to produce and construct. Additionally, the outcomes of the frequency sweep tests and the master curves demonstrated that the best outcomes in high temperature conditions were achieved when ASA polymer and nanosilica were combined. The modification technique resulted in the changed asphalt binder samples having greater stiffness and decreased flexibility. As a result of phase separation or agglomeration of the polymer and the asphalt matrix, the samples manufactured with an ASA 5% concentration were discovered to be the worst-performing asphalt binders. The optimum asphalt binder was ultimately determined with the help of the testing findings' multi-criteria decision analysis, which considered rotational viscosity, penetration, softening point, rutting, and fatigue resistance variables.

The PROMETHEE multi-criteria decision analysis method was used to rank and assess several asphalt binders according to their benefits and drawbacks. The approach depends on a pairwise comparison of the options, where the user gives the most desired alternative (Phi+) a preference index and the least preferred alternative (Phi-) a dispreference index. The dispreference index is subtracted from the preference index to arrive at the final index (Phi). The choices are then ranked according to their Phi values, starting with the option with the greatest value. As a result of having the highest preference indices and the lowest dispreference indices, ASA 5% has the highest Phi values and the highest ranks, according to the PROMETHEE analysis results. Based on the findings of the PROMETHEE investigation, ASA 5% is the asphalt binder that performs the best. It's crucial to note that this assessment is based on the precise test conditions and specifications of the study, and the outcomes may differ depending on the particular project or application.

Using the Multi Criteria Decision Analysis approach and TOPSIS, the performance of several asphalt binders at various temperatures was evaluated and ranked. An ideal material, or the material that performs the best, is what the comparison is made on in terms of similarity between the various materials. The results in Table 3 show that ASA/Si 3% exhibits the highest performance across all temperatures. This substance has the highest similarity index (SI+) and is most aligned to the ideal solution (CI). The finding that the rank of the materials changes with temperature offers more proof that the best performing material may vary depending on the particular temperature conditions of the project. Overall, it appears that the most effective asphalt binder depends on the specific project requirements and the balance of the various aspects.

Promethee and TOPSIS assess and compare the options in different ways, which is why there is a difference in how the two results are ranked. The difference between the positive and negative outflows is the basis for Promethee's ranking of the options. A high outflow in the positive direction indicates a strong preference for an option, whereas a large outflow in the negative direction indicates a significant dispreference. The ranking of the options is determined by the preference index (Phi), which is derived as the difference between the positive outflow (Phi+) and negative outflow (Phi-).

According to TOPSIS, the ranking of the alternatives is determined by how close each one is to the ideal and anti-ideal solutions. The best outcome for the criteria taken into account can be represented by the ideal solution, whilst the worst outcome can be represented by the anti-ideal solution. The normalized positive attribute values (SI+) and the normalized negative attribute values (SI-) are used to construct the separation measure (CI), and the closer the separation measure is to 1, the better the alternative is thought to be, although both methods use different algorithms to evaluate and compare the alternatives, they both aim to provide a comprehensive and objective evaluation of the alternatives based on the criteria considered. The results of the two methods may differ depending on the data and criteria used, but both methods can provide valuable information and support for multi-criteria decision-making.

6.2 Recommendations

The following suggestions can be made for choosing the best performing asphalt binder based on the findings of the rotating viscosity, frequency sweep, and rutting, fatigue resistance tests, PROMETHEE, and TOPSIS

- Lower rotational viscosity is favorable for reducing energy costs in production and construction of asphalt mixes.
- Incorporation of nanosilica and ASA polymer together yielded the best performance at high temperature environment conditions, as observed from the complex modulus results.
- Control sample was the optimum option against resistance to fatigue cracking, as deduced from the phase angle results.
- The worst performing asphalt binder was observed to be for the asphalt samples prepared by Base AC concentration which possibly resulted because of the occurrence of phase separation or the agglomeration of the polymer and due to variations in density and the solubility of the polymer particles in the asphalt matrix.
- The materials with the highest Phi values are ASA 5% at different temperatures, which indicates that these materials have the highest preference indices and the lowest dispreference indices in PROMETHEE.
- The rank of the materials can vary depending on the temperature range considered, but ASA 5% consistently ranks first.
- The final ranking of the materials should be considered in relation to the specific application and the temperature range that the asphalt binder will be exposed to.

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APPENDICES

Appendix A Experimental Test Results

Model 1: Which material is the best when we consider the performance of the materials one at low temperature (10 oC) and one at high temperature (45 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 10 oC					When temperature is 45 oC				When temperature is 10 oC					When temperature is 45 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
10-45	Base AC (10 oC - 45 oC)	7,038,000	8,327,000	15,250,000	23,290,000	29,420,000	31,870	74,470	138,700	194,700	62.8	61.1	55.12	51.27	48.73	82.95	80.84	77.74	75.68	22112355	26033	0.5	0.13	Low
	ASA 3% (10 oC - 45 oC)	6,453,000	7,570,000	12,970,000	18,500,000	23,310,000	111,800	248,900	443,300	617,600	55.08	53.85	47.94	44.63	42.41	77.15	73.28	69	67.92	17744287	61733	0.58	0.15	Moderate
	ASA 5% (10 oC - 45 oC)	11,230,000	12,980,000	21,240,000	29,460,000	36,530,000	131,000	278,200	473,900	645,800	51.11	49.6	43.54	40.89	38.8	72.82	72.88	72.44	68.65	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (10 oC - 45 oC)	8,724,710	13,146,982	19,473,437	29,882,155	40,087,817	393,998	577,118	855,118	1,049,998	56.45	54.86	48.82	45.56	43.24	77.74	73.65	72.02	69.80	21333843	303808	0.64	0.21	High
	ASA/Si 5% (10 oC - 45 oC)	18,813,000	21,638,500	38,775,000	51,886,837	55,758,147	380,000	530,000	835,000	1,205,000	54.14	52.28	46.35	43.28	40.98	82.57	79.16	77.53	73.57	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 2: Which material is the best when we consider the performance of the materials one at low temperature (10 oC) and one at high temperature (55 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 10 oC					When temperature is 55 oC				When temperature is 10 oC					When temperature is 55 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
10-55	Base AC (10 oC - 55 oC)	7,038,000	8,327,000	15,250,000	23,290,000	29,420,000	7,339	17,990	34,670	50,910	62.8	61.1	55.12	51.27	48.73	86.79	85.24	83.69	82.69	22112355	26033	0.5	0.13	Low
	ASA 3% (10 oC - 55 oC)	6,453,000	7,570,000	12,970,000	18,500,000	23,310,000	20,300	42,380	80,980	117,800	55.08	53.85	47.94	44.63	42.41	83.37	80.88	78.62	77.28	17744287	61733	0.58	0.15	Moderate
	ASA 5% (10 oC - 55 oC)	11,230,000	12,980,000	21,240,000	29,460,000	36,530,000	28,980	65,510	115,400	161,000	51.11	49.6	43.54	40.89	38.8	80.91	77.65	74.67	72.73	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (10 oC - 55 oC)	8,724,710	13,146,982	19,473,437	29,882,155	40,087,817	96,598	154,894	277,954	390,178	56.45	54.86	48.82	45.56	43.24	84.79	82.13	79.57	77.96	21333843	303808	0.64	0.21	High
	ASA/Si 5% (10 oC - 55 oC)	18,813,000	21,638,500	38,775,000	51,886,837	55,758,147	133,125	204,375	326,250	480,000	54.14	52.28	46.35	43.28	40.98	84.08	80.87	77.53	75.44	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 3: Which material is the best when we consider the performance of the materials one at low temperature (10 oC) and one at high temperature (65 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 10 oC					When temperature is 65 oC				When temperature is 10 oC					When temperature is 65 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
10-65	Base AC (10 oC - 65 oC)	7,038,000	8,327,000	15,250,000	23,290,000	29,420,000	1,825	4,523	8,531	12,690	62.8	61.1	55.12	51.27	48.73	88.22	86.82	85.97	85.24	22112355	26033	0.5	0.13	Low
	ASA 3% (10 oC - 65 oC)	6,453,000	7,570,000	12,970,000	18,500,000	23,310,000	4,530	11,030	20,790	31,020	55.08	53.85	47.94	44.63	42.41	85.83	85.02	83.54	82.41	17744287	61733	0.58	0.15	Moderate
	ASA 5% (10 oC - 65 oC)	11,230,000	12,980,000	21,240,000	29,460,000	36,530,000	7,124	18,470	34,070	48,410	51.11	49.6	43.54	40.89	38.8	85.3	83.26	80.87	79.59	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (10 oC - 65 oC)	8,724,710	13,146,982	19,473,437	29,882,155	40,087,817	31,498	46,198	83,998	125,998	56.45	54.86	48.82	45.56	43.24	88.00	86.58	84.73	83.61	21333843	303808	0.64	0.21	High
	ASA/Si 5% (10 oC - 65 oC)	18,813,000	21,638,500	38,775,000	51,886,837	55,758,147	58,455	88,965	167,500	265,000	54.14	52.28	46.35	43.28	40.98	88.49	87.13	84.51	83.24	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 4: Which material is the best when we consider the performance of the materials one at low temperature (10 oC) and one at high temperature (75 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 10 oC					When temperature is 75 oC				When temperature is 10 oC					When temperature is 75 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
10-75	Base AC (10 oC - 75 oC)	7,038,000	8,327,000	15,250,000	23,290,000	29,420,000	697	1,339	2,785	4,143	62.8	61.1	55.12	51.27	48.73	88.96	86.49	88.96	86.49	22112355	26033	0.5	0.13	Low
	ASA 3% (10 oC - 75 oC)	6,453,000	7,570,000	12,970,000	18,500,000	23,310,000	1,313	2,998	5,865	9,146	55.08	53.85	47.94	44.63	42.41	88.12	87.42	86.45	86.12	17744287	61733	0.58	0.15	Moderate
	ASA 5% (10 oC - 75 oC)	11,230,000	12,980,000	21,240,000	29,460,000	36,530,000	1,896	5,181	10,210	14,860	51.11	49.6	43.54	40.89	38.8	85.71	85.2	85.08	83.83	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (10 oC - 75 oC)	8,724,710	13,146,982	19,473,437	29,882,155	40,087,817	8,818	15,118	29,398	46,198	56.45	54.86	48.82	45.56	43.24	86.27	85.99	85.30	84.76	21333843	303808	0.64	0.21	High
	ASA/Si 5% (10 oC - 75 oC)	18,813,000	21,638,500	38,775,000	51,886,837	55,758,147	16,250	31,000	52,500	90,500	54.14	52.28	46.35	43.28	40.98	86.44	88.20	82.61	81.55	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 5: Which material is the best when we consider the performance of the materials one at low temperature (15 oC) and one at high temperature (45 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 15 oC					When temperature is 45 oC				When temperature is 15 oC					When temperature is 45 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
15-45	Base AC (15 oC - 45 oC)	2,825,000	3,361,000	6,670,000	10,640,000	13,900,000	31,870	74,470	138,700	194,700	69.04	67.93	62.92	59.15	56.77	82.95	80.84	77.74	75.68	22112355	26033	0.5	0.13	Low
	ASA 3% (15 oC - 45 oC)	2,946,000	3,545,000	6,457,000	9,660,000	12,620,000	111,800	248,900	443,300	617,600	61.81	60.04	54.69	51.3	49.29	77.15	73.28	69	67.92	17744287	61733	0.58	0.15	Moderate
	ASA 5% (15 oC - 45 oC)	5,414,000	6,241,000	10,910,000	15,860,000	20,290,000	131,000	278,200	473,900	645,800	57.86	55.98	50.4	47.37	45.45	72.82	72.88	72.44	68.65	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (15 oC - 45 oC)	3,807,014	6,584,821	11,363,755	16,538,809	22,197,397	393,998	577,118	855,118	1,049,998	63.00	61.48	55.86	52.41	50.33	77.74	73.65	72.02	69.80	21333843	303808	0.64	0.21	High
	ASA/Si 5% (15 oC - 45 oC)	8,433,008	11,099,149	19,912,925	29,643,080	38,816,661	380,000	530,000	835,000	1,205,000	60.30	59.04	52.77	49.33	47.43	82.57	79.16	77.53	73.57	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 6: Which material is the best when we consider the performance of the materials one at low temperature (15 oC) and one at high temperature (55 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 15 oC					When temperature is 55 oC				When temperature is 15 oC					When temperature is 55 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
15-55	Base AC (15 oC - 55 oC)	2,825,000	3,361,000	6,670,000	10,640,000	13,900,000	7,339	17,990	34,670	50,910	69.04	67.93	62.92	59.15	56.77	86.79	85.24	83.69	82.69	22112355	26033	0.5	0.13	Low
	ASA 3% (15 oC - 55 oC)	2,946,000	3,545,000	6,457,000	9,660,000	12,620,000	20,300	42,380	80,980	117,800	61.81	60.04	54.69	51.3	49.29	83.37	80.88	78.62	77.28	17744287	61733	0.58	0.15	Moderate
	ASA 5% (15 oC - 55 oC)	5,414,000	6,241,000	10,910,000	15,860,000	20,290,000	28,980	65,510	115,400	161,000	57.86	55.98	50.4	47.37	45.45	80.91	77.65	74.67	72.73	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (15 oC - 55 oC)	3,807,014	6,584,821	11,363,755	16,538,809	22,197,397	96,598	154,894	277,954	390,178	63.00	61.48	55.86	52.41	50.33	84.79	82.13	79.57	77.96	21333843	303808	0.64	0.21	High
	ASA/Si 5% (15 oC - 55 oC)	8,433,008	11,099,149	19,912,925	29,643,080	38,816,661	133,125	204,375	326,250	480,000	60.30	59.04	52.77	49.33	47.43	84.08	80.87	77.53	75.44	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 7: Which material is the best when we consider the performance of the materials one at low temperature (15 oC) and one at high temperature (65 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 15 oC					When temperature is 65 oC				When temperature is 15 oC					When temperature is 65 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
15-65	Base AC (15 oC - 65 oC)	2,825,000	3,361,000	6,670,000	10,640,000	13,900,000	1,825	4,523	8,531	12,690	69.04	67.93	62.92	59.15	56.77	88.22	86.82	85.97	85.24	22112355	26033	0.5	0.13	Low
	ASA 3% (15 oC - 65 oC)	2,946,000	3,545,000	6,457,000	9,660,000	12,620,000	4,530	11,030	20,790	31,020	61.81	60.04	54.69	51.3	49.29	85.83	85.02	83.54	82.41	17744287	61733	0.58	0.15	Moderate
	ASA 5% (15 oC - 65 oC)	5,414,000	6,241,000	10,910,000	15,860,000	20,290,000	7,124	18,470	34,070	48,410	57.86	55.98	50.4	47.37	45.45	85.3	83.26	80.87	79.59	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (15 oC - 65 oC)	3,807,014	6,584,821	11,363,755	16,538,809	22,197,397	31,498	46,198	83,998	125,998	63.00	61.48	55.86	52.41	50.33	88.00	86.58	84.73	83.61	21333843	303808	0.64	0.21	High
	ASA/Si 5% (15 oC - 65 oC)	8,433,008	11,099,149	19,912,925	29,643,080	38,816,661	58,455	88,965	167,500	265,000	60.30	59.04	52.77	49.33	47.43	88.49	87.13	84.51	83.24	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 8: Which material is the best when we consider the performance of the materials one at low temperature (15 oC) and one at high temperature (75 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 15 oC					When temperature is 75 oC				When temperature is 15 oC					When temperature is 75 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
15-75	Base AC (15 oC - 75 oC)	2,825,000	3,361,000	6,670,000	10,640,000	13,900,000	697	1,339	2,785	4,143	69.04	67.93	62.92	59.15	56.77	88.96	86.49	88.96	86.49	22112355	26033	0.5	0.13	Low
	ASA 3% (15 oC - 75 oC)	2,946,000	3,545,000	6,457,000	9,660,000	12,620,000	1,313	2,998	5,865	9,146	61.81	60.04	54.69	51.3	49.29	88.12	87.42	86.45	86.12	17744287	61733	0.58	0.15	Moderate
	ASA 5% (15 oC - 75 oC)	5,414,000	6,241,000	10,910,000	15,860,000	20,290,000	1,896	5,181	10,210	14,860	57.86	55.98	50.4	47.37	45.45	85.71	85.2	85.08	83.83	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (15 oC - 75 oC)	3,807,014	6,584,821	11,363,755	16,538,809	22,197,397	8,818	15,118	29,398	46,198	63.00	61.48	55.86	52.41	50.33	86.27	85.99	85.30	84.76	21333843	303808	0.64	0.21	High
	ASA/Si 5% (15 oC - 75 oC)	8,433,008	11,099,149	19,912,925	29,643,080	38,816,661	16,250	31,000	52,500	90,500	60.30	59.04	52.77	49.33	47.43	86.44	88.20	82.61	81.55	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 9: Which material is the best when we consider the performance of the materials one at low temperature (25 oC) and one at high temperature 45 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (Θ))	Rutting parameter (G/sin (Θ))	RV		Economy
		When temperature is 25 oC					When temperature is 45 oC				When temperature is 25 oC					When temperature is 45 oC								
		Complex modulus at different frequencies									Phase angle at different frequencies											Temperature		
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (Θ)	0.2 (Θ)	0.5 (Θ)	1 (Θ)	1.592 (Θ)	2 (Θ)	5 (Θ)	10 (Θ)	15 (Θ)			135 oC	165 oC	
25-45	Base AC (25 oC - 45 oC)	255,800	322,800	787,900	1,365,000	1,893,000	31,870	74,470	138,700	194,700	80.23	80.74	74.96	71.38	70.96	82.95	80.84	77.74	75.68	22112355	26033	0.5	0.13	Low
	ASA 3% (25 oC - 45 oC)	369,100	474,800	1,047,000	1,713,000	2,418,000	111,800	248,900	443,300	617,600	75.29	74.16	68.15	64.08	62.78	77.15	73.28	69	67.92	17744287	61733	0.58	0.15	Moderate
	ASA 5% (25 oC - 45 oC)	730,800	930,400	1,910,000	3,007,000	4,136,000	131,000	278,200	473,900	645,800	70.76	69.26	63.79	60.34	59.36	72.82	72.88	72.44	68.65	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (25 oC - 45 oC)	1,236,453	1,483,744	2,378,542	3,490,922	5,586,383	393,998	577,118	855,118	1,049,998	77.32	75.95	69.54	65.31	64.60	77.74	73.65	72.02	69.80	21333843	303808	0.64	0.21	High
	ASA/Si 5% (25 oC - 45 oC)	1,258,086	2,006,606	3,444,436	5,386,456	7,893,778	380,000	530,000	835,000	1,205,000	79.33	76.02	67.95	62.33	62.23	82.57	79.16	77.53	73.57	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 10: Which material is the best when we consider the performance of the materials one at low temperature (25 oC) and one at high temperature (55 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 25 oC					When temperature is 55 oC				When temperature is 25 oC					When temperature is 55 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
25-55	Base AC (25 oC - 55 oC)	255,800	322,800	787,900	1,365,000	1,893,000	7,339	17,990	34,670	50,910	80.23	80.74	74.96	71.38	70.96	86.79	85.24	83.69	82.69	22112355	26033	0.5	0.13	Low
	ASA 3% (25 oC - 55 oC)	369,100	474,800	1,047,000	1,713,000	2,418,000	20,300	42,380	80,980	117,800	75.29	74.16	68.15	64.08	62.78	83.37	80.88	78.62	77.28	17744287	61733	0.58	0.15	Moderate
	ASA 5% (25 oC - 55 oC)	730,800	930,400	1,910,000	3,007,000	4,136,000	28,980	65,510	115,400	161,000	70.76	69.26	63.79	60.34	59.36	80.91	77.65	74.67	72.73	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (25 oC - 55 oC)	1,236,453	1,483,744	2,378,542	3,490,922	5,586,383	96,598	154,894	277,954	390,178	77.32	75.95	69.54	65.31	64.60	84.79	82.13	79.57	77.96	21333843	303808	0.64	0.21	High
	ASA/Si 5% (25 oC - 55 oC)	1,258,086	2,006,606	3,444,436	5,386,456	7,893,778	133,125	204,375	326,250	480,000	79.33	76.02	67.95	62.33	62.23	84.08	80.87	77.53	75.44	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 11: Which material is the best when we consider the performance of the materials one at low temperature (25 oC) and one at high temperature (65 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 25 oC					When temperature is 65 oC				When temperature is 25 oC					When temperature is 65 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
25-65	Base AC (25 oC - 65 oC)	255,800	322,800	787,900	1,365,000	1,893,000	1,825	4,523	8,531	12,690	80.23	80.74	74.96	71.38	70.96	88.22	86.82	85.97	85.24	22112355	26033	0.5	0.13	Low
	ASA 3% (25 oC - 65 oC)	369,100	474,800	1,047,000	1,713,000	2,418,000	4,530	11,030	20,790	31,020	75.29	74.16	68.15	64.08	62.78	85.83	85.02	83.54	82.41	17744287	61733	0.58	0.15	Moderate
	ASA 5% (25 oC - 65 oC)	730,800	930,400	1,910,000	3,007,000	4,136,000	7,124	18,470	34,070	48,410	70.76	69.26	63.79	60.34	59.36	85.3	83.26	80.87	79.59	14631404	113061	0.7	0.19	Moderate
	ASA/Si 3% (25 oC - 65 oC)	1,236,453	1,483,744	2,378,542	3,490,922	5,586,383	31,498	46,198	83,998	125,998	77.32	75.95	69.54	65.31	64.60	88.00	86.58	84.73	83.61	21333843	303808	0.64	0.21	High
	ASA/Si 5% (25 oC - 65 oC)	1,258,086	2,006,606	3,444,436	5,386,456	7,893,778	58,455	88,965	167,500	265,000	79.33	76.02	67.95	62.33	62.23	88.49	87.13	84.51	83.24	25428472	230172	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min

Model 12: Which material is the best when we consider the performance of the materials one at low temperature (25 oC) and one at high temperature (75 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 25 oC					When temperature is 75 oC				When temperature is 25 oC					When temperature is 75 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
25-75	Base AC (25 oC - 75 oC)	255,800	322,800	787,900	1,365,000	1,893,000	697	1,339	2,785	4,143	80.23	80.74	74.96	71.38	70.96	88.96	86.49	88.96	86.49	543	1,789,436	0.5	0.13	Low
	ASA 3% (25 oC - 75 oC)	369,100	474,800	1,047,000	1,713,000	2,418,000	1,313	2,998	5,865	9,146	75.29	74.16	68.15	64.08	62.78	88.12	87.42	86.45	86.12	992	1,523,297	0.58	0.15	Moderate
	ASA 5% (25 oC - 75 oC)	730,800	930,400	1,910,000	3,007,000	4,136,000	1,896	5,181	10,210	14,860	70.76	69.26	63.79	60.34	59.36	85.71	85.2	85.08	83.83	1,639	1,713,616	0.7	0.19	Moderate
	ASA/Si 3% (25 oC - 75 oC)	1,236,453	1,483,744	2,378,542	3,490,922	5,586,383	8,818	15,118	29,398	46,198	77.32	75.95	69.54	65.31	64.60	86.27	85.99	85.30	84.76	5,467	2,204,065	0.64	0.21	High
	ASA/Si 5% (25 oC - 75 oC)	1,258,086	2,006,606	3,444,436	5,386,456	7,893,778	16,250	31,000	52,500	90,500	79.33	76.02	67.95	62.33	62.23	86.44	88.20	82.61	81.55	7,707	3,047,337	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min	Min

Model 13: Which material is the best when we consider the performance of the materials one at low temperature (35 oC) and one at high temperature (45 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 35 oC					When temperature is 45 oC				When temperature is 35 oC					When temperature is 45 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
35-45	Base AC (35 oC - 45 oC)	18,660	38,190	96,640	173,100	218,600	31,870	74,470	138,700	194,700	87.07	85.12	77.28	77.86	76.85	82.95	80.84	77.74	75.68	26,033	207,025	0.5	0.13	Low
	ASA 3% (35 oC - 45 oC)	59,610	80,600	153,700	267,200	359,100	111,800	248,900	443,300	617,600	79.57	78.56	77.37	69.19	71.05	77.15	73.28	69	67.92	61,734	348,509	0.58	0.15	Moderate
	ASA 5% (35 oC - 45 oC)	105,780	145,800	301,800	518,700	721,400	131,000	278,200	473,900	645,800	74.19	73.33	72.14	71.14	68.49	72.82	72.88	72.44	68.65	113,062	493,703	0.7	0.19	Moderate
	ASA/Si 3% (35 oC - 45 oC)	219,749	319,749	448,000	897,400	1,232,000	393,998	577,118	855,118	1,049,998	83.88	83.15	77.12	75.92	74.47	77.74	73.65	72.02	69.80	303,808	676,448	0.64	0.21	High
	ASA/Si 5% (35 oC - 45 oC)	257,137	328,691	562,579	1,044,225	1,523,744	380,000	530,000	835,000	1,205,000	85.48	83.41	78.03	71.87	72.96	82.57	79.16	77.53	73.57	230,173	997,633	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min	Min

Model 14: Which material is the best when we consider the performance of the materials one at low temperature (35 oC) and one at high temperature (55 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 35 oC					When temperature is 55 oC				When temperature is 35 oC					When temperature is 55 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
35-55	Base AC (35 oC - 55 oC)	18,660	38,190	96,640	173,100	218,600	7,339	17,990	34,670	50,910	87.07	85.12	77.28	77.86	76.85	86.79	85.24	83.69	82.69	5,488	207,025	0.5	0.13	Low
	ASA 3% (35 oC - 55 oC)	59,610	80,600	153,700	267,200	359,100	20,300	42,380	80,980	117,800	79.57	78.56	77.37	69.19	71.05	83.37	80.88	78.62	77.28	12,509	348,509	0.58	0.15	Moderate
	ASA 5% (35 oC - 55 oC)	105,780	145,800	301,800	518,700	721,400	28,980	65,510	115,400	161,000	74.19	73.33	72.14	71.14	68.49	80.91	77.65	74.67	72.73	23,625	493,703	0.7	0.19	Moderate
	ASA/Si 3% (35 oC - 55 oC)	219,749	319,749	448,000	897,400	1,232,000	96,598	154,894	277,954	390,178	83.88	83.15	77.12	75.92	74.47	84.79	82.13	79.57	77.96	54,670	676,448	0.64	0.21	High
	ASA/Si 5% (35 oC - 55 oC)	257,137	328,691	562,579	1,044,225	1,523,744	133,125	204,375	326,250	480,000	85.48	83.41	78.03	71.87	72.96	84.08	80.87	77.53	75.44	79,568	997,633	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min	Min

Model 15: Which material is the best when we consider the performance of the materials one at low temperature (35 oC) and one at high temperature (65 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 35 oC					When temperature is 65 oC				When temperature is 35 oC					When temperature is 65 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
35-65	Base AC (35 oC - 65 oC)	18,660	38,190	96,640	173,100	218,600	1,825	4,523	8,531	12,690	87.07	85.12	77.28	77.86	76.85	88.22	86.82	85.97	85.24	1,441	207,025	0.5	0.13	Low
	ASA 3% (35 oC - 65 oC)	59,610	80,600	153,700	267,200	359,100	4,530	11,030	20,790	31,020	79.57	78.56	77.37	69.19	71.05	85.83	85.02	83.54	82.41	3,469	348,509	0.58	0.15	Moderate
	ASA 5% (35 oC - 65 oC)	105,780	145,800	301,800	518,700	721,400	7,124	18,470	34,070	48,410	74.19	73.33	72.14	71.14	68.49	85.3	83.26	80.87	79.59	6,080	493,703	0.7	0.19	Moderate
	ASA/Si 3% (35 oC - 65 oC)	219,749	319,749	448,000	897,400	1,232,000	31,498	46,198	83,998	125,998	83.88	83.15	77.12	75.92	74.47	88.00	86.58	84.73	83.61	16,803	676,448	0.64	0.21	High
	ASA/Si 5% (35 oC - 65 oC)	257,137	328,691	562,579	1,044,225	1,523,744	58,455	88,965	167,500	265,000	85.48	83.41	78.03	71.87	72.96	88.49	87.13	84.51	83.24	30,011	997,633	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min	Min

Model 16: Which material is the best when we consider the performance of the materials one at low temperature (35 oC) and one at high temperature (75 oC)

Temperature	Materials	Anticipated frequency																		Fatigue parameter (G*sin (θ))	Rutting parameter (G/sin (θ))	RV		Economy
		When temperature is 35 oC					When temperature is 75 oC				When temperature is 35 oC					When temperature is 75 oC						Temperature		
		Complex modulus at different frequencies									Phase angle at different frequencies													
		0.159 (G*)	0.2 (G*)	0.5 (G*)	1 (G*)	1.592 (G*)	2 (G*)	5 (G*)	10 (G*)	15 (G*)	0.159 (θ)	0.2 (θ)	0.5 (θ)	1 (θ)	1.592 (θ)	2 (θ)	5 (θ)	10 (θ)	15 (θ)			135 oC	165 oC	
35-75	Base AC (35 oC - 75 oC)	18,660	38,190	96,640	173,100	218,600	697	1,339	2,785	4,143	87.07	85.12	77.28	77.86	76.85	88.96	86.49	88.96	86.49	543	207,025	0.5	0.13	Low
	ASA 3% (35 oC - 75 oC)	59,610	80,600	153,700	267,200	359,100	1,313	2,998	5,865	9,146	79.57	78.56	77.37	69.19	71.05	88.12	87.42	86.45	86.12	992	348,509	0.58	0.15	Moderate
	ASA 5% (35 oC - 75 oC)	105,780	145,800	301,800	518,700	721,400	1,896	5,181	10,210	14,860	74.19	73.33	72.14	71.14	68.49	85.71	85.2	85.08	83.83	1,639	493,703	0.7	0.19	Moderate
	ASA/Si 3% (35 oC - 75 oC)	219,749	319,749	448,000	897,400	1,232,000	8,818	15,118	29,398	46,198	83.88	83.15	77.12	75.92	74.47	86.27	85.99	85.30	84.76	5,467	676,448	0.64	0.21	High
	ASA/Si 5% (35 oC - 75 oC)	257,137	328,691	562,579	1,044,225	1,523,744	16,250	31,000	52,500	90,500	85.48	83.41	78.03	71.87	72.96	86.44	88.20	82.61	81.55	7,707	997,633	0.73	0.24	High
	Min/Max	Min	Min	Min	Min	Min	Max	Max	Max	Max	Min	Min	Min	Min	Min	Min	Min	Min	Min	Max	Min	Min	Min	Min

Appendix B Ethics Certificate

NEAR EAST UNIVERSITY

SCIENTIFIC RESEARCH ETHICS COMMITTEE

30.11.2022

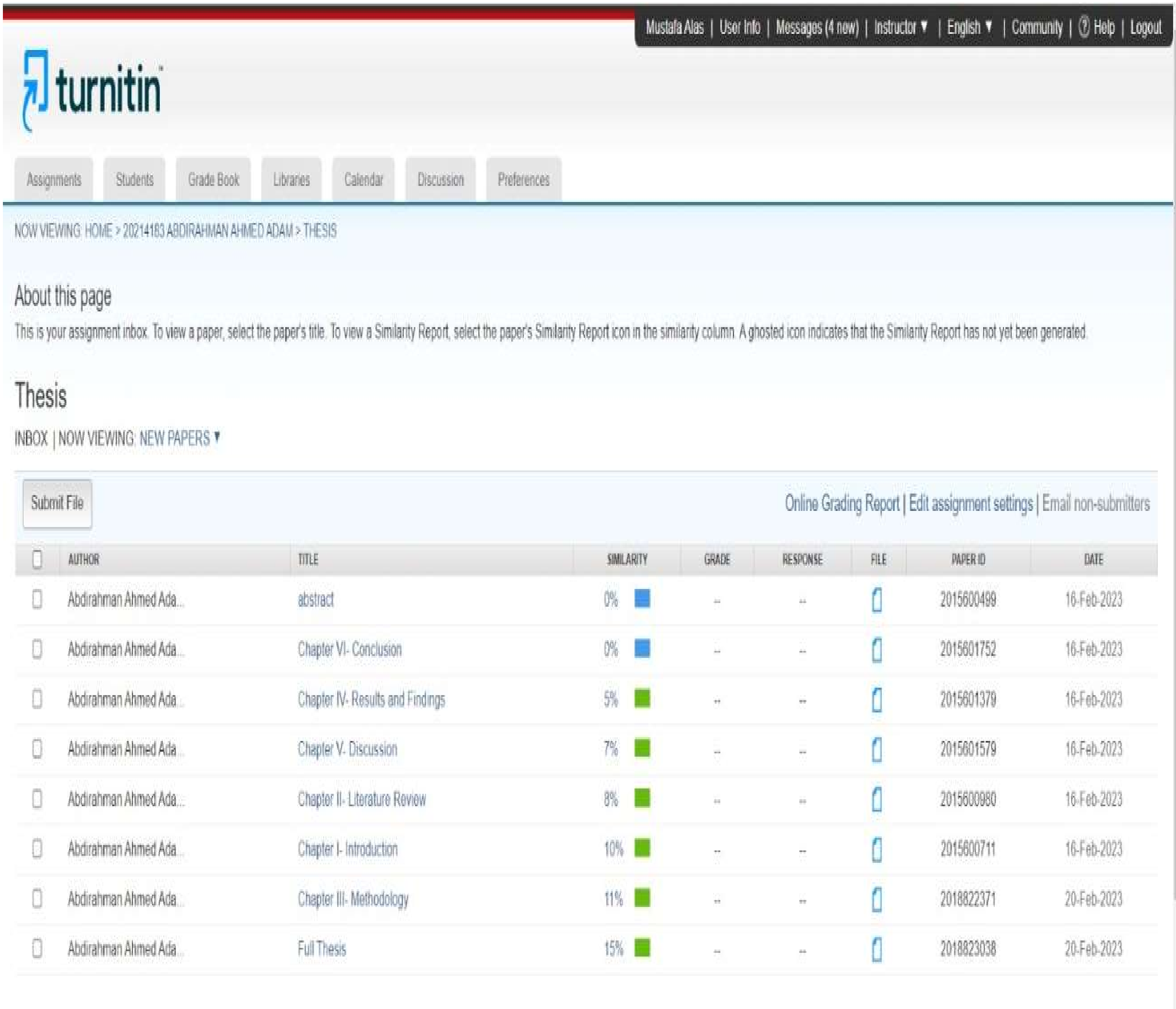
Dear Abdirahman Ahmed Adam

Your project **"Modelling the optimum performing Asphalt Binder by using Fuzzy Promethee and Analytical Hierarchy Process "** has been evaluated. Since only secondary data will be used the project does not need to go through the ethics committee. You can start your research on the condition that you will use only secondary data.

Prof. Dr. Aşkın KİRAZ

The Coordinator of the Scientific Research Ethics Committee

Appendix C Turnitin Similarity Report



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