Developing a Master Curve (E*) Database for Asphalt Mixtures Containing Various percentages of Recycled Asphalt

University of Agder, Master's thesis

(BYG508)

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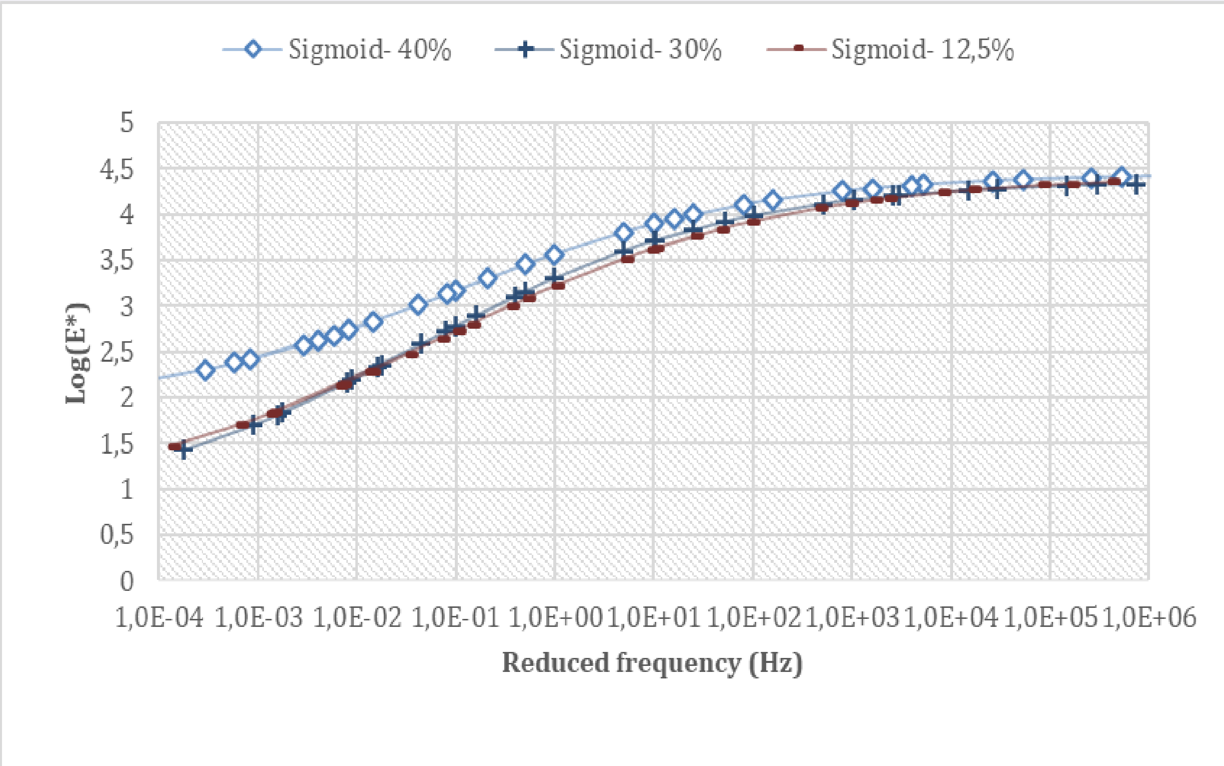

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Preface:

This Master's project was completed at the Engineering Science Department within the Building Design program at the University of Agder. The Master project is the final task for BYG508 course and was completed in the fourth and last semester.

I want to thank my supervisor at the University of Agder, Dr. Ephrem Taddese, and Senior Engineer and Safety Delegate Rita Sølvi Ditlefsen, for their commitment, direction, and valuable input. I would also like to thank NCC for supporting me by providing the coarse and fine aggregates.

The goal of this Master's project is to determine the obstacles and difficulties related to using recycled asphalt in asphalt mixtures, and to investigate potential uses for enhancing its use by creating a Master Curve (E*) Database for Asphalt Mixtures AC11 with varying percentages of recycled asphalt (12.5%, 30%, and 40%).

Abstract

This thesis investigates how the mechanical properties of asphalt mixtures change when different amounts of recycled asphalt are added and Dynamic modulus testing value is used to study the effects of adding various quantities of recycled asphalt. The dynamic modulus (E*) is an important parameter that describes how asphalt mixtures respond to different temperatures and loading frequencies, essential for evaluating pavement performance. The research involved thorough lab testing at the University of Agder using a Universal Testing Machine on asphalt mixture AC11, analyzing levels of RA content at 12.4%, 30%, and 40%. The testing protocol followed the standards outlined in AASHTO T 378-17(2021), ensuring consistency and reliability in the measurements.

By applying the principle of time-temperature superposition, master curves for dynamic modulus were created using sigmoidal modeling. The created master curves show how the material changes as time passes, offering a single equation for E* values in different temperature and frequency ranges.

The study found important connections between dynamic modulus, temperature, and frequency, showing that materials become less rigid at higher temperatures and more pliable at higher frequencies. Analysis comparing dynamic modulus values at varying RA contents revealed greater stiffness and durability at higher RA levels. Significantly, asphalt mixtures with 40% RA showed increased stiffness, suggesting improved performance and sustainability.

Analysis of the shift factor revealed different rheological properties depending on the amount of RA in the specimens, with 40% RA samples showing increased stiffness and resistance to deformation at lower temperatures. Nevertheless, under high temperatures, these samples showed a higher vulnerability to rutting, highlighting the importance of a well-rounded strategy when incorporating RA.

The research highlights the significance of taking into account RA content in asphalt mixes in order to enhance performance and sustainability in road building. Overall, this study adds to the creation of a thorough Master Curve (E*) database for asphalt mixtures containing recycled asphalt, providing important knowledge for pavement engineering.

Further research is needed to study how various types of aggregate and aging periods affect the performance of asphalt mixtures in order to establish reliable design standards for sustainable pavement solutions.

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LIST OF ABBREVIATIONS:

AADT	Annual average daily traffic
AC	Asphalt concrete
α(T)	Shift factor
C1 and C2	Model parameter in William-Landel-Ferry equation
δ, α, β and γ	Model parameter in standard logistic sigmoidal model
ε	Strain
E*	Complex modulus
|E*|	Dynamic modulus
fr	Reduced frequency
G*	loss modulus
HMA	Hot mix asphalt
LVDT	Linear variable differential transformers
ME	Mechanistic-empirical
NCC	Nordic construction company
Pen25°C	Penetration at 25 °C
R	Radius
Rap	Reclaimed Asphalt Pavement
RA	Recycle Asphalt
σ	Sinusoidal Stress
σ0	Stress amplitude
σ(t)	Stress at a certain time
t	Time
T	Temperature
Tr	Reference temperature
tr	Reduced time of loading at reference temperature
UiA	University of Agder
UTM	Universal testing machine
WLF	William-Landel-Ferry
δ	Minimum value of E*
δ + α	Maximum value of E*
ΔEa	The apparent activation energy (J/mol)
ε0	Peak (maximum) strain
ϕ	Phase angle, degrees
ω	Angular velocity

1. Introduction

Global economic growth has led to significant infrastructure development worldwide, particularly in road engineering. During the construction of roads, asphalt and aggregate are commonly used materials. This has resulted in an extraordinary boost in global economic growth. The fact that finite resources are non-renewable suggests moderation to preserve their availability for future uses, even though their depletion is imminent with extensive usage. Additionally, the construction of asphalt pavements requires a significant amount of energy and high emissions during construction in order to comply with current environmental protection regulations. It may therefore be possible to resolve these problems by recycling asphalt mixtures, which are a potential solution to these problems [1].

The use of recycled asphalt pavements (RAP) and asphalt shingles (RAS) to create asphalt mixtures reduces costs, waste, and the need for new materials. As a result of uncertainty regarding the impact of recycled material on composition, authorities set limits on the amount of recycled material (known as RAM) that can be used to ensure the quality and long-term performance of these mixtures [2]. As a result of its environmental benefits, increasing the RAM content has become increasingly popular. It is critical to ensure that recycled binder is readily available when designing RAM content mixtures as it is an integral component of the mixture [3] [4] [5]. As a result of recycled binder availability (RBA), a percentage of new asphalt may be blended with recycled binder from a source when constructing an asphalt mixture.

A majority of asphalt pavements removed during highway rehabilitation or reconstruction are recycled back into hot mix asphalt (HMA), but only about 20% of these materials are disposed of using normal waste stream channels in the United States [6]. Even though these materials have undesirable properties that can be used to create surfacing layers, they still have to be subject to certain constraints set out in the specifications. The hot mix recycling process involves combining RAP material with new aggregate and asphalt binder in a hot mix plant with a recycling agent. Hot mix asphalt combined with RAP is capable of similar or better performance than mixtures made with virgin materials when proper materials evaluation and mix design are used. In spite of recycling being beneficial to reducing virgin material consumption, highway pavement performance should not be compromised in order to reduce costs [7]. HMA pavements with RAP can perform as well as conventional mixtures if properly designed and constructed [8], and RAP has been accepted as a feasible constituent. According to studies conducted in Europe and the United States, more than 80% of the recycled material is used in the construction of roads. However, regulations remain strict regarding the inclusion of RAP in proportions ranging from 5 to 50% when preparing new asphalt mixtures [7].

In studies conducted in the United States, reclaimed asphalt mixtures with up to 30% reclaimed asphalt have shown to be just as effective as conventional mixtures without adversely affecting performance [2] [9].

Asphalt mixtures with more than 25% RAP are classified as high RAP mixtures [10]. As a general rule, RAP should not exceed 50% in asphalt mixtures [11]. Because of the large amount of aged binder found in the RAP material, incorporating a high percentage of RAP can result in a reduction in cracking resistance in asphalt mixtures.

A number of studies indicate that the mechanical properties of mixes are not significantly affected when RAP is incorporated at low levels (up to 15% RAP). According to previous researchers, replacement of RAP at proportions below 50% is viable for producing new HMA mixtures with satisfactory mechanical properties. Furthermore, it is possible to produce new HMA mixtures with RAP replacement at proportions above 50%, which provide satisfactory mechanical performance [7].

It has also been demonstrated in other laboratory studies that asphalt mixtures that contain 100% RA material are capable of delivering satisfactory results [12] [13] [14].

The concept of 100% recycling needs to be further validated by laboratory studies in order to validate the idea that asphalt mixtures can only be produced by using only reclaimed asphalt, bitumen, and rejuvenators to create the asphalt mixture. In most laboratory experiments, reclaimed asphalt (RA) has been modified by modifying its binding properties by introducing either a softer binder, or by adding binder additives, or by introducing rejuvenators. Rejuvenators adjust the properties of RA binder to improve the performance of final mixtures [15].

RAP binder can be partially blended with virgin mineral materials and virgin binder when the hot mix asphalt is mixed. In order to determine the degree of blending between the RAP and the virgin materials, certain portions of the RAP have been limited. The composition and properties of RAP HMA can be improved by properly selecting the weight by percent of all materials and their recycling technology.

Reclaimed Asphalt Pavement (RAP) is a term that is used in the field of recycling asphalt pavement. It refers to the materials that are produced by crushing aged out asphalt pavements that have reached the end of their desired lifespan [16].

The RAP components that make up natural aggregate particles are covered in old bitumen and constitute 93-97% of their weight in aggregate from natural sources, with the remaining 3%-7% consisting of hardened asphalt cement [17].

These materials can be encountered in various forms, including by-products and loose particulate forms that are sometimes utilized in pavement rehabilitation [18].

Recycled asphalt pavement (RAP) has been shown to be an effective method for reducing waste problems in the construction industry. RAP is a valuable substitute for aggregate and supplement for asphalt cement in highway building, providing economic and environmental advantages. RAP can serve several purposes such as being utilized as a coarse base or subbase, stabilized aggregate, landslide material, or fill material to help maintain high-quality pavement infrastructure [19].

RAP is becoming a standard component in asphalt mixtures throughout several nations due to its outstanding benefits. Using RAP has been shown to be effective in reducing building costs, reducing emissions of greenhouse gases, and improving the longevity and durability of constructions, according to a number of studies that have been conducted. Additionally, RAP conserves natural resources and lessens the use of petroleum-based products by utilizing less asphalt and virgin aggregate during road construction operations. The incorporation of recycled asphalt pavement (RAP) into asphalt mixtures led to a reduction of roughly 21.2 million tons of greenhouse gas emissions between the years 2009 and 2019. In addition, nations who have been utilizing RAP have been successful in developing asphalt pavements that are sustainable in terms of both the environment and the economy [20].

FIGURE 1.1: ASPHALT PAVEMENT RECYCLING CIRCLE [21].

Asphalt roads are an important part of our transportation systems because they make it easy for people and things to move around the world. However, understanding the materials used in the construction of these roadways is necessary to achieve design and long-term performance. Asphalt mixtures are one essential component that have a big impact on how the road functions. An instrument known as the dynamic modulus master curve is used by researchers and engineers to comprehend and forecast the behavior of these combinations under various circumstances.

Asphalt roadways are subject to a variety of obstacles, including fluctuations in temperature, heavy traffic burdens, and moisture exposure. In order to deal with these problems successfully, experts have come up with improved ways to test the mechanical features of asphalt mixtures. The dynamic modulus is among the most significantly critical of these properties. This gives information on the material's stiffness, resilience, and damping qualities, as well as describing how the material deforms when it is subjected to repeated loads.

A master curve has been generated by utilizing the data obtained from the modulus test. This graph determines the modulus at various temperatures and frequencies in relation to a particular temperature, for the purpose of comparison.

The dynamic modulus master curve integrates data from tests carried out at various temperatures and loading frequencies to form a complete depiction of dynamic modulus values. This curve is a significant prediction tool for engineers to forecast the performance of asphalt mixes in different situations. It influences choices about pavement construction, maintenance, and restoration, ultimately leading to safer and cost-efficient transportation systems [22].

The modulus of asphalt concrete plays an important role in determining the pavement's performance when the pavement is designed by applying mechanistic empirical principles to ensure that the pavement is designed correctly. It is critical to note that the master curve illustrates how the modulus of the asphalt changes with changes in temperature and load rate, and that a standardized test method, known as AASHTO Provisional Standard TP62-03, was developed to determine this modulus. In accordance with AASHTO TP62-03, it is recommended that two samples be examined at a variety of temperatures (ranging from -10°C to 54.4°C) and at a variety of loading frequencies (25, 10 5 1.0, 0.5, and 0.1 Hz) during the testing process. As soon as this process is completed, 60 modulus measurements are generated as a result. To construct the master curve using optimization techniques, these measurements can then be used to determine the parameters required to produce the master curve [23].

The main goal of this master's thesis is to develop a comprehensive Master Curve (E*) database for asphalt mixes that contain different amounts of Recycled Asphalt Pavement (RAP), with 12.5%, 30% and 40% RAP being the main targets. This study aims to give useful information about the mechanical behavior and performance of sustainable asphalt mixes by systematically characterizing dynamic modulus (E*) properties across a range of temperatures and loading frequencies. The final database will be very useful for improving the planning, building, and upkeep of road infrastructure, which will help the asphalt industry be eco-friendlier and more cost-effective.

2. Societal perspective

2.1. Global Perspectives

Over the years there has been a rising need for energy due to the development of industries, population growth and economic advancements. It is important to note that buildings play a part in this trend as they utilize approximately 40% of the energy and are responsible, for 36% of carbon dioxide emissions. As a result, they contribute to greenhouse gas emissions. Without intervention experts predict that these emissions could double by the year 2030 [24].

The use of RA I pavement despite being costly helps reduce the consumption of petroleum-based products and brings about impacts, on society. The 2018 IPCC report stresses the importance of cutting CO2 emissions by 45% by 2030 compared to the levels in 2010. Additionally, as per the 2019 IPCC reports it is projected that developed nations will have to achieve a 43% reduction in greenhouse gas emissions by 2030. It is crucial that we meet the goals outlined in the Paris Agreement to combat warming and tackle the effects of climate change such, as droughts, heatwaves, and heavy rainfall [25].

2.2. Environmental perspective

Creating a Master Curve Database, for Asphalt Mixes that include Recycled Asphalt is crucial for promoting sustainability. By incorporating materials into asphalt production, we can reduce our reliance on resources aligning with the Sustainable Development Goal 12s focus on responsible consumption and production practices. This project demonstrates a dedication to addressing poverty, inequality and environmental damage as outlined in the United Nations Sustainable Development Agenda. Using recycled materials in asphalt production can greatly benefit the environment by decreasing dependence on resources. Assisting in the preservation of natural resources, decreasing energy usage, and reducing waste production, ultimately supports a more sustainable and circular economy [26, 27].

Additionally, this initiative aims to create job opportunities boost growth and contribute to waste reduction and resource conservation. By advocating for the use of recycled asphalt we not lessen the impact of asphalt production but also help reduce carbon emissions supporting SDG 13s goal of combating climate change. Moreover, by reducing the need to extract and transport materials over distances this effort helps greenhouse gas emissions [28].

It can also minimize the impact of road construction on ecosystems by recycling and reusing asphalt, which reduces the need for landfills. As a result of these combined efforts, we will be able to promote an infrastructure that emphasizes environmental responsibility and economic development. In order to reduce the environmental impact of extraction and processing, it is beneficial to use recycled asphalt rather than new raw materials. The use of recycled asphalt mixes can also help conserve natural resources and reduce energy consumption.

Further, recycled asphalt makes pavements perform better, so they don't need to be repaired and maintained as often. In addition to saving money, it helps keep road infrastructure sustainable. Incorporated recycled materials in asphalt mixes can also lead to new technologies and processes, helping to advance sustainable construction.

2.3. Social Impact and economic perspectives:

Besides the environmental impact, the project has had a lot of other impacts on society. In the course of the project, the primary objective is to enhance infrastructure quality and longevity. It is in direct line with Sustainable Development Goals 9 (Industry, Innovation, and Infrastructure) as well as Sustainable Development Goal 11 (Sustainable Cities and Communities) [29] [30].

The development of advanced asphalt mixtures incorporating recycled materials is an integral part of this effort. In addition to their enhanced durability, these innovative mixtures can also provide a longer lifetime, which is a key component of this effort. As a result, they significantly reduce the costs associated with road maintenance as well as lengthen the lifespan of roads at the same time, which proves advantageous to both the environment and the economy in the long run.

Furthermore, by integrating recycled materials into the construction process, we are able to contribute to reducing the amount of waste that goes to landfills by a significant amount. Furthermore, this project also contributes directly to Sustainable Development Goal 3 (Good Health and Well-Being) by reusing the waste materials generated: from road construction, contributing directly to the reduction of pollution caused by the accumulation of waste [31] [32].

Aside from infrastructure improvements, the project's efforts have far-reaching effects. It not only keeps roads in good shape, but also enhances the quality of life in the communities they serve by ensuring their longevity. By fostering resilient infrastructure and simultaneously addressing social and environmental needs, the project serves as a tangible example of sustainable development principles.

2.4. Safety and Health Considerations:

Additionally, it is imperative to ensure that both employees and the local community are well cared for and protected. In order to maintain a comprehensive Health, Safety, and Environment (HSE) program, it is necessary to adhere to health, safety, and environmental regulations. The development of high-quality asphalt mixes, along with the proper handling and utilization of recycled materials, can create a safe working environment. This project is aligned with Sustainable Development Goal 8 (Decent Work and Economic Growth) because of the opportunity it creates for employment and the provision of a secure working environment. In addition to providing employees with a safe and comfortable work environment, the project aims to protect the environment and ensure the well-being of all its employees. In addition, the project will provide employment opportunities for locals, which is an integral part of Sustainable Development Goal 8 [33].

This project aims at ensuring an environmentally conscious work environment for employees while at the same time minimizing the impact of the project on the environment. It is also worth noting that in its construction procedures, the project emphasizes the integration of cutting edge, environmentally friendly materials such as recycled asphalt. This paper emphasizes the need to convert construction materials into sustainable ones. As a result of this focus on sustainability, which focuses on recycling processes' energy efficiency, this goal aligns well with Sustainable Development Goal 7 (Affordable and Clean Energy). The fact that this technology can mine aggregates and process them to produce asphalt enables it to contribute greatly to meeting Sustainable Development Goal 15 (Life on Land) [34], due to the extent to which it is used.

2.5. Asphalt recycling: Concerns, about the environment and economy:

For sustainable development to last for many years to come, we must find a balance between our current economic and social needs and our future environmental demands. In order to make sure that we can satisfy the needs of future generations in terms of the economy, society, and the environment, it is imperative that we are able to meet their expectations. By meeting three fundamental sustainability criteria, the construction industry plays a key role in achieving this sustainable future.

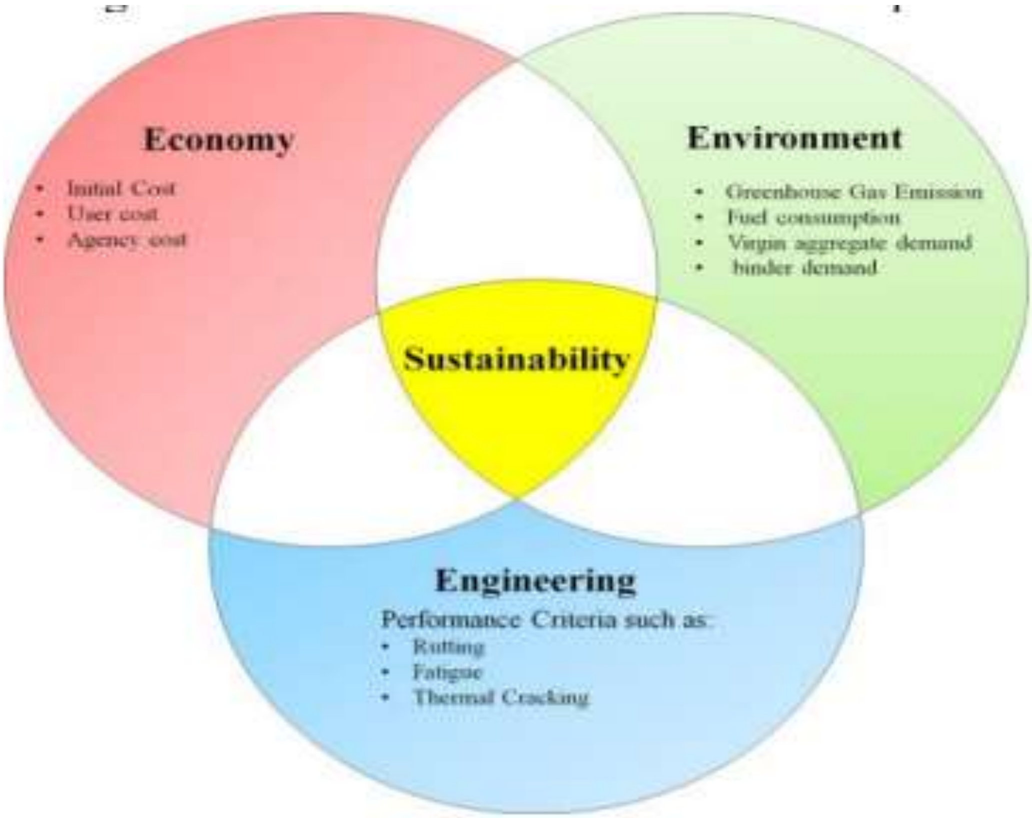

FIGURE 2.1: SUSTAINABILITY OF PAVEMENT MATERIALS[18].

As a result of the collaboration between researchers and industry professionals, goods are being repurposed, repaired, and recycled, thus advancing the circular economy concept. It is possible to reuse and repurpose asphalt waste in industries that generate substantial amounts of waste in an effective manner. The waste can be recycled effectively. It has been widely recognized that asphalt waste is a valuable resource for sustainable development. This is because it helps close the RA cycle loop and contributes to a more sustainable future as a result.

It is possible to greatly reduce the environmental impact of construction projects by using recycled asphalt (RA) while simultaneously reducing construction costs. As a result of this approach, environmentally friendly environments can prioritize resource efficiency in order to produce fewer resources and thus utilize fewer materials. In summary, using recycled asphalt pavements (RAP) as building materials is not only environmentally beneficial and it also saves money. Additionally, RA also reduces the amount of waste sent to landfills, thus reducing the amount of pollution released into the atmosphere [35] [36].

3. Theoretical background:

In today's transportation system asphalt roads play a role because of their durability and cost efficiency. With the growing need, for eco construction materials researchers are exploring the use of recycled materials in asphalt mixtures to find options. Recycled asphalt pavement (RAP) has emerged as an environmentally friendly solution by reusing asphalt pavement in new road construction. This recycling practice does not only help conserve resources by reducing the need for materials but also minimizes the environmental impact of road building through energy savings. By incorporating asphalt pavement materials, we can both preserve resources and reduce our environmental footprint. This discussion aims to delve into the principles, key ideas, and significance of establishing a database for Master Curve (E*), for asphalt mixes containing different percentages of recycled asphalt pavement. Focusing on 12.5%, 30% and 40% RAP levels to assess their source, strength, and durability.

When analyzing asphalt mixtures, including those with recycled asphalt it's essential to create a database known as the Master Curve (E) database. Asphalt engineers have long relied on Master Curves as a method to characterize the viscoelastic properties of asphalt mixtures across various temperatures and loading frequencies. This paper will delve into the foundations necessary for establishing a database to store the characteristics of blends comprising recycled asphalt being mixed with asphalt. The Master Curve (E) serves as the designated database, for this purpose.

3.1. Defining Asphalt Mixtures:

The blend used for asphalt typically comprises three main elements: aggregates, binder and optional additives that may be included. The binder plays a crucial role in enhancing the strength and cohesion of the aggregates, thereby improving their overall durability and stability. Various additives are added to asphalt mixtures to enhance their physical properties, such as resistance to cracking and rutting. By using this type of pavement material, one can ensure it is specifically engineered to provide the necessary durability, strength and flexibility required for different construction projects in our area – including roads, parking lots, airport runways and other surface applications. Asphalt mixtures are commonly manufactured at specialized plants before being transported to construction sites for installation [37].

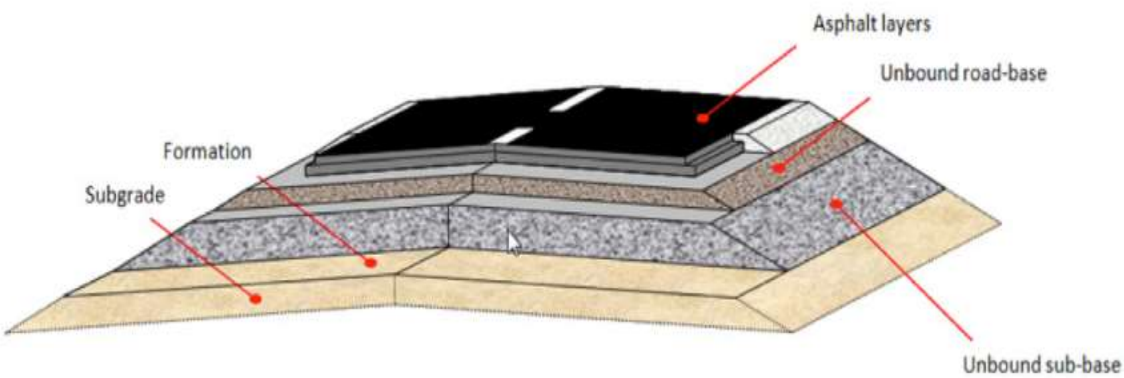

FIGURE 3.1: ASPHALT LAYERS FOR SURFACE PAVEMENT [37].

3.2. Components of Asphalt Mixtures:

In asphalt mixtures, the key components are aggregates, which play a crucial role in providing the load bearing capacity and make up most of the mixture's volume. The proportion of these materials in the mixture by weight is normally 90 to 95 percent, and by volume, 75 to 85 percent [38].

Aggregates: Aggregates are categorized into fine and coarse fractions, with the fine fraction helping reduce water absorption and the coarse fraction contributing to strength and rigidity. It is crucial to have the right balance between these fractions for optimal performance of asphalt [39]. Aggregates can come from various sources, including natural ones like crushed stone, sand, gravel, as well as includes reclaimed asphalt pavement, reclaimed concrete aggregates, and many other recycled products. Choosing and grading aggregates carefully is essential for achieving desired properties like stability, durability, skid resistance and abrasion resistance in asphalt mixtures [40].

Binder: Bitumen or asphalt cement, which acts as a binder in asphalt mixes, is one of the most important components in holding aggregates together. The purpose of these ingredients is to ensure that the mixture is durable and cohesive. The properties of binders can be adjusted by using different grades of binders and additives for different factors such as viscosity, sensitivity to temperature, and resistance to aging. A variety of environmental conditions and traffic volumes must be considered when creating asphalt mixes to get the best performance. The binder is a very important component of asphalt pavement, as it ensures its integrity [41].

To ensure that a pavement lasts for years and can withstand heavy traffic, the right type of binder must be used. Asphalt pavements should also be maintained and repaired regularly to ensure their longevity and function efficiently. Furthermore, binders play a crucial role in increasing the stiffness and strength of asphalt pavements, the resistance to cracks, fatigue, and rutting [42].

Additives: Additives are capable of enhancing the performance of asphalt mixtures. These additives can include polymers, fibers, or even chemicals. They can improve the strength, durability, and waterproofing of asphalt mixtures [43]. In addition, when fibers are added to a mixture, they can make it tougher and reduce cracking. Polymers can increase mixture resistance to cracking, aging, and cracking. The use of antistripping agents is necessary to ensure that the binder and aggregate are adhered effectively to each other in order to prevent moisture-related damage to them. This means it reduces pavement porosity and increases its resistance to water penetration [44] [45].

3.3. Asphalt mixture types:

In this paper, asphalt cement is called hot mix asphalt, but it is also known as asphalt mixtures or conventional mixtures. It is a commonly used binder known as asphalt cement for its versatility. Based on the information provided by the EAPA, hot mix asphalt can be produced in different ways depending on factors like traffic volume or weather conditions to maximize efficiency.

- Hot Mix Asphalt (HMA) the traditional method used in building asphalt roads, is manufactured at a site known as a hot mix plant. It consists of high-quality materials, like top grade aggregates and asphalt cement. The process involves coating the aggregates with asphalt cement to create a mixture. This blend is then heated to temperatures above 150 degrees Celsius to promote adhesion and cohesion. HMA is well known for its construction and lasting quality, making it a favored option for road construction projects. Therefore, it's crucial to produce HMA with precision, at facilities to guarantee the longevity and effectiveness of asphalt roads [46] [47].

- Warm mix asphalt is made at a temperature that is approximately 20 to 40 degrees Celsius cooler than hot mix asphalt. Warm Mix Asphalt (WMA) technologies operate at temperatures exceeding 100 degrees Celsius, leading to reduced water content in the mixture. Various techniques are used to reduce the viscosity of the binder to achieve full coverage and compactness at reduced temperatures. This procedure uses energy, enhances working conditions during paving, and enables an earlier road opening [48] [47].
- Cold mixtures can be produced without the need for preheating the aggregates prior to compaction or mixing. This is made achievable through the utilization of a specialized emulsion that undergoes a breaking process during compaction or mixing. Once the emulsion breaks, it envelops the aggregate, gradually enhancing its strength over time. Cold mixtures are particularly recommended for roads with low traffic volume due to their advantageous properties [47].

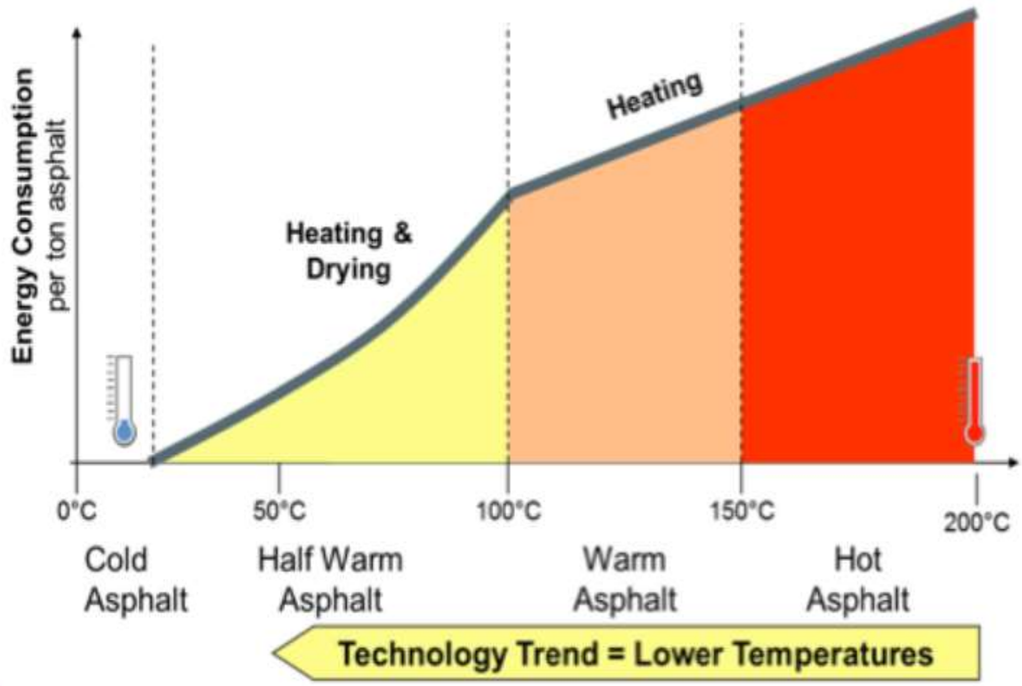

FIGURE 3.2: CLASSIFICATION BY TEMPERATURE RANGE [48].

When asphalt is manufactured at lower temperatures, research has demonstrated that utilizing a mixture of materials at a lower temperature can decrease both emissions and energy consumption in the production process. For asphalt production, three types of mixtures are used: cold mixtures, warm mixtures, and hot mixtures, are utilized for producing asphalt and each possess varying characteristics [49].

Rubio et al.'s recent study highlighted that the manufacturing temperatures of hot mix asphalt products greatly influence their quality and performance [50]. When it comes to cold mix asphalt, it is made at temperatures under 60°C, while half-warm mix asphalt is usually created at temperatures ranging from 70°C to 95°C according to the mix design. At the same time, a warm mix asphalt is created at temperatures ranging from 110°C to 140°C, and a hot mix asphalt is made at temperatures ranging from 150 to 170 °C significantly warmer than cold mix asphalt.

Though cold mix asphalt is not as effective as hot mix asphalt, it is specifically used for repairing damaged pavements used by lighter vehicles. However, both hot mixes and half-hot mixes demonstrate comparable performance to warm mixes.

Different technologies like Aspha-min, Sasobit, and Evoterm are utilized in warm mix asphalt to lower compaction temperature. The expectation is that by using these mixes together, there will be a significant decrease in CO2 and greenhouse gas emissions due to less energy being used during production and compaction compared to hot mixes, leading to a lower output of greenhouse gases [51].

3.3. Recycled Asphalt (RAP) in Asphalt Mixtures:

Using RAP in the construction of a road is an environmentally friendly alternative that reduces the impact on the environment. As a result of the RAP process, ageing asphalt is mixed with fresh asphalt, which produces a road that is more environmentally friendly. RAP is a material made by crushing and processing old asphalt pavement. This reduces waste and lessens the need for new raw materials in making asphalt pavements, resulting in decreased waste production and the demand for fresh raw materials. Because of this approach, the environment is being conserved and the quantity of waste being disposed in landfills is reducing. RAP can decrease construction costs by reducing the necessity of buying extra materials and minimizing waste generation. It is an environmentally friendly choice because it reduces the volume of greenhouse gases released into the air [52] [53].

RAP must be considered in terms of its properties and quality before it can be incorporated into new asphalt mixtures due to its unique characteristics. Using RAP as aggregates and binder in combination with fresh aggregates and binders can create an asphalt mixture that is cost-effective and environmentally friendly. This asphalt mixture can be applied to both hard surfaces and soft surfaces for the purpose of reducing erosion. RAP can be safely incorporated into a new mixture for a variety of reasons, including how old it is, how in good condition it is, and the specifications of the project, but there are several factors that can influence the amount of RAP that can be safely incorporated. RAP must also be evaluated to ensure that the material is in good condition and does not contain hazardous materials that can damage the new mixture. The asphalt mixture must also be mixed properly to ensure that the RAP is evenly distributed, and that the new mixture performs as expected.

RAP can be utilized in the production of asphalt in a variety of ways, by reducing the amount of energy consumed in the process, reducing the amount of greenhouse gases released, and reducing the cost of the project. Asphalt producers, therefore, should be careful in balancing the use of RAP with the characteristics of the pavement that they want it to have in order to meet the desired performance characteristics [54] [55].

3.4. Mechanical Properties of Asphalt Mixtures:

Viscoelastic Behavior: Asphalt mixtures display a viscoelastic nature by combining reversible elastic and irreversible viscous characteristics, which result from the interaction of the bituminous binder and mineral aggregates. This interaction enables asphalt to change shape under pressure and return to its original form when the pressure is no longer applied, while also showing durability against gradual deformation. Understanding viscoelasticity is crucial because it determines the way asphalt pavements react to both traffic loads and environmental factors. This understanding allows engineers to create durable pavements that can withstand daily wear and tear and environmental pressures, guaranteeing longevity, safety, and optimal functioning of road infrastructure [56].

Importance of stiffness: When discussing asphalt roads, stiffness is highly crucial. The focus is on the road's flexibility when a car is driving on it. If the road isn't firm enough, it may become excessively curved and develop waves, a condition referred to as rutting. Alternatively, if it is overly rigid, it may also crack. Engineers employ dynamic modulus to determine the stiffness of the road. The number varies based on factors such as temperature and the frequency of car traffic. A high dynamic modulus indicates that the road is extremely rigid. If the road is not elevated, it is not as firm, which can result in issues such as potholes [57].

Adding extra binder, a sticky material that binds everything, can increase the firmness of the road. This strengthens the road and reduces the chances of excessive bending. Another option is to utilize specific types of rocks that are difficult to compress, thereby enhancing the durability of the road.

At times, engineers may add fibers or polymers to increase the stiffness of the road. These extra reinforcements help the road remain robust and endure for a longer period without becoming uneven or damaged. Therefore, by increasing the rigidity of the road, we can ensure its durability over a prolonged period.

Resistance to fatigue and rutting: Considering both fatigue and rutting resistance is important when evaluating how well a pavement performs. Fatigue resistance refers to the pavements ability to handle loads without developing cracks or separation. Rutting resistance on the hand deals with how the pavement can withstand deformation from repeated loads. It assesses how asphalt mixtures hold up against loading cycles from passing vehicles. Fatigue cracking is an issue, in asphalt roads. Can significantly impact their overall effectiveness. Rutting resistance meanwhile looks at how a mixture can endure deformation caused by traffic and environmental factors. Managing fatigue and rutting resistance carefully is essential, for maintaining the strength and long-term performance of road pavements [58] [59].

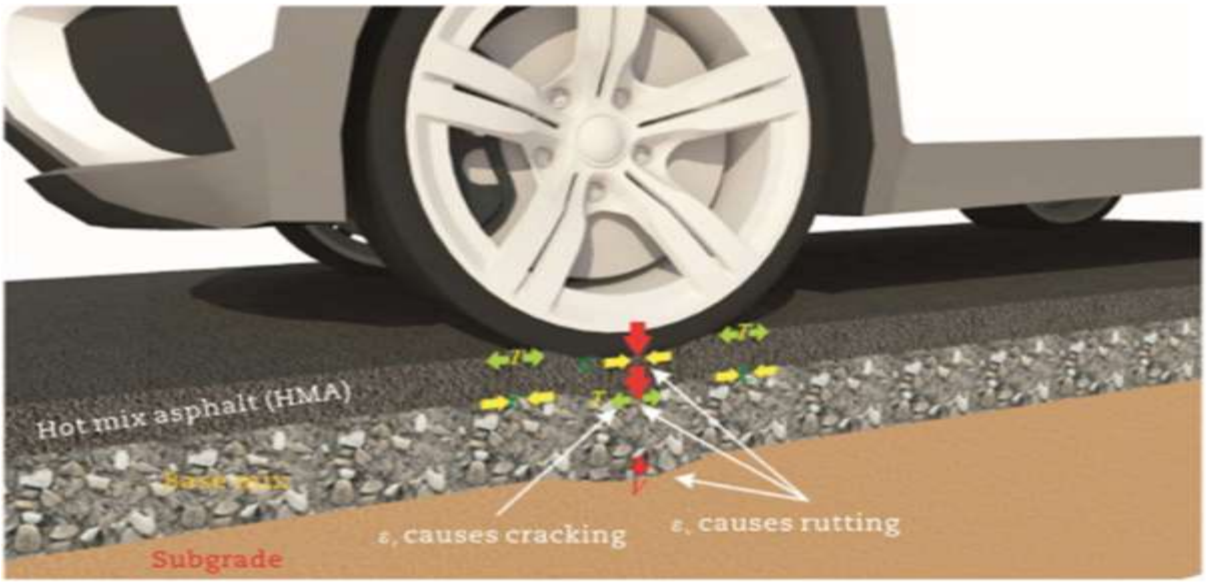

Figure 3.3: Stress formation in AC layer due to tire loading [59]

3.5. Elastic Modulus (E) in Asphalt Mixtures:

The elastic modulus of asphalt mixtures plays a role, in determining their integrity and ability to resist cracks. The stiffness and rigidity of these materials are influenced by how stress relates to strain within the range of deformation. In the context of asphalt mixtures, the elastic modulus is a factor that influences both their performance and crack resistance [60].

In asphalt mixtures the E value serves as a measure of the materials stiffness and rigidity reflecting how well the mixture performs. It plays a role, in determining the durability and lifespan of asphalt pavements. The E value directly influences the performance of these pavements. A higher E value indicates a mixture enhancing its ability to bear heavy loads and resist deformation caused by intense traffic. Hence aiming for an E value is key to ensuring the longevity and durability of asphalt pavements. The ideal range for the E value in asphalt pavements falls between 25-30. If the E value is too low the pavement will be prone to damage under traffic conditions. Conversely if the E value is too high it will result in a pavement that cannot effectively absorb impacts, from heavy traffic [61] [62].

The E values of asphalt mixtures are influenced by factors such, as the characteristics of the asphalt binder, the type and size distribution of aggregates, temperature, loading rate and the presence of additives and modifiers. To construct pavements that can withstand traffic loads it is essential to comprehend how asphalt mixtures with recycled asphalt behave in terms of E. The incorporation of recycled asphalt in these mixtures can significantly affect their E values by modifying the properties of both the asphalt binder and the overall mixture resulting in changes in stiffness and elasticity. Therefore, having an understanding of how E behaves in asphalt mixtures containing materials is crucial, for designing robust pavements capable of enduring traffic loads effectively.

3.6. Dynamics modulus (E*):

The dynamic modulus (E*) plays a vital role in pavement engineering as it indicates the stiffness of viscoelastic materials like asphalt when subjected to dynamic or cyclic loads. It helps us comprehend how these materials react to the pressures and deformations caused by repeated vehicle traffic on roads. E* is typically measured in stress units like Pascals (Pa) or psi and can be determined through dynamic mechanical analysis (DMA) tests by gauging stress and strain [63]. DMA tests also enable the assessment of temperature and frequency ranges within which viscoelastic materials display their characteristics. This data is valuable for creating more precise models and design criteria for pavements. By refining pavement models and design specifications with the help of dynamic modulus (E*) and DMA tests, we can enhance road durability, ensuring that roads are better prepared to endure the recurrent pressures from vehicle loads, thereby cutting down maintenance expenses and extending infrastructure longevity [64].

Nevertheless, it's worth noting that conducting dynamic mechanical analysis (DMA) tests has its drawbacks. For example, these assessments can be time intensive and costly, potentially restricting their feasibility for large scale pavement initiatives.

Furthermore, DMA tests offer insights based on a particular temperature and frequency range, but they may not fully reflect how materials behave in real world scenarios. Hence, it's important to acknowledge these constraints and complement DMA test outcomes with other assessment approaches for a thorough and precise pavement design [65].

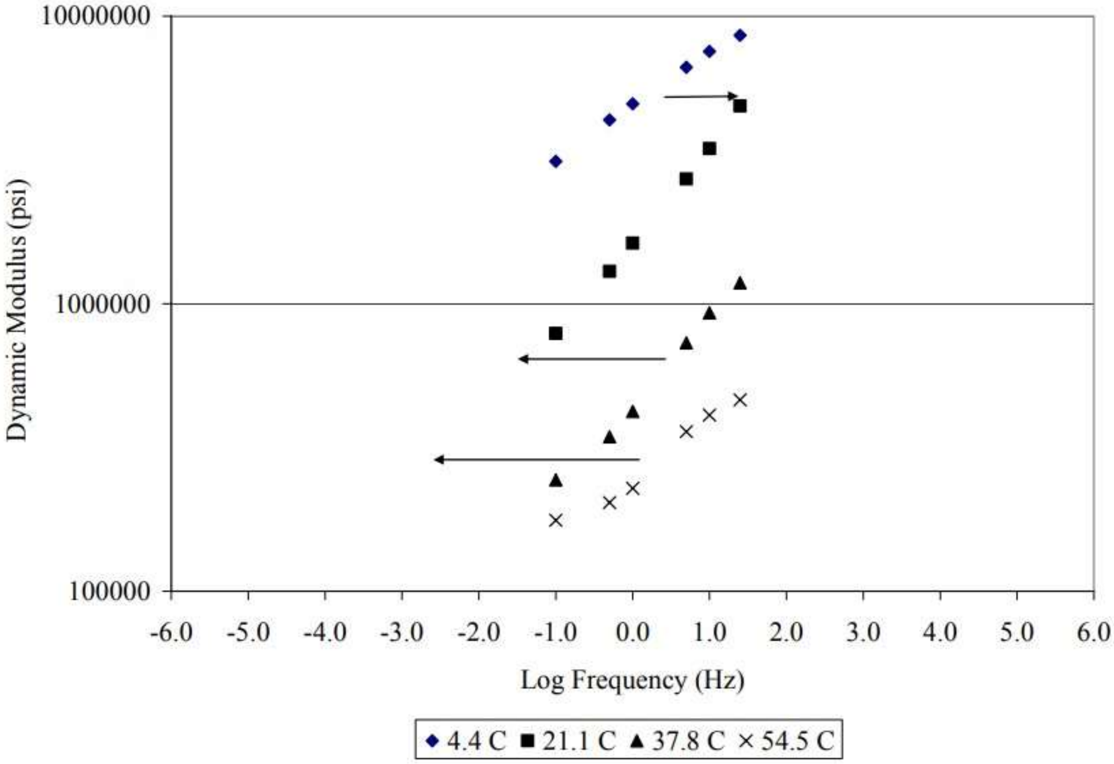

FIGURE 3.4: RESULTS OF DYNAMIC MODULUS TEST ON HMS SAMPLE[66].

The complex modulus, represented by |E*|, describes the connection between the intensity of a sinusoidal stress (σ = σ0 sin(ωt)) and a sinusoidal strain (ε = ε0 sin(ωt ϕ)), occurring simultaneously at a certain time 't' and angular load frequency 'ω'. The value of |E*| is calculated as σ0/ε0, indicating the magnitude of the complex modulus that measures the ratio of stress to strain. This information offers valuable insights into how materials behave mechanically, assisting engineers and scientists in analyzing and predicting material responses under different loads and frequencies. Such knowledge is essential for designing materials suited for specific applications, ensuring structural stability, and optimizing performance of various components and systems. This definition applies when a stable response is observed, as illustrated in **Figure 3.5** [67].

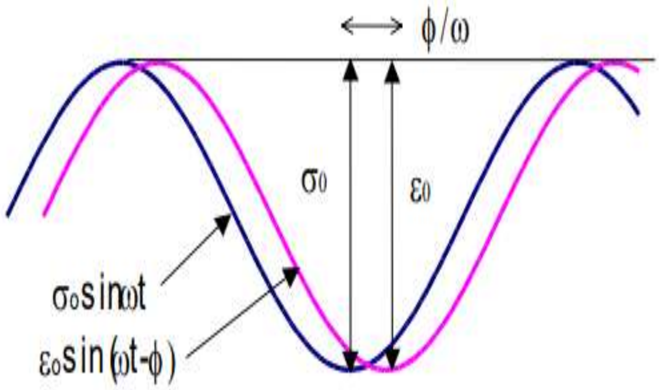

FIGURE 3.5: DYNAMIC (COMPLEX) MODULUS [49].

The mathematical representation of the complex dynamic modulus (E*) is as follows:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 e^{i\omega t}}{\varepsilon_0 e^{i(\omega t-\phi)}} = \frac{\sigma_0 \sin \omega t}{\varepsilon_0 \sin(\omega t - \phi)} \quad \text{Equa 1}$$

Where,

$\sigma 0$ = peak (maximum) stress

$\varepsilon 0$ = peak (maximum) strain

ϕ = phase angle, degrees

ω = angular velocity

t = time, seconds

It's worth mentioning that the value of E* isn't constant; rather, it changes based on the temperature and how often it's loaded. This variability stems from the material's viscoelastic characteristics, which involve both immediate deformation (acting like an elastic) and gradual flow over time (acting like a viscous substance). Since the dynamic modulus shows how well a material can withstand deformation under dynamic stresses, it plays a crucial role in designing and analyzing pavements.

The concept of a master curve plays a crucial role in pavement engineering by simplifying the complex behavior of materials like asphalt, which can be influenced by factors such as temperature and frequency. This approach relies on the principles of time temperature superposition and time frequency superposition to represent the dynamic modulus (E*) of the material in a way that is applicable in various scenarios. By adopting this method, engineers can construct pavement structures that consistently perform well across different temperatures and loads [68]. It enables engineers to predict how pavements will fare in diverse climates more accurately, facilitating the optimization of pavement designs and materials to lower maintenance expenses and extend the lifespan of pavements effectively [69].

3.7. Time-temperature superposition Principle

The principle of time-temperature superposition in materials science and rheology posits that the response of a material at various temperatures can be forecasted by adjusting and combining the time-dependent behavior at a chosen reference temperature. This principle enables scientists to infer information from experiments done at varying temperatures and gain a full comprehension of how the material behaves across a broad temperature spectrum. There are various benefits to utilizing the time-temperature superposition principle in experimental planning. Initially, researchers can save time and resources by performing experiments at one standard temperature and then utilizing this principle to forecast the material's response at different temperatures. This removes the necessity of conducting numerous experiments at various temperatures. Furthermore, the principle allows researchers to gain a more extensive comprehension of the material's behavior by supplying data across a broad temperature spectrum, allowing for more precise forecasts and the development of materials with particular attributes [70] [71].

3.8. Master Curve Concept and Shift factor:

The Master Curve idea, frequently linked with the Superpave approach, is seen as a highly effective tool in asphalt materials engineering. Through this analysis, asphalt mixtures with different temperatures, such as E, can be systematically evaluated based on their mechanical properties. The model presented in this paper is derived from the time-temperature superposition model. Hence, a reference temperature obtained from studying a specific material specimen can be utilized to forecast the material's performance. This study aims to determine the behavior of the material at varying temperatures and loading rates in comparison to the reference temperature based on the collected data at that temperature [72].

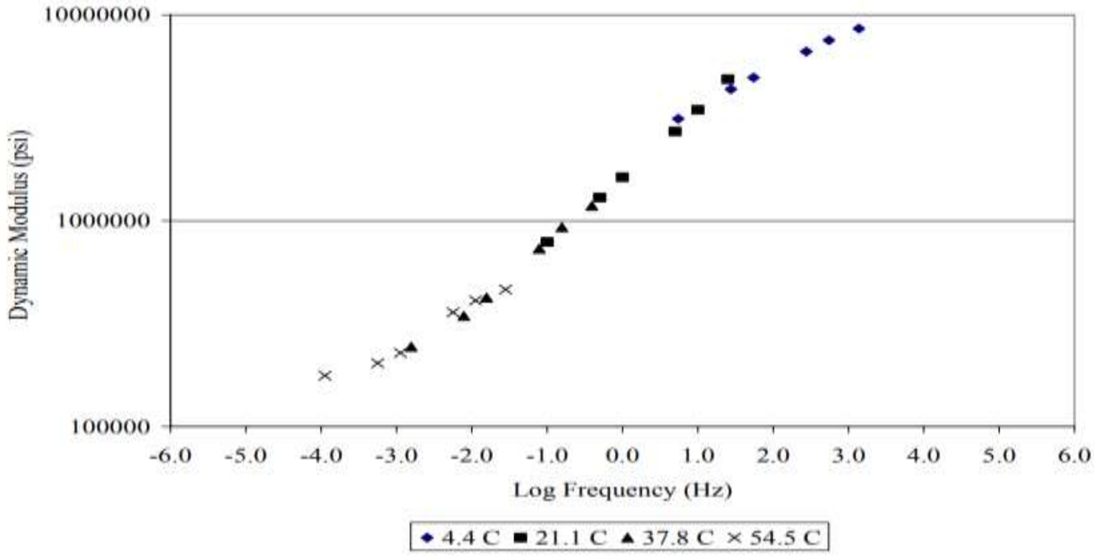

FIGURE 3.6: TEST DATA SHIFTED TO FORM MASTER CURVE [66].

In the updated MEPDG, the HMA stiffness is considered across all temperature ranges and the loading rate over time is established by creating a master curve employing the time-temperature principle at a standardized temperature the state of being in multiple positions at once.

In most cases, the master modulus curve can be characterized by a sigmoidal function, which is defined as:

$$\text{Log}\,|\,\text{E*}\,| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}} \qquad \text{------------------- Equ:2}$$

Where,

tr = reduced time of loading at reference temperature

δ = minimum value of E*

δ + α = maximum value of E*

β, γ = parameters describing the shape of the sigmoidal function

fr = f(aT)

In this study, |E*| denotes the dynamic modulus, fr is the frequency at 20 °C, and δ, α, β, and γ are the fitting parameters. The range of |E*| is shown by δ and δ + α, while the shape of the SLS model is characterized by β and γ in **Figure 3.7.**

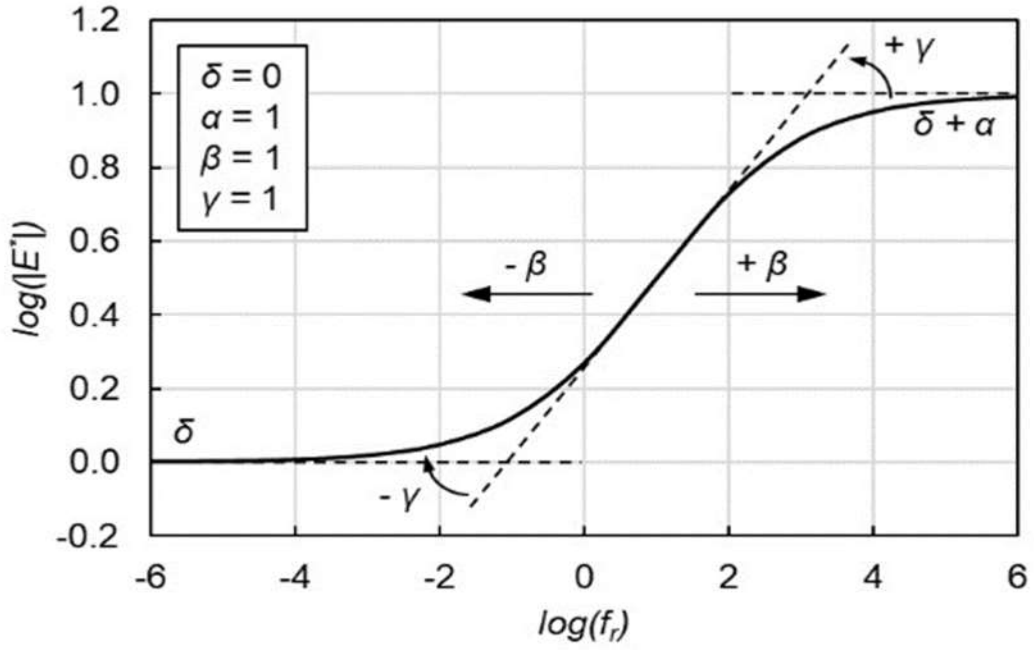

FIGURE 3.7: VISUAL REPRESENTATION OF SLS MODEL

The Williams-Landel-Ferry (WLF) equation is a practical empirical model that connects temperature to the time-related characteristics of polymers. It is especially important in the study of rheology, which focuses on the movement and distortion of substances. The WLF equation assists in translating temperature fluctuations into temporal adjustments for polymer characteristics.

where,

aT = the shift factor as a function of temperature T,

log aT = $\frac{\boldsymbol{\Delta Ea}}{\mathbf{2.303R}}\left(\frac{1}{T}-\frac{1}{Tr}\right)$ = - C1(T-Tr)/(T-Tr)+C2-----------------Equ:3. WLF Equation

where,

ΔEa = the apparent activation energy (J/mol)

R = the universal gas constant (= 8.314 J/K2^-mol)

T = the temperature (K)

Tref = the temperature at reference temperature (K).

By utilizing this data, one can adjust the constitutive models and simulate the material behavior under different conditions by considering the temperature and loading rate factors. Because of this, this test is a valuable tool for comprehending the mechanical characteristics of asphalt mixtures and holds significant practical importance [73].

The Master Curve for E is created by performing various tests on asphalt mixtures at different temperatures and loading rates to establish a variety of tests on asphalt mixtures. The data obtained can be shifted to a reference temperature using shift factors from time-temperature equivalence principles based on the temperature-time curve. Engineers can use this technique to forecast E values for any mixture under any temperature and loading rate, enhancing pavement design and performance prediction across a wide range of conditions. The principle of equivalence between time and temperature is a crucial tool for forecasting pavement behavior and designing pavements that can endure the impacts of loads and temperature variations over time [74].

3.9. Challenges in Developing a Master Curve for Recycled Asphalt Mixtures:

Developing a curve, for asphalt mixes containing recycled asphalt presents challenges due to the irregular nature of the recycled materials. The mechanical characteristics of RAP material may differ from those of materials due to variations in composition, age and quality. Therefore strategies, for building databases must take these distinctions into account. Devise tailored approaches to address them throughout the development process [75].

In the process of developing a database, it is essential to consider the impact of recycled asphalt binder on the aging and rejuvenation of the material. Careful examination of how the RAP binder impacts the overall E of the mixture is crucial, as it could display varying rheological properties from the virgin binder. In addition, the RAP binder can affect the asphalt mixture's ability to resist cracking and fatigue. Ultimately, the heat resistance of the mixture can be affected by the RAP binder as well [76] [77].

This implies that the RAP binder has the potential to enhance the longevity of the asphalt mixture. Moreover, the RAP binder has the potential to decrease the required bitumen quantity in the mixture, leading to cost savings [78].

4. Research question

4.1. purpose of the study:

The main goal of this master's thesis is to develop a comprehensive Master Curve (E*) database for asphalt mixes containing varying percentages of Recycled Asphalt Pavement (RAP), particularly targeting 12.5%, 30% and 40% RAP. The database will be used to systematically characterize dynamic modulus (E*) properties across a range of loading frequencies and temperatures in order to provide valuable insights into the mechanical behavior and performance of sustainable asphalt mixes, which will improve the eco-friendliness and affordability of road infrastructure. Additionally, the master's thesis will serve as a central repository for critical mechanical properties and performance data, enabling more accurate design and promoting advancements in the use of recycled materials in asphalt mixtures.

4.2. Research question:

In this study my primary research question is:

- "What are the effects of incorporating varying percentages of recycled asphalt – specifically 12.4%, 30%, and 40% – on the development of a Master Curve (E*) database for asphalt mixtures in different temperature and frequency"?

Sub Questions:

To delve into this topic further, I have included the following specific questions:

- What are the effects of temperature and frequency variations on asphalt mixes that contain recycled asphalt in terms of dynamic modulus (E)?
- How do these effects influence the overall performance and sustainability of the resulting asphalt mixes for road pavement design?"

Limitations:

To address this task effectively, it is important to establish certain boundaries and limitations.

- The study only examined the short-term effects of using recycled asphalt content without considering its long-term performance or aging.
- The research paper specifically examined different percentages of recycled asphalt content but simplified the investigation by solely focusing on AC11 asphalt binder.
- It is important to note that this paper primarily focuses on laboratory-based investigations and does not delve into discussions about field trials conducted on site or, in depth examinations of long-term pavement performance assessments.
- The study is not examined or focused on the different types of aggregates using to Asphalt make AC11 asphalt binder and aging periods in the different asphalt binders with containg RA.

5. Case/Materials

5.1. Materials:

When it comes to choosing the asphalt binder for building roads in Norway there are various factors to consider much like in many other countries. Factors such as the weather conditions, traffic volume and environmental impacts play a significant role in the decision-making process. Different types of asphalt binders are on hand each categorized by their penetration level and softening point. Among these variations the penetration grade asphalt binder stands out as a choice due to its softer texture and lower melting point. This specific type of binder is well suited for use in regions because of its increased flexibility during pavement construction.

Opting for penetration grade asphalt binder, in climates brings about several benefits. The enhanced flexibility of the pavement helps it endure the strains from freezing and thawing cycles reducing the risk of cracks and prolonging its lifespan considerably. Moreover, the lower melting point of penetration grade asphalt binder encourages bonding and sealing of aggregates resulting in a more resilient and longer lasting road surface [79].

On the other hand, the viscosity grade asphalt binder has a higher melting point and is more rigid, making it ideal for warmer climates. Finally, the cutback asphalt binder is a type of asphalt binder that has a low melting point and is highly soluble in solvents [80].

5.2. Materials Collection:

In this thesis, the crushed stone 8/11 mm, gravel 0/8mm and sand 0/4 mm with a bitumen penetration grade of 70/100 were obtained from NCC for research purposes, with NCC conducting the gradation and size analysis work. The aggregates were analyzed for gradation and size following the guidelines set by ASTM.

This research focused on analyzing primarily one type of asphalt mixture, with the aggregate gradation for these mixtures provided in **Appendix A or in Table 5.1**. The project focused on the asphalt binder with 12.5%, 30% and 40% of reclaimed asphalt (RA), samples of RAP were collected from the RAP stockpile.

The mixtures that were analyzed are: AC11 containing surf binder RA 70/100 (AC11). The AC11 is a mix modified with polymer (binder grade 70/100 and content 5.3%), primarily for use in pavements with heavy traffic.

AC11 asphalt is used on roads with an Annual Average Daily Traffic (AADT) of over 1,500 and in places where there are stationary loads. Typically applied in either one or two layers, the recommended thickness is varying from 3 to 5 cm based on the site. The mixture of asphalt is produced within a temperature range of 140 to 180 degrees Celsius.

AC11 asphalt is particularly suitable for driveways, private roads, and analogous circumstances. It provides a polished appearance and longer lasting durability.

FIGURE 5.1: SHOWING WHERE THE COARSE AND FINE AGGREGATE IS COLLECTED.

TABLE 5.1: THE GRADATION AND SIZE ANALYSIS CONDUCTED BY NCC

	µm				mm						
	63	125	250	500	1	2	4	5.6	8	11.2	16
Tils	8.0	12.0	16.0	23.0	30.0	39.0	51.0	60.0	74.0	96.0	100.0
Tol.	2.0	4.0	4.0	4.0	4.0	6.0	6.0	6.0	6.0	6.0	2.0

TABLE 5.2: PHYSICAL PROPERTIES OF AC11 SURF BINDER RA 70/100

Physical property	**Unit**	**Bitumen 70/100 Specification**	**AC11**
Penetration at 25 °C	0.1 mm	100	
Softening point (Ring and Ball)	°C	43-51	
Resistance to Hardening	°C	163	
Fraass breaking point	◦C	-16	
Maximum aggregate size (mm)	mm		11
Rap Content	%		12.5%, 30% and 40%
Air Voids (%)	%		±4
Binder Content (%)	%		5,3

5.2.1. Material Calculation

The material is calculated based on the receipt from the NCC by analyzing the quantities. This information is then used to determine the total amount of material needed for each amount of mixtures in different recycle asphalts.

Table 5.3: Materials used to make AC11 containing surf binder RA 70/100 with 12.5% RA:

Materials	Size(mm)	Quary region	Quantity in %	Quantity in Kg
Crushed stone	8-11	Landvik	27%	8,1
Gravel	0-8	Landvik	31%	9,3
Sand	0-4	Rugsland N	10%	3
Filler	0-0,063	Egen	2 %	0,6
Recycled asphalt	0-11	Arendal	10%	3
Asphalt cement		Egen	4%	1,2
Amin		Egen	0,3% of 4%	0,0036
Asphalt rejuvenation.		Egen	4,3% of 4%	0.0408
Total				31,2

Table 5.4: Materials used to make AC11 containing surf binder RA 70/100 with 30% RA

Materials	Size(mm)	Quary region	Quantity in %	Quantity in Kg
Crushed stone	8-11	Landvik	27%	8,1
Gravel	0-8	Landvik	31%	9,3
Sand	0-4	Rugsland N	10%	3
Filler	0-0,063	Egen	2 %	0,6
Recycled asphalt	0-11	Arendal	30%	9
Asphalt cement		Egen	4%	1,2
Amin		Egen	0,3% of 4%	0,0036
Asphalt rejuvenation.		Egen	4,3% of 4%	0.0408
Total				31,2

5.3. Asphalt binder mixing preparation:

All Aggregates were mixed together in a Pavemix mixer at a temperature of 160 °C in the laboratory located at the University of Agder, as illustrated in **Figure 5.2**. To achieve optimal blending and consistency throughout the mixture, the asphalt cement and the recycling asphalt was heated carefully to a mixing temperature of 160 °C for duration of 2 hours. This procedure required mixing the asphalt cement intermittently to avoid excessive heating in one area. This ensured an even spread of heat, while also avoiding harm to the mixture. The aggregates were kept at a temperature of 110 °C while being heated for a duration of 24 hours. To mix, the Pavemix mixer had coarse and fine aggregates, filler, a small amount of amin, recycled asphalt, and asphalt rejuvenation, followed by adding the necessary amount of asphalt cement. The combination was blended until thoroughly covered, for about 5 minutes. To get the compaction molds, spoons, and spatulas ready, they were put in the oven and heated to a mixing temperature of around 160 degrees Celsius about an hour before mixing. This made sure that the tools were heated to match the temperature of the asphalt mixture, resulting in improved consistency and workability while mixing.

Figure 5.2: The pave-mix mixer used to mix the HMA samples.

5.3.1. The purpose of Heating aggregate and asphalt cement

Heating up the aggregates and the asphalt cement before mixing is crucial because it helps reduce the thickness of the asphalt cement, making it easier to spread over the aggregates. This improves the connection, between the asphalt and aggregates, resulting in a durable and higher-quality mix. Additionally, heating the aggregates also helps remove any moisture or impurities present, which ultimately enhances the performance of the asphalt mixture.

FIGURE 5.3: HEATING UP THE AGGREGATES BEFORE MIXING IN 110 °C FOR 24 HOURS.

5.3.2. Asphalt rejuvenation.

Asphalt rejuvenation is essential in the mixing process as it renews the aged asphalt binder back to its initial properties. Replenishing essential oils and resins that may have been lost due to oxidation over time helps enhance the durability and performance of the mixture. This guarantees that the asphalt mix retains its flexibility, durability against cracking, and overall standard.

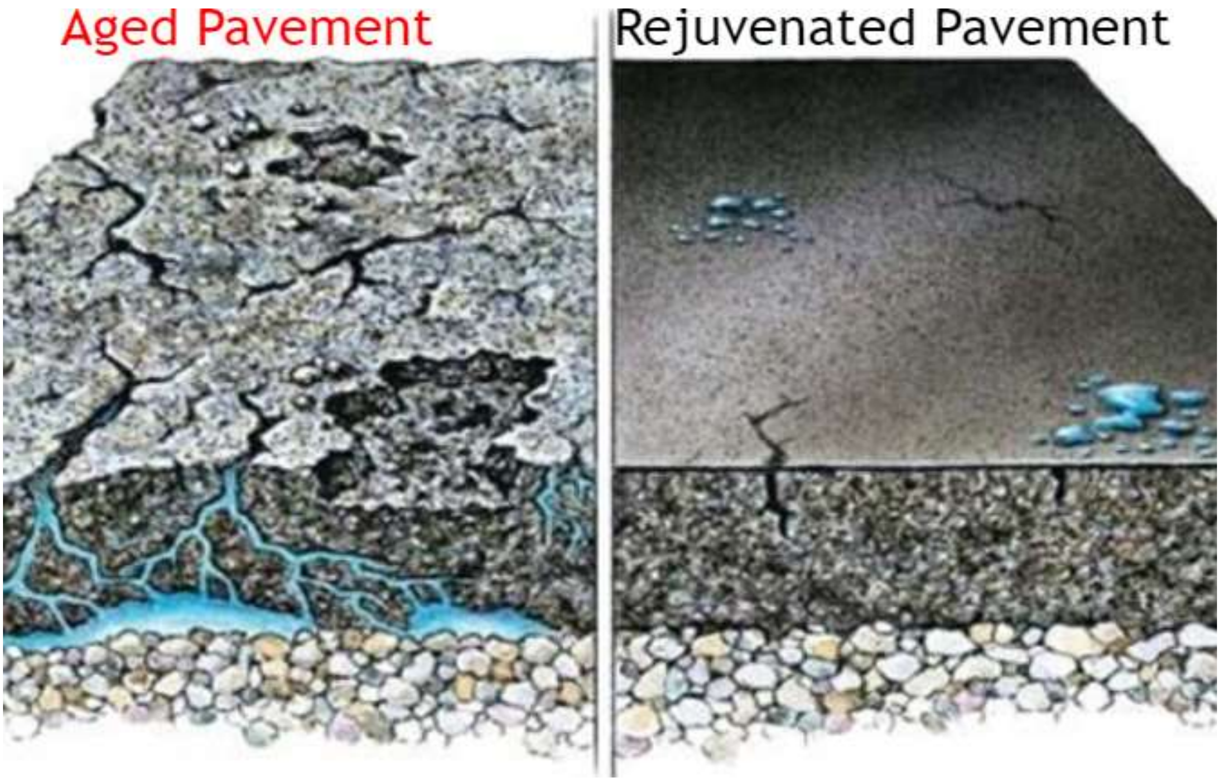

FIGURE 5.4: REJUVENATED PAVEMENT[81].

5.4. Specimen Preparation:

The preparation of samples is crucial for accurate laboratory testing of asphalt. Care was taken to ensure the samples were as uniform as possible, which is especially important when testing materials like asphalt mix that are not consistent throughout. Therefore, the specimens should ideally reflect real pavement conditions. Homogenizing the field samples before testing and collecting them at various points in the field were crucial to ensuring they accurately reflected the pavement conditions. The samples need to be tested promptly after they are collected. It is essential to test samples right after collection because asphalt characteristics may fluctuate over time, mainly because of temperature and moisture changes. By promptly conducting tests on the samples, any potential alterations in the material can be precisely detected, leading to more dependable and precise test outcomes. This is particularly crucial for asphalt materials utilized outdoors, as the weather can significantly affect their durability and functionality. The most effective way to guarantee accurate results is by testing the samples immediately after they are collected [82].

AASHITO Criteria for prepare and test specimen:

The AASHITO Criteria for Dynamic Modulus Test Specimen Acceptance lay down necessary requirements for specimen preparation to guarantee accurate and reliable test results. These standards include elements such as specimen size, form, material integrity, and lack of imperfections. Following these criteria allows researchers to obtain accurate and significant data from the dynamic modulus test. This helps researchers and engineers make more reliable conclusions and informed decisions through confident data analysis and interpretation.

TABLE 5.5: AASHITO CRITERIA FOR PREPARE AND TEST SPECIMENT.

Criterion Items	Requirements
Specimen size	Diameters range from 100 millimeters to 104 millimeters on average. A height of between 147.5mm and 152.5mm is average.
Gyratory Specimens	Make specimens with a height of 175 mm and void content of 5% (AAHITO T 312)
Coring	Test specimens of nominal 100 mm diameter are cored from the center of the gyratory specimen as part of the core process. The test specimen should be rounded with smooth, parallel sides that are free from steps, ridges, and grooves.
Diameter	It is recommended that the standard deviation should not exceed 2.5 millimeters.
End Preparation	Within a tolerance of 0.05 mm, the specimen ends must have cut surface waviness heights. The specimen ends must not deviate more than 1 degree from perpendicular to the specimen's axis.
Replicates	In the case of three LVDTs, a minimum of two replicates were performed with an accuracy limit of 13.1%
Sample Storage	Samples should be wrapped in polyethylene and stored in an environment protected. from the elements between 5 and 26.7° C and should not be stored for more than two weeks before testing.
Air Void Content	No more than 1.0 percent of voids in the test specimen in comparison to the target
Aging	Min 2 hour at 140°C
Testing frequencies	25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, 0.1 Hz
Testing temperatures	-10 °C, 5 °C, 20 °C, 40 °C, 54 °C

5.4.1. Compaction

The purpose was to create three samples for AC11 surf 70/100 (AC11) asphalt mix with 12.5%, 30% and 40% Rap content. After blending the asphalt binder AC11 containing 40% Rap, mixture was aged in an oven for 2 hours at 140°C and then compacted using AASHTO R 30 standards. The reason for placing the mixture in the oven at 140°C for 2 hours is to replicate the impacts of extended aging on the asphalt mixture. This method enables the assessment of the blend's effectiveness in actual aging circumstances, by detecting any possible alterations in the asphalt's physical and mechanical characteristics. The asphalt binder AC11 containing 12.5 and 30% Rap was aged in just 15 minutes. 12 asphalt mixture specimens were made in the laboratory at the university in Agder using a gyratory compactor at 600 kPa pressure, with a gyratory angle of 17.45 mrad (equivalent to 1.25°) and compacted with 100 gyrations at 600 kPa pressure.

FIGURE 5.4: SUPERPAVE GYRATORY COMPACTOR (SGS)

The Superpave gyratory compaction procedure was used with a gyratory compactor to create cylindrical test specimens measuring 175 mm in height and 150 mm in diameter, in accordance with AASHTO T 312-07. To prepare one cylinder, it was necessary to have between 7500 and 8000 grams of asphalt binder.

FIGURE 5.5: GYRATORY COMPACTED SAMPLE

5.4.2. Coring & Sawing

After compacting, the samples were removed from the compaction molds, marked, and left to cool down to room temperature. Then, the compressed samples were drilled and cut to produce a test sample measuring 150 mm in height and 100 mm in diameter, with air voids ranging from 4.5 ± 1 %. A diamond-studded core barrel was used to drill through the dense material for coring the samples. The core barrel, specifically created for this task, guaranteed a neat and accurate cut, enabling the retrieval of a 100 mm diameter cylindrical sample. This technique made sure that the necessary testing dimensions were met, as depicted in **Figure 5.7**.

FIGURE 5.6: BORING AND CUTTING TO REQUIRED SAMPLE HEIGH.

The samples were cut with a specialized saw blade to achieve a height of 150 mm as illustrated in **Figure 5.8**. The cutting process required a saw designed for compacted materials. The sample was cut with precision using a carefully guided saw blade to ensure a straight cut. This procedure enabled the removal of a cylindrical asphalt specimen measuring 150 mm in height, suitable for dynamic modulus testing.

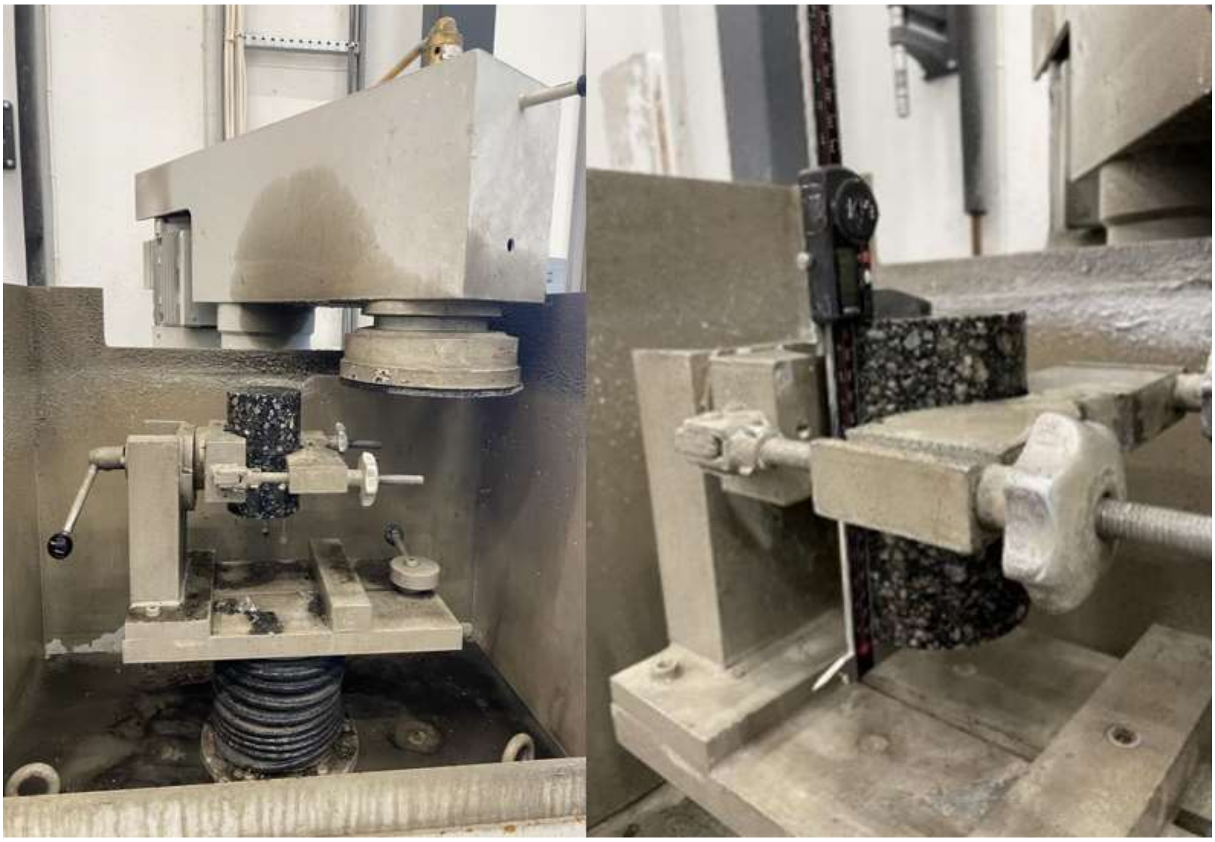

FIGURE 5.7: CUTTING AND SLIPPING TO REQUIRED SAMPLE HEIGHT

The HMA test samples were then examined to ensure they met the sample requirements outlined in AASHTO TP 62-03. The standards for approving the samples were detailed in **Table 5.5**. Adhering to AASHTO TP 62-03 is essential to guarantee that the HMA test samples meet the necessary specifications and standards. This ensures that the samples meet the necessary quality and performance standards for their specific use in construction projects.

5.4.3. Preparing specimens for dynamic modulus testing.

The samples that satisfied all requirements were attached with six steel studs to support three linear variable displacement transducers (LVDTs). The gauge length of the LVDT is 101.6 millimeters. Great attention was given to ensuring that the studs were positioned accurately, 101.6mm apart and 50.8mm from the center of the sample. After the epoxy dried and the studs were securely attached to the sample, they were prepared for testing. A sample prepared for dynamic modulus testing is illustrated in **Figure 5.9.**

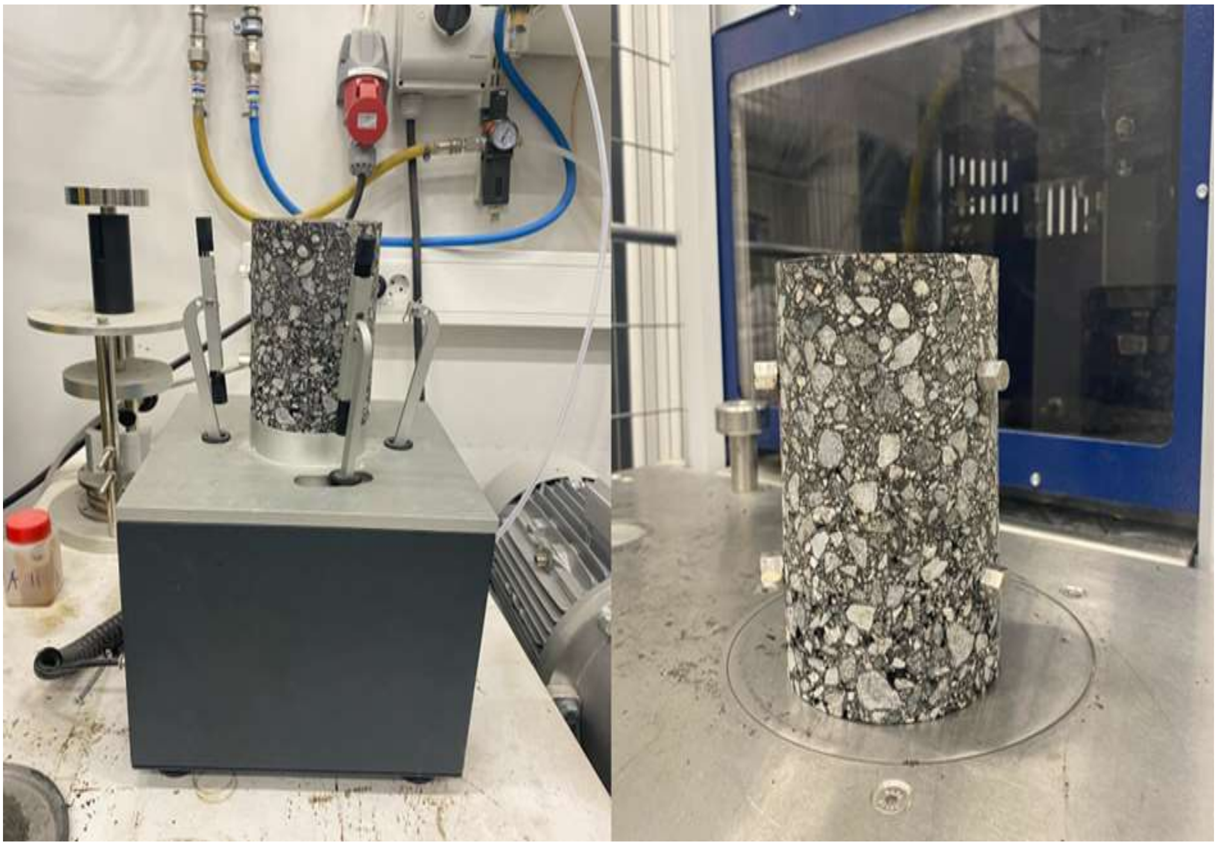

FIGURE 5.8: ATTACHED SPECIMENS WITH SIX STEEL STUDS TO SUPPORT LVDTS.

Three LVDTs (Linear Variable Differential Transformers) with a gauge length of 70 mm were placed at 120° intervals for measuring purposes. The load is used to reach a level of 50-70 macrostrains in the specimen. The testing protocol adhered to the standards specified in AASHTO T378-17(2021). Placing the LVDTs every 120° guarantees that the collected data accurately reflects the entire sample, as it enables a thorough evaluation of deformation and strain across the sample. By distributing the LVDTs evenly around the sample, it is possible to detect changes in deformation in different directions, leading to a better comprehension of the sample's behavior when loaded.

5.5. Dynamic modulus test:

The dynamic modulus tests were conducted using the UTM 130, a Universal Testing Machine made by IPC in Australia. has the ability to maintain a steady pressure of up to 210 kilopascals and a testing environment chamber for control. temperatures ranging from -40 degrees Celsius to +90 degrees Celsius. The laboratory tests were conducted at the Grimstad campus. Three advanced sensors (LVDTs) were installed on the UTM 130 to assess the dynamic modulus of materials in different temperatures and loading conditions. The experiments included exposing the samples to various frequencies and amplitudes of loading, which helped us evaluate the stiffness and damping characteristics of the material. The tests yielded important information about how the materials perform and behave under dynamic loading conditions.

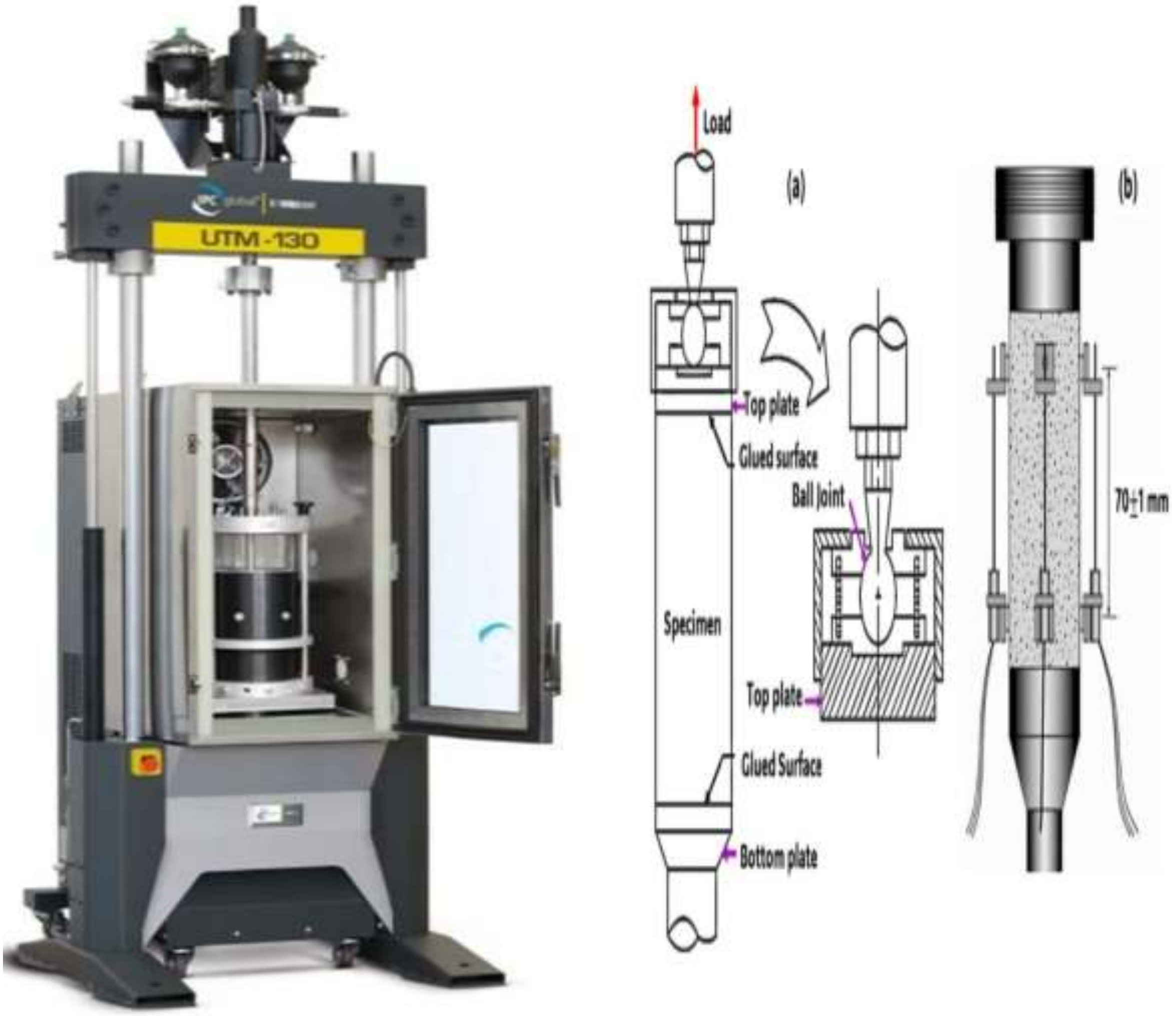

FIGURE 5.9: UNIVERSAL TESTING MACHINE (UTM- 130)

In this study, I performed the dynamic modulus test at six different frequencies: 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz and 25 Hz. These specific frequencies were chosen thoughtfully to encompass a broad spectrum of loading conditions and simulate real world situations. By subjecting the materials to varying frequencies in the dynamic modulus test, spanning from low (0.1 Hz) to high (25 Hz), we could evaluate how the materials reacted to different dynamic forces and vibrations. This comprehensive method offered a detailed insight into the stiffness and damping characteristics of the materials under various loading scenarios.

The tests are conducted within a specific temperature range to assess how the materials perform and behave in different environmental conditions. The experiments were carried out at five various temperatures from -10°C to 54°C to evaluate the impact of extreme cold and heat on the stiffness and damping properties of the materials. This information is essential for applications in which materials will experience various temperature changes, guaranteeing their appropriateness and longevity in actual situations.

FIGURE 5.10: FIXING LVDT SUPPORTING SYSTEM, LVDT MOUNTED SAMPLE IN THE TASTING-CHAMBER TEMPERATURE CONTROLLER, DATA ACQUISITION SYSTEM OF UTM-130 KN.

The amount of force used in the experiments differed greatly based on the temperature range. At -10°C, 4°C, and 20°C, the pressure varied from 138 to 965 kPa, showing an increased level of strain. Nevertheless, at 40°C and 54°C, the pressure varied between 21 and 68 kPa, suggesting a reduced level of strain. This implies that the materials exhibited different behaviors at different temperatures, with higher forces needed to cause deformation at lower temperatures.

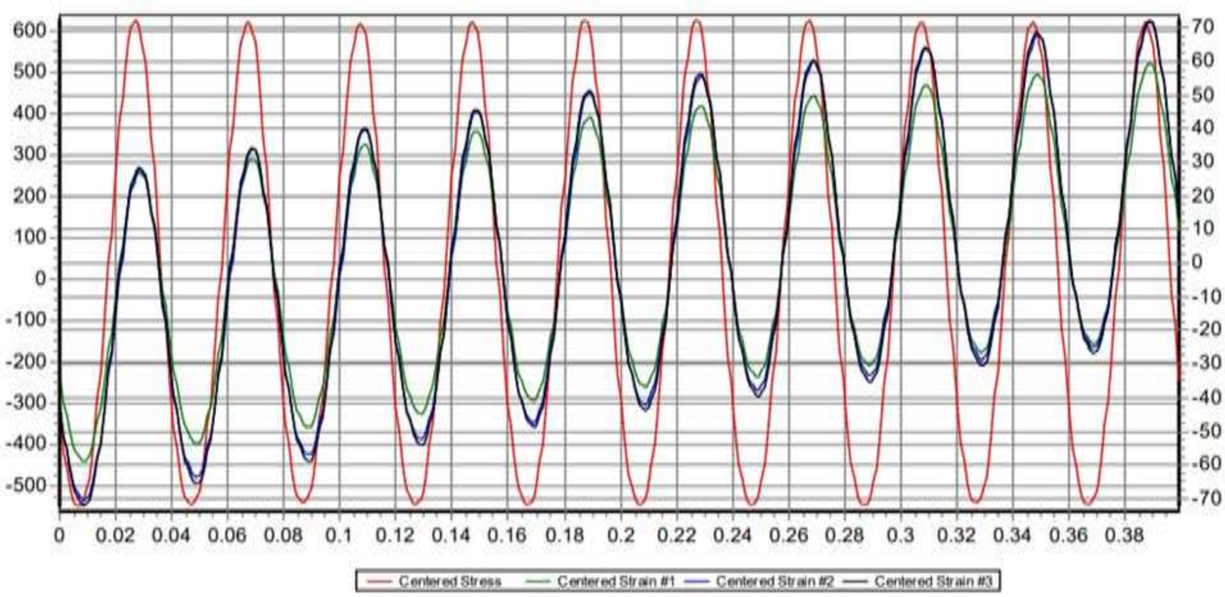

FIGURE 5.12: SPECIMEN TEST RESULTS OF DYNAMIC MODULUS TEST (1 CURVE) AND STRAIN (2 CURVES) IN DYNAMIC LOADING USING 10HZ FREQUENCY AT THE TEMPERATURE OF 4°C.

The amount of dynamic load is influenced by the stiffness of the specimen and usually falls within a certain range of between 15 and 2800 kPa are equivalent measurements. Increased load is necessary in lower temperatures. Table 5 shows average levels of stress that change with temperature fluctuations [83].

TABLE 5.6: LOAD RANGES AT DIFFERENT TEMPERATURES FOR THE TEST [83].

Temperature (°C)	Load Range, KPa
-10	1400 to 2800
4.4	700 to 1400
21.1	350 to 700
37.8	140 to 250
54.4	35 to 70

Examine the samples in order from the coldest temperature of -10°C to the hottest temperature of 54°C. Apply the loading in descending frequency order at each temperature, starting from the highest frequency.

from 25 Hz down to 0.1 Hz. Prior to testing, condition the sample with 200 cycles at a frequency of 25 Hz at the stress level as indicated in **Table 5.6**. Next, place the sample as directed in **Table 5.7**. The break between each frequency run is 2 minutes. The break time allowed cannot surpass 30 minutes for any reason, including two instances of frequency testing [83].

TABLE 5.7: NUMBER OF PRECONDITIONING CYCLES PERFORMED AT EACH FREQUENCY [83].

Frequency (Hz)	Number of Cycles
25	200
10	200
5	100
1	20
0.5	15
0.1	15

Between each frequency, there was a resting period of 120 seconds to enable a certain amount of regeneration to occur. This regeneration ensures that the materials have enough time to recover and stabilize before being subjected to the next frequency. It also helps in maintaining the accuracy and reliability of the test results by minimizing any carry-over effects or residual stress from the previous frequency.

Based on data from numerous lab tests, the following **Table 5.8** below shows the minimum times required to reach equilibrium temperatures from said tests [84]. Increasing the load capacity of the testing equipment is necessary to meet the -10°C low temperature test requirement, leading to a notable rise in the cost of the environmental system. Furthermore, managing moisture condensation and ice formation is challenging, potentially leading to damage to the loading machine from rigid specimens. High temperatures also negatively affect strain measurement accuracy, causing significant harm to LVDT gags, supports, and holders [85].

TABLE 5.6: RECOMMENDED EQUILIBRIUM TIMES SPECIMEN [84].

Specimen Temperature, °C	Time from Room Temperature 25°C , hrs.	Time from Previous Test Temperature, hrs.
-10	Overnight	-
4	Overnight	4hr or Overnight
20	1	3
40	2	2
54	2	1

TABLE 5.7: SUMMARY OF TEST PARAMETERS

Test types	**AC 11- (12.5% RA)** Dynamics modulus	**AC11- (30% RA)** Dynamics modulus	**AC11- (40% RA)** Dynamics modulus
Test Standard	AASHTO T378	AASHTO T378	AASHTO T378
Specimen size (height to diameter)	150x 100 Cm	150X 100 Cm	150X 100cm
Number of duplicates	3	3	3
Temperature, °C	−10, 4, 20, 40,54	−10, 4, 20, 40,54	-10,5,20,40,54
Frequency, Hz	25, 10,5,1,0.5, 0.1	25,10,5, 1, 0.5, 0.1	25,10,5, 1, 0.5, 0.1
Density, kg/m^3	2601	2598	
Gyrations	100	100	100
Conditioning temperature time	-10 °C ~ Overnight 4 °C ~ 4 h or overnight 20 °C ~ 3 h 40 °C ~ 2 h 54 °C ~ 1 h	-10 °C ~ Overnight 4 °C ~ 4 h or overnight 20 °C ~ 3 h 40 °C ~ 2 h 54 °C ~ 1 h	-10 °C ~ Overnight 4 °C ~ 4 h or overnight 20 °C ~ 3 h 40 °C ~ 2 h 54 °C ~ 1 h

Different temperatures and frequencies were utilized in the experiments, ranging from the coldest to the warmest temperature. Due to this approach, the destruction of samples was reduced, the testing equipment and personnel's safety was guaranteed, a clearer understanding of the materials or systems being studied was achieved, and the results were consistent and comparable.

By applying the concept of time-temperature superposition, master curves were developed for each mixture by utilizing a 20°C reference temperature for computations. Utilizing a standard temperature of 20°C enables relevant comparisons and assessments among various combinations. By standardizing the data to a shared benchmark, we can effectively evaluate the behavior and performance of materials or systems across different temperature ranges, offering important insights for use in diverse settings.

Summary:

TABLE 5.8: CYLINDRICAL SAMPLE PREPARATION AND TASTING STANDARDS [86].

Metode	Test standard
Cylindrical samples of 150-mm diameter and 170-mm height	AASHTO T 312-07
The bulk density and the theoretical maximum density	AASHTO T 166-07 and
	AASHTO T 209-05
The |E*| tests were conducted using	AASHTO T 378-17(2001)

Summary of the process of collecting materials and preparing asphalt binder with different percentages of Recycled Asphalt (RA):

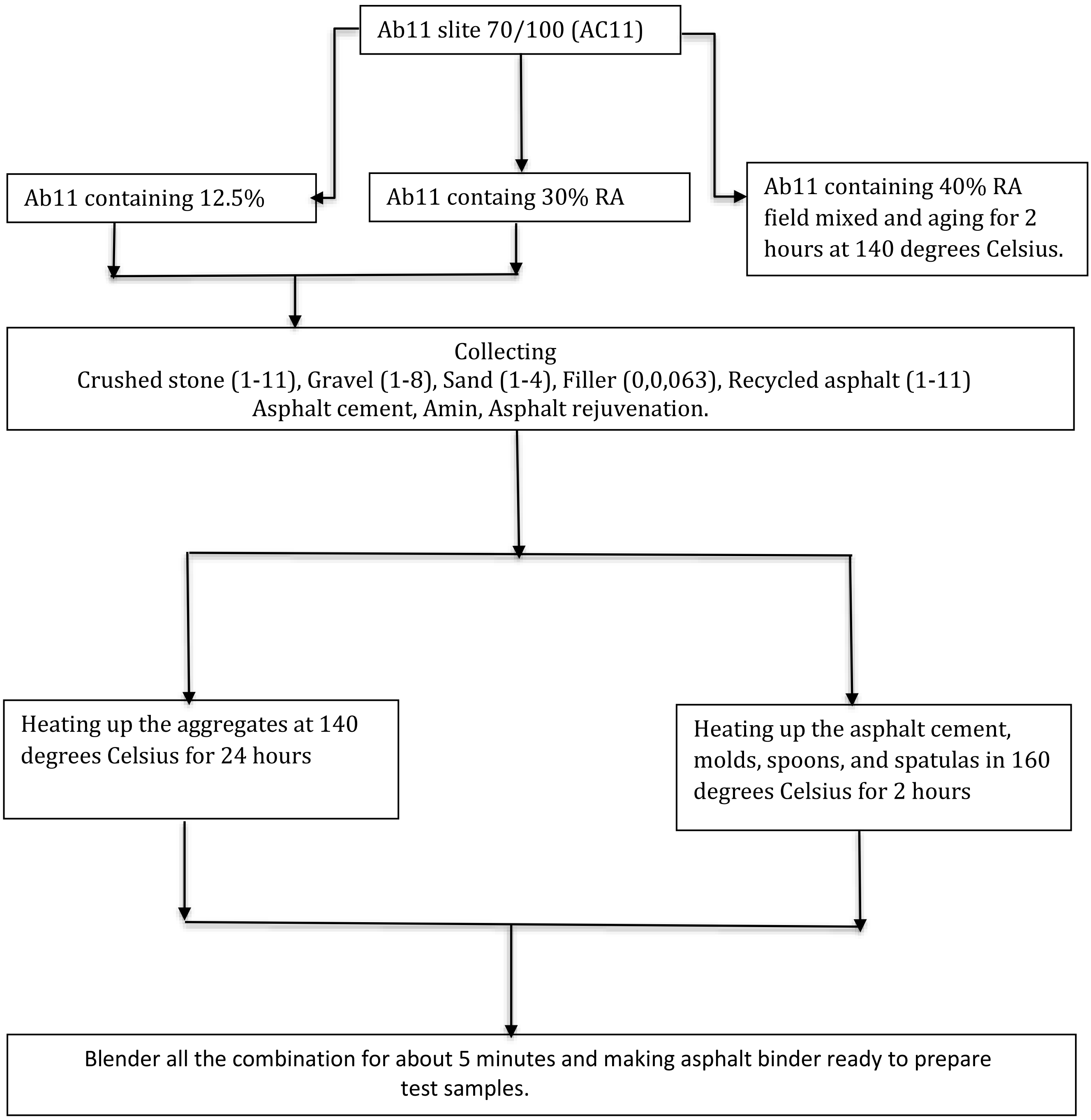

FIGURE 5.13: COLLECTING MATERIALS AND PREPARING ASPHALT BINDER WITH DIFFERENT PERCENTAGES OF RECYCLED ASPHALT(RA)

Summary of the preparing the testing specimen to test dynamic modulus.

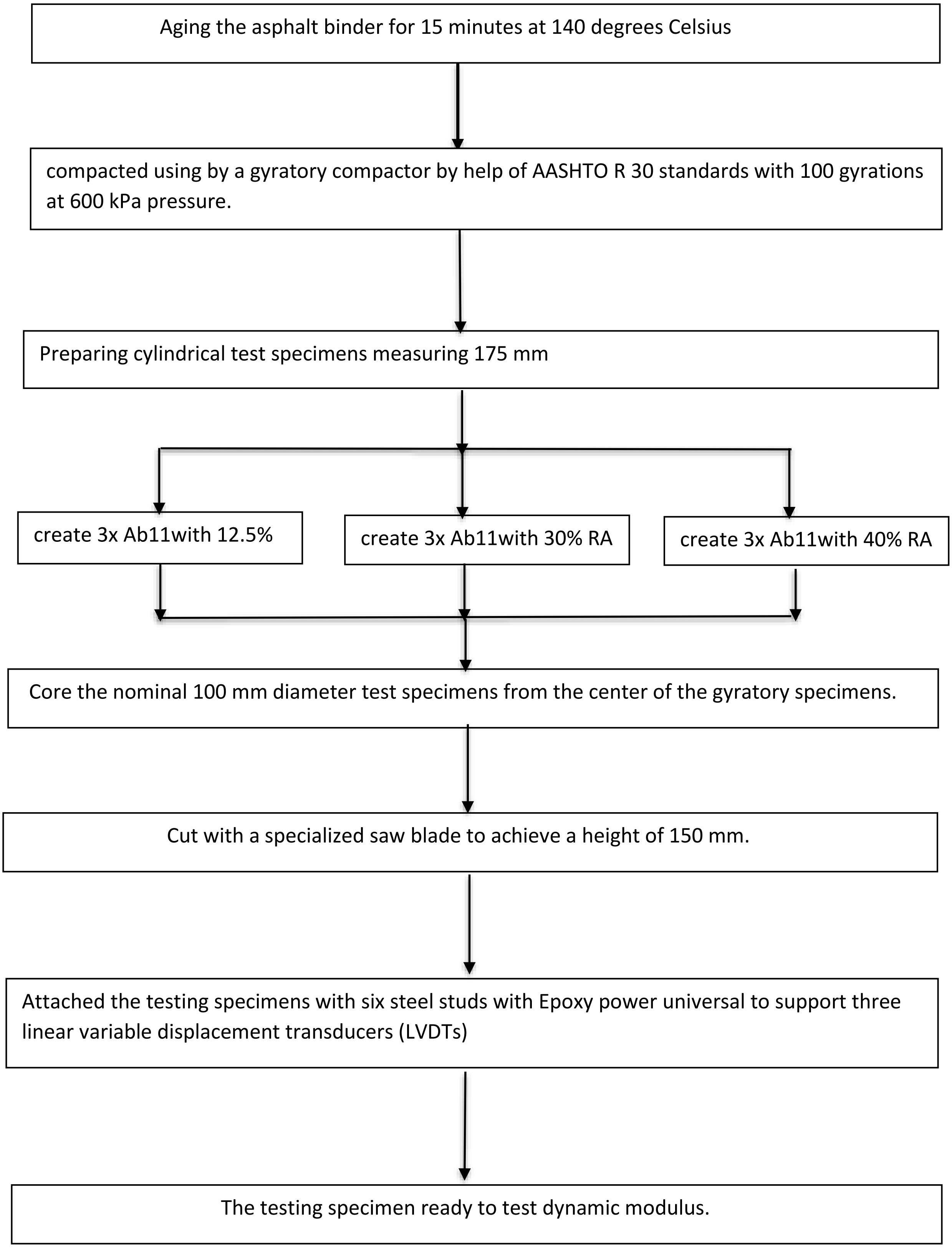

FIGURE 5.14: PREPARING THE TESTING SPECIMEN TO TEST DYNAMIC MODULUS.

Summary of testing dynamic modulus test and phase angle.

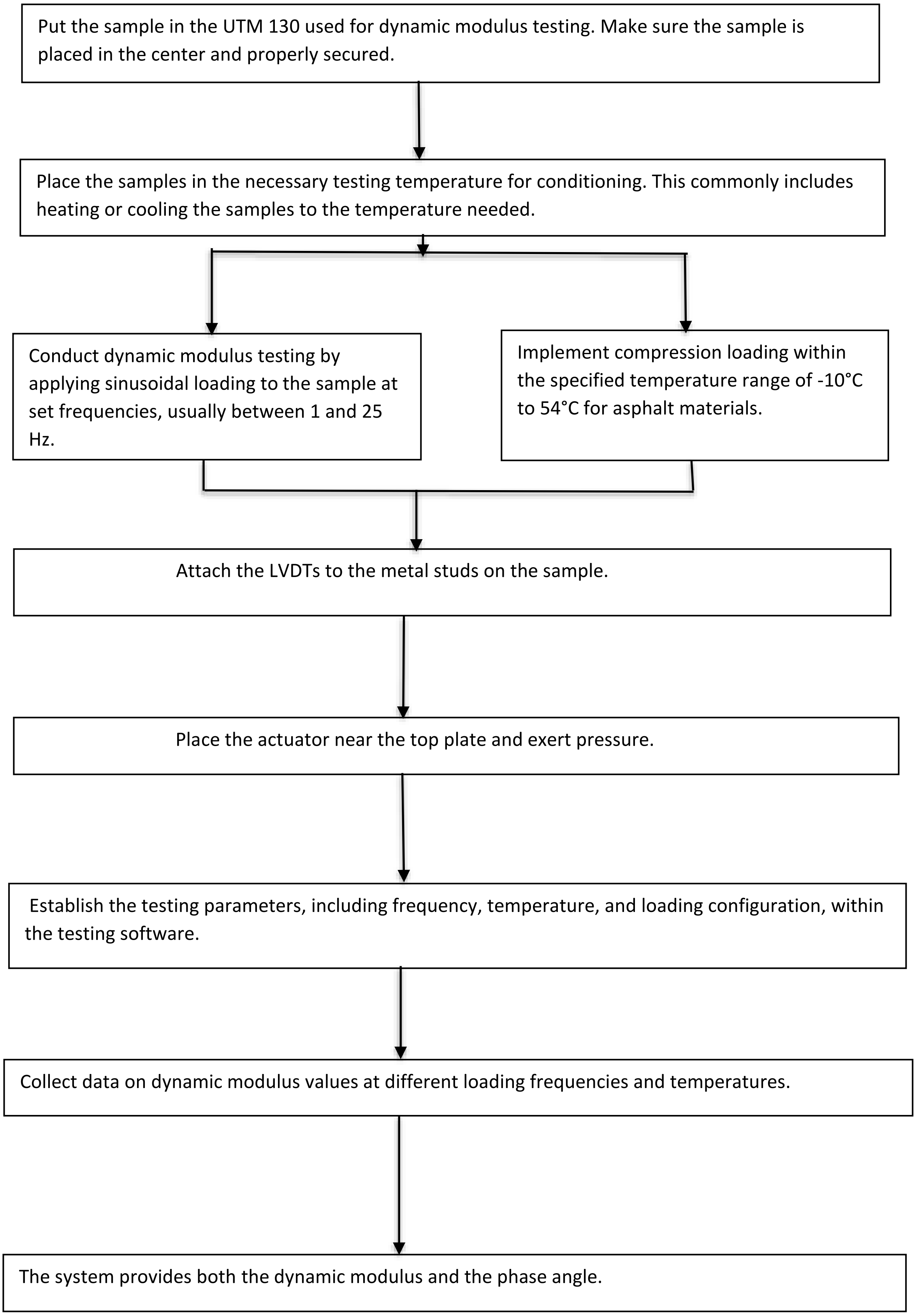

FIGURE 5.15: TEST PROCEDURES FOR DYNAMIC MODULUS OF HMA SAMPLES.

6. Method

6.1. Techniques for Searching:

In order to accomplish this task, I decided to conduct an in-depth literature review. It is vital, though, to emphasize the importance of using a reliable search engine when conducting this literature review. Due to its excellent effectiveness at efficiently gathering and accessing results, Science-Direct was selected as the search engine for this master's thesis. It was also chosen because it provided easy access to results when logged in with a student account. In addition, they excel at efficiently gathering results. The user-friendly interface of Science Direct is another reason i chose it for my master research, as it delivers findings in plain, organized, and structured language, which makes it a great choice for providing findings in a straightforward and accessible format. The research methodology also included utilizing various platforms such as Scopus, ResearchGate, Web of Science, Google Scholar, and Google in conjunction with ScienceDirect for the purpose of discovering additional sources of information as an additional step to ensure comprehensive coverage. The findings from this study were then integrated into the IEEE database in order to make sure that there is a comprehensive range of data.

I started by gathering terms for our chosen subject. These terms were used to search for information in ScienceDirect with the query "Development of a Master Curve (E*) Database for Asphalt Mixtures with Recycled Asphalt". The initial search returned a total of 97 results. To narrow down the focus to studies I filtered by publication date. Looking at research published between 2014 and 2024. As a result, I narrowed my search to 72 studies. By applying data filters and concentrating on engineering topics it can further reduce the results to around 23 studies.

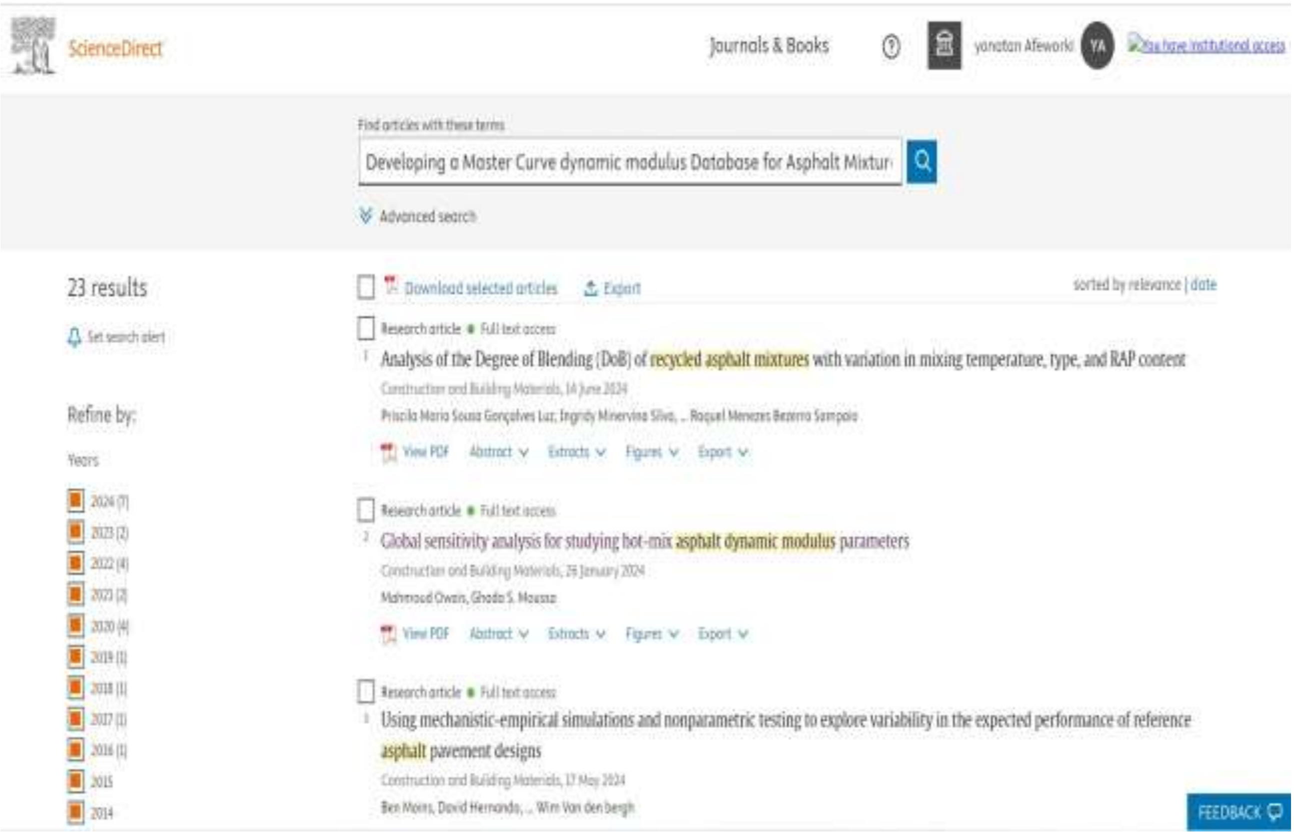

FIGURE 6.1: SCREENSHOT OF RESULT PAGE IN SCIENCEDIRECT.

The criteria I used when choosing articles to be included in my research were rigorous, so I could ensure the relevance, credibility, and quality of my findings. I consulted journals and databases to ensure the article was recent, had a clear purpose, and was correctly cited. I also consulted experts in the field to ensure my articles were reliable and up to date. Finally, I examined the methodology used to ensure the validity of the results.

The important thing for me to note, however, is that not all of these findings apply directly to my project, so please keep that in mind. Based on the results, I carefully sifted through the articles and selected those that could be downloaded and were relevant to our research question. For a more comprehensive understanding of the chosen articles, these articles were downloaded. After confirming that each article I downloaded contained scientific investigations and results, I carefully examined the abstracts of the papers I had downloaded. The articles that were considered to be highly relevant were earmarked for further usage, and a thorough evaluation of their methodology, findings, and conclusions was conducted to establish their credibility and dependability. I was able to select the most trustworthy sources for my study based on my systematic and transparent approach.

As part of my selection process, specific criteria for exclusion have been established to improve the efficiency of the selection process. These criteria prioritize articles that directly address my research question:

- All studies whose keywords were not included in my search terms were eliminated from the analysis.
- In order to ensure my research was relevant to my research question, I carefully reviewed abstracts to exclude studies I decided were irrelevant, based on the findings.
- The studies I considered were all freely accessible to the public, with the exception of those that required payment.

6.1.1. Choosing Relevant Articles

Based on the findings of this study the significance of the articles depended largely on the language in which they were published. This review focuses on articles written in English and Norwegian with a preference, for English articles that're least ten pages long. The selection of research studies mentioned in these articles was not limited by location. My criteria for choosing articles included conducting investigations presenting results and conclusions to our research question and sub questions.

When searching for information on "Development of a Master Curve Database for Asphalt Mixtures Containing Recycled Asphalt " I did not restrict based on publication dates, to available information. I prioritized publications during my selection process until I found sources that addressed my thesis question adequately. Ultimately, I selected articles that significantly contributed to my conclusions and discoveries.

7. Result

The modulus of the mixtures (|E*|) test was conducted on three samples containing the same asphalt binder composition, AC11, but varying amounts of recycled asphalt at 12.5%, 30%, and 40%. The data for the 40% recycled asphalt was collected and tested by Dr. Ephrem Taddesse. Utilizing triple samples during the test enables a more precise and dependable evaluation of the mixture's modulus. By examining various samples containing identical compositions but varying levels of recycled asphalt, discrepancies can be recognized and considered, leading to more accurate results and inferences. The test involved conducting approximately 270 individual tests, resulting from 3 mixes, 3 replicates, 5 temperatures, and 6 frequencies. This test provided data on two attributes: modulus (|E*|) and phase angle (δ). By utilizing the |E*| values, the loss modulus (G*) was determined at different frequencies, and the complex modulus test provides insight into both the elastic and viscous characteristics of a compound.

Tables 7.1 through 7.6 below illustrate the results for dynamic modulus and phase angle of asphalt concrete 11 at 12.5%, 30% and 40% Ra content.

TABLE 7.1. TEST MIXTURES: RATIO OF E* OF THE AC11 WITH 12.5% RA MIX

Temp (°C)	Freq (Hz)	Conditioning Temperatu-time	E* Ratio MasterCurve AC11 Conte 12.5% Rap (sample 1)	E* Ratio aster Curve, AC11 Conte- 12.5 % Rap (sample 2)	E* Ratio Master Curve, AC 11 Conte- 12.5% Rap(Sample 3)
-10	25	Overnight	25184	23815	26218
-10	10	Overnight	23562	22181	24327
-10	5	Overnight	22248	20596	22816
-10	1	Overnight	18964	17322	19252
-10	0,5	Overnight	17471	15980	17655
-10	0,1	Overnight	14018	12823	14205
4	25	Overnight	13508	13608	15380
4	10	Overnight	11547	11658	13277
4	5	Overnight	10107	10246	11714
4	1	Overnight	7033	7127	8379
4	0.5	Overnight	5911	6030	7158
4	0.1	Overnight	3663	3766	4635
20	25	3h	5447	5962	6638
20	10	3h	4059	4499	5068
20	5	3h	3183	3568	4058
20	1	3h	1560	1791	2165
20	0,5	3h	1163	1337	1660
20	0,1	3h	541,4	605,9	788
40	25	2h	835,6	796,8	870,5
40	10	2h	605,9	583,1	604,7
40	5	2h	432,7	431,8	418,1
40	1	2h	155,2	153,6	144,9
40	0,5	2h	109,8	99,8	101,5
40	0,1	2h	68,2	65,6	56,5
54	25	2h	302,5	287	308,5
54	10	2h	243,5	188,6	253,5
54	5	2h	196	126,9	206,1
54	1	2h	52,6	72,6	59,1
54	0,5	2h	41,1	53,9	44
54	0,1	2h	30,2	40,5	32,3

TABLE 7.2: TEST MIXTURES: PHASE ANGLE OF AC11 WITH 12.5% RA MIX

		Phase angle (Degrees)		
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
-10	25	6,78	7,7	6,95
-10	20	7,64	8,62	7,88
-10	5	8,42	9,45	8,61
-10	1	10,65	11,50	10,81
-10	0,5	11,79	12,65	11,91
-10	0,1	15,10	15,90	14,93
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
4	25	15,19	15,19	14,01
4	20	17,52	17,49	16,22
4	5	19,42	19,30	17,85
4	1	24,61	24,25	22,36
4	0,5	26,59	26,13	24,21
4	0,1	31,85	31,24	29,25
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
20	25	28,94	28,73	27,4
20	20	31,67	31,85	30,01
20	5	33,19	33,63	31,47
20	1	37,87	38,51	35,91
20	0,5	37,49	38,67	36,04
20	0,1	37,76	38,89	36,51
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
40	25	43,81	48,12	46,01
40	20	35,92	39,38	39,84
40	5	34,29	37,33	39,15
40	1	36,10	40,07	42,58
40	0,5	34,26	36,76	39,81
40	0,1	27,66	35,01	35,97
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
54	25	50,39	57,62	52,07
54	20	31,48	18,58	31,35
54	5	32,15	59,72	32,00
54	1	32,33	31,39	34,33
54	0,5	31,25	29,72	33,68
54	0,1	21,47	8,71	14,93

TABLE 7.3: TEST MIXTURES: RATIO OF E OF THE AC11 WITH 30% RA MIX*

Temp (°C)	Freq (Hz)	Conditioning Temperatu-time	E* Ratio MasterCurve AC11 Conte 30 % Rap (sample 11)	E* Ratio aster Curve, AC 11 Conte- 30 % Rap (sample 2)	E* Ratio Master Curve, AC 11 Conte- 30% Rap Sample 3
-10	25	Overnight	24271	25372	23976
-10	10	Overnight	22642	23638	22294
-10	5	Overnight	21391	22293	21120
-10	1	Overnight	18183	18876	18093
-10	0,5	Overnight	16845	17420	16909
-10	0,1	Overnight	13648	14078	14030
4	25	Overnight	15914	16288	16219
4	10	Overnight	13851	14191	14117
4	5	Overnight	12341	12684	12562
4	1	Overnight	8981	9228	9107
4	0.5	Overnight	7767	7967	7805
4	0.1	Overnight	5179	5234	5223
20	25	3h	6280	6339	7483
20	10	3h	4738	4808	5853
20	5	3h	3767	3820	4762
20	1	3h	1955	1945	2597
20	0,5	3h	1460	1441	1959
20	0,1	3h	671,9	651	947
40	25	2h	1077	1151	1403
40	10	2h	656,1	714,4	859,4
40	5	2h	438,6	473,5	585,8
40	1	2h	142,9	150	195,3
40	0,5	2h	101,7	102,8	138,7
40	0,1	2h	49,2	57,8	68,2
54	25	2h	237,9	387,8	454,5
54	10	2h	206,4	304,9	332,6
54	5	2h	172,7	203,4	225,6
54	1	2h	62,1	59,6	68,1
54	0,5	2h	48,2	40,3	54,6
54	0,1	2h	28,1	30,4	33,7

TABLE 7.4: TEST MIXTURES: PHASE ANGLE OF AC11 WITH 30% RA MIX

		Phase angle (Degrees)		
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
-10	25	6,94	7,25	6,86
-10	20	7,84	8,18	7,57
-10	5	8,56	8,95	8,21
-10	1	10,7	11,16	10,17
-10	0,5	11,79	12,28	11,15
-10	0,1	14,73	15,29	13,88
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
4	25	13,16	13,32	13,49
4	20	15,08	15,25	15,47
4	5	16,71	16,88	17,07
4	1	21,21	21,34	21,47
4	0,5	23,01	23,19	23,25
4	0,1	28,12	28,45	27,97
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
20	25	27,63	27,41	25,33
20	20	30,72	30,37	27,99
20	5	32,57	32,12	29,60
20	1	37,94	37,06	34,26
20	0,5	38,59	37,86	35,06
20	0,1	39,82	39,84	36,17
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
40	25	41,35	41,11	40,88
40	20	40,27	39,09	39,82
40	5	39,85	38,85	39,37
40	1	41,96	42,13	41,79
40	0,5	38,73	39,89	38,77
40	0,1	30,40	27,58	34,36
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
54	25	51,48	50,51	46,48
54	20	28,02	34,68	34,33
54	5	42,39	35,87	44,25
54	1	33,95	35,40	38,01
54	0,5	30,49	33,43	35,48
54	0,1	29,86	25,93	35,44

TABLE 7.3: TEST MIXTURES: RATIO OF E OF THE AC11 WITH 40% RA MIX*

Temp (°C)	Freq (Hz)	Conditioning Temperatu-time	E* Ratio MasterCurve AC11 Conte 40 % Rap (sample 1)	E* Ratio aster Curve, AC 11 Conte- 40 % Rap (sample 2)	E* Ratio Master Curve, AC11 Conte- 40% Rap Sample 3
-10	25	Overnight	30125	27412	30213
-10	10	Overnight	28739	26015	29243
-10	5	Overnight	27581	25025	27112
-10	1	Overnight	24655	22190	24078
-10	0,5	Overnight	23401	21045	22728
-10	0,1	Overnight	20365	18312	19601
4	25	Overnight	20343	20890	19934
4	10	Overnight	18412	18877	18116
4	5	Overnight	16860	17372	16531
4	1	Overnight	13239	13844	12992
4	0.5	Overnight	11731	12372	11514
4	0.1	Overnight	8422	9130	8231
20	25	3h	9779	10431	9508
20	10	3h	7924	8528	7652
20	5	3h	6603	7220	6319
20	1	3h	3955	4565	3781
20	0,5	3h	3116	3679	2945
20	0,1	3h	1643	1985	1511
40	25	2h	1720	1965	1908
40	10	2h	1114	1246	1229
40	5	2h	800,2	888,8	950,6
40	1	2h	404,9	455,7	448,8
40	0,5	2h	331,9	375,5	353,6
40	0,1	2h	234,4	263	272,3
54	25	2h	861	1027	630
54	10	2h	476,8	650	418,2
54	5	2h	468,6	481,9	336,9
54	1	2h	201,5	261,6	193,4
54	0,5	2h	177,2	238,4	181
54	0,1	2h	146,5	190	160,1

TABLE 7.4: TEST MIXTURES: PHASE ANGLE OF AC11 WITH 40% RA MIX

		Phase angle (Degrees)		
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
-10	25	4,97	6,53	6,25
-10	20	5,31	6,81	6,3
-10	5	5,84	7,31	6,32
-10	1	6,8	8,25	7,48
-10	0,5	7,31	8,47	7,96
-10	0,1	8,88	9,64	9,76
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
4	25	10,09	9,86	10,52
4	20	11,27	10,96	11,78
4	5	12,31	11,87	12,82
4	1	15,36	14,68	16,28
4	0,5	16,94	16,06	17,78
4	0,1	21,31	19,9	21,93
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
20	25	19,74	19,56	20,44
20	20	22,46	22,28	23,41
20	5	24,69	24,31	25,34
20	1	30,73	29,57	31,06
20	0,5	32,9	31,41	33,04
20	0,1	39,75	35,32	36,57
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
40	25	20,78	37,78	40,88
40	20	28,73	37,41	39,57
40	5	32,16	36,35	38,27
40	1	37,2	31,93	36,08
40	0,5	38,4	28,38	31,34
40	0,1	37,6	20,16	22,34
Temp(°C)	**Freq (Hz)**	**Sample 1**	**Sample 2**	**Sample 3**
54	25	15,62	36,26	39,7
54	20	21,48	32,44	34,36
54	5	26,29	30,24	31,07
54	1	29,94	24,3	24,49
54	0,5	32,24	21,27	19,17
54	0,1	39,36	13,65	13,13

N.B: The summary of the dynamic modulus and phase angle of the model, as well as their overall averages, can be found in **Appendix C and D**

The Excel database of dynamic modulus was generated by entering test results from the Universal Testing Machine (UTM 130) into an Excel sheet for plotting dynamic modulus, master curve, and phase angle. The information consisted of the frequencies at which loads were applied, varying temperatures, and dynamic modulus values corresponding to different amounts of Rap asphalt (12.5%, 30%, and 40%) in the AC11 mix with a penetration grade of 70/100 and was obtained from NCC for use in this study. This database enabled a thorough examination and comparison of the dynamic moduli values at different frequencies and temperatures. Analyzing and comparing dynamic modulus values at different frequencies and temperatures gave important information on the asphalt mixture's behavior. By studying how the dynamic modulus varied with various loading frequencies and temperatures, they could pinpoint the best conditions for optimal performance of the asphalt mixture. This data could steer future asphalt design and construction methods to improve durability and lifespan.

The average value of the dynamic modulus test data, calculated from three types of data replications during the test, is plotted on the master curve in **Figure 8.1**, Is described in **Appendix F, G and H**. This curve represents an asphalt mixture of AC11 with 12,5, 30 and 40% Rap. The frequencies consist of 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz. In addition, testing was conducted at five different temperatures: -10°C, 4°C, 20°C, 40°C, and 55°C.
The specifics of these findings will be addressed in the discussion section.
The graph in **Figure 7.1, 7.2 and 7.3** displays a dynamic modulus test done on an AC11 mix with 12.5% ,30% and 40% Rap asphalt. Both the x-axis (loading frequency) and y-axis (dynamic modulus) are represented in natural numbers on an arithmetic scale.

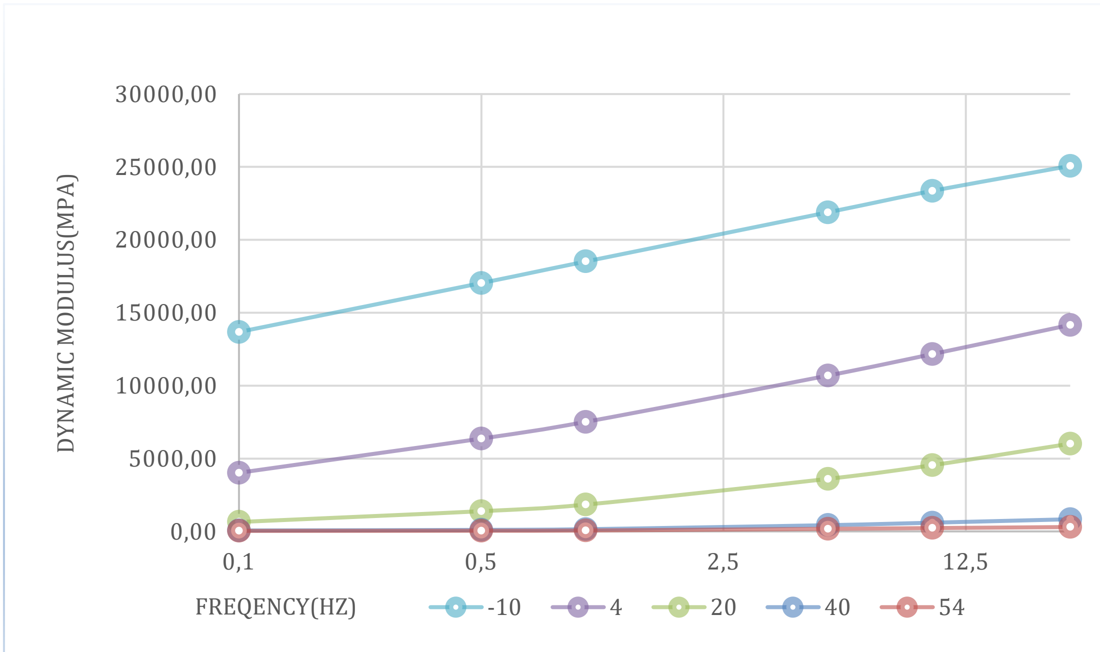

FIGURE 7.1: DYNAMIC MODULUS TEST OF AC11 WITH CONTENT OF 12,5% RA ASPHALT MIXTURE.

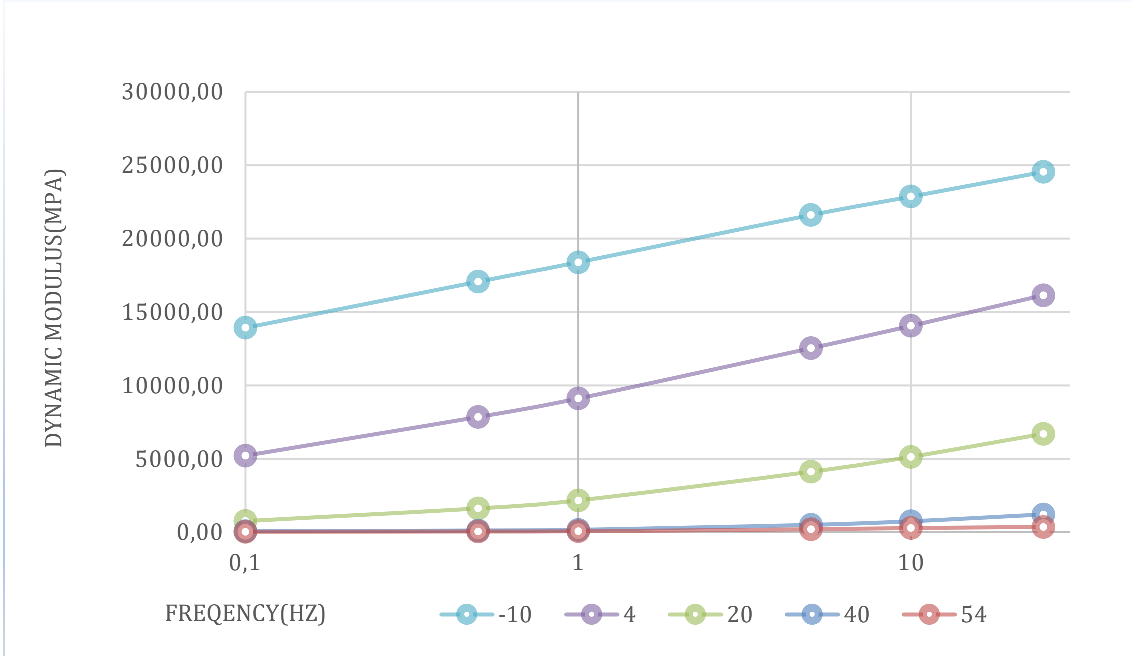

FIGURE 7.2: DYNAMIC MODULUS TEST OF AC11 WITH CONTENT OF 30% RA ASPHALT MIXTURE.

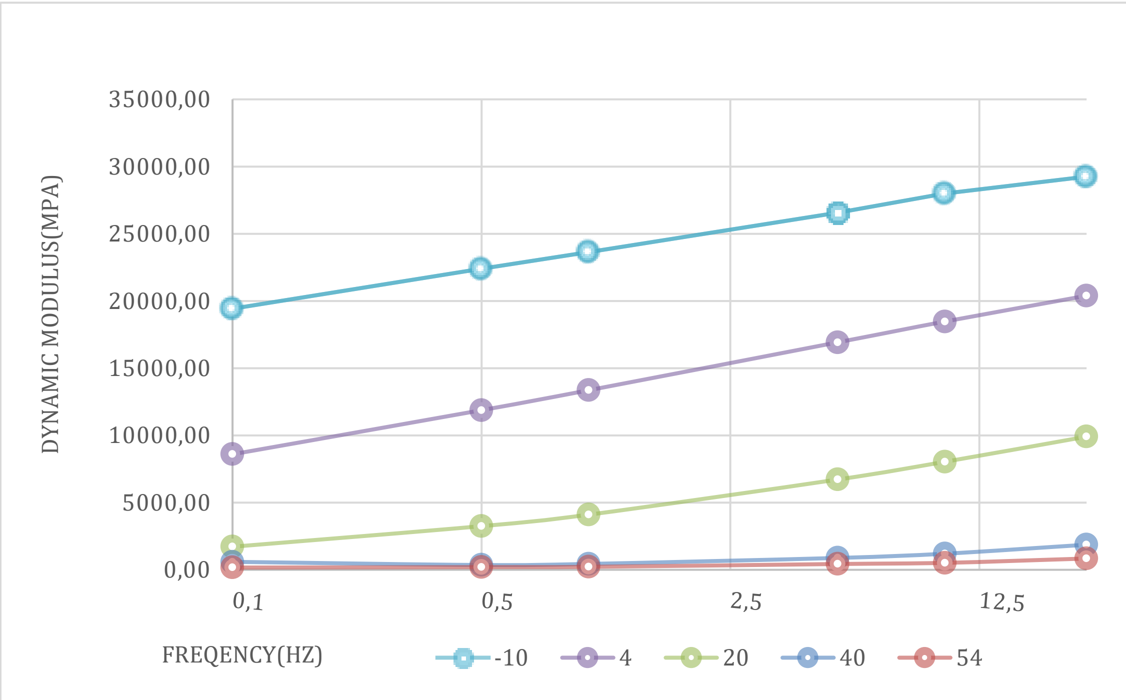

FIGURE 7.3:DYNAMIC MODULUS TEST OF AC11 WITH CONTENT OF 40% RA ASPHALT MIXTURE.

Below, in **Figure 7.4 to 7.6** shows a Phase angle test conducted on an AC11 blend with 12.5, 30 and 40% Rap asphalt, where the x-axis represents the loading frequency, and the y-axis represents the Phase angle in whole numbers on an arithmetic scale.

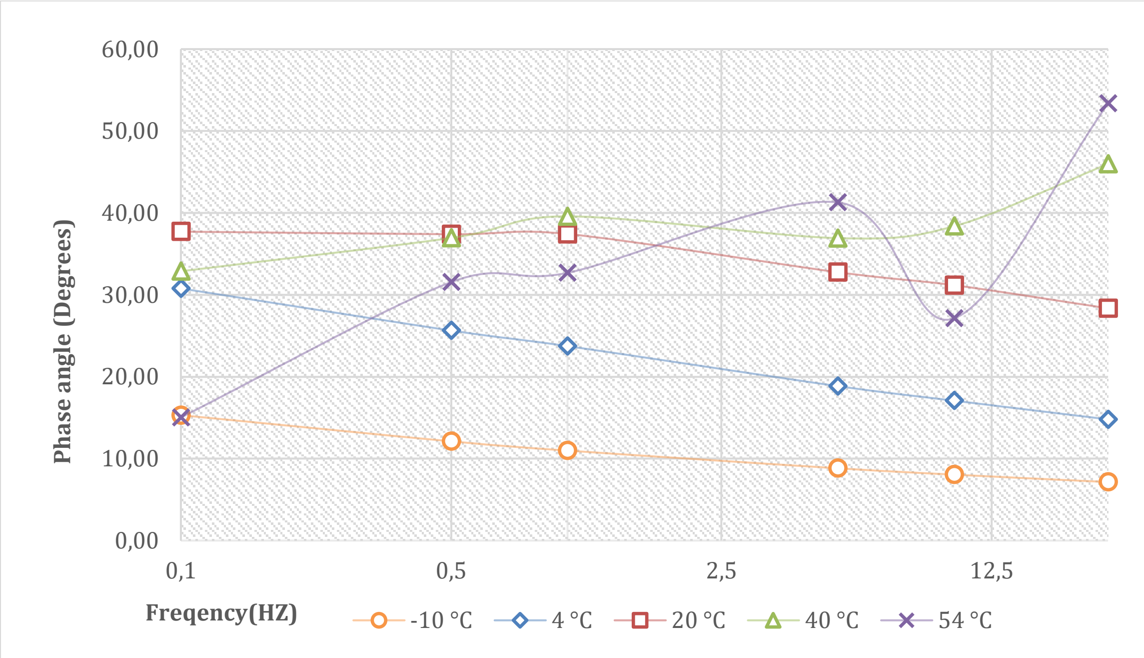

FIGURE 7.4: PHASE ANGLE OF AC11 WITH CONTENT OF 12,5% RA ASPHALT MIXTURE.

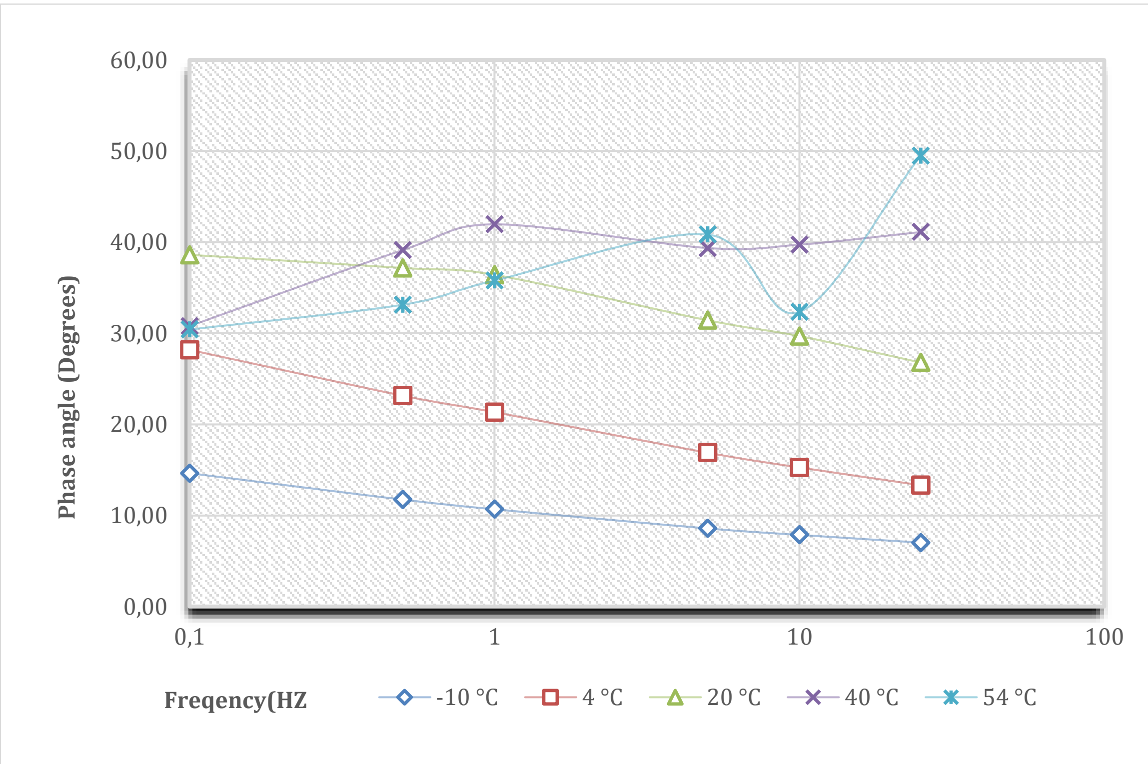

FIGURE 7.5: PHASE ANGLE OF AC11 WITH CONTENT OF 30% RA ASPHALT MIXTURE.

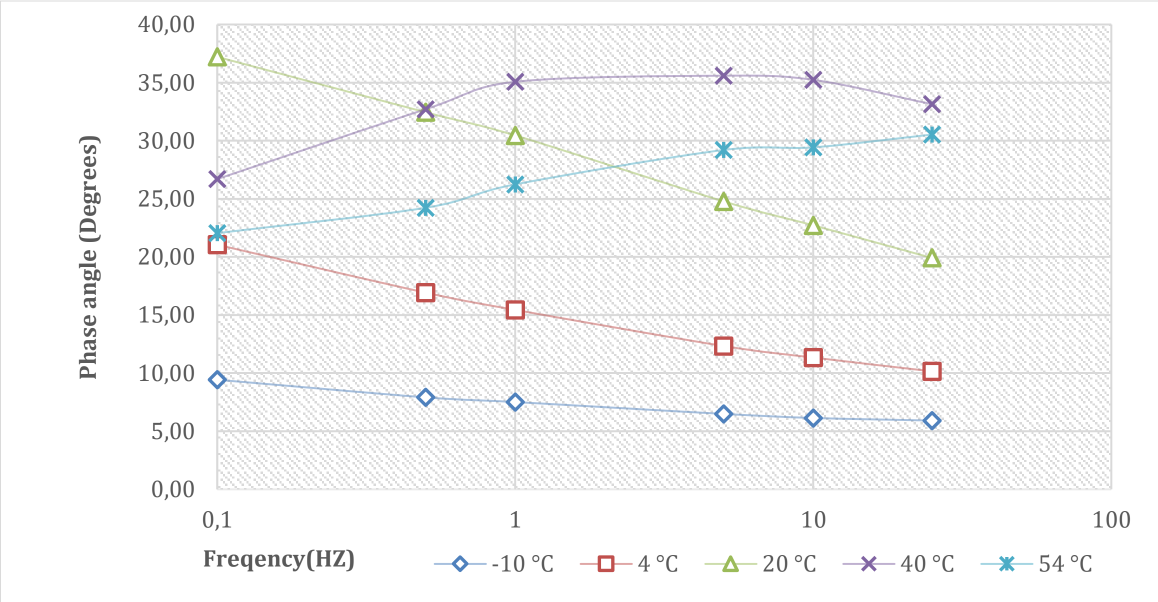

FIGURE 7.6: PHASE ANGLE OF AC11 WITH CONTENT OF 40% RA ASPHALT MIXTURE.

The master curve shown in **Figure 7.7, 7.8 and 7.9** below was created using data from the dynamic modulus test. The Sigmoid function was used to calculate this data as showed in appendix, F,G and H resulting in the master curve displayed in **Figure 7.7, 7.8 and 7.9**. The illustration below depicts loading frequency on the x-axis using numbers and on the y-axis using a semi-logarithmic scale.

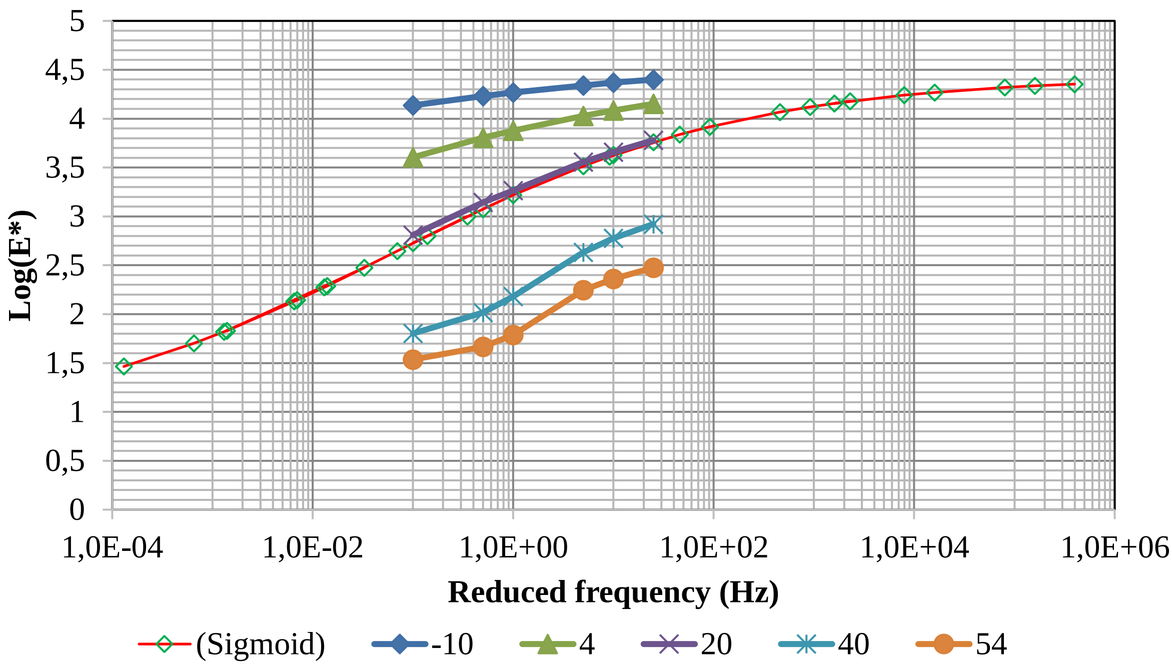

FIGURE 7.7: SHOWS THE RELATIONSHIP BETWEEN LOG(E*) AND LOADING FREQUENCY FOR THE MASTER CURVE OF AC11 MIXTURE CONTAINING 12.5% RA ASPHALT, AT 5 TEMPERATURES AND 6 FREQUENCIES.

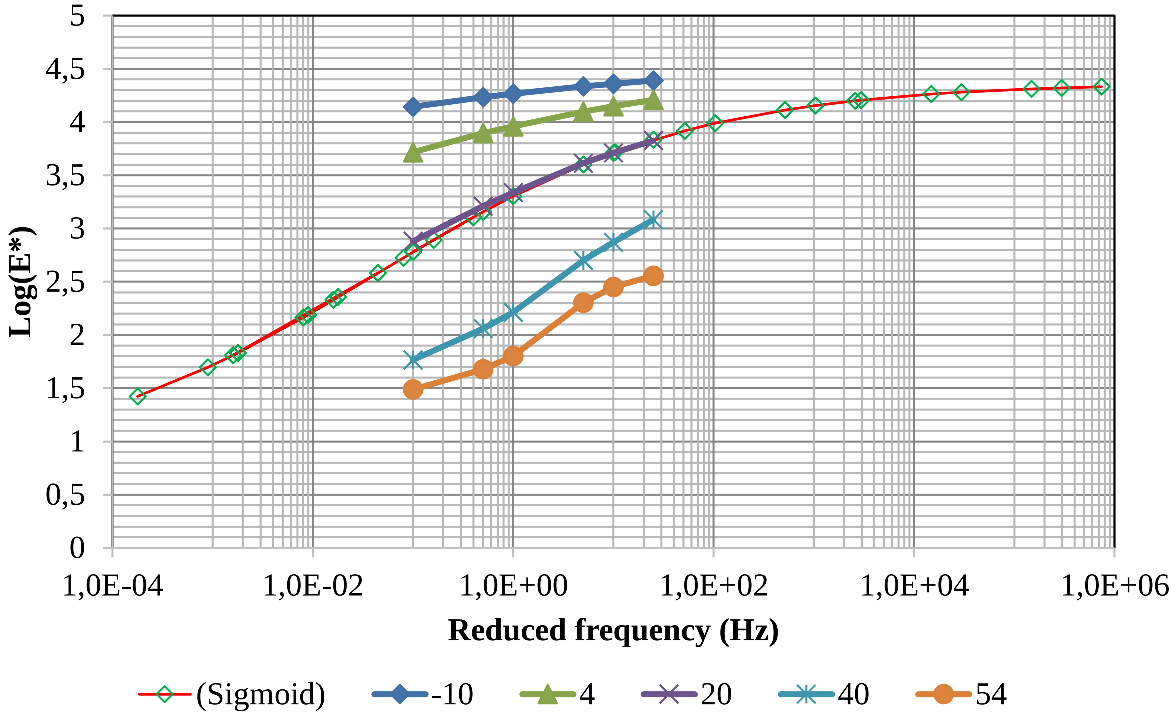

FIGURE 7.8: SHOWS THE RELATIONSHIP BETWEEN LOG(E*) AND LOADING FREQUENCY FOR THE MASTER CURVE OF AC11 MIXTURE CONTAINING 30% RA ASPHALT, AT 5 TEMPERATURES AND 6 FREQUENCIES.

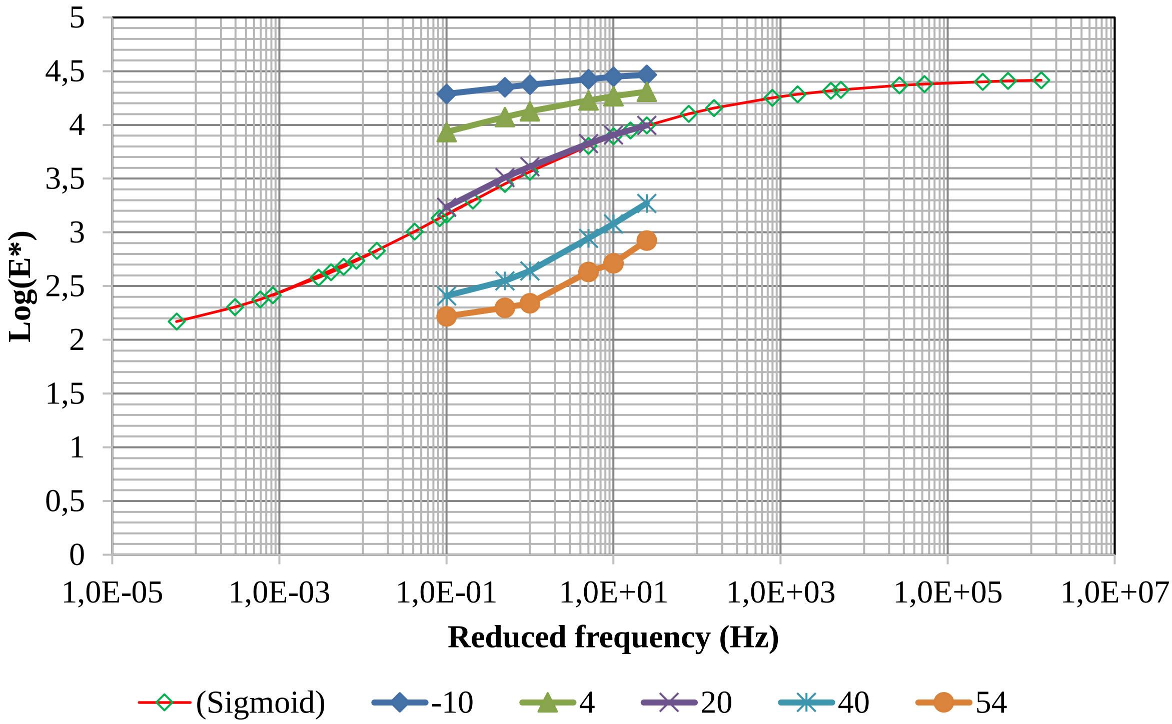

FIGURE 7.9: SHOWS THE RELATIONSHIP BETWEEN LOG(E*) AND LOADING FREQUENCY FOR THE MASTER CURVE OF AC11 MIXTURE CONTAINING 40% RA ASPHALT, AT 5 TEMPERATURES AND 6 FREQUENCIES.

The shift factor shown in **Figure 7.10, 7.11 and 7.12** below was created using data from the dynamic modulus test. The WLF equation was used for determining the shift factor of asphalt mixtures by relating to temperature. calculate this data as showed in appendix, F, G and H resulting in the master curve displayed in **Figure 7.10, 7.11 and 7.12**. The illustration below depicts temperature on the x-axis using numbers and, on the y-axis, using log-linear equation.

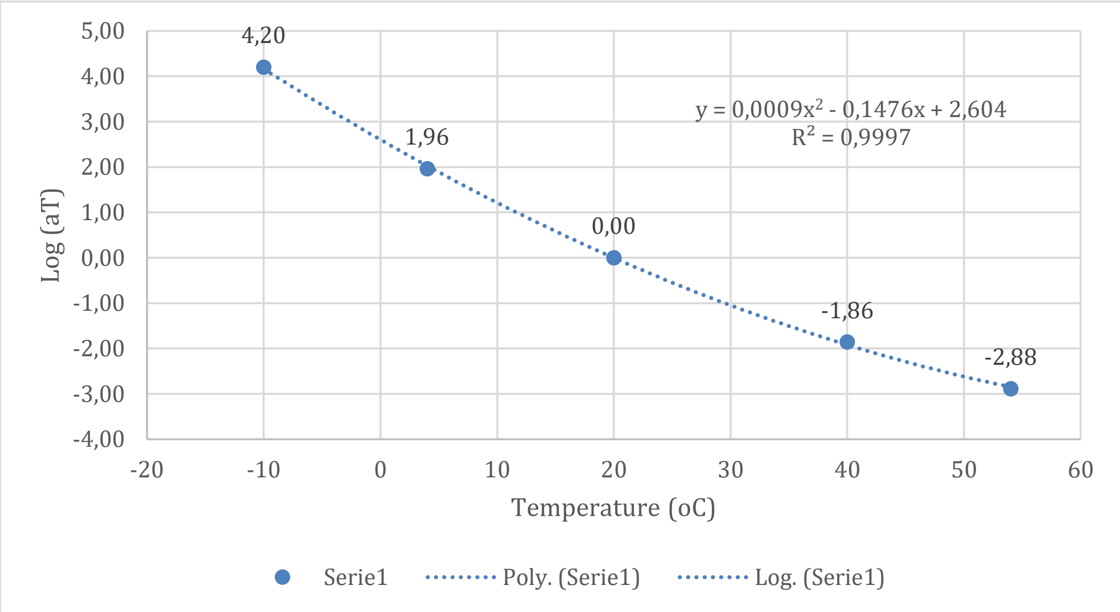

FIGURE 7.10: SHIFT FACTOR VERSUS TEMPERATURE FOR AC11 WITH 12,5% RA

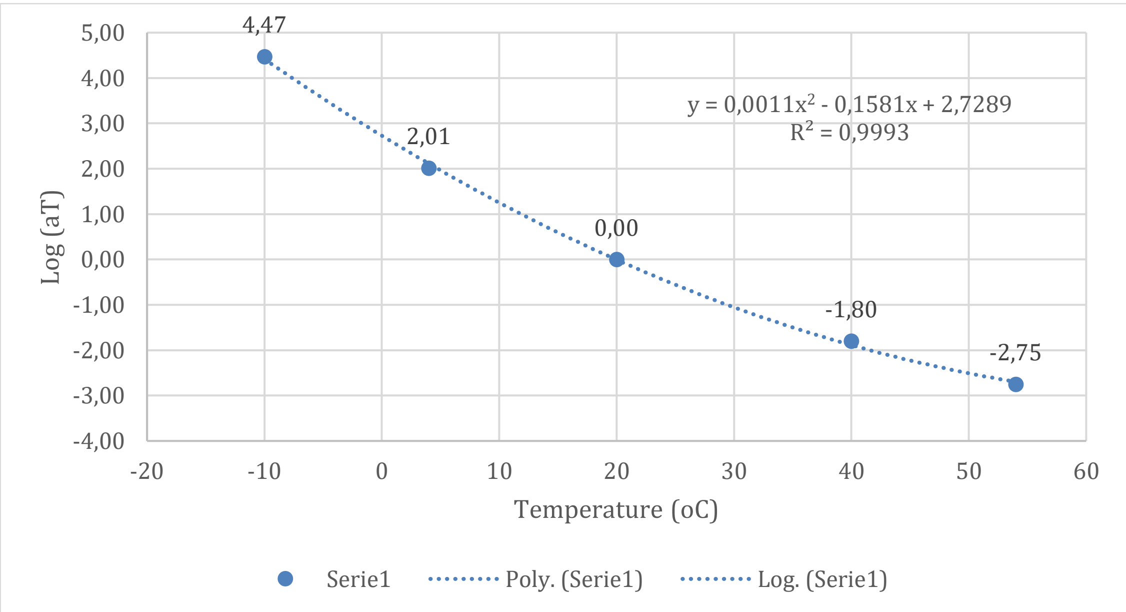

FIGURE 7.11: SHIFT FACTOR VERSUS TEMPERATURE FOR AC11 WITH 30% RA

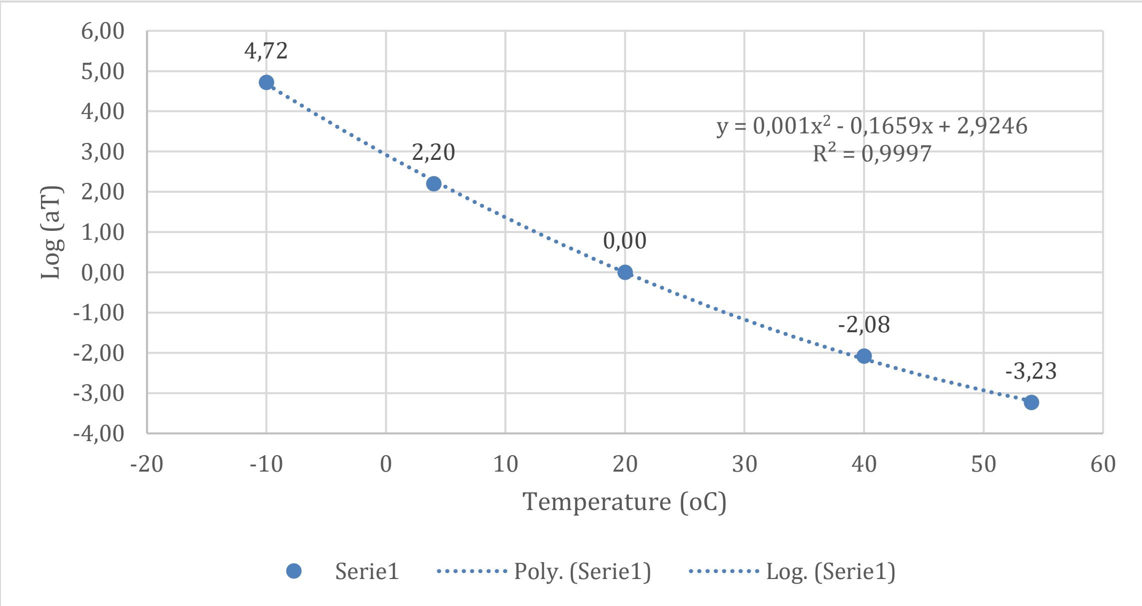

FIGURE 7.12: SHIFT FACTOR VERSUS TEMPERATURE FOR AC11 WITH 40% RA

8. Discussion

8.1. Findings from Dynamic Modulus Testing on Asphalt Mix AC11

The dynamic modulus tests carried out on the asphalt mixture AC11 offer important information on the material's response to varying temperatures and frequencies. By conducting thorough testing, engineers gain valuable understanding of a material's stiffness, strength, and durability when subjected to actual stresses in the real world - essential factors in determining its suitability for various uses. This research assessed the dynamic modulus by testing different temperature conditions from -10 to 54°C and six frequency ranges from 25 to 0.1 Hz, to understand the influence of these factors on the dynamic modulus measurement. Surprisingly, at a temperature of 54°C, the decline in these values is not as significant. At this temperature, the behavior may be mainly affected by the aggregates interlocking, followed by the asphalt binder properties. This study helps in creating a Master Curve Database for Asphalt Mixtures that have Recycled Asphalt in them.

8.1.1. Effect of temperature and frequency on dynamic modulus

In **Figure 7.1, 7,2 and 7,3** shows over in the results, there is a noticeable correlation between dynamic modulus, temperature, and frequency. Increasing frequency leads to an increase in dynamic modulus, while increasing temperature leads to a decrease in dynamic modulus. This trend demonstrates the material's reactions to various loading situations. The first dynamic modulus tests done at each temperature serve as a baseline for determining later dynamic moduli at different temperatures and frequencies.

Understanding the mechanical behavior of materials is crucial, with temperature and frequency playing a key role in influencing the dynamic modulus. As temperatures increase, materials usually become less stiff and more pliable because molecules move more easily due to increased thermal energy. This enhanced mobility decreases the ability to resist deformation, resulting in decreased dynamic modulus values. On the other hand, increased frequencies can increase flexibility by reducing the time for energy dissipation processes such as viscoelasticity, leading to higher values of dynamic modulus. Nonetheless, materials exhibit increased viscous behavior at lower frequencies, leading to reduced values of dynamic modulus. This complex connection demonstrates how materials exhibit diverse reactions to different types of stress, with temperature and frequency playing crucial roles in determining dynamic modulus values. Comprehending these impacts is crucial for enhancing material functionality in various uses and conditions.

- Frequency increases, the dynamic modulus also increases.
- Temperature increases, the dynamic modulus decreases.

8.1.2. Effect of temperature and frequency on phase angle

The chart in **Figure 7.4, 7.5 and 7.6** illustrates how temperature and frequency have a strong impact on the phase angle of materials, especially in asphalt mixes. At decreased temperatures, asphalt shows greater flexibility, approaching a phase angle of zero, because of a rise in bitumen viscosity. On the other hand, with increasing temperatures, the viscosity of bitumen decreases, resulting in a higher phase angle and a more viscous consistency. This change shows a reduction in the rigidity of the asphalt mix. Moreover, the importance of frequency cannot be overstated: increased frequencies lead to reduced phase angles and show more elastic behavior, whereas decreased frequencies cause larger phase angles at higher temperature, demonstrating a more viscous response. Comprehending how temperature and frequency impact phase angle is crucial for maximizing material performance, particularly in applications such as Hot Mix Asphalt (HMA). Nevertheless, accurate measurement of phase angles can be difficult when temperature and frequency intersect, as there may be challenges such as gage points loosening, especially in fine aggregate matrices with moisture conditioning. This requires careful attention during testing and analysis. **Figure 7.4 to 7.6** illustrates, how the phase angle of each asphalt mixture changes with loading frequency. This shows that the change in phase angle with frequency varies depending on the temperature. As the frequency of loading increases at test temperatures of -10°C, 5°C, and 20°C, the phase angle gradually decreases. This pattern suggests that the cold temperature leads to lower viscosity and higher elasticity in the asphalt mixture as the loading frequency increases. At test temperatures of 40°C and 54°C, the phase angle of the asphalt mix increases in line with the frequency growth. This shows that as temperatures increase, the viscosity of the asphalt mix increases, and its elasticity decreases as the loading frequency rises.

- Frequency decreases, the phase angle decreases at -10, 5 and 20 degrees Celsius and vice versa frequency increases, the phase angle increases in 40 and 54 degrees Celsius.

8.1.3. Obstacles in Material Damage and Uniformity during dynamic modulus testing

Raising the load capacity for -10°C tests on the testing equipment results in a notable increase in the cost of the environmental system. Controlling moisture and preventing ice formation can be challenging due to the potential for harm to fragile specimens. At a temperature of -10°C, materials such as polymers and asphalt binders lose their flexibility, affecting dynamic modulus tests. High temperatures can also impact the precision of strain measurements, particularly at 54°C, causing asphalt mixtures to potentially soften and altering stiffness characteristics and stress distribution. High temperatures reaching 54°C can impair strain measurement precision and harm LVDT sensors, emphasizing the need to factor in real-world constraints during testing or conduct multiple tests. Engineers need to be careful to ensure accurate outcomes, particularly when faced with challenging material resilience [85].

8.2. Comparison of dynamic modulus values for asphalt mixtures with various RA contents

According to the **Table 7.1, 7.3 and 7.5**, there were significant differences in the performance of asphalt mixtures with different levels of recycled asphalt (RA) content based on the analysis of dynamic modulus values. Mixtures with 12.5% and 30% RA showed similar performance, indicating that using less recycled asphalt can still produce similar dynamic modulus values. Nonetheless, the dynamic modulus values were notably affected by the addition of 40% Reclaimed Asphalt Pavement (RAP), suggesting that increasing the amount of recycled asphalt could improve performance measurements.

The significant effect seen with 40% RAP content highlights the advantages of increased amounts of recycled asphalt. Mixtures containing higher RAP content showed increased stiffness and enhanced resistance to deformation, indicated by higher dynamic modulus values. This indicates that increasing the amount of recycled asphalt in the mixture can improve performance and durability, providing important information for optimizing asphalt formulas.

Notice:

- **The asphalt binder AC11 with 40% recycled asphalt (RA) content from Velde, after being aged at 140°C for two hours for to make cylinders to test the dynamic modulus.**

- **The coarse and fine aggregate was collected from NCC, mixed the asphalt binder AC11 with 12,5% and 30% recycled asphalt (RA) in the laboratory in the university of Agder, after being aged at 140°C for 15 minutes for to make cylinders to test the dynamic modulus.**

It means that as it is mentioned above the study was conducted, by collection asphalt mixtures from different suppliers with different aggregate types and aging scenarios, but a study was not conducted to evaluate the impact of various types of aggregates and aging intervals on the performance of asphalt mixtures.

8.3. Developing a Master Curve and Employing Sigmoidal Modeling

Master curves for the modulus were developed in this study to account for how materials change over time using the principle of time temperature superposition. This involved adjusting the modulus data at temperatures based on loading frequency and confinement pressure ensuring a smooth transition of graphs, into a unified function. The research utilized a sigmoidal function and an order polynomial shift factor as outlined in AASHTO T 378-17(2001) to create these master curves. The equations defining the form of the master curve and shift factor functions are provided in order to **Equation (2) and Equation (3).** The Microsoft Excel Solver was then used to determine the parameters by minimizing the differences between measured and predicted values at each temperature/frequency combination for varying levels of confinement pressure.

The master curves of dynamic modulus for samples made using two equations was used. Developed using the sigmoidal function and WLF equation for improved model accuracy described in the theoretical background Section 3.8. The values for R^2 are presented in **Table 8.1.** R^2 values for all asphalt mixtures varied from 0.9993 to 0.9997.

TABLE 8.1: MASTER CURVES AND SHIFT PARAMETERS

Mixture Description	C1	C2	δ	α	β	γ	R^2
AC 11with 12,5% RA	13,7	128,33	0,83	4,43	-0,68	0,57	0,9997
AC 11with 30% RA	11,31	105,84	0,76	4,37	-0,87	0,63	0,9993
AC 11with 40% RA	15,36	127,57	1,89	4,44	-0,65	0,65	0,9997

Table 2 provides a list of master curves and shift parameters. The three shift parameters from Table 2 are applied in **Equation 2 and Equation 3** to find the * E of each blend at various temperatures and loading frequencies within the same range used in * E testing at 20 degree Celsius, after superposition.

The data at different temperatures were adjusted based on frequency until the master curve combined into a singular sigmoidal function, illustrating the master curve with a second-order polynomial correlation between the log E* of the shift factor and the temperature as shown in **Figure 7.2, 7.4 and 7.6**. Time-temperature superposition involved solving the four coefficients (δ, α, β, and γ) of the sigmoidal function simultaneously as outlined in **Equations 2 and 3** specified the values of three coefficients (a, b, and c - where c is a constant) in the second-order polynomial.

8.3.1. Comparison of dynamic modulus master curve under different RA content

Figure 8.1 displays the dynamic modulus master curves at different RA contents. The comparison of dynamic modulus values is done between -10 °C and 10 Hz (low-temperature) and 54 °C and 0.1 Hz (high-temperature).

The inclusion of RA led to an overall rise in the stiffness of the mixes (E*) for all mixes tested, across the temperature and loading frequency range in the E* tests. For instance, Figure 6 illustrates a comparison of master curves displaying the three AC 11 mixtures with varying amounts of RA. In this instance, the E* stiffness of the AC 11 asphalt mixtures is affected by the addition of RA.

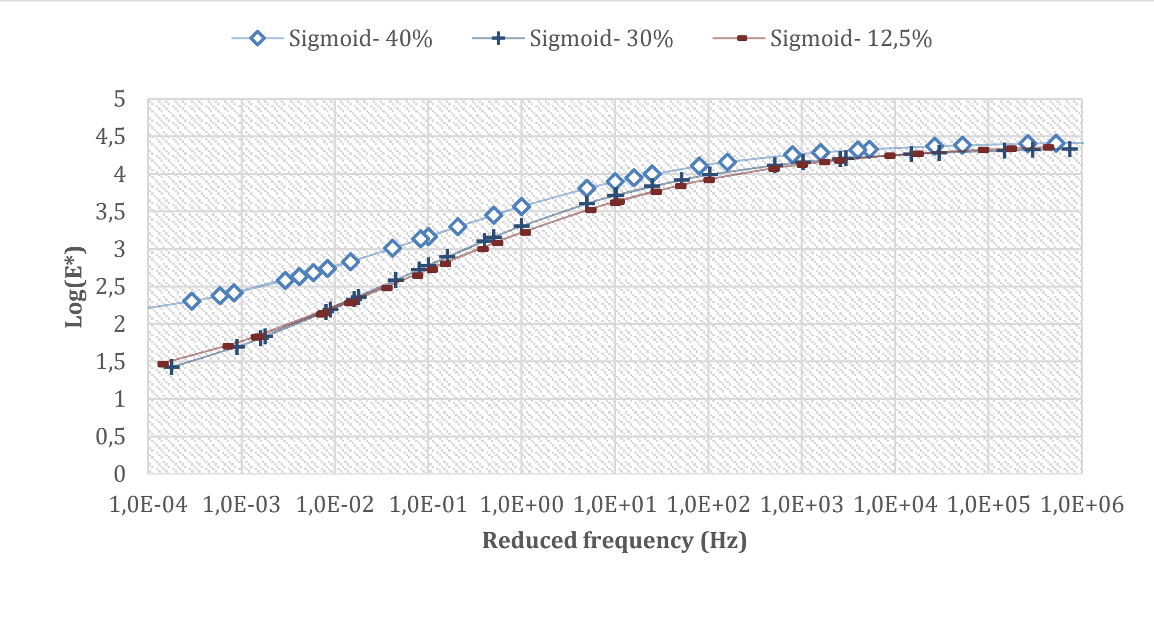

FIGURE 8.1: DEVELOPED DYNAMIC MODULUS MASTER CURVES FOR AC11 CONTAINING 12,5, 30 AND 40% RA

Based on **Figure 8.1**, the dynamic modulus of master curves is greater for AC mixtures with 40% RA compared to AC mixtures with 12.5% and 30% RA. It is believed that AC mixtures with 40% RA have a higher dynamic modulus compared to AC mixtures with 12.5% and 30% RA, indicating that a higher RA percentage leads to increased strength and durability. This discovery underscores the advantages of utilizing a greater proportion of RA in asphalt blends to improve effectiveness and eco-friendliness, while also suggesting further research on the asphalt binder AC11 mixture with 40% RA extracted from the field in a confidential manner to examine the type of aggregate, filler, rejuvenator, and binder, in addition to undergoing 1 hour and 45 minutes more aging than AC11 with 12.5 and 30% RA.

Moreover, Figure 8.1 shows that the dynamic moduli master curve derived from tests on three asphalt concrete mixes, each containing 12.5%, 30%, and 40% reclaimed asphalt, remains consistent across the frequency range of 100 Hz to 10^6 Hz. Differences were observed in the dynamic moduli master curve containing 40% RA when the frequency exceeded 10^-4 Hz or fell below 100 Hz. The dynamic modulus of AC 11 with different amounts of RA showed a significant variation at lower frequencies during the three tests but remained relatively stable at higher frequencies.

8.3.2. Comparison of shift factor under different RA contents

Figure 8.2 displays the WLF shift factor curves for 12.5, 30, 40% RA contents. It was discovered that, the shift factor's logarithm decreased in a linear manner as the temperature rose. The straight regression outcomes are computed based on the linear formula stated under in **Table 8.1**, y represents the projected shift factor, while x represents the temperature. The R^2 of the AC11 containing with 12.5 and 40% RA were higher than containing 30% RA.

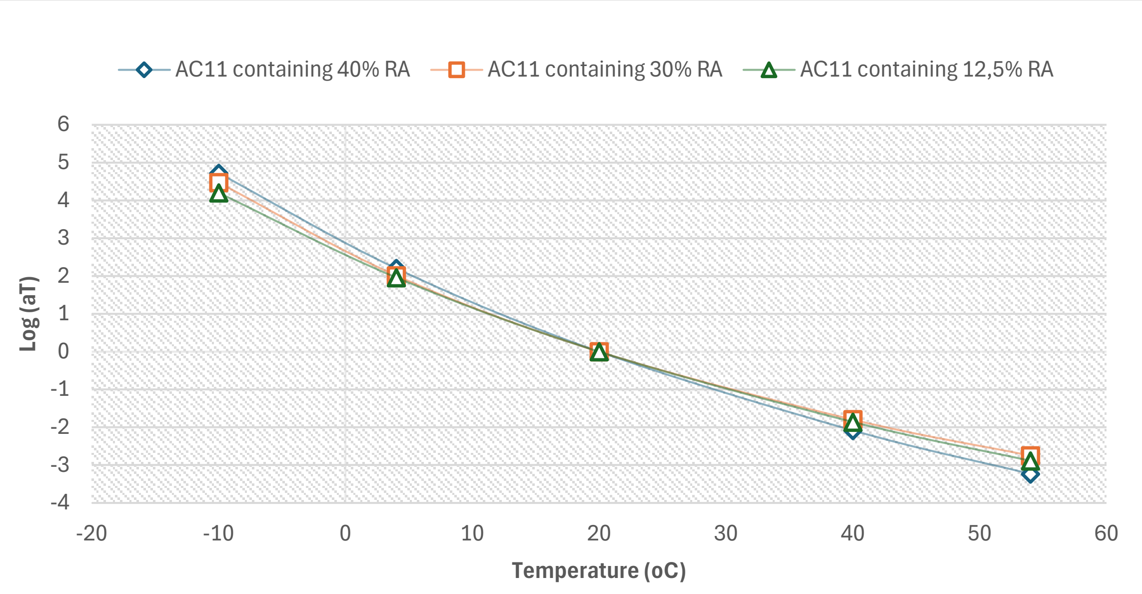

FIGURE 8.2: SHIFT FACTOR CONSTRUCTED CURVES FOR AC11 CONTAINING 12,5, 30 AND 40% RA

TABLE 8.2: SHIFT FACTOR LINEAR REGRESSION EQUATION OF FOR AC11 CONTAINING 12.5, 30 AND 40% RA

Mixture Type	Linear Regression Equation	R^2
AC 11 containing 12,5% Ra	$y= 0,0009x^2 - 0,1476x + 2,604$	0.9997
AC 11 containing 30% Ra	$y= 0,0011x^2 - 0,1581x + 2,7289$	0.9993
AC 11 containing 40% Ra	$y = 0,001 x^2 - 0,1659x + 2,9246$	0.9997

Figure 8.2, illustrates that the shift factor of AC11 includes various RA. At a temperature of -10 °C, the specimens made with 40% RA displayed a greater shift factor compared to the specimens made with 12.5% and 30% RA. At a temperature of 54°C, the AC 11 specimens with 40% RA had a lower shift factor compared to the AC11 containing 12.5 and 30% RA specimens. These findings showed that the shift in amplitude of the dynamic modulus curve was greater in AC11 with 40% RA compared to AC11 with 12.5% and 30% RA, at all temperatures. The varying shift factors at various temperatures indicate that the rheological characteristics of the AC11 blend are impacted by the quantity of recycled asphalt (RA) utilized. In cooler conditions, specimens containing 40% RA show a greater shift factor, reflecting improved stiffness and deformation resistance. Nonetheless, when temperatures increase, the 40% RA specimens tend to have a lower shift factor compared to specimens with less RA, indicating a higher susceptibility to rutting and permanent deformation.

9. Conclusion:

Influence of temperature and frequency on dynamic modulus and phase angle:

- The dynamic modulus decreases with rising temperature but increases with increasing frequency.
- Changes in temperature also impact the phase angle, with decreased temperatures leading to increased flexibility and reduced phase angles, and increased temperatures leading to higher phase angles and a more viscous consistency. These results are essential for comprehending how materials behave mechanically under different loading scenarios, particularly in scenarios like hot mix asphalt (HMA) applications.

Evaluation of dynamic modulus values for various proportions of recycled asphalt.

- Blends containing more recycled asphalt, notably 40% RAP, demonstrate higher stiffness and better resistance to deformation when compared to mixtures with less recycled asphalt. This shows that greater quantities of recycled asphalt can improve performance and longevity in asphalt mixtures.

Designing master curves and employing sigmoidal modeling:

- Master curves were created to comprehend how materials evolve with time by applying the concept of time-temperature superposition.
- The master curves, demonstrating the correlation between dynamic modulus and temperature/frequency, were constructed using sigmoidal modeling.
- The findings show that as the RA content increases, the dynamic modulus values also increase, suggesting improved strength and durability.

In summary:

- The research question focused on how using varying percentages of recycled asphalt affects the creation of a Master Curve database for asphalt mixtures under different conditions. The results show that higher levels of recycled asphalt enhance the performance and durability of asphalt mixtures. This emphasizes the importance of additional research to comprehend intricate material responses and enhance asphalt formulations for different uses and situations.

10. Recommendations:

There are a few recommendations that should be considered regarding the the asphalt mixture and dynamic modulus tests:

- It is recommended to use the same type of aggregate and RA to prepare the samples.

- The aging period of the asphalt mixture should be standardized to obtain reliable results.

- It is advised to utilize a dummy sample in the environmental chamber for measuring temperature with properties resembling those of the test specimens.

- When conducting dynamic modulus tests, it is strongly recommended to use secure gages that are fastened to the surface of specimens to prevent loosening from high temperatures and frequencies, in order to avoid potential problems.

- To ensure accurate results, it is advisable to perform several tests when the temperature reaches 54 °C.

- Explore the option of using AI or ML algorithms for analyzing dynamic modulus test data. This could result in a more effective analysis of data, offering important perspectives on the behavior of asphalt mixtures in various situations.

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12. Appendix

12.1. Appendix A: Asphalt binder AC11 Surf 70/100 data collected from NCC.

Sør

NCC Kontrollgrunnlag for bituminøse vegdekker og bærelag

Reseptnr.	243311004694	Produksjonssted	Klodeborg 1111-08-0307
Produktnavn	Ab 11 slite 70/100 RA	Dekketype	AC 11 surf 70/100 Ab 11
Reseptdato	14.12.2023	Asfaltleverandør	NCC INDUSTRY AS

	Tilsiktet	Toleranse	Kompaktering	Marshall 2*50 slag
Bindemiddel (%)	5.3	0.4	Maks.densitet ρ_m (Mg/m³)	2.651
Hulrom (%)	3.5	1.5	Romdensitet ρ_b (Mg/m³)	2.590
Forbruk (kg/m²)			Hulrom (%)	2.3
Massetemp prod. (°C)	160.0	20.0	Bitumenfylt hulrom (%)	86.1
Dekkets densitet ρ_b (Mg/m³)	2.563		Stabilitet (N)	8433
Maks.teoretisk densitet ρ_m (Mg/m³)	2.656		Flyt (mm)	2.9
Maks. vanninnhold (%)			Stab:Flyt (N/mm)	2908
			Ind. strekkst. (kPa)	

Bindemiddeltype	70/100

	µm				mm						
	63	125	250	500	1	2	4	5.6	8	11.2	16
Tils	8.0	12.0	16.0	23.0	30.0	39.0	51.0	60.0	74.0	96.0	100.0
Tol.	2.0	4.0	4.0	4.0	4.0	6.0	6.0	6.0	6.0	6.0	2.0

Bit = 40 KG
Filler = 45 KG
Stein = 915 KG

100 t/t 30% Gj. Broh
8 - 11 - 27
0 - 8 = 31
58
SAND = 10
Gj. Broh = 30

Tilslag	Forekomst	Dens.	FI	LA	Mølle	Sort	Andel
Pukk	Landvik	3.01	15.0	20	14.0	8-11	27.0
Grus	Landvik	3.01	20.0	20	14.0	0-8	31.0
Grus	Rugsland N	2.66				0-4	10.0
Filler	Egen	3.01				0-0.063	2.0
Asfaltgranulat		2.83				0-11	30.0

Tilsetningsstoff		Mengde (% av bindem.)	
Vedheftningsmiddel	Amin	Mengde (% av bindem.)	0.3

Sted:________________ Dato: 17.01.2024

Underskrift: Damian Serwin

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12.2. Appendix B: Asphalt binder AC11 Surf 70/100 data collected from VELDE.

VELDE

Hoved region

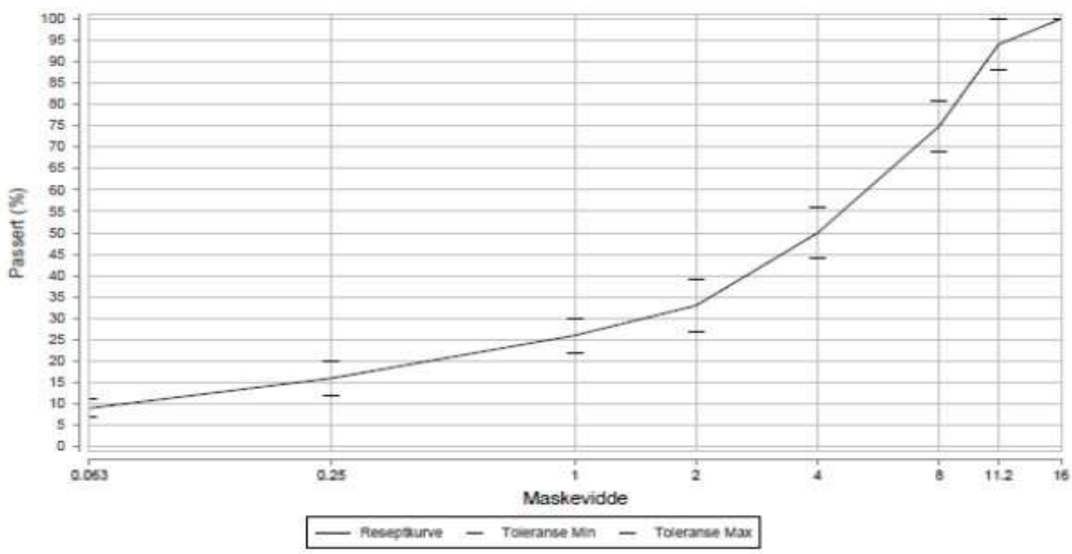
Arbeidsresept for bituminøse vegdekker og bærelag

Reseptnr.	S1111140SLG10V5	Produksjonssted	VELDE PRODUKSJON AS SVILAND
Produktnavn	Ab 11	Dekketype	AC 11 surf 70/100 Ab 11
Reseptdato	30.04.2019	Asfaltleverandør	Velde Produksjon AS

	Tilsiktet	Toleranse	Kompaktering	Marshall 2*50 slag
Bindemiddel (%)	5.8	0.4	Maks.densitet ρ_m (Mg/m³)	2.440
Hulrom (%)	3.5	1.5	Romdensitet ρ_b (Mg/m³)	2.374
Forbruk (kg/m²)			Hulrom (%)	2.7
Massetemp prod. (°C)	160.0	20.0	Bitumenfylt hulrom (%)	83.0
Dekkets densitet ρ_b (Mg/m³)	2.342		Stabilitet (N)	
Maks.teoretisk densitet ρ_m (Mg/m³)	2.427		Flyt (mm)	
Maks. vanninnhold (%)			Stab:Flyt (N/mm)	
			Ind. strekkst. (kPa)	

Bindemiddeltype	70/100 (Renewer 0,3% av bind)

	µm		mm					
	63	250	1	2	4	8	11.2	16
Tils	9.0	16.0	26.0	33.0	50.0	75.0	94.0	100.0
Tol.	2.0	4.0	4.0	6.0	6.0	6.0	6.0	0.0



Tilslag	Forekomst	Dens.	FI	LA	Mølle	Sort	Andel
Filler	Velde Fremmedfiller	2.64		25	10.0	Filler	2.2
Asfaltgranulat	Velde-G10	2.68	20.0	25	10.0	0-11	40.0
Steinmel	Velde	2.64	10.0	25	10.0	0.25-2	11.1
Pukk	Velde	2.64	10.0	25	10.0	2-5	11.8
Pukk	Velde	2.64	10.0	25	10.0	5-8	11.2
Pukk	Velde	2.64	10.0	25	10.0	8-11	21.5
Filler	Velde Egen filler	2.64		25	10.0	Filler	2.2

Tilsetningsstoff	Cellulose	Mengde (% av bindem.)	3.4
Vedheftningsmiddel	Amin	Mengde (% av bindem.)	0.3

Sted: Sandnes

Dato: 01.02.2021

Underskrift: Hernan Mujica

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12.3. Appendix C: The average for the 3 replicates of the data collected from dynamic modulus testing and phase angle with 12.5% Rap mixture.

Average Ratio of E* With 10% Rap mix.

	Dynamic modulus (MPa)					Phase angle (Degrees)			
-10 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	25184	23815	26218	25072,33	6,78	7,7	6,95	7,14
	10	23562	22181	24327	23356,67	7,64	8,62	7,88	8,05
	5	22248	20596	22816	21886,67	8,42	9,45	8,61	8,83
	1	18964	17322	19252	18512,67	10,65	11,5	10,81	10,99
	0,5	17471	15980	17655	17035,33	11,79	12,65	11,91	12,12
	0,1	14018	12823	14205	13682,00	15,1	15,9	14,93	15,31
4 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	13508	13608	15380	14165,33	15,19	15,19	14,01	14,80
	10	11547	11658	13277	12160,67	17,52	17,49	16,22	17,08
	5	10107	10246	11714	10689,00	19,42	19,3	17,85	18,86
	1	7033	7127	8379	7513,00	24,61	24,25	22,36	23,74
	0,5	5911	6030	7158	6366,33	26,59	26,13	24,21	25,64
	0,1	3663	3766	4635	4021,33	31,85	31,24	29,25	30,78
20 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	5447	5962	6638	6015,67	28,94	28,73	27,4	28,36
	10	4059	4499	5068	4542,00	31,67	31,85	30,01	31,18
	5	3183	3568	4058	3603,00	33,19	33,63	31,47	32,76
	1	1560	1791	2165	1838,67	37,87	38,51	35,91	37,43
	0,5	1163	1337	1660	1386,67	37,49	38,67	36,04	37,40
	0,1	541,4	605,9	788	645,10	37,76	38,89	36,51	37,72
40 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	835,6	796,8	870,5	834,30	43,81	48,12	46,01	45,98
	10	605,9	583,1	604,7	597,90	35,92	39,38	39,84	38,38
	5	432,7	431,8	418,1	427,53	34,29	37,33	39,15	36,92
	1	155,2	153,6	144,9	151,23	36,1	40,07	42,58	39,58
	0,5	109,8	99,8	101,5	103,70	34,26	36,76	39,81	36,94
	0,1	68,2	65,6	56,5	63,43	27,66	35,01	35,97	32,88
54 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 2/3	Average
	25	302,5	287	308,5	299,333333	50,39	57,62	52,07	53,36
	10	243,5	188,6	253,5	228,533333	31,48	18,58	31,35	27,1366667
	5	196	126,9	206,1	176,333333	32,15	59,72	32	41,29
	1	52,6	72,6	59,1	61,4333333	32,33	31,39	34,33	32,6833333
	0,5	41,1	53,9	44	46,3333333	31,25	29,72	33,68	31,55
	0,1	30,2	40,5	32,3	34,3333333	21,47	8,71	14,93	15,0366667

12.4. Appendix D: The average for the 3 replicates of the data collected from dynamic modulus testing and phase angle with 30% Rap mixture.

Average Ratio of E* With 30% Rap mix.

	Dynamic modulus (MPa)						Phase angle (Degrees)			
-10 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average		Sample 1	Sample 2	Sample 3	Average
	25	24271	25372	23976	24539,67		6,94	7,25	6,86	7,02
	10	22642	23638	22294	22858,00		7,84	8,18	7,57	7,86
	5	21391	22293	21120	21601,33		8,56	8,95	8,21	8,57
	1	18183	18876	18093	18384,00		10,7	11,16	10,17	10,68
	0,5	16845	17420	16909	17058,00		11,79	12,28	11,15	11,74
	0,1	13648	14078	14030	13918,67		14,73	15,29	13,88	14,63
4 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average		Sample 1	Sample 2	Sample 3	Average
	25	15914	16288	16219	16140,33		13,16	13,32	13,49	13,32
	10	13851	14191	14117	14053,00		15,08	15,25	15,47	15,27
	5	12341	12684	12562	12529,00		16,71	16,88	17,07	16,89
	1	8981	9228	9107	9105,33		21,21	21,34	21,47	21,34
	0,5	7767	7967	7805	7846,33		23,01	23,19	23,25	23,15
	0,1	5179	5234	5223	5212,00		28,12	28,45	27,97	28,18
20 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average		Sample 1	Sample 2	Sample 3	Average
	25	6280	6339	7483	6700,67		27,63	27,41	25,33	26,79
	10	4738	4808	5853	5133,00		30,72	30,37	27,99	29,69
	5	3767	3820	4762	4116,33		32,57	32,12	29,6	31,43
	1	1955	1945	2597	2165,67		37,94	37,06	34,26	36,42
	0,5	1460	1441	1959	1620,00		38,59	37,86	35,06	37,17
	0,1	671,9	651	947	756,63		39,82	39,84	36,17	38,61
40 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average		Sample 1	Sample 2	Sample 3	Average
	25	1077	1151	1403	1210,33		41,35	41,11	40,88	41,11
	10	656,1	714,4	859,4	743,30		40,27	39,09	39,82	39,73
	5	438,6	473,5	585,8	499,30		39,85	38,85	39,37	39,36
	1	142,9	150	195,3	162,73		41,96	42,13	41,79	41,96
	0,5	101,7	102,8	138,7	114,40		38,73	39,89	38,77	39,13
	0,1	49,2	57,8	68,2	58,40		30,4	27,58	34,36	30,78
54 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average		Sample 1	Sample 2	Sample 3	Average
	25	237,9	387,8	454,5	360,066667		51,48	50,51	46,48	49,49
	10	206,4	304,9	332,6	281,3		28,02	34,68	34,33	32,3433333
	5	172,7	203,4	225,6	200,566667		42,39	35,87	44,25	40,8366667
	1	62,1	59,6	68,1	63,2666667		33,95	35,4	38,01	35,7866667
	0,5	48,2	40,3	54,6	47,7		30,49	33,43	35,48	33,1333333
	0,1	28,1	30,4	33,7	30,7333333		29,86	25,93	35,44	30,41

12.5. Appendix E: The average for the 3 replicates of the data collected from dynamic modulus testing and phase angle with 40% Rap mixture.

Average Ratio of E* With 40% Rap mix.

	Dynamic modulus (MPa)					Phase angle (Degrees)			
-10 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	30125	27412	30213	29250,00	4,97	6,53	6,25	5,92
	10	28739	26015	29243	27999,00	5,31	6,81	6,3	6,14
	5	27581	25025	27112	26572,67	5,84	7,31	6,32	6,49
	1	24655	22190	24078	23641,00	6,8	8,25	7,48	7,51
	0,5	23401	21045	22728	22391,33	7,31	8,47	7,96	7,91
	0,1	20365	18312	19601	19426,00	8,88	9,64	9,76	9,43
4 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	20343	20890	19934	20389,00	10,09	9,86	10,52	10,16
	10	18412	18877	18116	18468,33	11,27	10,96	11,78	11,34
	5	16860	17372	16531	16921,00	12,31	11,87	12,82	12,33
	1	13239	13844	12992	13358,33	15,36	14,68	16,28	15,44
	0,5	11731	12372	11514	11872,33	16,94	16,06	17,78	16,93
	0,1	8422	9130	8231	8594,33	21,31	19,9	21,93	21,05
20 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	9779	10431	9508	9906,00	19,74	19,56	20,44	19,91
	10	7924	8528	7652	8034,67	22,46	22,28	23,41	22,72
	5	6603	7220	6319	6714,00	24,69	24,31	25,34	24,78
	1	3955	4565	3781	4100,33	30,73	29,57	31,06	30,45
	0,5	3116	3679	2945	3246,67	32,9	31,41	33,04	32,45
	0,1	1643	1985	1511	1713,00	39,75	35,32	36,57	37,21
40 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	1720	1965	1908	1864,33	20,78	37,78	40,88	33,15
	10	1114	1246	1229	1196,33	28,73	37,41	39,57	35,24
	5	800,2	888,8	950,6	879,87	32,16	36,35	38,27	35,59
	1	404,9	455,7	448,8	436,47	37,2	31,93	36,08	35,07
	0,5	331,9	375,5	353,6	353,67	38,4	28,38	31,34	32,71
	0,1	234,4	1263	272,3	589,90	37,6	20,16	22,34	26,70
54 °C	F(hz)	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
	25	861	1027	630	839,33333	15,62	36,26	39,7	30,5266667
	10	476,8	650	418,2	515	21,48	32,44	34,36	29,4266667
	5	468,6	481,9	336,9	429,13333	26,29	30,24	31,07	29,2
	1	201,5	261,6	193,4	218,83333	29,94	24,3	24,49	26,2433333
	0,5	177,2	238,4	181	198,86667	32,24	21,27	19,17	24,2266667
	0,1	146,5	190	160,1	165,53333	39,36	13,65	13,13	22,0466667

12.6. Appendix F: Excel calculation using to drawing the dynamic modulus, phase diagram, master curve and shift factor diagram with 12,5% RA

	10 %					Yonatan.A	
		Measured				(Sigmoid)	
T	f	E*	Log(E*)	fR	log(f)	log(E*)	Error
-10	25	25072,33	4,40	4,0E+05	5,60	4,353	0,00
-10	10	23356,67	4,37	1,6E+05	5,20	4,335	0,00
-10	5	21886,67	4,34	8,0E+04	4,90	4,319	0,00
-10	1	18512,67	4,27	1,6E+04	4,20	4,269	0,00
-10	0,5	17035,33	4,23	8,0E+03	3,90	4,241	0,00
-10	0,1	13682,00	4,14	1,6E+03	3,20	4,156	0,00
4	25	14165,33	4,15	2,3E+03	3,36	4,178	0,00
4	10	12160,67	4,08	9,2E+02	2,96	4,120	0,00
4	5	10689,00	4,03	4,6E+02	2,66	4,068	0,00
4	1	7513,00	3,88	9,2E+01	1,96	3,917	0,00
4	0,5	6366,33	3,80	4,6E+01	1,66	3,837	0,00
4	0,1	4021,33	3,60	9,2E+00	0,96	3,613	0,00
20	25	6015,67	3,78	2,5E+01	1,40	3,760	0,00
20	10	4542,00	3,66	1,0E+01	1,00	3,627	0,00
20	5	3603,00	3,56	5,0E+00	0,70	3,515	0,00
20	1	1838,67	3,26	1,0E+00	0,00	3,218	0,00
20	0,5	1386,67	3,14	5,0E-01	-0,30	3,076	0,00
20	0,1	645,10	2,81	1,0E-01	-1,00	2,726	0,01
40	25	834,30	2,92	3,5E-01	-0,46	2,999	0,01
40	10	597,90	2,78	1,4E-01	-0,86	2,799	0,00
40	5	427,53	2,63	6,9E-02	-1,16	2,645	0,00
40	1	151,23	2,18	1,4E-02	-1,86	2,289	0,01
40	0,5	103,70	2,02	6,9E-03	-2,16	2,143	0,02
40	0,1	63,43	1,80	1,4E-03	-2,86	1,831	0,00
54	25	299,33	2,48	3,3E-02	-1,49	2,476	0,00
54	10	228,53	2,36	1,3E-02	-1,88	2,276	0,01
54	5	176,33	2,25	6,5E-03	-2,19	2,130	0,01
54	1	61,43	1,79	1,3E-03	-2,88	1,819	0,00
54	0,5	46,33	1,67	6,5E-04	-3,19	1,701	0,00
54	0,1	34,33	1,54	1,3E-04	-3,88	1,465	0,01

$$log|E^*| = \delta + \frac{(\alpha - \delta)}{1 + e^{(\eta - \gamma log f_R)}}$$

T (oC)	T-Tr	aT	log(aT)
-10	-30	15920,52	4,20
4	-16	91,57	1,96
20	0	1,00	0,00
40	20	0,0138974	-1,86
54	34	0,001304	-2,88

	C1	13,77
	C2	128,34
min	δ	0,83
maks	α	4,43
	η	-0,68
	γ	0,57
	LSE	0,09

Shift factor Functions

- **WLF Function:**

$$log(a_T) = -\frac{C_1(T - T_r)}{(T - T_r) + C_2}$$

			DATA		
f,Hz	T,oC	Sample 1	Sample 2	Sample 2/3	Average
25	-10	25184	23815	26218	25072,33
10	-10	23562	22181	24327	23356,67
5	-10	22248	20596	22816	21886,67
1	-10	18964	17322	19252	18512,67
0,5	-10	17471	15980	17655	17035,33
0,1	-10	14018	12823	14205	13682
25	4	13508	13608	15380	14165,33
10	4	11547	11658	13277	12160,67
5	4	10107	10246	11714	10689
1	4	7033	7127	8379	7513
0,5	4	5911	6030	7158	6366,333
0,1	4	3663	3766	4635	4021,333
25	20	5447	5962	6638	6015,667
10	20	4059	4499	5068	4542
5	20	3183	3568	4058	3603
1	20	1560	1791	2165	1838,667
0,5	20	1163	1337	1660	1386,667
0,1	20	541,4	605,9	788	645,1
25	40	835,6	796,8	870,5	834,3
10	40	605,9	583,1	604,7	597,9
5	40	432,7	431,8	418,1	427,5333
1	40	155,2	153,6	144,9	151,2333
0,5	40	109,8	99,8	101,5	103,7
0,1	40	68,2	65,6	56,5	63,43333
25	54	302,5	287	308,5	299,3333
10	54	243,5	188,6	253,5	228,5333
5	54	196	126,9	206,1	176,3333
1	54	52,6	72,6	59,1	61,43333
0,5	54	41,1	53,9	44	46,33333
0,1	54	30,2	40,5	32,3	34,33333

12.7. Appendix G: Excel calculation using to drawing the dynamic modulus, phase diagram, master curve and shift factor diagram with 30% RA

	30 %					Yonatan.A	
		Measured				(Sigmoid)	
T	f	E*	Log(E*)	fR	log(f)	log(E*)	Error
-10	25	24539,67	4,39	7,4E+05	5,87	4,331	0,00
-10	10	22858,00	4,36	3,0E+05	5,47	4,320	0,00
-10	5	21601,33	4,33	1,5E+05	5,17	4,311	0,00
-10	1	18384,00	4,26	3,0E+04	4,47	4,280	0,00
-10	0,5	17058,00	4,23	1,5E+04	4,17	4,262	0,00
-10	0,1	13918,67	4,14	3,0E+03	3,47	4,206	0,00
4	25	16140,33	4,21	2,6E+03	3,41	4,200	0,00
4	10	14053,00	4,15	1,0E+03	3,01	4,155	0,00
4	5	12529,00	4,10	5,2E+02	2,71	4,114	0,00
4	1	9105,33	3,96	1,0E+02	2,01	3,988	0,00
4	0,5	7846,33	3,89	5,2E+01	1,71	3,918	0,00
4	0,1	5212,00	3,72	1,0E+01	1,01	3,715	0,00
20	25	6700,67	3,83	2,5E+01	1,40	3,834	0,00
20	10	5133,00	3,71	1,0E+01	1,00	3,710	0,00
20	5	4116,33	3,61	5,0E+00	0,70	3,602	0,00
20	1	2165,67	3,34	1,0E+00	0,00	3,303	0,00
20	0,5	1620,00	3,21	5,0E-01	-0,30	3,155	0,00
20	0,1	756,63	2,88	1,0E-01	-1,00	2,780	0,01
40	25	1210,33	3,08	4,0E-01	-0,40	3,105	0,00
40	10	743,30	2,87	1,6E-01	-0,80	2,893	0,00
40	5	499,30	2,70	8,0E-02	-1,10	2,725	0,00
40	1	162,73	2,21	1,6E-02	-1,80	2,329	0,01
40	0,5	114,40	2,06	8,0E-03	-2,10	2,164	0,01
40	0,1	58,40	1,77	1,6E-03	-2,80	1,809	0,00
54	25	360,07	2,56	4,5E-02	-1,35	2,581	0,00
54	10	281,30	2,45	1,8E-02	-1,75	2,356	0,01
54	5	200,57	2,30	8,9E-03	-2,05	2,190	0,01
54	1	63,27	1,80	1,8E-03	-2,75	1,832	0,00
54	0,5	47,70	1,68	8,9E-04	-3,05	1,695	0,00
54	0,1	30,73	1,49	1,8E-04	-3,75	1,423	0,00

$$log|E^*| = \delta + \frac{(\alpha - \delta)}{1 + e^{(\eta - \gamma log f_R)}}$$

T (oC)	T-Tr	aT	log(aT)
-10	-30	29630,37	4,47
4	-16	103,11	2,01
20	0	1,00	0,00
40	20	0,0159710	-1,80
54	34	0,001784	-2,75

	C1	11,30
	C2	105,84
min	δ	0,76
maks	α	4,37
	η	-0,87
	γ	0,63
	LSE	0,08

Shift factor Functions

- **WLF Function:**

$$log(a_T) = -\frac{C_1(T - T_r)}{(T - T_r) + C_2}$$

			DATA		
f,Hz	T,oC	Sample 1	Sample 2	Sample 2/3	Average
25	-10	24271	25372	23976	24539,67
10	-10	22642	23638	22294	22858
5	-10	21391	22293	21120	21601,33
1	-10	18183	18876	18093	18384
0,5	-10	16845	17420	16909	17058
0,1	-10	13648	14078	14030	13918,67
25	4	15914	16288	16219	16140,33
10	4	13851	14191	14117	14053
5	4	12341	12684	12562	12529
1	4	8981	9228	9107	9105,333
0,5	4	7767	7967	7805	7846,333
0,1	4	5179	5234	5223	5212
25	20	6280	6339	7483	6700,667
10	20	4738	4808	5853	5133
5	20	3767	3820	4762	4116,333
1	20	1955	1945	2597	2165,667
0,5	20	1460	1441	1959	1620
0,1	20	671,9	651	947	756,6333
25	40	1077	1151	1403	1210,333
10	40	656,1	714,4	859,4	743,3
5	40	438,6	473,5	585,8	499,3
1	40	142,9	150	195,3	162,7333
0,5	40	101,7	102,8	138,7	114,4
0,1	40	49,2	57,8	68,2	58,4
25	54	237,9	387,8	454,5	360,0667
10	54	206,4	304,9	332,6	281,3
5	54	172,7	203,4	225,6	200,5667
1	54	62,1	59,6	68,1	63,26667
0,5	54	48,2	40,3	54,6	47,7
0,1	54	28,1	30,4	33,7	30,73333

12.8. Appendix H: Excel calculation using to drawing the dynamic modulus, phase diagram, master curve and shift factor diagram with 40% RA

	40 %					Yonatan.A	
		Measured				(Sigmoid)	
T	f	E*	Log(E*)	fR	log(f)	log(E*)	Error
-10	25	29250,00	4,47	1,3E+06	6,12	4,415	0,00
-10	10	27999,00	4,45	5,3E+05	5,72	4,408	0,00
-10	5	26572,67	4,42	2,6E+05	5,42	4,401	0,00
-10	1	23641,00	4,37	5,3E+04	4,72	4,380	0,00
-10	0,5	22391,33	4,35	2,6E+04	4,42	4,367	0,00
-10	0,1	19426,00	4,29	5,3E+03	3,72	4,327	0,00
4	25	20389,00	4,31	4,0E+03	3,60	4,318	0,00
4	10	18468,33	4,27	1,6E+03	3,20	4,284	0,00
4	5	16921,00	4,23	8,0E+02	2,90	4,253	0,00
4	1	13358,33	4,13	1,6E+02	2,20	4,157	0,00
4	0,5	11872,33	4,07	8,0E+01	1,90	4,104	0,00
4	0,1	8594,33	3,93	1,6E+01	1,20	3,948	0,00
20	25	9906,00	4,00	2,5E+01	1,40	3,997	0,00
20	10	8034,67	3,90	1,0E+01	1,00	3,894	0,00
20	5	6714,00	3,83	5,0E+00	0,70	3,805	0,00
20	1	4100,33	3,61	1,0E+00	0,00	3,565	0,00
20	0,5	3246,67	3,51	5,0E-01	-0,30	3,450	0,00
20	0,1	1713,00	3,23	1,0E-01	-1,00	3,165	0,00
40	25	1864,33	3,27	2,1E-01	-0,68	3,296	0,00
40	10	1196,33	3,08	8,3E-02	-1,08	3,131	0,00
40	5	879,87	2,94	4,1E-02	-1,38	3,008	0,00
40	1	436,47	2,64	8,3E-03	-2,08	2,735	0,01
40	0,5	353,67	2,55	4,1E-03	-2,38	2,629	0,01
40	0,1	256,57	2,41	8,3E-04	-3,08	2,415	0,00
54	25	839,33	2,92	1,5E-02	-1,83	2,828	0,01
54	10	515,00	2,71	5,9E-03	-2,23	2,681	0,00
54	5	429,13	2,63	2,9E-03	-2,53	2,579	0,00
54	1	218,83	2,34	5,9E-04	-3,23	2,376	0,00
54	0,5	198,87	2,30	2,9E-04	-3,53	2,304	0,00
54	0,1	165,53	2,22	5,9E-05	-4,23	2,170	0,00

$$log|E^*| = \delta + \frac{(\alpha - \delta)}{1 + e^{(\eta - \gamma log f_R)}}$$

T (oC)	T-Tr	aT	log(aT)
-10	-30	52758,03	4,72
4	-16	159,36	2,20
20	0	1,00	0,00
40	20	0,0082957	-2,08
54	34	0,000587	-3,23

	C1	15,35
	C2	127,52
min	δ	1,89
maks	α	4,44
	η	-0,65
	γ	0,65
	LSE	0,06

Shift factor Functions

- **WLF Function:**

$$log(a_T) = -\frac{C_1(T - T_r)}{(T - T_r) + C_2}$$

		DATA			
f,Hz	T,oC	Sample 1	Sample 2	Sample 2/3	Average
25	-10	30125	27412	30213	29250
10	-10	28739	26015	29243	27999
5	-10	27581	25025	27112	26572,67
1	-10	24655	22190	24078	23641
0,5	-10	23401	21045	22728	22391,33
0,1	-10	20365	18312	19601	19426
25	4	20343	20890	19934	20389
10	4	18412	18877	18116	18468,33
5	4	16860	17372	16531	16921
1	4	13239	13844	12992	13358,33
0,5	4	11731	12372	11514	11872,33
0,1	4	8422	9130	8231	8594,333
25	20	9779	10431	9508	9906
10	20	7924	8528	7652	8034,667
5	20	6603	7220	6319	6714
1	20	3955	4565	3781	4100,333
0,5	20	3116	3679	2945	3246,667
0,1	20	1643	1985	1511	1713
25	40	1720	1965	1908	1864,333
10	40	1114	1246	1229	1196,333
5	40	800,2	888,8	950,6	879,8667
1	40	404,9	455,7	448,8	436,4667
0,5	40	331,9	375,5	353,6	353,6667
0,1	40	234,4	263	272,3	256,5667
25	54	861	1027	630	839,3333
10	54	476,8	650	418,2	515
5	54	468,6	481,9	336,9	429,1333
1	54	201,5	261,6	193,4	218,8333
0,5	54	177,2	238,4	181	198,8667
0,1	54	146,5	190	160,1	165,5333

12.9. Appendix I: The Job Safety Analysis

Beskrivelse av arbeidsoppgave/aktivitet:	**Deltakere på SJA:**	**Dato:**	6.04.2024
En sylindrisk prøve med en høyde på 150 mm og en diameter på 100 mm skal bli fremstilt ved kjerneboring og kutting. Dynamiske modulprøver skal ble utført ved hjelp av UTM 130, Disse testene blir gjennomført på laboratoriet ved Grimstad-campusen. Den dynamiske modultesten omfattet seks ulike frekvenser: 0,1 Hz, 0,5 Hz, 1 Hz, 5 Hz, 10 Hz og 25 Hz. I tillegg ble testene gjennomført ved fem ulike temperaturer: -10°C, 4°C, 20°C, 40°C og 54°C. Formålet med disse testene var å utvikle en database for hovedkurven (E*) for asfaltblandinger som inneholder resirkulert asfalt.	❖ Yonatan Afeworki ❖ Dr. Ephrem Taddesse	**Enhet:**	
		SJA-ansvarlig:	Yonatan Afeworki

#	**Deloppgaver** Del arbeidsoppgaven/aktiviteten inn i deloppgaver i den rekkefølgen de skal utføres	**Uønskede hendelser** Hvilke uønskede hendelser kan oppstå i forbindelse med deloppgavene. Er det noen spesielle farekilder som kan føre til disse?	**Tiltak** Innfør tiltak som kan forebygge uønskede hendelser. Innfør også tiltak for å begrense konsekvensene dersom en uønsket hendelse skulle forekomme.
1	• Forberedelse og håndtering av varmt bitumen	• Innånding ved å varm bitumen • Lekkasje av bitumen • Brann eller eksplosjon pga. oppvarming av bitumen. • Forbrenning eller brannskader ved kontakt med varm asfalt.	• Bruk personlig verneutstyr som varmebestandige (vernebriller, hansker og beskyttelsesklær) for å minimere risikoen for skader. vernehansker (EN 374 - 407). • Hold håndteringstemperaturene lave som mulig for å minimalisere avdamping

			• Sørg for god ventilasjon inne i bygninger eller lukkede rom. • Godkjent åndedrettsbeskyttelse og åndedrettsbeskyttelsesutstyr Håndvern EN 374 - 407. • Bruk beskyttelsesklær - Etablere nød-prosedyre og brannslukningsmidler
2	• Forming av sylindriske med Gyratory.	• Feilaktig montering av prøver i Gyratory. • Ustabilitet under testing som kan føre til skader på utstyret eller personskader.	• Sørge for riktig opplæring i bruk av Gyratory. • Sikre riktig montering og stabil plassering av prøvene.
3	• Boring av sylindriske asfaltene	• Skade på utstyret eller personskader under boring. • Innånding/inhalasjon av støv og partikler fra asfalt. • Feilaktig boring av prøver som gir upålitelige resultater.	• Støvkontrolltiltak (støvmasker, ventilasjon) som bruk av støvmasker og god ventilasjon. • Personlig verneutstyr (vernebriller, hørselsvern) • Sørge for opplæring i riktig bruk av bore-maskiner. • Bruk av personlig verneutstyr som vernebriller og hørselsvern. • Sørge for opplæring i riktig bruk av boremaskiner.
4	• Sliping av sylindriske asfaltene	• Skade på utstyret eller personskader under sliping. • Støvinnånding og eksponering for partikler fra asfalt.	• Sørge for opplæring i riktig bruk av slipemaskiner. • Gjennomføre støvkontrolltiltak, som bruk av støvmasker og god ventilasjon.

			• Bruk av personlig verneutstyr som vernebriller og hørselsvern.
5	• Testing av sylindriske prøver med Universal Testing Machine (UTM-130)	• Krasj eller skade på prøver eller utstyret. • Feilaktig håndtering av prøver som kan føre til personskader. • Brann skade • Klemskade	• Sørge for opplæring i bruk av UTM-130. • Bruk av riktig personlig verneutstyr for å beskytte seg mot varme, kulde, kjemiske stoffer, klem og mulige fallulykker. • Etablere en nød-prosedyre i tilfelle en uønsket hendelse skulle oppstå, inkludert førstehjelp og brannsikkerhetstiltak.
6	• Innsamling og sortering av avfall	• Miljøskadelige	• reduser avfallsmengden til et minimum i den grad det er mulig. • Avfallsemballasjen bør resirkuleres.

Er det innført tilstrekkelige tiltak, slik at arbeidsoppgaven kan gjennomføres på en trygg måte? *(sett kryss)*		**Ja**
		Nei - *Arbeidet skal ikke utføres før tilstrekkelige tiltak er på plass*