COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

(ROAD AND TRANSPORT ENGINEERING)

Performance evaluation of crumb rubber with kaolin modified asphalt for sustainability of flexible pavement

By

Deguamlak Shumu

A Thesis submitted in Partial Fulfilment of the Requirements of for the Degree of Masters of Science in Civil Engineering (Road and Transport Engineering)

Addis Ababa, Ethiopia

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ADDIS ABABA UNIVERSITY

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DECLARATION

This thesis entitled **"performance evaluation of crumb rubber with kaolin modified asphalt for sustainability of flexible pavement"** was made by me with the guidance of my advisors, I hereby declare. The work presented here is entirely my own, except where explicitly otherwise stated in the report. This work has never been submitted, in whole or in part, for any other degree of professional qualification.

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Abstract

The growth of traffic demand needs sustainable and durable asphalt pavement. Currently the price of bitumen has increased due to the increase in price of crude oil. Sustainable and durable pavement materials are needed to partially replace bitumen. This research aims to evaluate the performance of crumb rubber with kaolin modified bitumen asphalt for sustainability of flexible pavement. An experimental type of research was conducted to evaluate the properties of crumb rubber with kaolin modified asphalt. Six different content of CR and kaolin added to 80/100 penetration grade bitumen by weight. Physical and rheological test including penetration, ductility, softening point test, flash and fire point test, RTFOT and DSR test was conducted for both control and modified binder. Double wheel track test, indirect tensile modulus test and ITS test were conducted for control and modified asphalt mixture to evaluate the mechanical performance of asphalt. The result of study indicates crumb rubber and kaolin bitumen modification improves the physical and rheological properties of asphalt binder. Both CR and kaolin modified binder improves the stiffness, temperature susceptibility and elastic property of asphalt binder. One way ANOVA statistical analysis indicates that kaolin and crumb rubber has a significance effect on physical properties of binder. Based on the outcome of the study the optimum content of crumb rubber and kaolin were found as 3.5% and 10% respectively. 3.5% CR, 10% kaolin and the optimum combined mix improves rutting resistance of asphalt by 52.2%, 52.1% and 73.9%. These materials also improve load associated cracking and moisture damage effect of asphalt concrete. Crumb rubber and kaolin modified asphalt can reduce economical cost by 12.3% as compared to the conventional asphalt.

Key words: Crumb rubber, kaolin, Superpave, modified asphalt, Sustainability

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List of Symbols and Abbreviation

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CR	Crumb Rubber
CRMA	Crumb Rubber Modified Asphalt
CRMB	Crumb Rubber Modified Binder
CRMM	Crumb Rubber Modified Mix
EVA	Ethylene Vinyl Acetate
G*	Complex Shear Modulus
DSR	Dynamic Shear Rheometer
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
KN	kaolin
KNMB	Kaolin Modified Binder
KNMM	Kaolin Modified Mix
PG	Performance Grade
RTFOT	Rolling Thin Film-Oven Test
SBR	Styrene Butadiene Rubber
SBS	Styrene Butadiene Styrene
SHRP	Strategic Highway Research Program
TSR	Tensile Strength Ratio
VMA	Void in Mineral Aggregate
VFA	Void Filled with Asphalt
Va	Air Void
WITS	World Integrated Trade Solution

Chapter One

1. Introduction

1.1 Background of the study

Flexible pavement is one of the most important types of road infrastructure which designed to facilitate safe and efficient movement of people and goods. Bitumen has long been used for binder in flexible pavement construction due to its waterproofing, adhesion and flexible properties. The performance and durability of these pavements heavily depend on the properties of asphalt binder used. The conventional use of bitumen in flexible pavement poses performance and economical challenges. Issues associated with crude oil price, environmental sustainability and finite bitumen resource initiate interests in exploring innovative and alternative sustainable asphalt materials [1]. For this reason further study is needed to make them sufficient replacement of bitumen on an industrial scale to be a sustainable source of binder for flexible pavement.

The development of sustainable and durable pavement material has a critical issue in order to address performance, environmental impact and economic efficiency of pavement [2]. The study explores the long term significance viability of pavement including alternative materials such as recycled concrete, bio binders of asphalt, rubberized asphalt and polymer modified asphalt to create cost efficient and environmental safe bituminous pavement construction. The study suggests further study should be needed to address for environmental sustainability and pavement preservation.

The term "sustainability" in pavement engineering covers several aspects such as road material and performance, managing environmental condition and service life of road, analysing the environmental and economical impact raised by road infrastructure. Sustainability of pavement can be achieved by enhancing the performance of asphalt materials against traffic loads and environmental condition to extend the durability and service life of the road. [3]

Waste tire derived crumb rubber has been investigated as one alternative approach for cost effective and sustainable method to improve the longevity and performance of asphalt pavement. It can be applied for asphalt mixture through partial replacement of binder.

According to several studies, incorporating crumb rubber in to asphalt mixture improves mechanical, rheological and moisture resistance of the material. It can also improve the rutting resistance, fatigue resistance, increase stiffness, reducing moisture damage and temperature susceptibility of asphalt concrete. [4]

The growing demand of road transportation leads to several road issues includes road safety, durability and noise. Incorporating waste tire crumb rubber in to asphalt is a solution to improve the durability of asphalt mixture. In addition to this it is important to decrease road surface noise emission from tyre vibration [5].Crumb rubber modified asphalt sustainable as compared to conventional asphalt based on life cycle cost analysis. CRMA extends pavement service life by 2 to 4 years per each cycle to achieve sustainability. [6]

Road damage is the main issue which is a serious problem for driver and resulting accidents. Road damage can be caused by permanent or temporary deformation of pavement due to the weak performance of asphalt materials. Research has been conducted to ensure asphalt concrete can be serving for long time [7]. The study explores to strengthen the asphalt concrete pavement a natural resource alternative material called kaolin is incorporated. According to the study kaolin is a filler material which is used as a partial replacement material in asphalt mixture. The use of kaolin clay in the asphalt mixture results improving performance with good stability and stiffness.

Crumb rubber modified asphalt has high performance for high and low temperature condition, deformation and fatigue resistance compared to the conventional asphalt. However, the inclusion of CR in asphalt binder poses swelling and expanding property during mixing by absorbing oil components. This leads to increasing the viscosity of the material by decreasing light component of binder which affects the mixing, compaction and paving of CRMA. The study explores adding ethylene bis stearamide additives for reducing viscosity of CRMA and to improve rheological property for better compaction and workability.[8]

The purpose of this study is to evaluate the performance of asphalt using crumb rubber with kaolin modified binder. Crumb rubber and kaolin are used for partial replacement of bituminous material to minimize cost efficiency and to improve durability of asphalt.

Kaolin is naturally abundance clay mineral used for partial replacement for asphalt binder to enhance the physical and rheological properties of asphalt binder. It is used as a filler to improve the mechanical characteristics of asphalt concrete.

Crumb rubber is waste tire recycle material which is used as an additive for asphalt binder for asphalt concrete to improve the rheological properties of asphalt binder and performance of asphalt mix. It also contributes environmental sustainability by recycling waste tires. However crumb rubber important material for asphalt modification; it poses workability challenges due to its swelling behaviour when mixed with bitumen. For this reason, this study uses kaolin as a stabilizing material due to its cementitious property to improve the swelling, dispersion effect and workability of crumb rubber modified asphalt.

Combining crumb rubber with kaolin is a novel approach to improve the performance of asphalt to make it more resistance to deformation, less susceptible to moisture damage and can with stand high temperature susceptibility.

1.2 Statement of problem

The development of sustainable and durable pavement materials becomes critical with regard to performance and economical cost of pavement. Currently the price of bitumen has increased worldwide which leads to high cost in pavement construction. Especially in Ethiopia bitumen is imported from abroad making the project more expensive and vulnerable to price fluctuation.

Ethiopia purchased 21.76 million kilogram of bitumen and asphalt in 2023 by $19.62 million USD. Compared to the last seven and eight years the average price increased by $0.47/kg [9]. These challenges need the use of alternative materials to reduce reliance on bitumen and to reduce price index. Therefore there is an interest in exploring more affordable and locally available alternatives for binder modification and cost minimization including crumb rubber and mineral filler called kaolin. Waste tire crumb rubber and kaolin are additive materials which offer sustainable solution can partially replacing bitumen by lowering cost. Incorporating these materials in to asphalt mixture could provide benefit such as improving pavement performance and reducing cost.

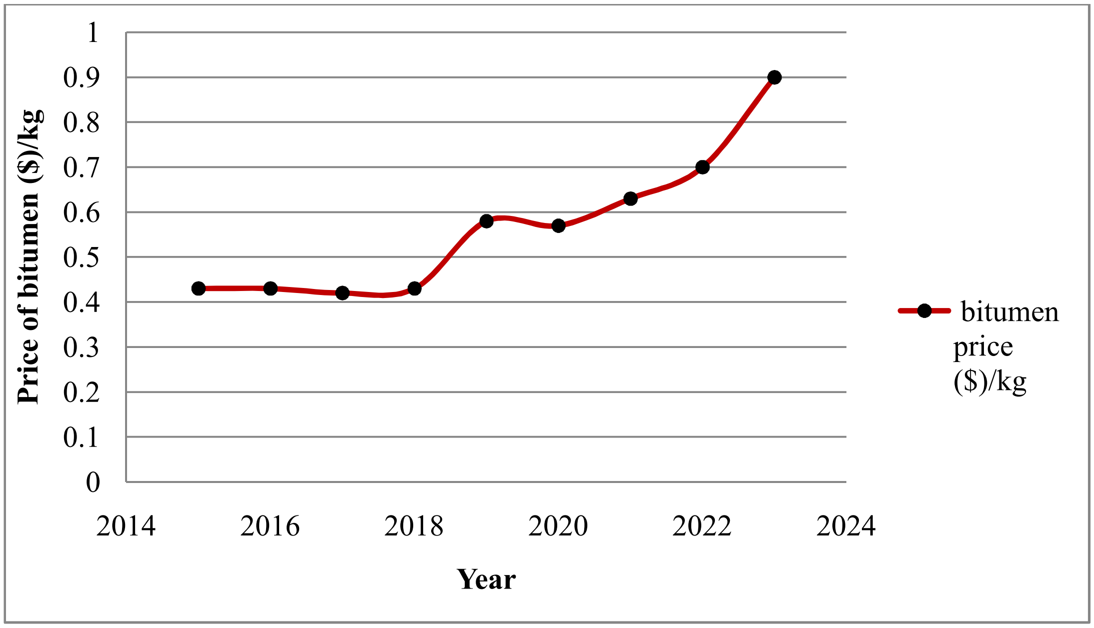


Figure 1.1 Ethiopian imported price index of bitumen asphalt based on WITS data

1.3 Research questions

This research is design to answer the following questions.

1. How sustainable crumb rubber with kaolin modified asphalt in terms of performance and cost effectiveness.
2. What should be the optimum level of crumb rubber and kaolin content used for asphalt binder?
3. How the optimum combination of crumb rubber with kaolin that maximizes asphalt performance?

1.4 Objectives of the research

This study aims to investigate crumb rubber with kaolin modified asphalt based on their modified binder to improve asphalt performance and cost efficiency aspect.

1.4.1 Main objective

The main objective of this study is to evaluate the performance of crumb rubber with kaolin modified asphalt using superpave mix design for sustainability of pavement.

1.4.2 Specific objectives

1. To analyse the performance of asphalt binder using crumb rubber additives and to determine optimum content.
2. To analyse the performance of asphalt binder using kaolin additives and to determine optimum content.
3. To evaluate optimum mix combination of crumb rubber and kaolin in modified asphalt that maximizes asphalt performance.
4. To assess the economical cost analysis of crumb rubber with kaolin modified asphalt for sustainability of pavement construction.

1.5 Significance of the research

Previously different types of modifiers have been used as bitumen modification. Crumb rubber with kaolin modified asphalt offers significant performance for asphalt and economical aspect making it a critical area of the research. By using recycled waste tire crumb rubber materials with naturally abundance kaolin material in to asphalt addresses the growing issues of asphalt performance and sustainability of pavement. Modified asphalt has advantages to improve pavement durability, increase resistance to deformation and also increases the service life of the pavement by reducing the cost.

1.6 Scopes of the study

The scope of this study mainly involves investigating the potential of using waste tire derived crumb rubber with kaolin modified asphalt for road construction. This study includes evaluating the physical and mechanical properties of modified asphalt such as its durability and performance. Bitumen penetration grade 80/100, crumb rubber and kaolin samples with various percentage used for this study.

1.7 Limitation of the research

The limitation of this research is mainly restricted on the scope of testing for waste tire rubber and kaolin modified asphalt. The study is limited to evaluating the performance of crumb rubber and kaolin modified binder through penetration test, softening point test, ductility test, flash and fire point test, DSR tests and RTFO test. It also includes performance test such as rutting test, modules test and moisture susceptibility test. Other several testes are not included due to different reasons such as lack of certain testing equipments, time and economic issues.

1.8 structure of the study

This study totally includes five chapters. The first chapter is the introduction which contains backgrounds of the study, statement of problems, objectives, significance, scope, limitation and structures of the study. The second chapter includes literature review by reviewing different literatures relevant to the study on the property of crumb rubber and kaolin for asphalt modification purpose. The third chapter is the methodology part which involves different testes conducted in binder and asphalt modification using the additive materials. The fourth and fifth chapter covers the expected outcome and conclusion of the study respectively. Lastly reference and appendix of the study were included.

Chapter Two

2. Literature Review

2.1 Introductions

This chapter covers the main finding of previous studies for bitumen and asphalt modification based on crumb rubber and Kaolin materials.

2.2 Bitumen

Bitumen is black, adhesive and waterproofing material that comes from crude oil present in asphalt. It is highly viscous and nearly solid at room temperature and it is entirely soluble in toluene. It is used as a binder for flexible pavement construction due to its adhesive properties. [10]

2.2.1 Bitumen Rheology

The word rheology is comes from Greek word "ρεω" meaning "river, flow" and "λογοο" meaning "science", which means the study of flow or flow science. Rheology is the study of flow and deformation for time and temperature dependent materials like bitumen which is stressed by forces. It is the basic measurement of flow and deformation properties of bitumen. Therefore knowing them is essential for performance of pavement. Asphalt mixture having extreme flow and deformation leads to rutting, while excessive stiffness may leads to fatigue and cracking. [11]

Know a day, the rheological properties of bitumen is determined by an experimental tool called dynamic shear rheometer (DSR).DSR is first introduced in 1993, during strategic highway research program (SHRP).It is used to determine elastic, viscoelastic and viscous characteristics of bitumen across a range of temperature and frequencies. The rheological properties are presented in terms of rutting parameter, phase angle and complex modules. Other tools like bending beam rheometer (BBR) are used for low temperature; however these tools are not available in our country.

2.2.2 Aging of Bitumen

Aging in bitumen occurs mainly in two ways one is short term aging and the second is long term aging. Short term aging occurs during mixing, storing, transporting and paving, while long term aging happen during service life of asphalt. Mainly long term aging occurs due to increase in global warming when gamma radiation and ultra violet emission increase during service life of bitumen asphalt [12]. According to the study field aging of bitumen can be simulated in the laboratory using RTFO test for short age simulation and PAV test for long term simulation

2.2.3 Performance grading (PG) of bitumen

Asphalt mixture is a composite of asphalt binder, aggregate and filler used for the construction of pavement. However, it exposed to deformation and cracking due to traffic loading and environmental condition. Asphalt binder used as an adhesive material its rheological property should be examined and tested before applied and placing in to the field. The study suggests that PG system is the first option to directly relate the physical properties of asphalt binder to the field performance over traditional grading such as viscosity and penetration grading system. [13]

The performance of asphalt pavement is depending on binder material, which is typically determined by its penetration grade. However, penetration grade is one of grading system; it is not enough for an adequate assessment of asphalt performance at different temperature or for damage like low temperature cracking and rutting [14]. The study examines low and high temperature effect on asphalt binder based on PG system. The output indicates enhancing low and high temperature performance of asphalt binder and offering social and economical benefits.

To build new highway and improve quality of pavement it is crucial to established asphalt quality criteria. Due to its viscoelastic property asphalt pavement is prone to rutting and low temperature. Therefore evaluating asphalt binder performance grading is essential to design distress resistance asphalt pavement that occurred to seasonal temperature fluctuation.[15]

Performance grade (PG) system refers to asphalt binder grading system based on their performance under different temperature and stress condition. It is first introduced by SHRP in 1993; it can be done by DSR test for high temperature performance evaluation, using BBR and direct tension test (DTT) for low temperature cracking. The system considers average seven day temperature for high temperature and the lowest temperature for low temperature condition.

2.2.4 Bitumen modification

Bitumen is petroleum based material used for binding asphalt materials for flexible pavement which has some adverse impact on environment. Alternative materials that are economical and environmentally sustainable are being investigated by researchers. Consideration are being given to bio based and waste products including cooking oil, bio oil, plastics , polymers and tire rubber. However some encouraging outputs are observed more study is needed to create a viable bitumen replacement in industrial scale to form sustainable binder material. [16]

2.3 Crumb rubber modified binder

Crumb rubber is waste tire material composed of natural rubber, carbon black, synthetic rubber steel, and fibre and processing oil. Waste tire crumb rubber used for asphalt binder modification was developed in ancient 1960 by Charles Mac Donald. He has working as a head of a material Engineer for the city of Phoenix, Arizona. He discovers crumb rubber modified binder by blending crumb rubber with original bitumen by allowing mixing time for 45 to 60 minutes. [17]

Due to the growing traffic density and inadequate maintenance service road structure have deteriorated quickly. Conventional bitumen should be improved to enhance performance related qualities such as rutting and fatigue cracking used for better pavement durability and water damage resistance. Using different improvement methods such as styrene butadiene styrene (SBS), styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA) and crumb rubber modifiers (CRM) modification of bitumen has been investigated. However, the use of SBS and SBR modifiers increase road construction cost due to its expensive market price, while the use of CRM are cost effective and environmental sustainable option for pavement construction. [18]

In 1975, Caltrans (California department of Transportation) starts laboratory experiments using rubber cheap seals and patches small testes. In 1978, Caltrans construct first dry process rubber modified asphalt concrete on Meyers. They incorporates one percent of ground rubber content by mass as fine aggregate replacement resulting in good pavement performance. In 1980, Caltrans construct the first wet process modified asphalt binder and dense graded asphalt. This implementation leads to the ground work for continuous development in California which improves pavement durability and sustainability. [19]

2.3.1 Waste tire rubber grinding process

In order to utilize crumb rubber for asphalt modification waste tire is grinding and shredding in to small sieve size by removing and screening steel materials. In order to perform this process there are two methods such as ambient grinding and cryogenic grinding process.[18]

Ambient grinding process refers to shredding of tire mechanically at room temperature producing different size rubber particles used for asphalt materials. While cryogenic grinding process involves liquid nitrogen to produce small crumb rubber size mesh. This method produces uniform and fine size particles that are suitable for rubberized asphalt modification. Cryogenic grinding process high cost than Ambient grinding process due to the addition of liquid nitrogen.

2.3.2 Preparation of crumb rubber

Basically crumb rubber is used in asphalt by three methods. These are through wet process, dry process and terminal blending methods. [20]

Wet process is a method of mixing crumb rubber in to asphalt binder used for hot mix asphalt. This can be done through adding crumb rubber percentage to heated bitumen and mix together at high temperature before adding the binder to form asphalt mixture.

Dry process refers to the incorporation of crumb rubber to asphalt by replacing the percentage of fine aggregate for asphalt concrete mixture not asphalt binder. A partial replacement of mineral aggregate by crumb rubber in dense graded hot mix asphalt is a sustainable option for improvement of asphalt mix design. [21]

Terminal blending involves the combination of wet and dry process. This can be done by mixing fine particles of crumb rubber with binder and adding additional crumb rubber as a fine aggregate to form asphalt mixture.

2.3.3 Crumb rubber and bitumen blending and interaction

The cross linkage structure of crumb rubber modified asphalt is depending on mixing time and temperature effect [22]. The study explores effect of processing temperature and time on cross linked structures of crumb rubber modified asphalt. The finding demonstrates that rubber particles can form a continuous phase structure following swelling with an expansion ratio 1.76-2.14.Extreme temperature and long processing period produced rubber degradation. Stirring for 45-60 minute at a temperature of 180°C-190°C was the best processing method.

2.3.4 Physical and rheological properties of crumb rubber modified binder

2.3.4.1 Penetration properties of CRMB

Penetration is a measure of softness or hardness of bituminous material which shows an effect by adding crumb rubber to bitumen. The performance of rubberized bitumen is affected by the amount of crumb rubber content and its blending condition. According to the study the experimental result indicated that penetration value decrease as the percentage of crumb rubber increases. This is due to the increase in stiffness of CRMB making it less susceptible to temperature effect. [23] the stiffening of asphalt due to light particles absorbed by crumb rubber particles leads to decrease in penetration value of the binder.

2.3.4.2 Ductility properties of CRMB

Ductility is defined as the distance measured by cm at which a standard sample briquette of the material can be elongated without breaking. The ductility value of crumb rubber modified binder is low as compared to original binder. [23] This is due to the physical interaction of crumb rubber particles with bitumen makes the binder stiffer.

2.3.4.3 Softening point properties of CRMB

Softening point refers to the temperature at which the bitumen attains a particular degree of softening. The incorporation of crumb rubber in bitumen modification increases in softening point of the binder. Higher softening point makes the asphalt binder stiffer and improves elastic property for better rutting resistance. [24]

2.3.4.4 Complex Modules (G*), G*/SinΔ and Phase angle properties of CRMB

Seasonal temperature change and traffic loading has a significant impact on asphalt due to its viscoelastic nature. These impact leads to distress such as rutting and fatigue cracking, occurs due to seasonal temperature change and traffic loading impact.[25] The study explores and evaluates rheological properties of binder by adding crumb rubber, low density and high density polyethylene to bitumen. The rheological property of binder is evaluated by dynamic shear rhemoter (DSR) test. According to the study the addition of crumb rubber significantly impacted the rheology of bitumen. It increases complex shear modules and rutting parameter ($G^*/Sin\Delta$), while decrease phase angle.

2.3.5 Performance of crumb rubber modified asphalt

Moisture damage is one of the biggest global issue and economic concern. Moisture damage and traffic loading on asphalt concrete can lead to weaken mechanical properties of asphalt. This can result material separation due to decrease in bond between asphalt and aggregate. The study explores performance of asphalt by incorporating crumb rubber. The finding of the study indicates that crumb rubber modified asphalt improves stability and moisture resistance. [26]

The use of crumb rubber in asphalt binder used for asphalt mixture enhances resistance of permanent deformation that occurs on the surface layers of pavement due to increasing of traffic loading. It also improves resistance of moisture damage and increases the resilient modules of material under repetitive pulse loading. [27]

2.4 kaolin material

Kaolin is fine clay minerals having cream and dark brown colours. Kaolin is also called china clay which is mainly consists Kaolinite, aluminium silicate linked by oxygen atoms. Kaolin formed by chemical weathering of rocks called hydrothermal alteration leading to the decomposition of feldspar minerals resulting in kaolinite formation. Generally it occurs in the form of residual (primary) and secondary (sedimentary) deposits. Residual deposit refers to resulting from in situ weathering product of feldspar rich rocks such as granite, pegmatite, genesis or sandstone. While sedimentary kaolin deposit is formed by when pre-existing deposits are transported through water and redeposit in basins and lakes. [28]

2.4.1 Kaolin in Ethiopia

Kaolin is a solid powder composed of SiO_2, AlO_2, and FeO2, which is used for various industrial applications. In Ethiopia, kaolin is important for financial growth of industrial sectors includes filler, ceramic production, and paint and paper preparations. [29]

Ethiopia is reached in kaolin deposit which is found in different region of the country including Amhara, Oromia, Southern nation's nationality and peoples. However due to deep mining advanced and ongoing researches on the occurrence and deposit of kaolin and a high level of mineral impurities make the commercial application are less viable. Debre Tabor kaolin is reached in kaolinite a rock material which is physically beneficiated, chemically leached and thermally treated for various applications. It is used for particularly industrial application of ceramic fabrication. [30]

Alemtena kaolin is located in Ethiopian rift valley, which is white in colour and formed by intensive weathering of volcanic rocks includes pumice and rhyolite. Geological, mineralogical, chemical and physical test provides evidence for the potentials of kaolin. It has high kaolinite, Al_2O_3 content and low FeO_2, TiO_2 content. It makes that suitable for various industrial applications include fillers, paper, ceramics, and pharmaceuticals. [31]

2.4.2 Kaolin based bitumen modification

Innovative technology for improving asphalt binder performance has been made viable by recent development in nanotechnology, particularly with the use of micro and nano size metakaoline. Metakaoline (MK) is made from thermally processed kaolin clay, which exhibits pozzolanic activity serve as high additives for asphalt modification. Kaolin based nano material are suitable for high temperature pavement application due to significance rutting resistance property. [32]

For asphalt mixture mineral filler is crucial to fill the gap or voids between aggregates. Meta kaolin is one of pozzolanic material which has a significant impact on improving the properties of hot mix asphalt. [33] The addition of Meta kaolin enhances martial properties of modified asphalt and indirect tensile strength test.

Due to increasing the cost of bitumen and growing of traffic volume it is important to enhance bitumen performance through modification. Nano kaolin clay emerged as a potential solution significantly improves binders quality. In general asphalt binder containing nano kaolin clay is more effective in enhancing the viscosity properties of asphalt before and after aging. [34]

The addition of kaolin clay for porous asphalt improves the physical properties of asphalt by decreasing penetration value and increasing the softening point and enhancing temperature susceptibility of the binder. The kaolin modified binder also improves porous asphalt durability, resistance to rutting and cracking. [35]
Pozzolana material can improve the stiffness and thermal stability of the binder. pozzolana enhances the viscosity and elasticity of the asphalt binder up to 15%.[36]

2.4.3 Physical and rheological properties of kaolin modified binder

The study that investigates the rheological properties of 50/70 penetration grade bitumen by adding kaolin clay additives derived from Turkish granite rock. It was discovered that the addition of kaolin increase viscosity and softening point of the binder while decrease penetration and ductility values of the bitumen. Based on the study Marshall Test was used to evaluate the mechanical properties of kaolin modified bitumen that increases the Marshall Stability values to 11.2% [37]. Nano kaolin clay improves the physical performance bitumen of by increases the softening point and storage stability asphalt binder.[38]

pozzolana improves the physical and rheological properties of asphalt binder. As the amount of pozzolana content increase the penetration and ductility value decrease while softening point, fire and flash point increased. Additionally it increases the complex modules and viscosity resulting in resistance for rutting and high temperature. [36]

The addition of metakaolin reduced asphalt binder penetration and ductility value while softening point increased. The decrease penetration value implies that enhancing thermal stability and structural integrity of the modified binder. Metakaolin modified binder exihibits enhancing elastic and stiffness of binder especially when nano metakaolin is used. Dynamic shear rheometr resultt shows that increase complex modules and reduced phase angle. Nano MK modified binder achived PG-76 due to its larger surface area compared to micro MK PG-64 and control binder PG-58. [32]

Chapter Three

3. Methodology and Testing

3.1 Research Design

Methodology of this study involves conducting experimental types of research for crumb rubber and kaolin modified asphalt binder to evaluate the optimum amount of additives used for asphalt mix design. The study includes various tests and statistical analysis to evaluate the physical and rheological property of original and modified binder. It includes different testing methods to evaluate mechanical performance of hot mix asphalt (HMA) concrete.

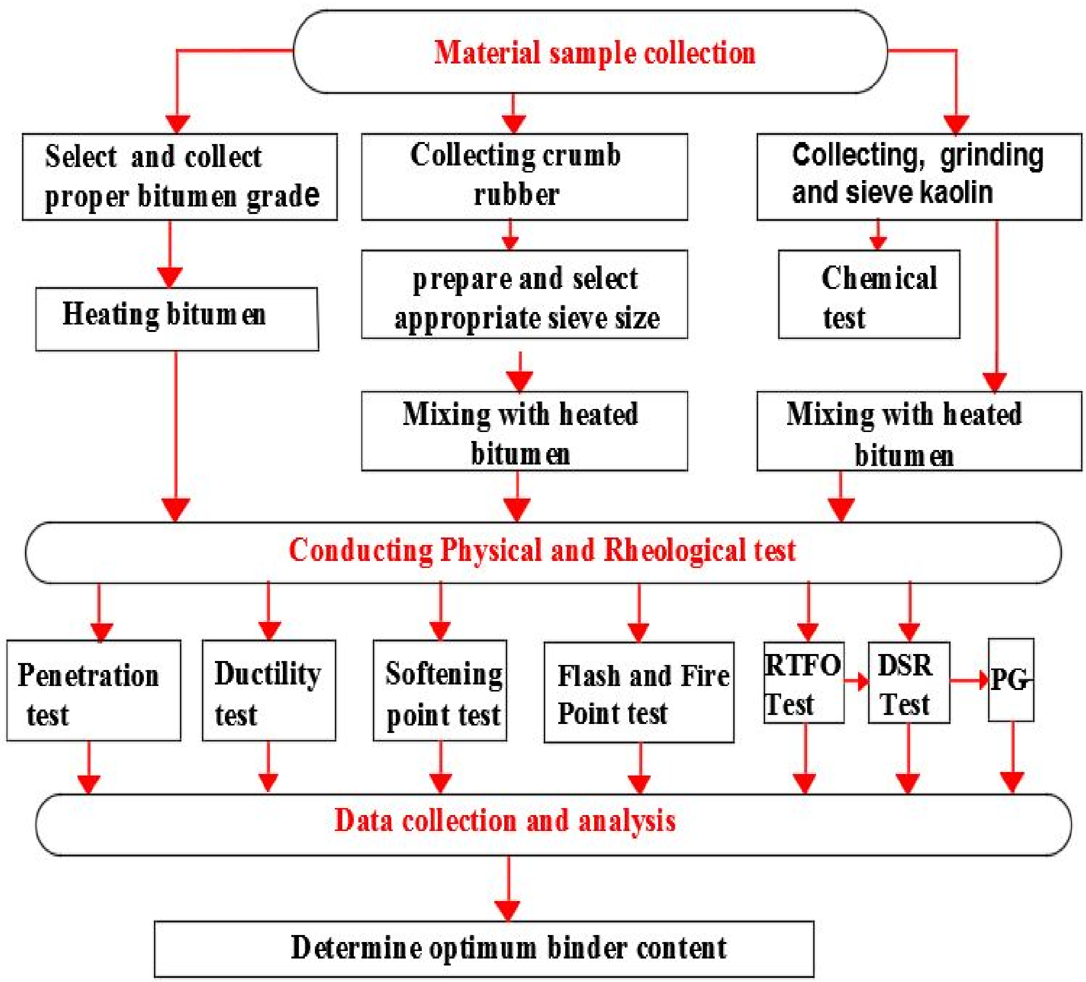


Figure 3.1 Methodology of the research for binder test

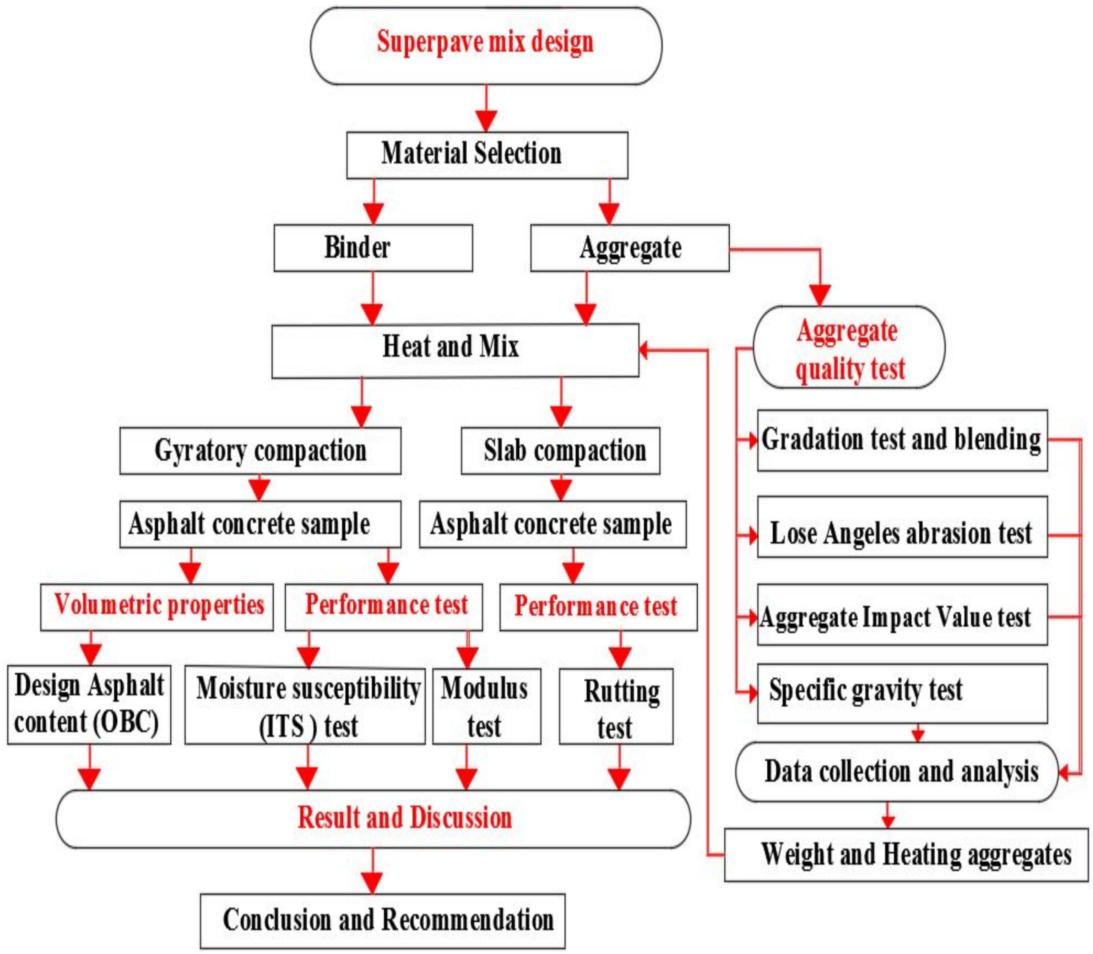


Figure 3.2 Methodology of the research for asphalt mix design

3.2 Materials

3.2.1 Bitumen

In this study, bituminous material having 80/100 bitumen penetration grade is used. Bitumen with penetration grade 80/100 denotes that the penetration ranges in between 80-100. This type of bitumen may have performance issues in hot climate region due to the tendency of material softness under high temperature which can lead to rutting and deformation. Hard bitumen is preferred for hot climate region it can strongly face the intense of heat without melting. The selection of this bitumen grade is due to limited high temperature resistance; to evaluate the stiffness, hardness and thermal resistance of the binder by adding CR and kaolin additives. 80/100 bitumen grade is collected from Asser construction Bolle Bulbula asphalt site.

3.2.2 Crumb rubber

Crumb rubber is waste tire recycle material which is initially made from natural and synthetic rubber, carbon, fibre and steel. Crumb rubber sample is collected from local tire retreading facilities kality, Addis Ababa.

Figure 3.2 Crumb rubber powder sample

3.2.3 Kaolin

Kaolin is a naturally abundant mineral filler material white and cream colour powder which is used for various applications. It is important for asphalt pavement to improve adhesion of binder and aggregate due to its cementitious property. Kaolin sample is obtained from Awash Melkassa chemical factory.

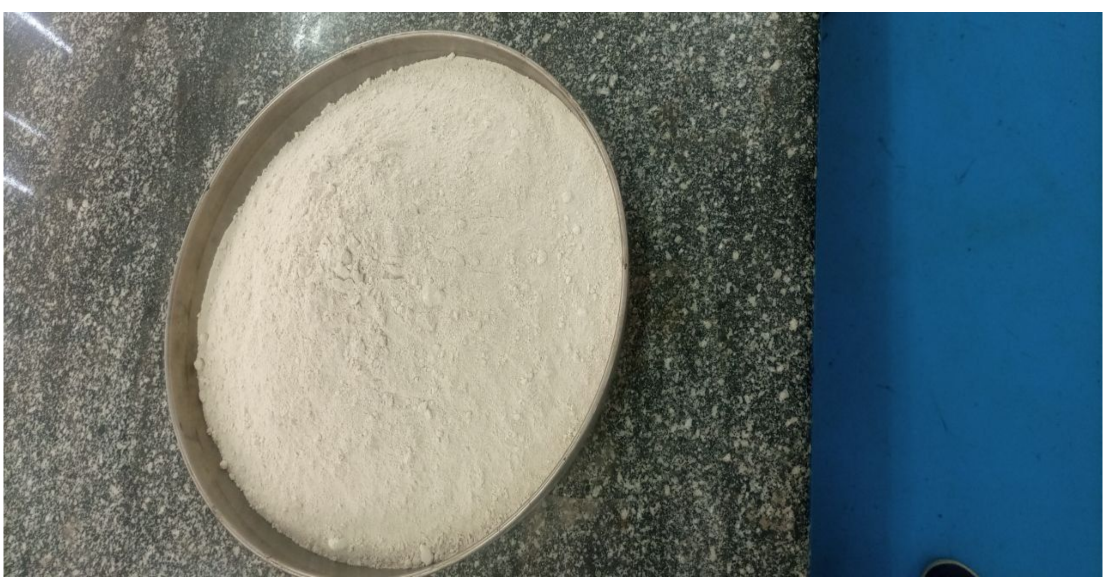


Figure 3.3 Kaolin powder samples

3.2.3.1 Chemical composition of kaolin

The chemical composition of kaolin was evaluated by X-ray fluorescence (XRF) spectrometer instrument. Kaolin sample is first sufficiently dry before testing to remove moisture. The test was conducted at chemical and construction input industry research and development centre.

Table 3.1 Elemental chemical composition of kaolin

Element	Si	Al	Ca	Mg	Fe	P	Cl	S	K	Nb	other
%	1.87	0.81	35.42	1.12	0.34	0.025	0.2	0.11	0.16	0.02	59.92

Table 3.2 Oxide form composition of kaolin

Oxide	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5	Cl_2O	SO_2	K_2O	Nb_2O_5
%	4.00	1.53	49.59	1.86	0.48	0.06	0.52	0.275	0.19	0.028

This test result indicates that the kaolin sample is highly rich in CaO content implies that it has cementiouse or lime property due to its pozzolanic behaviour. CaO reached Kaolin is crucial to improve the adhesion properties of asphalt mixture. It increases the bonding strength between aggregate and binder. Particularly this lime reach kaolin is important to enhance the adhesion properties and workability of crumb rubber modified binder. Crumb rubber alone is difficult to mix with bitumen and poor workability due to its swelling behaviour by absorbing the light component of binder. When we add kaolin in the crumb rubber bitumen mix it reduces swelling behaviour. Not only this, the incorporation of this kaolin material in asphalt mix can improve thermal resistance and reduce stripping risk of pavement.

3.3 Rheological and physical property testes for original and modified binder

This section involves determine the optimum amount of crumb rubber and kaolin used for asphalt binder. For this matter, several testes should be conducted on 80/100 bitumen, crumb rubber and kaolin with various percentage. All testes are selected and conducted based on AASHTO and ASTM standard methods of testing.

3.3.1 Sample preparation and mixing

Basically six different crumb rubber contents, which are 2%, 3.5%, 5%, 6.5%, 8% and 9.5% by weight, are used to modify asphalt binder. For kaolin modified asphalt binder, six different percentages of kaolin, including 5%, 7.5%, 10%, 12.5%, 15% and 17.5% by weight, are selected and used to replace and modify original bitumen. Particle size of passing 0.075 mm sieve size is used for both crumb rubber and kaolin modified asphalt binders.

For this study, wet methods of mixing for bitumen with additives are applied in such a way. Initially heat the original bitumen sample of 80/100 bitumen grade at a temperature of 160°C for one hour until it becomes fluid. Gradually add crumb rubber from 2% to 9.5% by weight of bitumen while maintaining a temperature of 180-190°C. Allow the sample to react at the same temperature for 60 minutes by continuously stirring to attain uniform dispersion. Similarly, for kaolin modified binder, adding kaolin content from 5% to 17.5% by weight of bitumen by maintaining a temperature of 160-170 °C. Allow the sample to react with the original bitumen at the same temperatures for 20 minutes to enhance uniform interaction. Similarly for the optimum CR with kaolin modified mix adding CR to heated bitumen then gradually adding kaolin and mix it at a temperature of 180-190°C for 45 minutes.

Table 3.3 Weight ratio of crumb rubber (CR) and bitumen for binder modification

%CR	weight of CR(gm)	Weight of bitumen (gm)	Total weight of binder(gm)
0	0	350	350
2	7	343	350
3.5	12.25	337.75	350
5	17.5	332.5	350
6.5	22.75	327.25	350
8	28	322	350
9.5	33.25	316.75	350

Table 3.4 Weight ratio of kaolin and bitumen for binder modification

%kaolin	weight of kaolin(gm)	Weight of bitumen (gm)	Total weight of binder(gm)
0	0	350	350
5	17.5	332.5	350
7.5	26.25	323.75	350
10	35	315	350
12.5	43.75	306.25	350
15	52.5	297.5	350
17.5	61.25	288.75	350

3.3.2 Penetration test

Penetration test determines the softness or hardness of bitumen for the purpose of grading. It is conducted based on AASHTO T-49; first bitumen is heated at temperatures of 160°C in the oven until it becomes sufficiently fluid. Heated bitumen sample is poured in to penetration test container and allowed to cool at room temperature for one hour. Then place the sample in the water bath for a temperature of 25°C for one hour. Offer and put the sample in to penetrometer ready for testing with penetration needle. The needle is positioned by slowly lowering it until it tips just made contact with the surface of sample. After that the pointer brought zero and the pointer is rapidly released for the allotted five seconds. Then a standard needle penetrates the sample at room temperature of 25°C (77°F), 100g load and five second penetration time for one tenth of mm unit. The final reading of the dial is recorded. The actual value of penetration is measure in one tenth of mm by subtracting the final reading of dial from initial reading or zero point.

Figure 3.4 Penetration test

3.3.3 Ductility test

Ductility test used to determine the elongation of bitumen before breaking measured by centimetre. It is conducted based on AASHTO T-51 standard by stretching standard –sized briquette of asphalt binder at a temperature of 25°C±0.5°C with a speed of 5cm/min ±5%. The ductility test is vital to ensure good adhesive property of asphalt binder and its ability to stretch. In asphalt mix the binder should form a thin ductile film around aggregate to improve the physical interlocking of aggregate. Ductile bitumen can prevent asphalt cracking and it makes the asphalt more resistant to traffic loads. Ductility of binder has a vital role for elastic property of asphalt mix to resist deformation under loading and various temperature conditions. Asphalt binders with insufficient ductility tend to crack when subjected to repeated traffic loads.

Ductility test are performed as bitumen is heated and poured in to glycerine coated plate mould. Then allow the sample to cool at room temperature for 40minutes duration. Then place the brass plate briquette specimen in to 25°C water bath for 90minutes. After that remove the briquette from the plate and the side pieces are detached. The rings were attached at each end of the pins or hooks in the testing machine or inside barometer. The two clips were pulled apart with a constant speed of 5cm/min until the sample ruptured or break. Record the distance in centimetre to know ductility value.

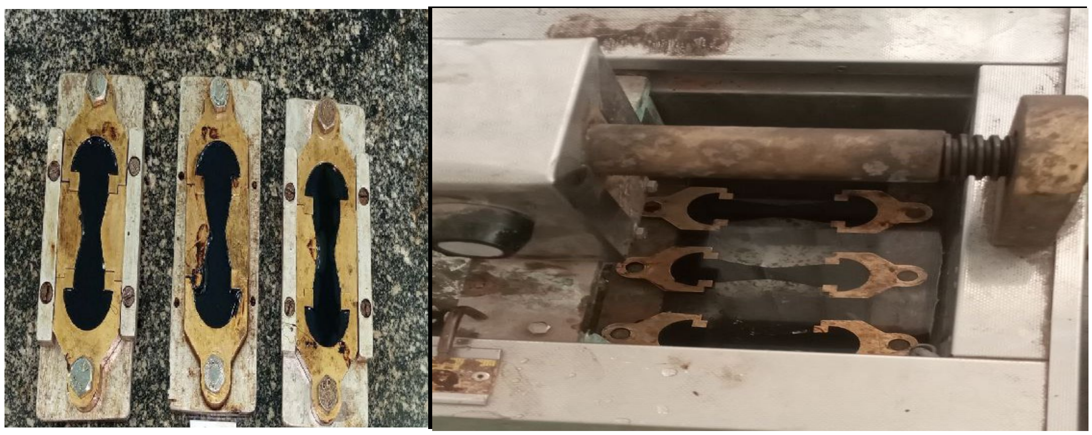


Figure 3.5 Ductility test

3.3.4 Softening point test

The softening point test is conducted using AASHTO T-53 standard test method using Ring and Ball Apparatus. It is used to determine the temperature at which the asphalt binder materials soften enough for a steel ball sinks through a ring. To conduct the test pour the liquid binder in to the ring, allow it to cool for 30 minutes and remove the extra bitumen with the heated knife when the sample cooled. Fill the water bath or beaker with water of 800 ml. fix the rings filled with binder in the support frame and place in the beaker. Place a 3.5 g steel ball on the centre of the sample. Put the beaker on heater and adjust the thermometer by allowing the sample to be heated at a uniform temperature of 5°C /min. The ball and asphalt binder drops down to the bottom of the beaker when the sample becomes soften. Record the temperature when each of the balls touches the plate and take the average values of the softening points of the two samples. The test must be conducted again if the test temperature difference of the two samples touching the bottom plate exceeds 1°C.

Figure 3.6 Softening point test

3.3.5 Flash and Fire point test

Flash point of the asphalt binder is the lowest temperature at which momentarily takes fire in the form of flash under a specified test conditions. This evolves vapour that will temporarily ignite or flash when a small flame is brought in contact with them. Whereas fire point refers to the temperature at which the evolved bituminous material gets ignited and continue to burn under specified test condition. Those tests are used to determine the maximum temperature at which the material heat safely for storing, handling and transporting. The test is conducted based on AASHTO T-48 standard through Cleveland open cup tester. Fill the test cup with pour binder until the filling line level. Place the test cup on the regulator by maintaining a temperature of rise rate 5°C to 17°C per minute reading on the thermometer. Record the temperature at which the temperature reaches the flash point. Continue heating the sample to determine fire point by increasing sample temperature 5°C to 6°C per minute. Record the temperature at which the flame appears over the surface and maintains at least 5 second.

Figure 3.7 Flash and fire point test

3.3.6 Dynamic shear Rheometer (DSR) Test

Dynamic shear rheometer test is the most important test used to determine the rheological properties of asphalt binder used in performance grade (PG) binder system.DSR is used to characterise the viscous and elastic properties of asphalt binder at medium to high temperature. It is also used to measure and determine complex shear modulus (G*), phase angle, G*/SinΔ and failure temperature of asphalt binder. This parameter is important for evaluating the performance of pavement in terms of its resistance to rutting. In this study, the test is applied for un-aged and RTFOT asphalt binder samples.

The test is conducted based on AASHTO T-315 standards. To run the test first heating the asphalt binder sufficiently fluid and pour in to the test specimen of 1mm thick and 25mm diameter. Select the appropriate test temperature in accordance with the asphalt binder grade and place the sample between the test plates. Move the test plate together and trim the sample around the edges of the test sample. The top plate oscillates at 10rad/sec in a sinusoidal wave form and the equipment measures the maximum applied stress, resulting strain and time lag between them. The software automatically generate an output data gives complex shear modulus (G*), phase angle, G*/SinΔ and failure temperature of asphalt binder. All testes are conducted at a test temperature of starting from 46°C, 52, 58, 64, 70 and 76°C with a 6°C increment.

Figure 3.8 DSR test

3.3.7 Rolling Thin Film Oven (RTFO) Test

Rolling thin film oven test is used to evaluate the effect of heat and air on asphalt binder and simulates the short term aging when the asphalt binder exposed to elevated temperature.

The test is conducted based on AASHTO T-240 test specification standards. A 35g heated binder samples are poured in to cylindrical glass bottle and allow the bottles to cool 60 to180 minutes. Place the weighted bottles in to rotating carriage inside oven. The carriage rotates at a rate of 15rev/min at a constant test temperature of 163°C for 85 minutes. When setting time finished remove the bottle from the carriage and record the mass loss by weighting. RTFO test measures the mass change due to heat and air in asphalt binder. The mass loss indicates loss of volatiles during mixing, transporting and placement of asphalt. The DSR test is conducted for RTFO aged samples.

Figure 3.9 RTFO test

3.4 Statistical analysis

A comprehensive statistical analysis is undertaken to asses and examines the reliability of binders quality test. The analysis includes penetration test, ductility test, softening point test, flash and fire point test to obtain empirical data from several binder samples. The test data has been analysed using descriptive statistics such as mean, median and standard deviation. To evaluate the consistency of test result and to examine the variation among the test groups, inferential statistics like analysis of variance (ANOVA) were used.

3.5 Superpave mix design

Superpave mix design system is one of a performance based asphalt mixture design method developed by strategic highway research program (SHRP) in 1993. It is a new method of asphalt mix design and it performs to improve the durability and performance of asphalt pavement by considering traffic load and environmental conditions.

The superpave mix design system includes the following basic steps and procedures

1. Aggregate selection
2. Asphalt binder selection
3. Sample preparation and production
4. Volumetric property determination
5. Optimum asphalt binder selection
6. Performance test evaluation
7. Moisture susceptibility evaluation

3.5.1 Aggregate selection and quality Test

The aggregate used in this study were collected from Asser construction Bole Bulbulla asphalt plant site having a range of (0-4.75)mm,(4.75-12.5)mm and (12.5-19)mm size. The selection of aggregate was done by considering superpave aggregate selection criteria to ensure suitability for intended mix design. The criteria include gradation and blending, flakiness and elongation index, angularity, strength and durability requirements.

3.5.1.1 Gradation test and aggregate blending

Gradation test is used to determine the particle size distribution of coarse and fine aggregate used for asphalt mix design. The test is conducted based on AASHTO T-27 and ASTM C-136 standard specification requirements. Weighted Dry aggregate samples are added and separated in to a series of sieve with a progressive of smaller openings. Record and measure the weight of sample on each sieve size retained. Particle size distributions on each sieve size are expressed as a percentage retained by weight and graphical format using 0.45 power curve.Aggregate blending is conducted by combining different aggregate size to achieve an optimal gradation that meets superpave gradation control limits. Finally an acceptable trial blend is selected in order to perform asphalt mix design.

Table3.5 Gradation and blending of aggregate

	Aggregate A	Aggregate B	Aggregate C	Filler	Total
Proportion 1	15	22	58	5	100
Proportion2	24	27	44	5	100
Proportion 3	30	35	30	5	100

sieve size (mm)	0.45 power sieve (mm)	max density	Agg.t A (12.5-19) mm	Aggr.t B (4.75-12.5) mm	Agg.t C (0-4.75) mm	Filler	Trial Blend 1	Trial Blend 2	Trial. Blend 3	Specification
25	4.257	100	100	100	100	100	100	100	100	
19	3.762	88	90.1	100	100	100	99	97.6	97.03	90-100
12.5	3.116	73	40.1	91.25	100	100	89	83.3	78.9	
9.5	2.754	65	20.64	69.55	100	100	81	72.7	65.5	
4.75	2.016	47	1.1	24.87	90.9	100	63	51.9	41.3	41-71
2.36	1.472	35		2.375	54.12	100	37	29.4	22.1	
1.18	1.077	25		0.75	33.55	100	25	19.9	15.3	
0.6	0.795	19			19.92	100	17	13.7	10.9	
0.3	0.582	14			12.85	100	12	10.7	8.9	
0.15	0.426	10			9.52	100	11	9.2	7.8	
0.075	0.312	7			7.07	100	9	8.1	7.1	5-16

Table 3.6 control point and restriction zone for 19mm nominal aggregate size

sieve size(mm)	Control Pont		Restriction zone	
	Lower	Upper	lower	upper
25	100			
19	90	100		
12.5		90		
2.36	23	49	34.6	34.6
1.18			22.3	28.3
0.6			16.7	20.7
0.3			13.7	13.7
0.075	2	8		

Based on the estimated properties as shown in the gradation curve in figure 3.10 trial blend 2 is selected as a design aggregate for this study to conduct superpave asphalt mix design.

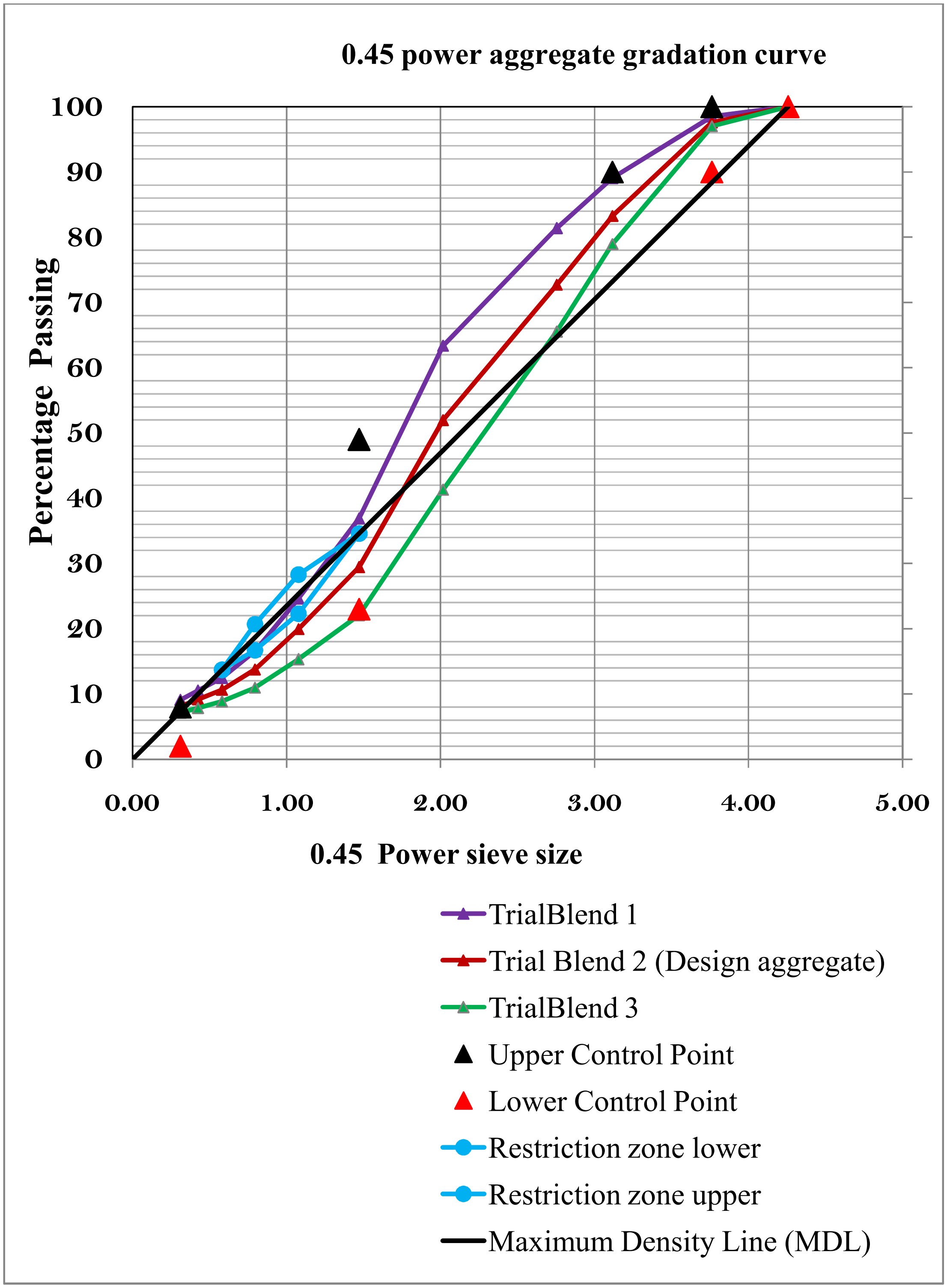


Figure 3.10 Aggregate gradation curve

3.5.1.2 Specific gravity and water absorption test

Specific gravity indicates the density and water absorption measures the material porosity to absorb water. Specific gravity test for coarse aggregate is conducted based on AASHTO T-85 standard specification. First perform dry sieve sample through sieve No.4 (4.75mm) and wash the sample retained. Dry sample through oven at a temperature of 105±5°C and cool the sample for 1 to 3hr at room temperature and immerse on water through a container for 15hr. Remove the sample from the container and drain any excess water from the aggregate through water absorbent close. Weight the aggregate under saturated surface dry (SSD) condition. Place the sample on water basket and submerge in water bath shake the container to remove the entrapped air and record the weight of the sample. Dry the sample on oven and record the weight of dry sample. Finally, bulk specific gravity, apparent specific gravity and water absorption are computed using the following equation.

- Bulk Specific Gravity, Gsb=A/B-C
- Bulk SSD Specific Gravity, Gsb SSD=B/B-C
- Apparent Specific Gravity, Gsa=A/A-C
- Water absorption, % Abs=(B-A/A)*100

Where, A= Weight of oven dry specimen in air (g), B= Weight of SSD specimen in Air (g) and C= Weight of SSD specimen in Water (g).

The specific gravity of fine aggregate is conducted based on AASHTO T-85 standard using Pycnometere. This test is used to determine the bulk specific gravity for dry and SSD condition and apparent specific gravity of aggregate.

- Bulk SSD Specific Gravity Gsb=A/B+S-C
- Bulk SSD Specific Gravity, Gsb SSD=S/B+S-C
- Apparent Specific Gravity Gsa=A/B+A-C
- Water absorption, % Abs=(S-A/A)*100

Where, A= Weight of Oven dry Sample (g), B= Weight of Pycnometer filled with water (g), C= Weight of SSD sample in Pycnometer with water (g) and S= Weight of SSD sample (g).

3.5.1.3 Coarse aggregate angularity

Coarse aggregate angularity (CAA) test is used to evaluate the percentage of fractured face of aggregate. This test is conducted based on AASTM D-5821 standard specifications methods. The test can be done as first select, sieve and weight samples of coarse aggregates. Identify one or more fractured face and two or more fractured face from the sample. Calculate and determine the weight of fractured aggregate particles. Based on evaluation coarse aggregate angularity is 98/95 and 96/91 % fractured face for 4.75mm and 12.5mm sieve retained coarse aggregate samples respectively.

3.5.1.3 Los Angeles Abrasion Test

Los Angeles Abrasion test is commonly used to measure aggregate toughness and abrasion characteristics. This test used to test aggregate resistance of crushing, degradation and disintegration to produce high quality HMA. The test is conducted based on AASHTO T-96 or ASTM C-131. 5000g dry weight coarse aggregate sample retained on 12.5 mm and 9.5mm sieve size is subjected to rotating steel drum containing a specified number of steel spheres. The drum is rotated for 500 revolutions at 30 or 33/rev/min. After the test is completed weight and sieve the aggregate sample retained on No.12 to determine the aggregate Los Angeles Abrasion values.

Los Angeles Abrasion values (LAAV) test result in Appendix E shows 13.6% which is on the recommended range AASHTO with maximum abrasion loss of 30% for surface course. This implies that the aggregate have high potential resistance to wear.

3.5.1.4 Aggregate Impact Test

Aggregate impact value test is used to measure the sudden impact resistance and toughness of aggregate. The test is conducted based on ASTM D-58-74 standard. It can be done by taking 1000 gm aggregate sample passing 12.5 mm sieve and retained on 9.5 mm sieve. The samples are washed and dry in the oven at a temperature of 105±5°C and cool down at room temperature before testing. The aggregate is filled in steel cylinder in three layers and a tamping is rod applied on the sample 25 times for each layer. Finally the aggregate samples are sieved through 2.36 sieve openings and record the weight passing it. According to the test aggregate crushing value is 6.66 %< 10% this indicates that the aggregate is strong.

3.5.2 Sample preparation and mixing

Proper sample specimen is prepared based on the selected aggregate and bitumen materials using superpave gyratory compaction. To conduct asphalt mixing, aggregates are dried, weight and blended based on mix proportion. Heating bitumen until it becomes fluid at a temperature of 165°C to allow it coating aggregate properly. Mixing of aggregate and binder together is performed in the laboratory using mechanical mixer to ensure homogeneous distribution of binder and to achieve desired workability of the mix. Once the asphalt mixture is ready performing compaction specimen using super pave gyratory compaction based on AASHTO T 312. Super pave gyratory compaction is carried out by applying a vertical pressure of 620kpa and gyratory motion of 30 rev/ minute to compact the asphalt mixture. It is important to simulate field condition and evaluate performance of asphalt in the laboratory. The compacted specimen is used to evaluate bulk density, volumetric properties of asphalt used to determine optimum asphalt content. In this study the design compaction is considered as $N_{initial}$, N_{design}, N_{max} is 8, 100 and 160 respectively.

Figure 3.11 Gyratory compaction and production of asphalt concrete specimen

3.5.3 Specific gravity of asphalt mixture

Assessing the density of asphalt mixture is important to evaluate the compaction and air void levels of compacted mix.

3.5.3.1 Theoretical Maximum specific gravity (Gmm) test

Theoretical maximum specific gravity test is the specific gravity of paving mix representing the dense state of mix with nearly no air voids. Gmm test is conducted based on AASHTO T-209 standard specification. For this test a loose asphalt paving mix is placed in a calibrated pycnometer to remove entrapped air. It can be calculated by dividing the dry mass of the mix by the volume it occupies without air voids.

Figure 3.12 Theoretical maximum specific gravity (Gmm) tests for asphalt mix

3.5.3.2 Bulk specific gravity (Gmb) test

Bulk specific gravity test refers to the specific gravity of the compacted asphalt mix includes the volume of air void in the compacted asphalt mix specimen. The test is conducted in accordance to AASHTO T-166. In this test a gyratory compacted asphalt mix dry mass were first measured, then saturated and saturated surface dry (SSD) mass measured. Finally Gmb is calculated based on the equation given below.

- $Gmb=A/B-C$ where, Gmb= Bulk specific gravity of compacted mix

  A= Dry mass of compacted asphalt mix in air

  B=Saturated surface dry (SSD) mass of specimen in air

  C=Saturated weight of specimen in water

Figure 3.13 bulk specific gravity (Gmb) tests for compacted asphalt mix

3.5.4 Volumetric property determination

3.5.4.1 Air void (Va)

Air void in asphalt mixture refers to the air space between asphalt compacted mixture. Based on AASHTO M323 superpave volume mix design recommends the design air void to be 4%. Air void of compacted asphalt mixture is computed as follows.

$$Va=100*(G_{mm}-G_{mb}) / G_{mm}$$

Where, Va= air void in the compacted specimen in percent

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

G_{mb}= bulk specific gravity of compacted mix

3.5.4.2 Voids in mineral aggregate (VMA)

Void in mineral aggregate refers to the volume between aggregate particles in a compacted asphalt mix. It is composed of air void effective asphalt binder. It can be determined by subtracting the volume of aggregate from the total volume of compacted mix. In asphalt mixture having inadequate design value of VMA is not recommended it causes ravelling of aggregate surface resulting for fatigue cracking. It is crucial to design a mix using recommended appropriate values of VMA.

$$VMA=100-(G_{mb}P_{s)}/G_{sb}$$

Where, VMA=Voids in mineral aggregate

G_{mb}=bulk specific gravity of compacted mix

G_{sb}= bulk specific gravity of aggregate

P_s= percent of aggregate in the total weight of mix

The Minimum value of VMA for asphalt compacted recommended as thirteen for nominal aggregate size of 19 mm.

3.5.4.3 Void filled with asphalt (VFA)

Void filled with asphalt refers to the percentage voids in the mineral aggregate that is filled by asphalt binder. It is also called volume of effective asphalt binder.

$$VFA=100*(VMA-V_a)/VMA$$

Where, VFA=Void filled with asphalt,

VMA= Void in mineral aggregate and

Va=air void

3.5.4.4 Selecting design asphalt content

Design asphalt content refers to the optimum asphalt content that provides 4% air void at N_{design} compaction. The selection of the proper asphalt content is important conduct uniform and proper asphalt gyratory compaction for asphalt mix design.

3.6 Performance test for asphalt

3.6.1 Rutting test

Rutting of asphalt mixture refers to a distress that occurs at high pavement temperature of traffic loading condition. Rutting or permanent deformation occurs when the pavement temperature increase the asphalt mixture becomes softer and subjects to movement under loading condition. For this study double wheel tracking test is applied to measure the rutting resistance of control and modified asphalt mixture.

3.6.1.1 Double wheel track test (DWTT)

Double wheel tracking test is performed to evaluate the rutting resistance of asphalt mix based on AASHTO T324 standard test method. For this study, testes conducted under wet condition to evaluate both rutting and moisture susceptibility. A 720N wheel load is applied to a compacted slab having (260x320x50) mm size at a test temperature of 50 °C. The test is run for 10000 cycles (20000 passes) or until a deformation of 20mm reached. Finally the output like rut depth are obtained after test completed.

3.6.2 Modulus (stiffness) test

Resilient modules (RM) test is a test used to evaluate the elastic response of asphalt under a repeated or cyclic loading. This test is important to evaluate load associated cracking under repeated pulse loading. The test is conducted according to the ASTM D7369 standard test method at a test temperature of 25°C. A repeated pulse load is applied to a cylindrical specimen with a subsequent rest period, usually 0.1second loading with either 0.9, 1.9 or 2.9 second rest period. Finally the stiffness modulus, deformation and pulse loading are maintained based on indirect tensile modules test output.

3.6.3Moisture Susceptibility test

Moisture susceptibility test is a test used to evaluate moisture damage resistance of materials for asphalt pavement. It involves conditioning samples in water and conducting mechanical test like indirect tensile strength test (ITS).

3.6.3.1Indirect Tensile Strength (ITS) Test

Indirect tensile strength (ITS) is common test to evaluate moisture susceptibility of asphalt. This test involves six compacted specimens, three specimens are for dry condition and the remaining is for wet condition of testing. Testing procedure is done based on AASHTO T 283 standards. For condition subset, three specimens are placed in freeze thaw at -16 C° for 16hrs. After a freeze cycle the specimens are submerged in water at a temperature of 60 C° for 24 hour. Finally, condition specimens are submerged in to water at 25 C° room temperature to bring them to a test temperature. For unconditioned subset, specimens are maintained at room temperature 25 C° either environmental chamber or water bath before indirect tensile strength testing.

Indirect tensile strength testing is performed for conditioned and unconditioned specimen by loading a specimen at a displacement rate of 50mm per minute. Tensile strength ratio (TSR) value is calculated by condition specimen over unconditioned specimen using the formula.

- ITS=$\frac{2000P}{Dt}$, ITS –in kpa

Where P- is the applied load at failure in N, D- is diameter of specimen in mm and t-is the thickness of the specimen in mm.

- TSR=$\frac{S1}{S2}x100$

S_1=Average tensile strength of conditioned specimen

$S_{2=}$ Average tensile strength of unconditioned specimen

Chapter Four

4. Result and Discussion

4.1 Introduction

In this section the physical and rheological property of original binder, crumb rubber and kaolin modified binder discussed widely based on the experimental test result of the samples. And also the performance of asphalt concrete for control and modified asphalt including rutting, stiffness modules and moisture susceptibility effect can be analysed.

Table 4.1 Physical property test result for original binder

Test	Penetration test (0.1mm)	Ductility Test (cm)	Softening point test (°C)	Flash Point test (°C)	Fire Point test (°C)
result	91.1	145	45.25	265	276
Specification	80-100	>100	45-49	>232	

Table 4.2 Physical property test result for the characteristics of CRMB

Test	0% CR	2% CRMB	3.5% CRMB	5% CRMB	6.5% CRMB	8% CRMB	9.5% CRMB	Specification
Penetration test (0.1mm)	91.1	79.2	72.2	64.8	54.9	47.5	41.9	
Ductility Test (cm)	145	121	106.6	90.3	75.7	59	46.7	>100
Softening pointtest (°C)	45.25	47.8	49	50.2	51.8	53.4	54.8	
Flash Point test (°C)	265	270	276	281	286	290	296	>232
Fire Point test (°C)	276	280	286	290	297	302	308	

Table 4.3 Physical property test results for Kaolin modified binder (KNMB)

Test	0% KN	5% KN	7.5% KN	10% KN	12.5% KN	15% KN	17.5% KN	Specification
Penetration test (0.1mm)	91.1	82.11	73.16	63.25	56.42	48.54	41.46	
Ductility Test (cm)	145	131	119	109.3	97	81	66.7	>100
Softening point test (°C)	45.25	47.6	48.65	49.98	51.5	52.37	53.47	
Flash Point test (°C)	265	272	281	289	295	303	309	>232
Fire Point test (°C)	276	285	293	299	305	312	319	

4.2. Penetration test

Penetration test is assessed to evaluate the impact of crumb rubber and kaolin asphalt binder modification for the consistency of asphalt for original and modified binder.

4.2.1. Effect of crumb rubber modification (CRM) on penetration

The finding in this study indicates that the penetration value decrease with the addition of crumb rubber. Test results in Figure 4.1 shows that the addition of crumb rubber has a significant effect on the penetration value. The result table 4.2 shows that the penetration value drops progressively 91.1, 79.2, 72.2, 64.8, 54.9, 47.5 and 41.9 tenth of mm at 0% , 2%, 3.5%, 5%, 6.5%, 8% and 9.5% CR content respectively. The penetration value of modified binder is lower as compared to the original bitumen. Lower penetration value indicates increased binder stiffness and better rutting resistance of binder. This is due to the increase in stiffness of materials when the rubber particles absorbing the light or oil components of bitumen during blending and mixing. This is consistent with previous study [23] the percentage of crumb rubber has a significant impact on decreasing the penetration value by increasing stiffness of CRMB. It makes the binder high resistance to temperature susceptibility and permanent deformation.

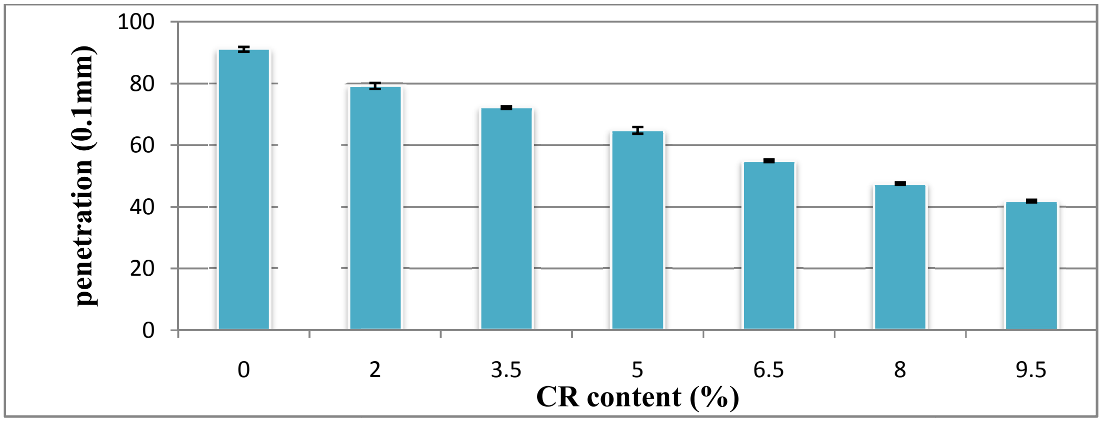


Figure 4.1 Penetration test result for CRMB

4.2.2 Effect of kaolin modification (KNM) on penetration

Adding kaolin to asphalt binder decreases the penetration value slightly, but to a lower extent as compared to crumb rubber modified binder. Based on the finding table 4.3 and figure 4.2 shows that lowering of penetration value from 91.1 tenth of mm at 0% kaolin content to 41.46 tenth of mm at 17.5% kaolin content. The decrease in the penetration value is because of kaolin material is filler that fills gaps in bitumen and resulting in strengthen and harden the binder. This indicates that the addition of kaolin enhances the hardness of binder and makes the binder better resistance for deformation and high temperature. This modification is crucial particularly for hot environment where rutting is concern. However at higher dosage of kaolin the binder becomes stiffer it may reduce flexibility. This study is consistent with earlier study by [32] due to fine particle size and better dispersion the addition of metakaolin especially in the nano form reduce penetration values of asphalt binder.

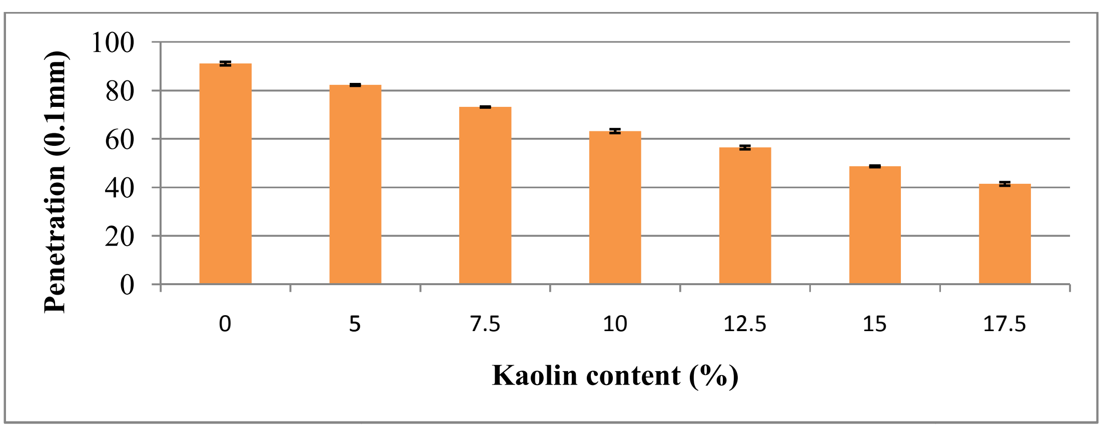


Figure 4.2 Penetration tests result for KNMB

4.3 Ductility test

To determine the elastic behaviour crumb rubber modified asphalt binder and its tensile property it is crucial to analyse the finding of ductility test conducted on samples.

4.3.1 Effects of crumb rubber modification on ductility

The ductility test result of original binder is 145cm based on test result table 4.1. It is above the minimum specification limit based on AASHTO T-51. The ductility value reduced to 121cm when adding 2% crumb rubber on original binder. The finding of test result in table 4.2 and figure 4.3 shows that ductility value of binder decreases from 145cm at 0% crumb rubber to 46.7cm at 9.5% crumb rubber content. This indicates that crumb rubber modified binder becomes stiffer when increasing percentage of crumb rubber as compared to original binder. Adding crumb rubber percent up to 3.5% the ductility value is within a recommended range of specification. Whereas adding more than 3.5% crumb rubber the binder becomes less ductile and highly stiffer it may tends to brittle. According to the study [23] the ductility value of modified binder decrease dramatically; which leads to a significance increase in binder mass and makes more elastic and high resistance to deformation.

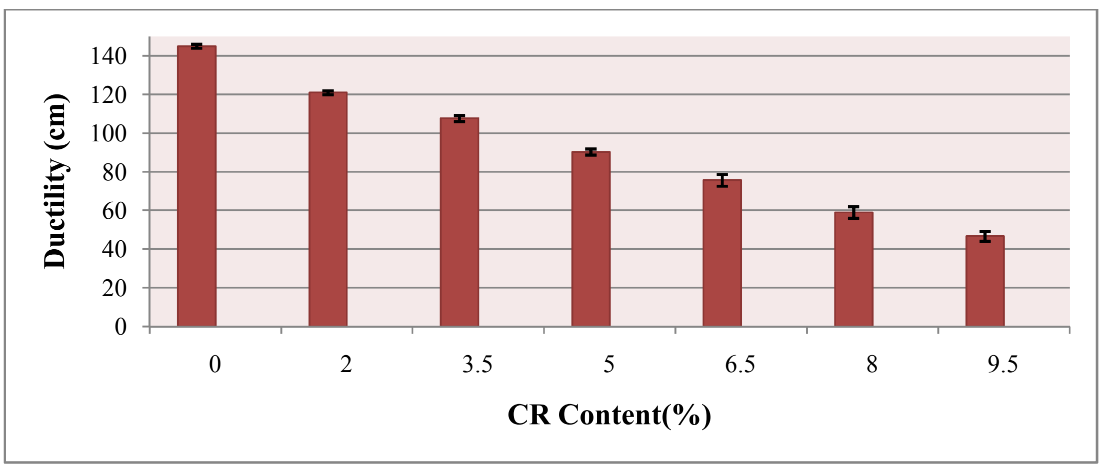


Figure 4.3 Ductility test result for CRMB

4.3.2 Effects of kaolin modified binder on ductility

The test result in figure 4.4 shows ductility value of kaolin added bitumen gradually decrease when the percentage of kaolin content increase from 0% to 17.5%. The modified binder test result in table 4.3 illustrates that with 5%, 7.5% and 10% kaolin content meets the minimum specification of AASHTO T-51 100cm, but the value falls below the standard for 12.5%, 15% and 17.5% kaolin content. The decline in ductility value reflects that negative impact on binder tensile behaviour as it becomes capable of stretching without breaking. This study aligns with the research by [32] who founds that reduction in ductility signifies that improve resistance to flow under high temperature, while lower elongation potential of binder and increasing brittleness.

Therefore however the incorporation of kaolin enhances stiffness and rutting resistance of the binder, adding high amount of kaolin may weaken binder's resistance to tensile deformation particularly in cold areas. Balanced optimum kaolin content is essential to maintain pavement strength and flexibility.

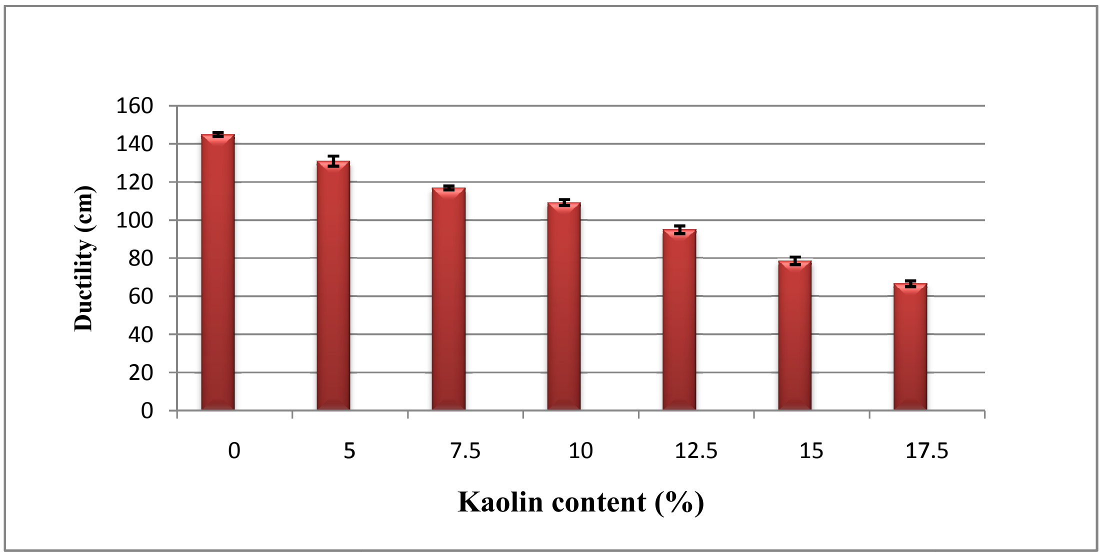


Figure 4.4 Ductility tests result for KNMB

4.4 Softening point test

4.4.1 Effects of crumb rubber modification on softening point

From the finding as shown in figure 4.5 below shows that the softening point increases as the percentages of crumb rubber content increase. The result in table 4.2 demonstrate that the softening point of original bitumen is 45.25°C which increased to 47.8°C, 49°C, 50.2°C, 51.8°C, 53.4°C and 54.8°C with 2%, 3.5%, 5%, 6.5%, 8% and 9.5% CR content respectively. This progressive increment shows that crumb rubber improves the potential of binder to resist softening at high temperature. Higher softening point in asphalt binder are desirable in hot climate can withstand higher temperature effect. This finding aligns with the study by [24] who get a nearly linear increase with increasing crumb rubber amount.

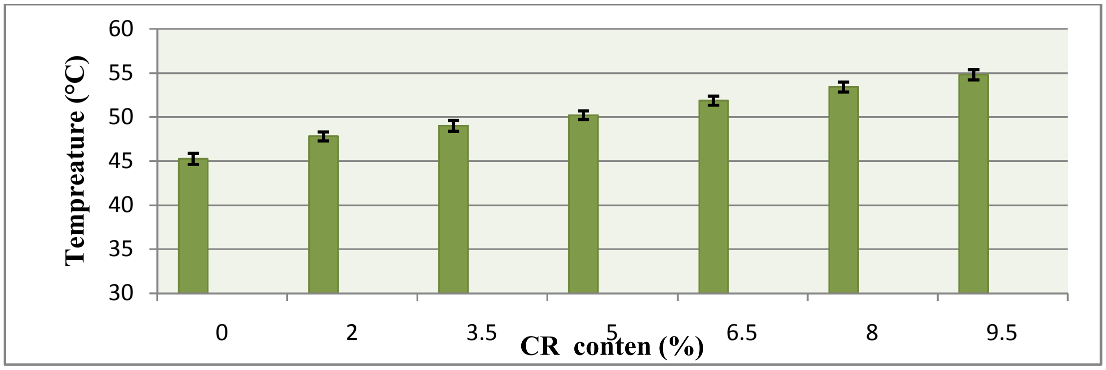


Figure 4.5 Softening point test result for CRMB

4.4.2 Effects of kaolin modified binder on softening point

Figure 4.6 illustrates that the relationship between softening point value and kaolin content. The result shows that the softening point value increase with increasing percentages of kaolin content to asphalt binder. Table 4.3 shows that softening point increased gradually to 47.6°C, 48.65°C, 49.98°C, 51.35°C and 52.37°C at 5%, 7.5%, 10%, 12.5%,15% and 17.5% kaolin content respectively. Higher softening point indicates that kaolin significantly improves thermal stability of binder. This is crucial to resist rutting and flow under traffic loading particularly in hot climate region. This study aligns with a research investigated by [32], which indicates that adding metakaolin (thermally treated form of kaolin) raises softening point of binder. They attributed that the dispersion of metakaolin particles within the asphalt matrix reduce light volatile materials and increase stiffness. Similarly the study [36] also found that adding pozzolana to bitumen raised softening point which enhances viscosity and temperature susceptibility.

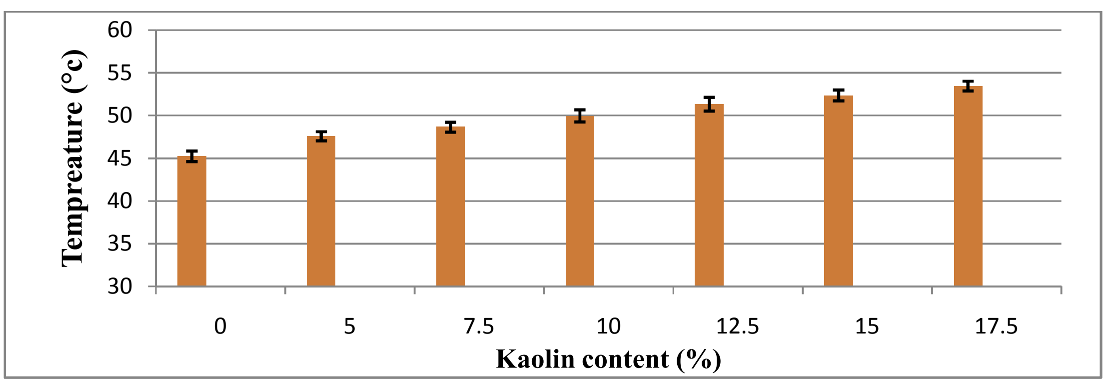


Figure 4.6 Softening point test result for KNMB

4.5 Flash and Fire point test

4.5.1 Effects of crumb rubber modified binder on flash and fire point

The experimental test result in table 4.1 indicates that flash and fire point of original binder measured 265°C and 276°C respectively. While adding 2% CR flash point rose to 270°C and fire point increased to 280°C. Table 4.2 and figure 4.7 indicates that flash and fire point increase with increasing the percentage of crumb rubber content. Based on the finding all specimens fulfil minimum AASHTO specification requirement i.e. 232°C. This implies that crumb rubber modified binder safer at high temperature.

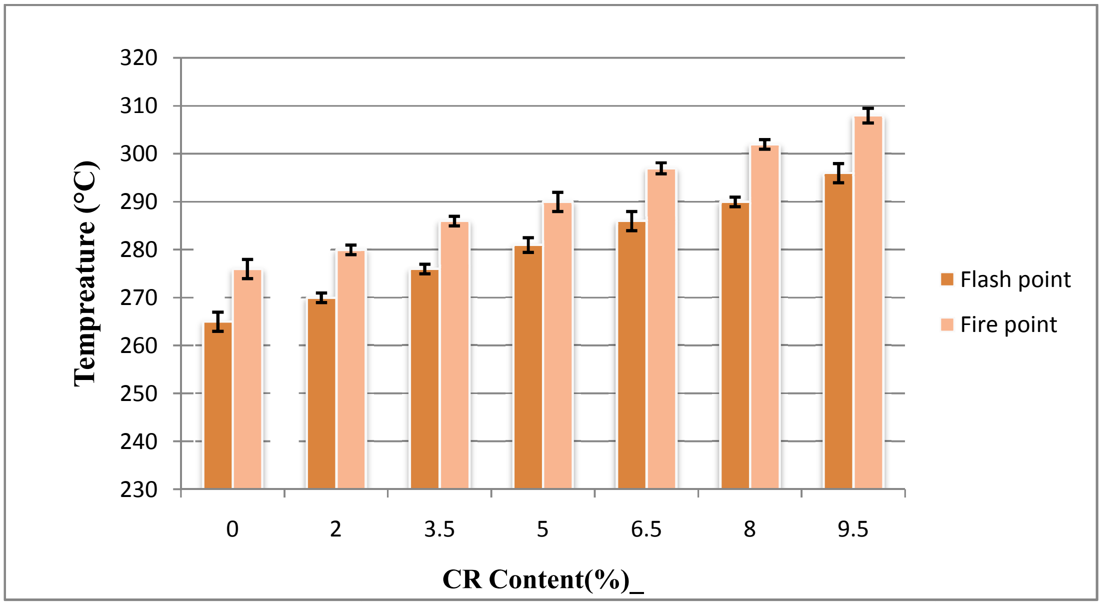


Figure 4.7 Flash and Fire point test result for CRMB

4.5.2 Effects of kaolin modified binder on flash and fire point

The result of kaolin modified binder as shown in table 4.2 and figure 4.8 demonstrates flash and fire point value increase with increasing kaolin content. The flash point result increases from 265 °C at 0% to 309 °C at 17.5%. This increase in flash and fire point implies that incorporation of kaolin improves binders safety and thermal resistance property reducing the flammability of binder. This study aligns with earlier research by [36] who confirming that the role of mineral modifiers like pozzolana in improving binders safety and performance under high temperature environment.

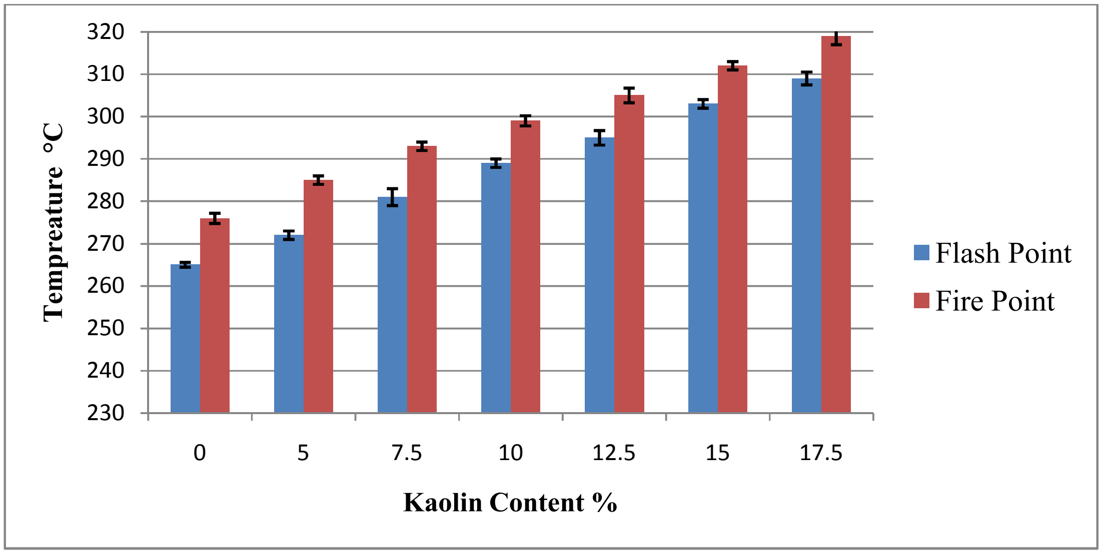


Figure 4.8 Flash and Fire point test result for KNMB

4.6 DSR test result

In this study, DSR test are used to evaluate the rheological characteristics of asphalt binder parameter such as rutting resistance, complex modules and phase angle from intermediate to high temperature. All finding of DSR test results are discussed below for both aged and un-aged asphalt binder.

4.6.1 DSR test result for crumb rubber modified binder

4.6.1.1 Complex modulus (G*)

Complex modulus refers to material stiffness it depends on testing temperature. Complex shear modules is evaluated for original and modified binder for both aged (RTFOT) and un-aged binder. Figure 4.9 and 4.10 shows that complex modules results of crumb rubber modified binder at different temperature. G* gradually increases as the percentage of crumb rubber content increase. Test result Appendix C shows at 46°C, original binder had a G* value of 8.34kpa, while 2%, 3.5%, 5%, 6.5%, 8% and 9.5% CRMB rise to 17.7, 18.7, 20.2, 23.2, 29.5 and 32.5 kpa respectively. Similar improvement were observed when the temperature increase to 52, 58 and 64°C the G* value increased. At high temperature the modified binder provides higher stiffness compared to the control binder. The increase in G* value indicates the material stiffness resulting high resistance for rutting or permanent deformation. This study aligns with the research by [25] who found that the role of crumb rubber improving complex modules and binders performance at elevated temperature.

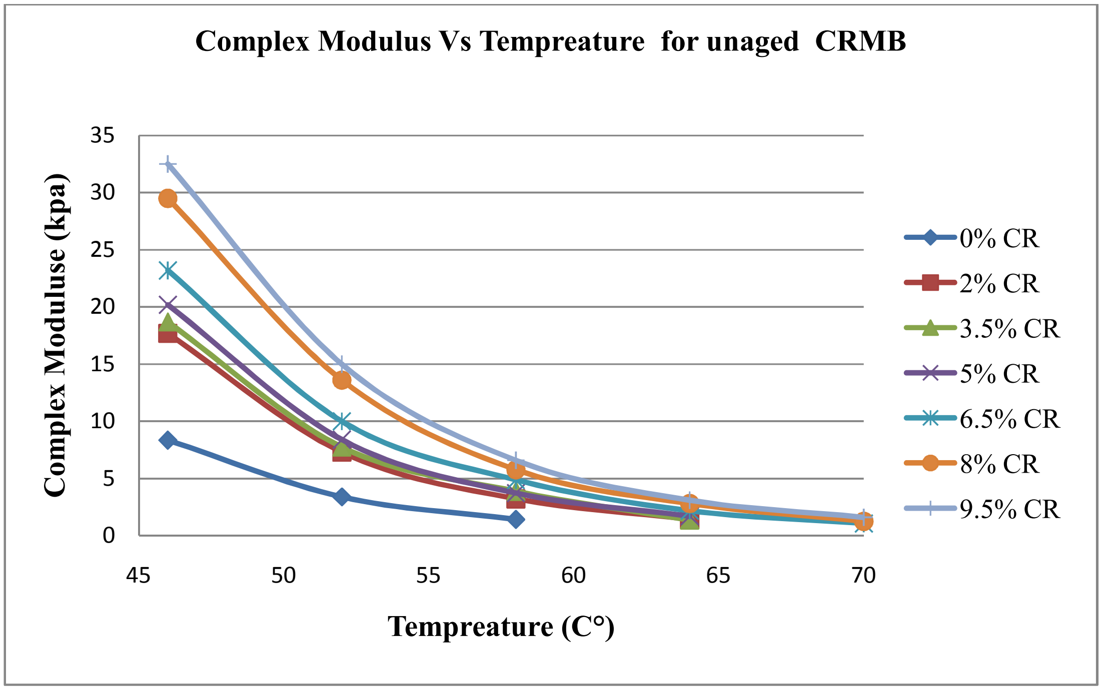


Figure 4.9 Complex modules versus temperature for un-aged CRMB

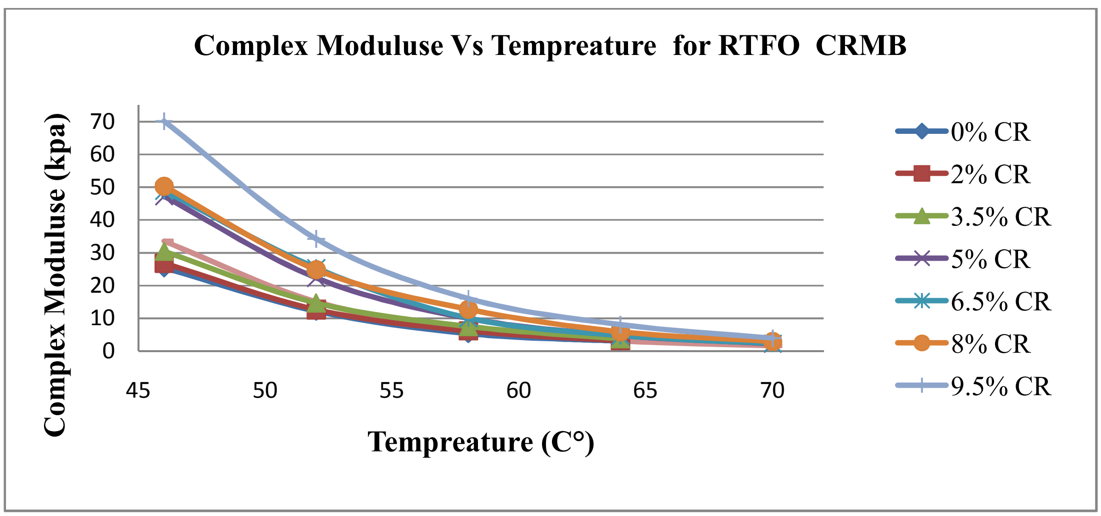


Figure 4.10 Complex modules versus temperature for RTFO CRMB

4.6.1.2 Rutting Parameter (G*/SinΔ)

Rutting Parameter (G*/SinΔ) is a superpave criteria to measure rutting resistance having a specification limit for which G*/SinΔ ≥1kpa for un-aged binder and G*/SinΔ ≥2.2kpa for aged (RTFOT) asphalt binder. The finding as shown in figure 4.11 and 4.12 shows the rutting parameter exponentially decreased at a high rate for low temperature and lower rate for high temperature. At 46°C, the value of original bitumen (0% CR) is 8.53kpa which rises to 16.5, 18.2, 21.9, 25.7, 32.9 and 35kpa at 2%, 3.5%, 5%, 6.5%, 8% and 9.5% CR respectively. Similar trends are observed at 52°C, 58°C, 64°C and 70°C, while the original binder do not meet the specification at 64°C. G*/SinΔ value increased when the percentage of crumb rubber content increase. This is due to elastic nature of CR indicates that adding crumb rubber to asphalt binder improves rutting resistance of asphalt by withstanding high temperature susceptibility under traffic loading. This finding is supported by earlier research by [25] who observed that CRMB improves rutting resistance for high temperature condition.

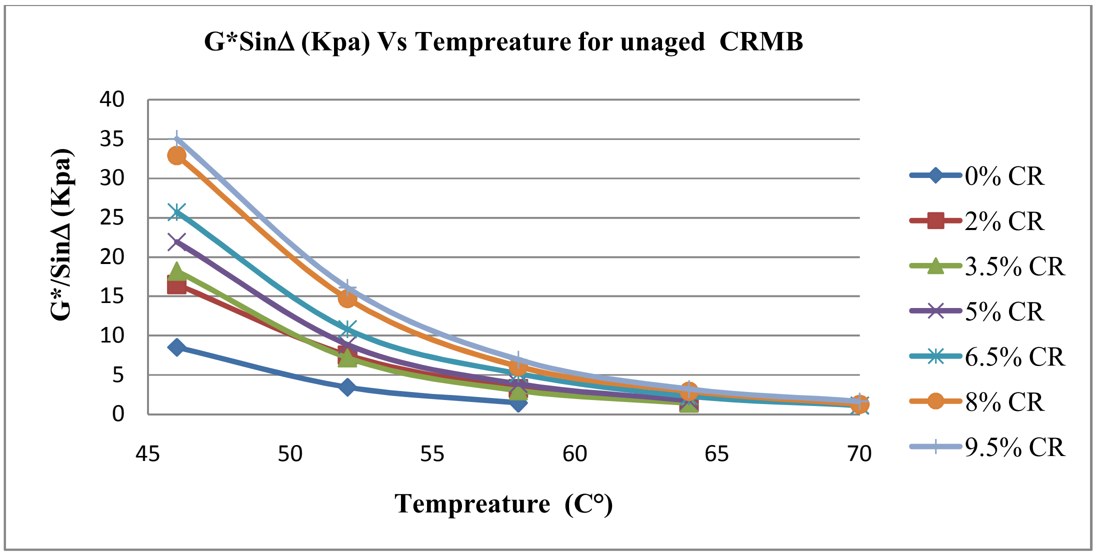


Figure 4.11 G*/SinΔ versus temperature for un-aged CRMB

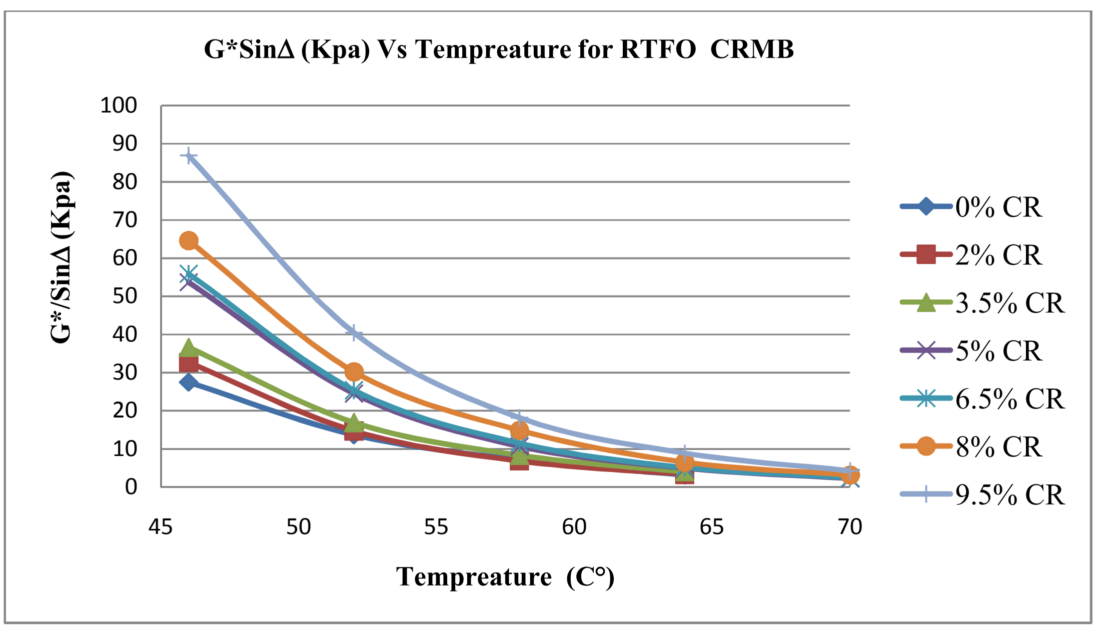


Figure 4.12 G*/SinΔ versus temperature for RTFOT CRMB

4.6.1.3 Phase angle

Phase angle describes the time lag between shear stress and shear strain. When the phase angle increases (approaches to 90°) the viscous properties of the asphalt binder increase. While, if it decreases the elastic properties of the material becomes increases. In this study phase angle is measured for both aged and un-aged asphalt binder using DSR test as a superpave criteria. Phase angle depends on the temperature effect as the temperature increase phase angle also increases. As the temperature increased from 46°C to 70°C, phase angle consistently increased across all crumb rubber concentration. Based on figure 4.13 and 4.14 the original binder (0% CR) sample shows that the highest phase angle values than among various CR percentages, this implies less elastic and more viscous properties. On the other hand, increasing percentage of crumb rubber from 2% to 9.5%, leads to a rapid decrease in phase angle values. This indicates that a stiffer and more elastic characteristics of crumb rubber modified binder. Totally the finding implies that adding CR affects viscoelastic properties of asphalt binder with higher content increase the stiffness and improves elastic behaviour. This study related with earlier studies [25] who explores that the increasing addition of crumb rubber reduces phase angle it makes the binder more elastic. The research [23], who emphasized that crumb rubber enhancing the elastic behaviour and high temperature performance of asphalt binder.

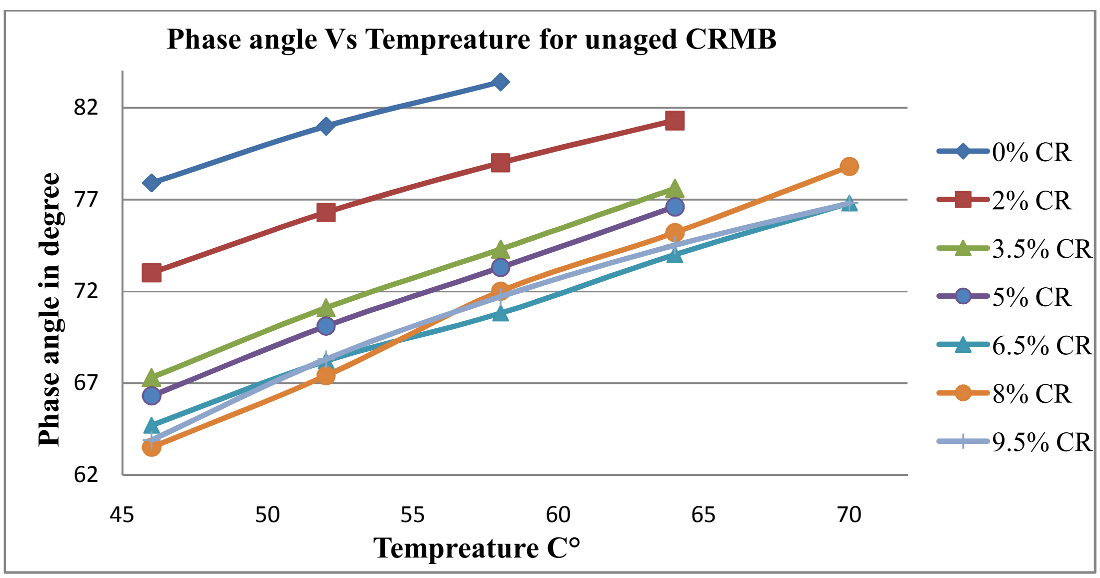


Figure 4.13 Phase angle versus temperature for un-aged CRMB

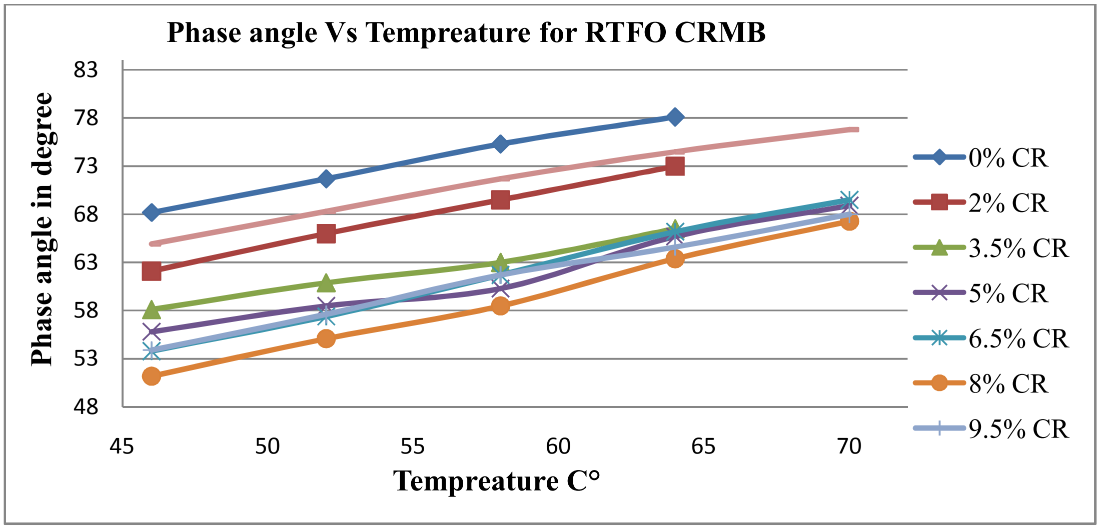


Figure 4.14 Phase angle versus temperature for RTFOT CRMB

4.6.2 DSR test result for kaolin modified binder

4.6.2.1 Complex modulus (G*)

The complex modulus result for kaolin modified asphalt binder as shown in figure 4.15 and 4.16 for un aged and aged binder demonstrates an exponentially decreasing G* value with increasing testing temperature from 46°C to 70°C. Based on the result of the finding G* value increases when the percentage of kaolin increase from 0% to 17.5%. This implies that kaolin added modified binder is stiffer for both aged and un-aged binder which can resist high temperature and improve deformation.

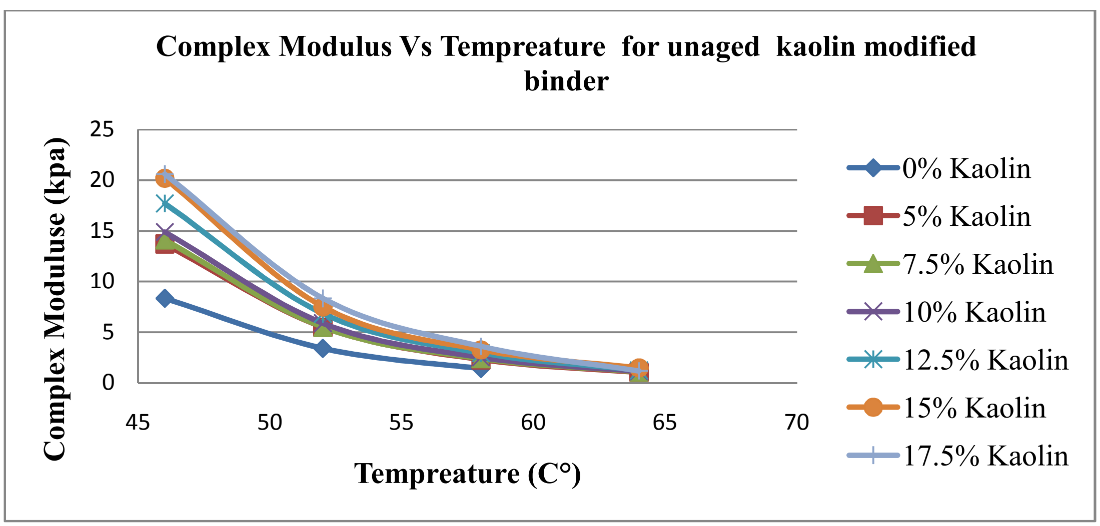


Figure 4.15 Complex modulus versus temperature for un-aged KNMB

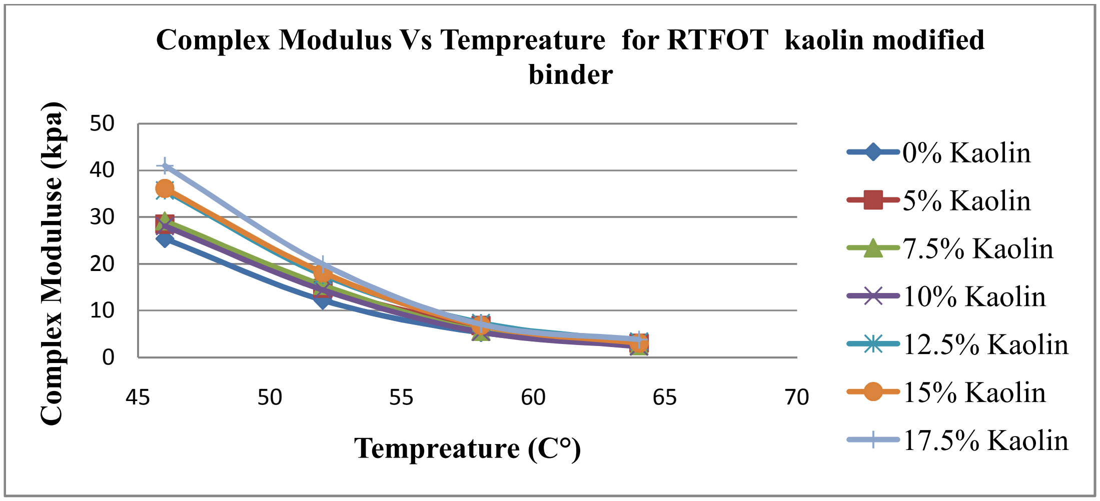


Figure 4.16 Complex modules versus temperature for RTFO kaolin modified binder

4.6.2.2 Rutting Parameter (G*/SinΔ)

DSR test is carried out for both aged and un-aged binder for original and modified binder. The finding in figure 4.17 and 4.18 shows G*/SinΔ value initially increases with increasing the percentage of adding kaolin content to the binder. This indicates that there is direct relationship between crumb rubber with G*/SinΔ. Based on the result G*/SinΔ decrease exponentially when test temperature raise. The magnitude of G*/SinΔ at 46°C is high and it becomes low at 70°C. Finally the finding of this study indicates that incorporating kaolin additive in to asphalt binder can withstand high temperature and improves rutting properties of asphalt binder. This is consistent with a research [32] who suggests the addition of metakaolin increased rutting parameter resulting in rutting resistance of deformation. A study [36] also found that pozzolana modified binder exhibits increasing G*/SinΔ leading to better rutting resistance.

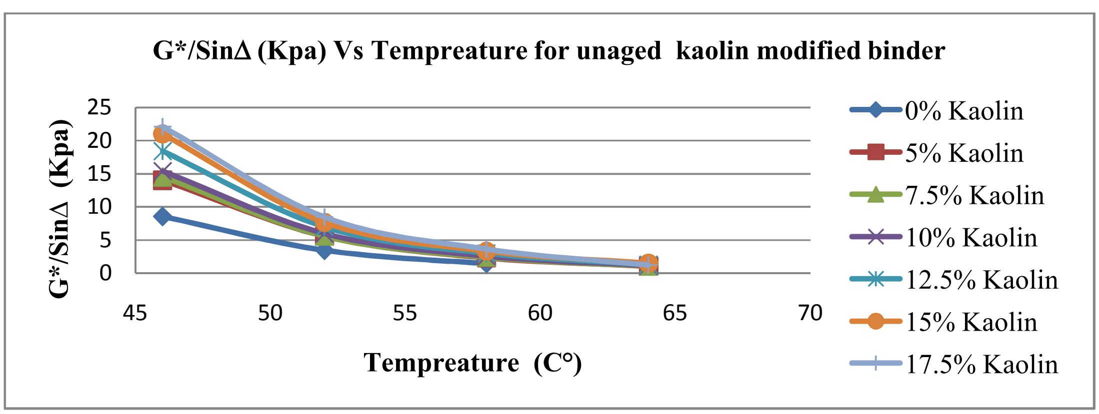


Figure 4.17 G*/SinΔ versus temperature for un-aged KNMB

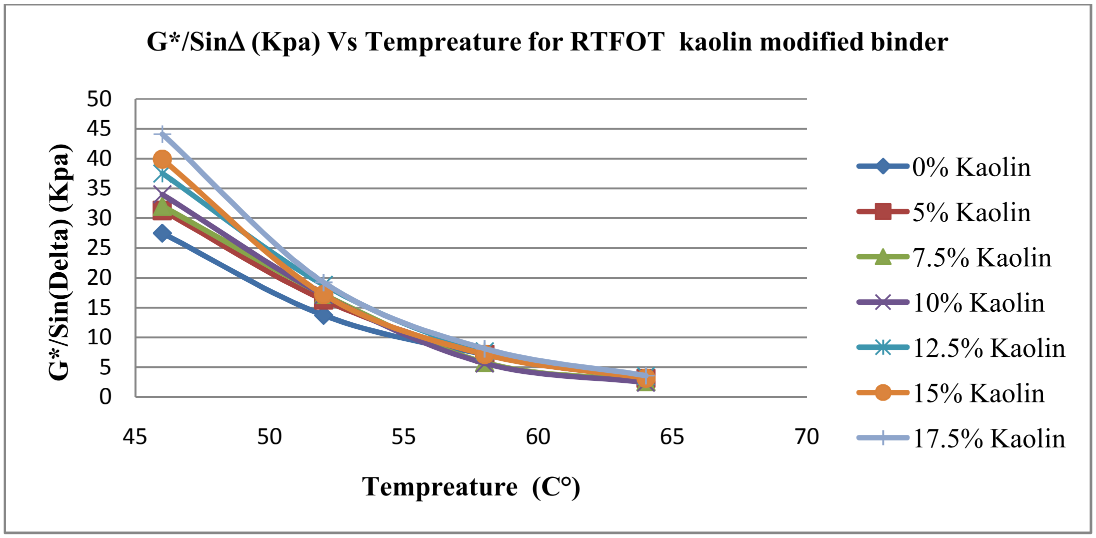


Figure 4.18 G*/SinΔ versus temperature for RTFO kaolin modified binder

4.6.2.3 Phase angle

In this study the result of phase angle decreased gradually when dosage of adding kaolin in to bitumen increase. Phase angle has an inverse relation with elastic property of asphalt binder a low value of phase angle indicates that the binder is more elastic. Figure 4.19 and 4.20 shows the value of phase angle decreases as the percentage of kaolin content increase for both un-aged and RTFO binders. This indicates kaolin additive material improves elastic property of the binder. This finding aligns with a research by [32] who attributed that the addition of micro and nano sized kaolin powder to asphalt binder lead to decreasing phase angle due to filler effects of kaolin based materials.

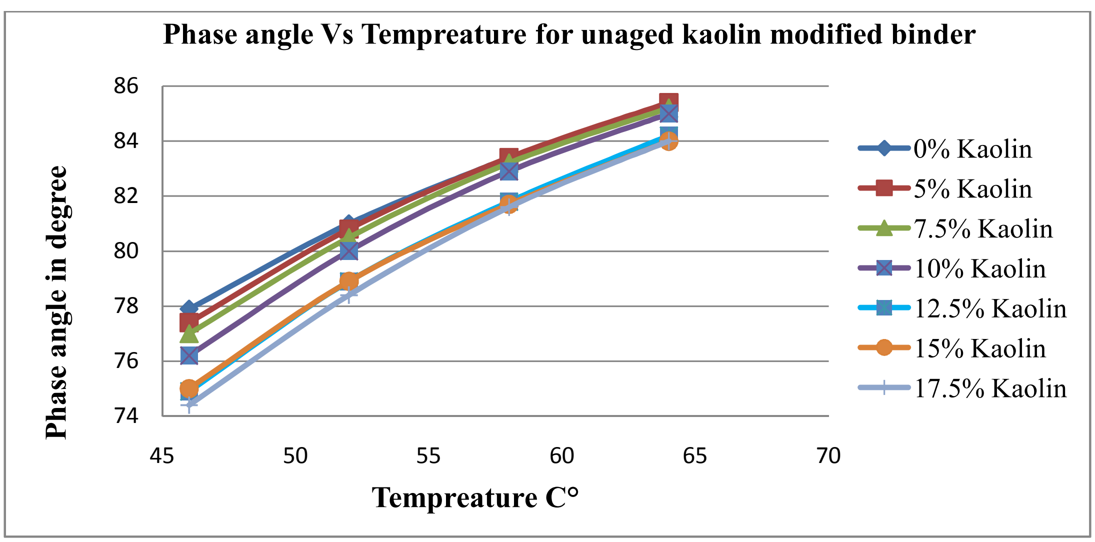


Figure 4.19 Phase angle versus temperature for un-aged KNMB

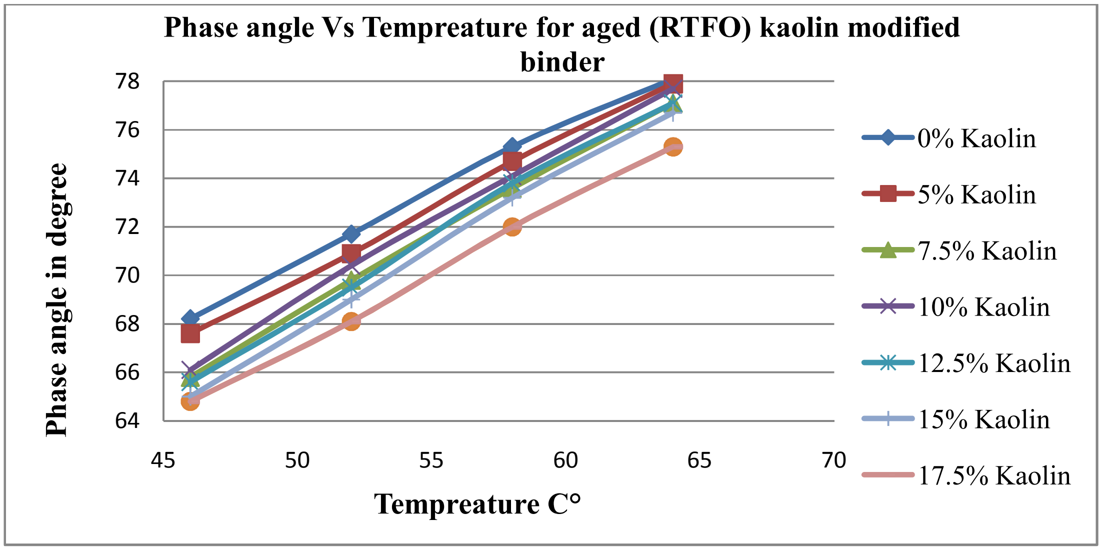


Figure 4.20 Phase angle versus temperature for RTFO KNMB

4.7 Asphalt binder performance grade

In this study performance grade (PG) was determined by using DSR test for both original and modified binders.

Table 4.4 Asphalt binder performance grade (PG) for control and CRMB

DSR Test	80/100 Bitumen	2% CR	3.5% CR	5% CR	6.5% CR	8% CR	9.5% CR	Superpave criteria
True-grade Temp. for Un aged binder	60.6	67.15	66.51	68.2	70.96	71.92	73.36	G*/SinΔ≥1 Kpa
Mass Loss	0.22	0.23	0.22	0.23	0.24	0.25	0.28	Mass Loss≤1%
PG	PG-64	PG-64	PG-64	PG-64	PG-70	PG-70	PG-70	
DSR Test true grade Temp. for RTFOT	68.8	67.81	69.06	70.22	70.6	72.95	75.37	G*/SinΔ≥2.2 Kpa
PG	PG-64	PG-64	PG-64	PG-70	PG-70	PG-70	PG-70	

Based on table 4.4 80/100 original binder has a PG-58, while the additions of 2%, 3.5%, 5% CR exhibits a performance grade of PG-64. Further increasing CR including 6.5%, 8% and 9.5% increases performance grade to PG-70.This indicates improvement for high temperature resistance with increasing CR content.

Table 4.5 Asphalt binder performance grade (PG) for control and KNMB

Test DSR Test	80/100 Bitumen	5% Kaolin	7.5% Kaolin	10% Kaolin	12.5% Kaolin	15% Kaolin	17.5% Kaolin	Superpave criteria
True-grade Temp. for Un-aged binder	60.6	64.22	64.68	64.94	65.88	67.05	68.38	G*/SinΔ≥1 Kpa
Mass Loss	0.22	0.24	0.26	0.26	0.29	0.31	0.3	Mass Loss≤ 1%
PG	PG-64	PG-64	PG-64	PG-64	PG-64	PG-64	PG-64	
DSR Test true grade Temp. for RTFOT	66.8	66.82	65.22	64.7	67.41	66.59	68.5	G*/SinΔ≥2.2 Kpa
PG	PG-64	PG-64	PG-64	PG-64	PG-64	PG-64	PG-64	

Based on the result in table 4.5 the original binder has a PG-58 while the addition of kaolin increases the performance grade to PG-64. This indicates that the addition of kaolin improves binders performance. This is suitable for enhancing rutting resistance and deformation.

4.8 Optimum binder content determinations

One of the critical factors to improve asphalt performance is choosing the appropriate optimum binder content. Based on the results of binder quality test the optimum binder content is 3.5% for CR and 10% for kaolin modified binder were selected. This decision is mainly depend on binder's penetration and ductility test. Based on asphalt binder physical and rheological outcome the percentage of crumb rubber and kaolin increase penetration and ductility values decreased. This indicates an increase in stiffness of the material. However performance grade, softening point and flash point increase resulting in high temperature performance. While too much reduction of ductility and penetration value may causes brittleness of the material.

4.9 physical and Rheological characteristics of combined modified binder

Combined modified binder is a combination of original binder with the optimum content of crumb rubber and kaolin. DSR test is used to evaluate the rheological properties and PG of these materials for both un-aged and RTFO phase. Based on test result the performance grade PG of combined modified binder is PG-64. This indicates improvements of performance of binder as compared to control binder increasing from PG-58 to PG-64.

4.9.1 Complex modules (G*)

The result in figure 4.21 and 4.22 illustrates that the combined modified binder has high complex modules than the control binder. At a test temperature of 46, 52 and 58°C the complex modules of control binder is 8.34, 3.4, and 1.42kpa respectively. Whereas for combined modified binder the G* value at a temperature of 46, 52, 58 and 64°C is 16.7, 6.89, 2.97 and 1.31kpa. This finding indicates that the modified binder has higher stiffness than the control binder which makes the binder more resistant to deformation for heavy traffic loading. Overall a 3.5% CR provides high stiffness improvement, while the combined modified binder (3.5%CR+ 10% kaolin) offered a balanced improvement in both stiffness and elasticity of binder property.

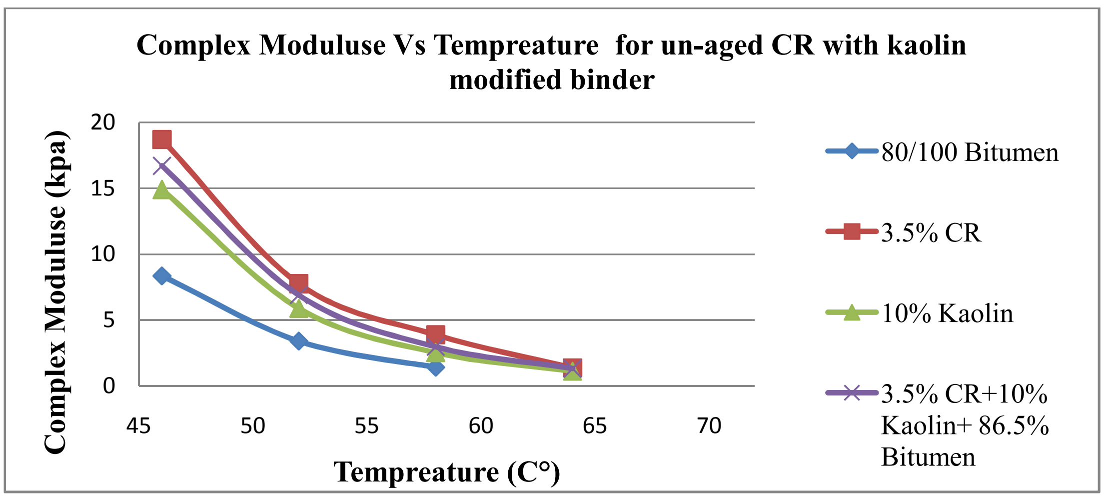


Figure 4.21 Complex modules versus temperature for un-aged combined MB

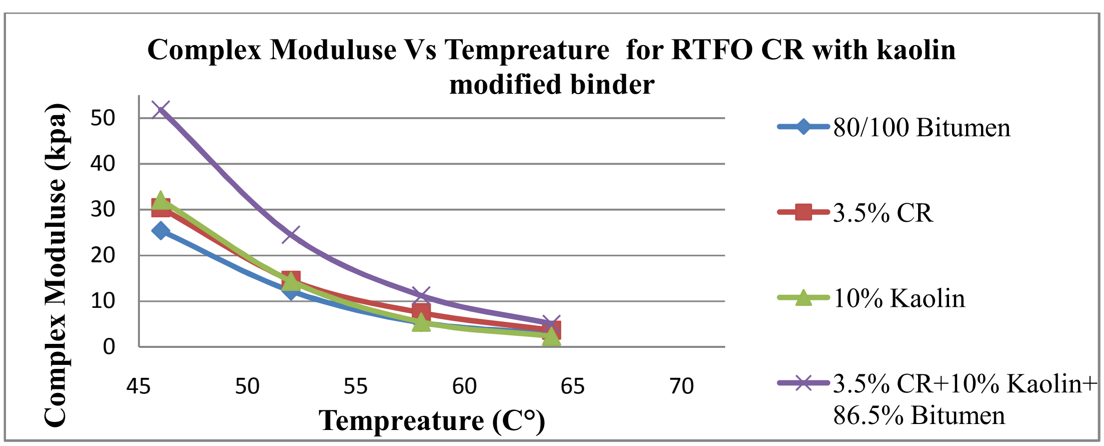


Figure 4.22 Complex modules versus temperature for RTFO combined MB

4.9.2 Rutting Parameter (G*/SinΔ)

The G*/SinΔ value for CRMB, kaolin MB and combined modified binder as shown in appendix C, figure 4.23 and 4.24 shows higher than the original bitumen. The G*/SinΔ value for combined modified binder at a test temperature of 46, 52, 58 and 64°C is 17.7, 7.15, 3.04 and 1.32kpa respectively. While the G*/SinΔ value of original bitumen at a test temperature of 46, 52 and 58°C is 8.53, 1.44 and 1.43kpa respectively. This implies that the combined blend (3.5%CR+10% K) modified binder has high rutting parameter as compared to control binder. Based on RTFOT result combined modified binder has high rutting enhancement as compared to CR and KNMB alone, however it is nearly similar for un aged binder. Overall optimum combination mix of CR and kaolin binder high resistance of elevated temperature and enhance rutting resistance as compared to original binder.

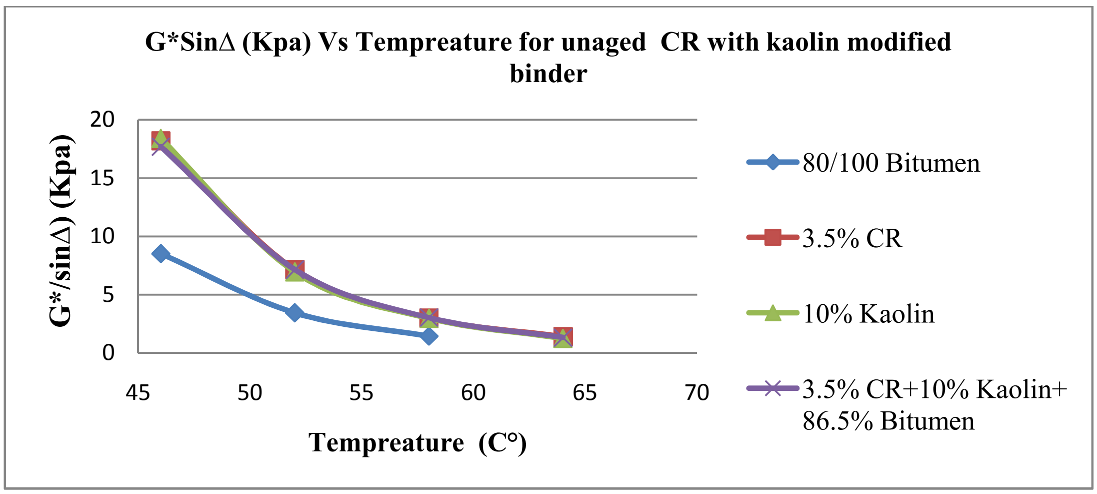


Figure 4.23 G*/SinΔ versus temperature for un-aged combined modified binder

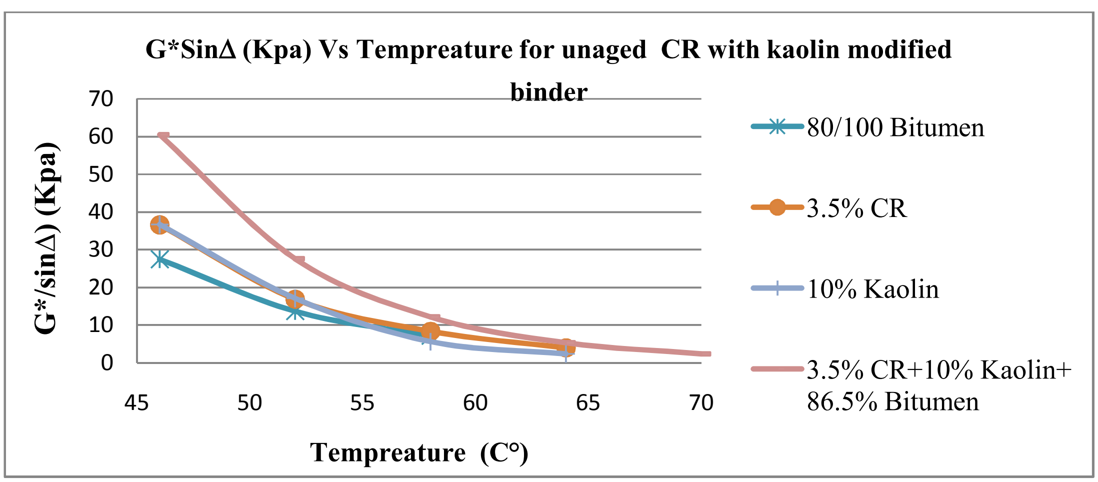


Figure 4.24 G*/SinΔ versus temperature for RTFO combined modified binder

4.9.3 Phase angle

The result in figure 4.25 and 4.26 illustrates that at 46°C, the phase angle for original binder, 3.5%CR, 10% kaolin and combined modified binder (3.5% CR and 10% kaolin) is 77.9°, 67.3°, 76.2°and 70.8° respectively. According to this finding the original binder is highest phase angle implies more viscous property.3.5% CR additive reduced the phase angle to 67.3° which enhances binder elasticity. While 10% kaolin addition resulting 76.2° phase angle which implies that partial enhancement of elasticity compared to CR. The combined modified binder exhibits a phase angle of 70.8°. This indicates the combined modified binder provides a balanced enhancement of elasticity property of binder as compared to the original binder.

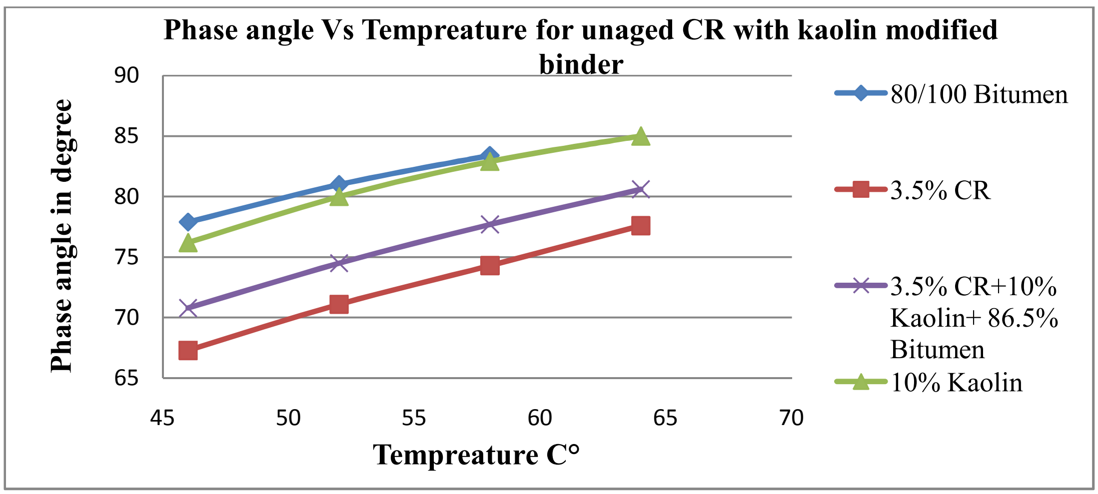


Figure 4.25 Phase angle versus temperature for un-aged combined modified binder

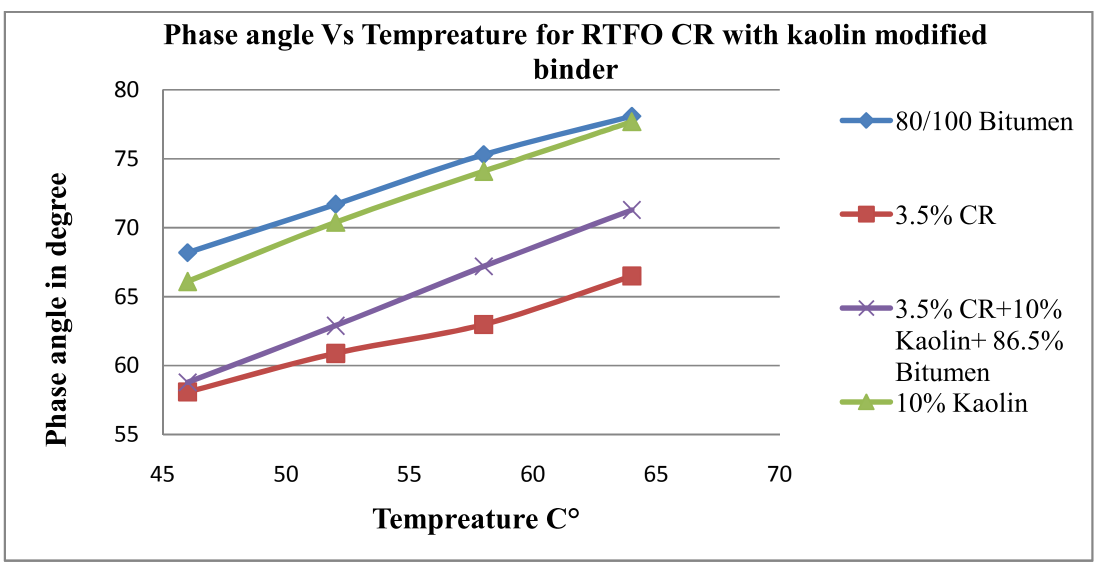


Figure 4.26 Phase angle versus temperature for RTFO combined modified binder

Table 4.6 Physical test result for combined modified binder

Test	Penetration test (0.1mm)	Ductility Test (cm)	Softening point test (°C)	Flash Point test (°C)	Fire Point test (°C)
result	70.5	101.5	50.1	295	301

The physical test result of combined modified binder in table 4.6 shows penetration and ductility value decrease as compared to original binder. Whereas softening point, flash and fire point test results increased.

4.10 Statistical analysis of test result

The quality characteristics of crumb rubber and kaolin modified binder were assed for this study using statistical analysis. The experimental results were evaluated with a combination of descriptive statistics and one way ANOVAs. Descriptive statistics summarized the central tendency, dispersion, normality and overall distribution of binder properties like penetration, ductility, softening point, flash and fire point test. Levenes statistics evaluated the homogeneity of variance across groups. One way ANOVA method is used to determine whether there were statistically significance difference values between binder samples modified with crumb rubber and kaolin. Based on this statistical analysis method this study aimed to verify the modified binder enhanced binder's quality and consistency. The statistics analysis for this study was conducted based on SPSS software.

4.10.1 one way ANOVA test result for crumb rubber modified binder (CRMB)

One way ANOVA test was conducted based on physical properties experimental test result of CRMB with varies percentage of crumb rubber including 0%, 2%,3.5%,5%,6.5%,8% and 9.5%. The results of all one way ANOVA test are shown below in the following table.

Table 4.7 One way ANOVA test result of CRMB for penetration test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Penetration value	Based on Mean	1.292	6	14	.323
	Based on Median	.667	6	14	.678
	Based on Median and with adjusted df	.667	6	8.536	.680
	Based on trimmed mean	1.247	6	14	.341

ANOVA					
Penetration value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5619.816	6	936.636	7959.758	.000
Within Groups	1.647	14	.118		
Total	5621.464	20			

Table 4.8 One way ANOVA test result of CRMB for ductility test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Ductility Value	Based on Mean	1.036	6	14	.443
	Based on Median	.611	6	14	.718
	Based on Median and with adjusted df	.611	6	8.816	.717
	Based on trimmed mean	1.008	6	14	.458

ANOVA					
Ductility Value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	21836.286	6	3639.381	813.053	.000
Within Groups	62.667	14	4.476		
Total	21898.952	20			

Table 4.9 One way ANOVA test result of CRMB for softening point test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Softening point	Based on Mean	6.309	6	14	.954
	Based on Median	1.552	6	14	.233
	Based on Median and with adjusted df	1.552	6	2.674	.401
	Based on trimmed mean	5.797	6	14	.962

ANOVA					
Softening point					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	197.381	6	32.897	494.336	.000
Within Groups	.932	14	.067		
Total	198.313	20			

Table 4.10 One way ANOVA test result of CRMB for flash point test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Flash point test value	Based on Mean	.432	6	14	.845
	Based on Median	.389	6	14	.874
	Based on Median and with adjusted df	.389	6	10.800	.871
	Based on trimmed mean	.430	6	14	.847

ANOVA					
Flash point test value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2194.571	6	365.762	147.712	.000
Within Groups	34.667	14	2.476		
Total	2229.238	20			

Table 4.11 One way ANOVA test result of CRMB for fire point test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Fire point test value	Based on Mean	.460	6	14	.827
	Based on Median	.352	6	14	.897

	Based on Median and with adjusted df	.352	6	10.800	.894
	Based on trimmed mean	.454	6	14	.831

ANOVA					
Fire point test value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2413.905	6	402.317	192.015	.000
Within Groups	29.333	14	2.095		
Total	2443.238	20			

Based on one way ANOVA statistical analysis test result for binder's physical test significant result were obtained including penetration, ductility, softening point, flash and fire point test conducted on CRMB. For this test a confidence interval of 95% used to evaluate the significance value. Based on test result of penetration, ductility, flash and fire point test Levenes test for homogeneity shows a P Value (Sig. >0.05), which is statistically insignificant implies that the variance between the groups is homogeneous. Whereas all statistical test result has a P value (Sig. =0.00), which indicates that all evaluated properties are statistically highly significant. This implies that the physical properties of the binder significantly affected by the addition of crumb rubber.

4.10.2 one way ANOVA test result for kaolin modified binder (KNMB)

Table 4.12 One way ANOVA test result of KNMB for penetration test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Penetration test values	Based on Mean	1.314	6	14	.314
	Based on Median	.471	6	14	.819
	Based on Median and with adjusted df	.471	6	10.433	.816
	Based on trimmed mean	1.237	6	14	.346

ANOVA
Penetration test values

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5807.408	6	967.901	10708.001	.000
Within Groups	1.265	14	.090		
Total	5808.673	20			

Table 4.13 One way ANOVA test result of KNMB for ductility test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Ductility value	Based on Mean	.830	6	14	.566
	Based on Median	.299	6	14	.927
	Based on Median and with adjusted df	.299	6	7.611	.920
	Based on trimmed mean	.787	6	14	.594

ANOVA					
Ductility value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	13716.667	6	2286.111	738.590	.000
Within Groups	43.333	14	3.095		
Total	13760.000	20			

Table 4.14 One way ANOVA test result of KNMB for softening point test

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Softening point test	Based on Mean	6.309	6	14	.653
	Based on Median	1.552	6	14	.233
	Based on Median and with adjusted df	1.552	6	2.674	.401
	Based on trimmed mean	5.797	6	14	.681

ANOVA					
Softening point test					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	197.381	6	32.897	494.336	.000
Within Groups	.932	14	.067		
Total	198.313	20			

Table 4.15 One way ANOVA test result of KNMB for flash point test

ANOVA					
Flash Point test value					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4516.476	6	752.746	415.991	.000
Within Groups	25.333	14	1.810		
Total	4541.810	20			

Table 4.16 one way ANOVA test result of KNMB for fire point test

ANOVA					
Fire point test					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4001.810	6	666.968	368.588	.000
Within Groups	25.333	14	1.810		
Total	4027.143	20			

Based on statistical analysis test result for kaolin modified binder physical property indicates that the incorporation of kaolin significantly impacts the properties of binder. In this test the Levenes test is used to check homogeneity test of variance P-value (sig.>0.05), indicates that the variance is homogeneous or displays equal variance. The results of all physical properties test of one way ANOVA all P-value (Sig. =0.00). This indicates highly statistical significant value. Overall the addition of kaolin for binder modification significantly affects penetration, ductility, softening point, flash and fire point test.

4.10.3 Regression Statistical analysis for rutting parameter

Regression analysis was conducted to ensure and evaluate the highest temperature performance of asphalt binder under various temperature conditions based on DSR test result. The test performed on original bitumen, optimum CRMB, optimum KNMB, and their combination. For the analysis two parameters were considered such as rutting Parameter as the dependent variable and varying temperature as independent variable.

Based on regression analysis of asphalt binder performance indicates a notable improvement with the additions of crumb rubber and kaolin materials. Based on the test result from regression analysis Appendix C, the original bitumen exhibits a 60.37°C, which increased to 64.35°C, 65.53°C and 65.63°C with optimum CR, kaolin and combined modified asphalt binder respectively. This demonstrates that enhancing temperature resistance with the addition of kaolin and crumb rubber modifiers. The incorporation of CR and kaolin for binder modification improves rutting resistance under elevated temperature as compared to original binder.

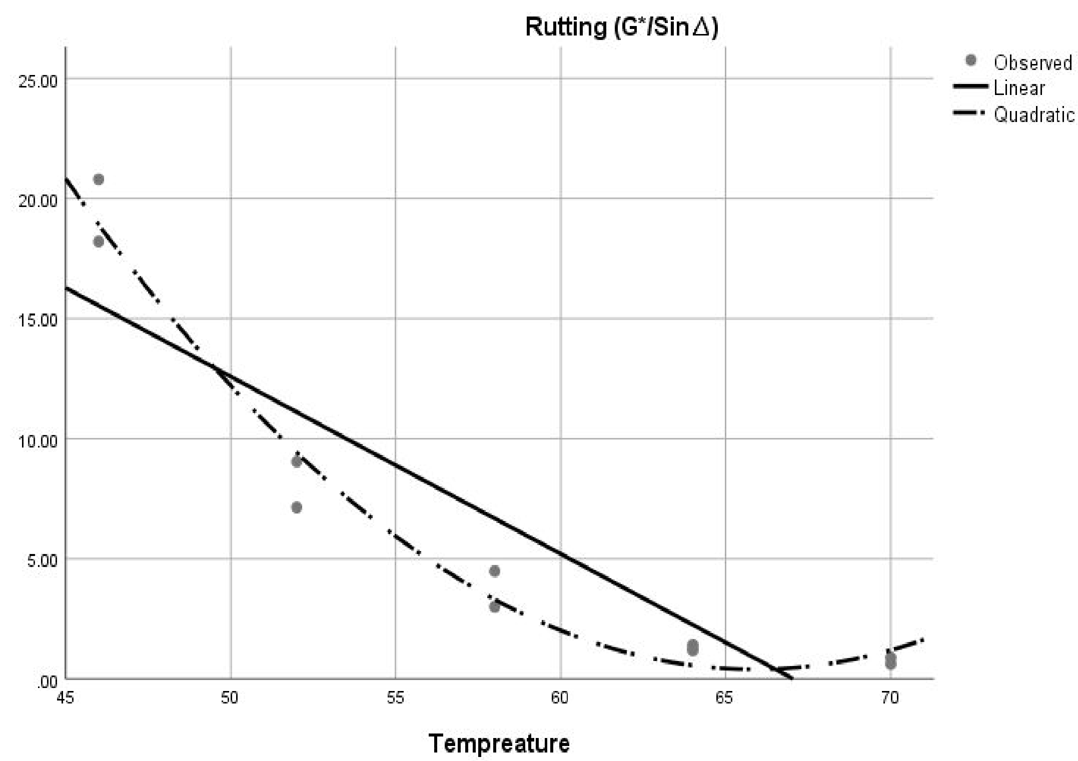


Figure 4.26 Regression analysis results for 3.5% crumb rubber modified binder

4.11 Volumetric property of asphalt mix result

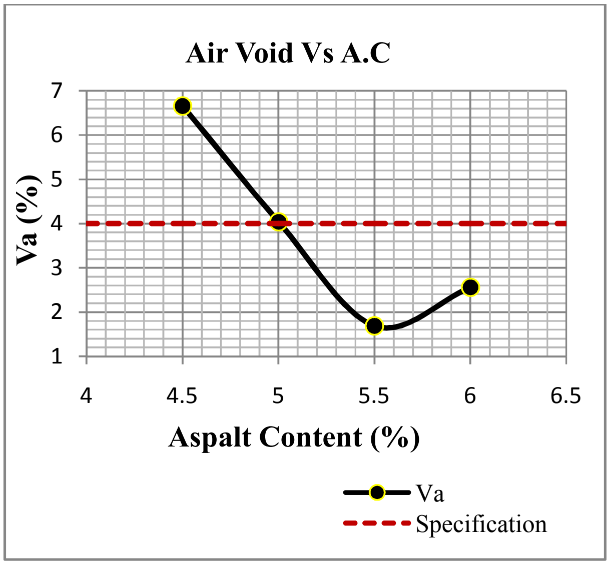
Table 4.17 Volumetric properties of asphalt concrete at N_{desig} 100 Gyratory compaction

A.C(%)	Gmm	Gmb	Va(%)	VMA(%)	VFA(%)	C_{design}
4.5	2.43	2.27	6.66	16.94	60.68	93.42
5	2.4	2.303	4.04	16.17	74.51	95.96
5.5	2.36	2.32	1.69	16	89.41	98.31
6	2.34	2.28	2.56	17.88	85.66	97.44
Specification			min 4%	≥13	65-75	

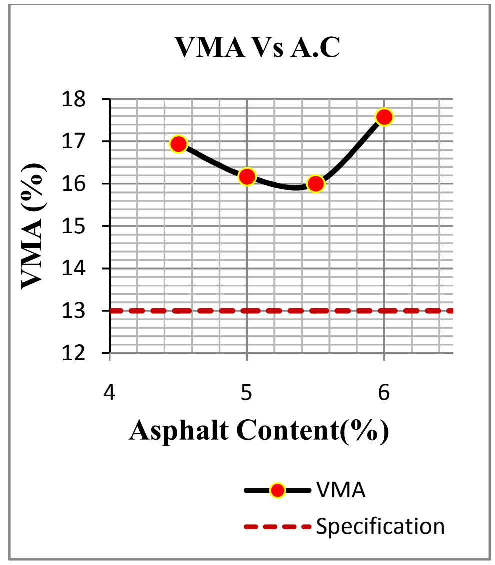
Volumetric properties of asphalt mixture are presented in table 4.17 at different asphalt content (A.C) levels of ranging from 4.5% to 6% with 0.5% asphalt content increment. Theoretical specific gravity (Gmm) of loose mix decrease slightly from 2.43 at 4.5% A.C to 2.34 at 6% A.C. On the other hand, bulk specific gravity of compacted asphalt mix value increase with increasing bitumen content from 4.5% A.C to 5.5% A.C and decreases at 6%. The values of air void (Va) falls as the asphalt content increases, from 6.66% at 4.5% A.C to 1.69% at 5.5% A.C, then slightly rising at 6% A.C. Based on the specification a minimum of 4% air void is required for superpave mix design which is achieved only at 5% A.C (4.04%), whereas 5.5% and 6% A.C falls below the threshold value.

The percent of voids in mineral aggregate (VMA) values are 16.94, 16.17, 16 and 17.88% at 4.5, 5, 5.5, and 6% A.C respectively. All VMA values of asphalt mixture are above the minimum specification limit (13%). This indicates that there is sufficient internal space among the mix to accommodate asphalt binder. The percentage of voids filled with asphalt (VFA) value increases significantly from 60.68% at 4.5% A.C to 89.4% at 5.5% A.C and fall to 85.66% at 6%A.C. VFA requires a specification in the range of 65 to 75% for the selected N_{design} compaction level, only 5% A.C meet the criteria. 5.5% and 6% asphalt mixture shows VFA values of 89.4% and 85.66% respectively. Which is above the threshold limit indicates that extremely rich binder mix.

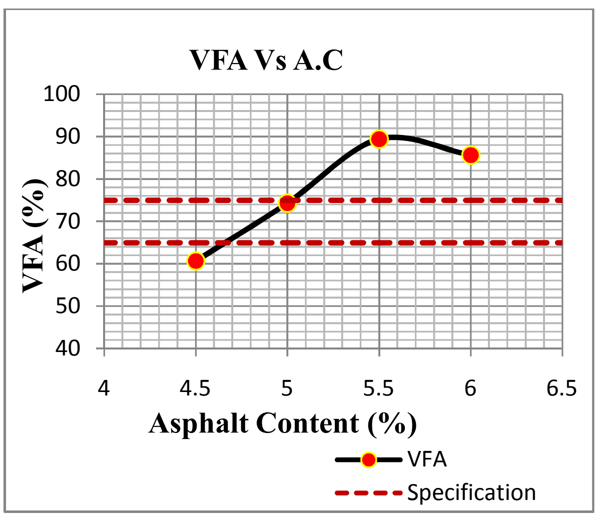
By considering all volumetric properties of asphalt mixture the optimal design asphalt content was selected as 5% OBC. The selection of this OBC satisfies all recommended asphalt standards specifications for Va, VMA and VFA. After OBC determination all compacted asphalt specimen for performance test including modulus, moisture susceptibility and rutting were produced and tested.



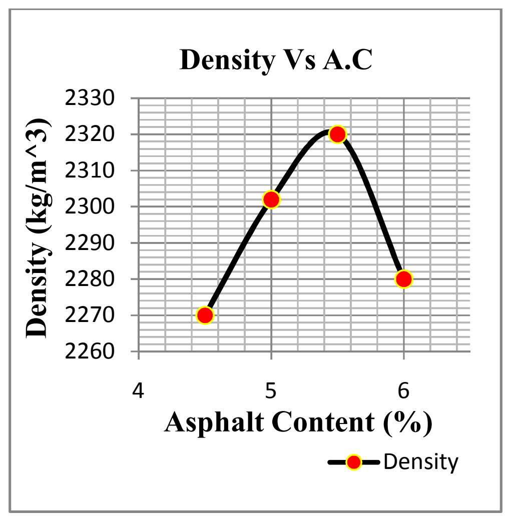
a) Air void Vs asphalt content



b) VMA Vs asphalt content



c) VFA Vs asphalt content



d) Density Vs asphalt content

Figure 4.27 Volumetric properties of asphalt mix test result

4.12 Asphalt performance test result

4.12.1 Rutting test result

Rutting test using a double wheel tracking test with 10,000 cycles (20,000 pass) at a temperature of 50°C was conducted in order to evaluate the permanent deformation of asphalt concrete. Tests were performed on control mix, 3.5% crumb rubber modified mix, 10%kaolin modified mix and CR with kaolin combined modified mix. All test results are on recommended specification limit of AASHTO T-324 and asphalt institute standard with maximum rut depth limitation of 20mm.

The rutting test result shows a distinct trend towards increasing rutting resistance when modifiers added. As a baseline for comparison, the control mix yields a rut depth of 15.76mm. The finding of the study in figure 4.28 shows that when 3.5% CR added to the mix the rut depth decreased to 7.53mm. This implies that 3.5% CR improves 52.2% performance of asphalt. It has a potential for asphalt rutting resistance. The addition of crumb rubber has a significant role in reducing permanent deformation for asphalt mixture [27].Similarly; incorporating 10% kaolin reduces rutting depth of asphalt deformation to 7.55mm as compared to control mix. Kaolin modification improves 52.1% asphalt performance as compared to conventional mix. Most remarkably, the highest performance was obtained with significantly smaller rut depth of 4.11mm when 3.5%CR and 10% kaolin combined together. This indicates 73.9% improves the performance of asphalt concrete in comparison to the control mix. In addition to that the combined effect of CR and kaolin improves moisture susceptibility or stripping effect of asphalt. Ultimately, the combination of crumb rubber with kaolin materials provides an effective improvement of asphalt performance to resist permanent deformation and moisture damage effect.

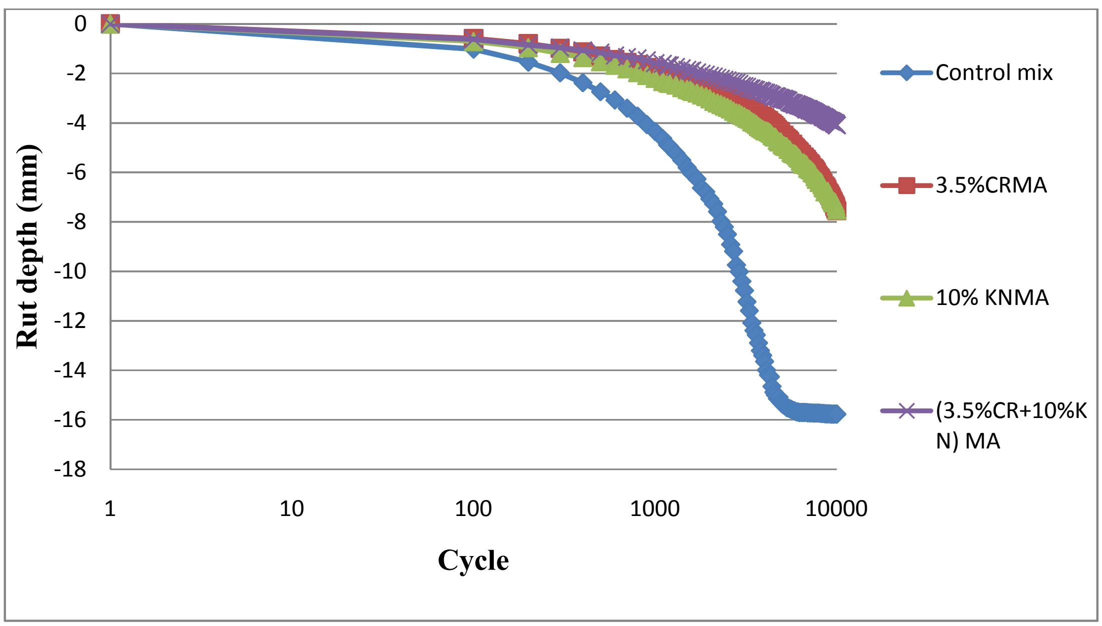


Figure 4.28 rutting test result

4.12.2 Modules (Stiffness) Test result

Indirect tensile modules test was performed to analyze the impact of control binder, crumb rubber, kaolin and optimum combinations of crumb rubber and kaolin on asphalt mixture.

Table 4.18 Indirect tensile modules test result

Sample	Stiffness modules (Mpa) at 25°C
Control mix	634.7
3.5% CRMA	786.1
10% KNMA	1008.1
(3.5% CR+10% KN)MA	1455.4

During testing repetitive pulse loading condition was applied to each sample in order to simulate the stress caused by traffic in real life of pavement. Based on the finding of this study as shown in table 4.18 shows that control mix recorded 634.7 Mpa stiffness at a temperature of 25°C.This is the lowest stiffness value as compared to the modified mix implies that lowest resistance to deformation under repetitive loading condition. While adding 3.5% CR increase the stiffness value to 786.1Mpa indicates better elastic response for pulse loading. 10% kaolin mix measures higher stiffness reached 1008.1Mpa which has a substantial role to resist deformation. The most significant improvement was observed in combined modified asphalt (CMA) of CR with kaolin. This achieved a stiffness value of 1455.4Mpa indicates two times higher than the control mix. Totally, the repetitive loading data emphasizes the combined modification significantly improves the stiffness properties of asphalt making it more appropriate for high stress and traffic loading condition to resist deformation and cracking. This makes a viable solution to handle traffic induced stress, deformation and load associated cracking crucial to construct highly performance and durable asphalt pavement.

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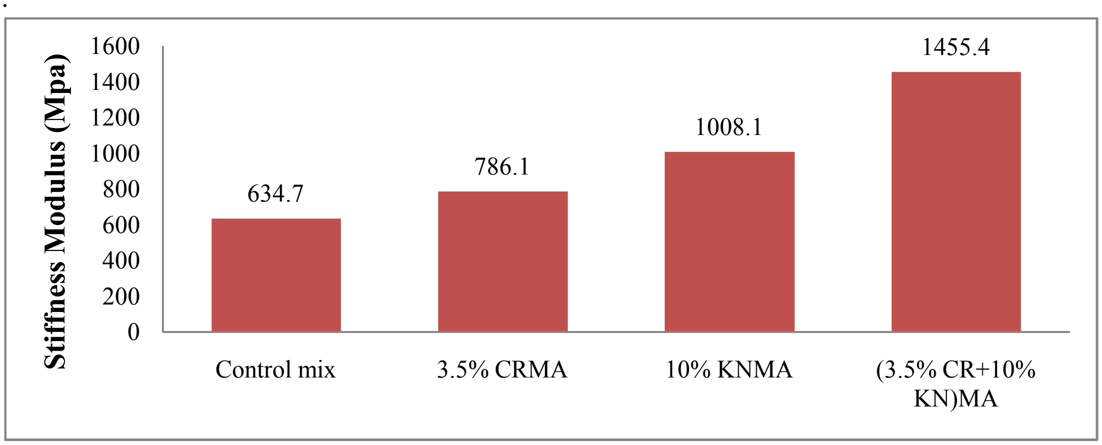

Figure 4.29 Stiffness modules test result

4.12.3 Moisture susceptibility analysis

Indirect tensile strength (ITS) test was used to evaluate the moisture damage of asphalt for both control and modified binder. Tensile strength ratio (TSR) is taken by the ratio of conditioned specimen over unconditioned specimen.

Table 4.19 ITS test result for control mix

specimen	sample	specimen diameter (mm)	Thickness (mm)	Load (P) (N)	ITS (KPa)	TSR (%)
Conditioned	1	150	90.5	2653	124.47	84.15
	2	150	90.6	2405	112.71	
	3	150	91	2530	118.05	
	average	150	90.7	2529.3	118.41	
unconditioned	1	150	90.3	3195	150.24	
	2	150	90.8	2914	136.27	
	3	150	90.7	2897	135.62	
	average	150	90.6	3002	140.71	

Table 4.20 ITS test result for crumb rubber modified asphalt (CRMA)

specimen	sample	specimen diameter (mm)	Thickness (mm)	Load (P) (N)	ITS (KPa)	TSR (%)
Conditioned	1	150	90.2	3290	154.88	88.33
	2	150	90.6	3253	152.46	
	average	150	90.4	3272	153.67	
unconditioned	1	150	90.3	3780	177.75	
	2	150	89.9	3603	170.18	
	average	150	90.1	3692	173.96	

Table 4.21 ITS test result for kaolin modified asphalt (KNMA)

specimen	sample	specimen diameter (mm)	Thickness (mm)	Load (P) (N)	ITS (KPa)	TSR (%)
Conditioned	1	150	90.4	3403	159.84	92.80
	2	150	90.3	3781	177.79	
	average	150	90.35	3592	168.82	
unconditioned	1	150	90.1	3858	181.82	
	2	150	89.5	3836	181.99	
	average	150	89.8	3847	181.90	

Table 4.22 ITS test result for combined modified asphalt (CMA)

specimen	sample	specimen diameter(mm)	Thickness (mm)	Load (P) (N)	ITS (KPa)	TSR (%)
Conditioned	C1	150	90.3	3710	174.45	94.2
	C2	150	90.1	3785	178.38	
	C3	150	89.7	5090	240.95	
	average	150	90.03	4195	197.93	
unconditioned	C1	150	90.1	4158	195.96	
	C2	150	89.9	4712	222.56	
	C3	150	90.04	4493	211.88	
	average	150	90.01	4454.3	210.13	

Table 4.19 shows that the control mix exhibits a TSR value of 84.15% which is within permissible limit of standards .The additions of 3.5% CR shown in table 4.20 raised the TSR value to 88.33% which implies that crumb rubber offer increased elasticity and moisture résistance. This enhancement is consistent with [27] that the additions of CR enhances asphalt concrete moisture resistance and reduce stripping effect. Based on the finding in table 4.21 a 10% kaolin modified asphalt (KNMA) demonstrates that a significance improvement of moisture damage effect achieved 92.8% TSR value. Kaolin is a fine powder that used to fill micro voids helps making to densify the mixture. It also

improves the adhesion of aggregate and binder due to its lime property. This makes that kaolin modified asphalt is contribute higher moisture resistance compared to CRMA.

The most effective enhancement was observed for (3.5%CR+10%KN) combined modified asphalt having a TSR value of 94.2% achieve. This indicates that the combined effects of CR and kaolin together make the mixture more resistance to moisture damage effect. Overall the modified mix improves durability and moisture damage effect compared to the control mix. Particularly the combined modified mix yields highest TSR value which indicates high performance of asphalt to resist moisture damage and stripping impact.

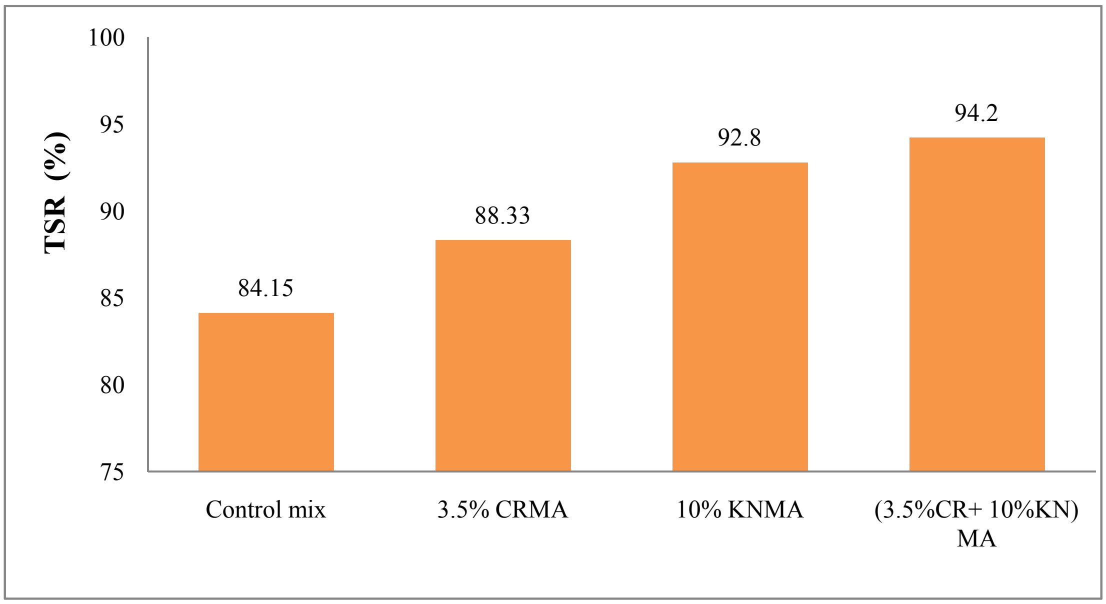

Figure 4.30 TSR test result for control and modified mix

4.13 Economical cost analysis

In flexible pavement construction replacing asphalt material is essential for sustainability and cost effectiveness aspect. The incorporation of crumb rubber and kaolin not only improves asphalt performance but also it provides an affordable solution for cost minimization due to its low cost. In this study 1km length, 7m width and 5cm thick road with 5% bitumen consider for cost analysis. Material quantity and cost breakdown for asphalt bitumen is done in the following ways.

- **Material cost of bitumen**
  - Cost of bitumen = cost per kg of bitumen* quantity of bitumen
  - Cost of bitumen per barrel = 25000ETB,
  - 1barrel of bitumen=160-164kg=162kg on average
  - Cost of bitumen per kg=154.32ETB
  - Volume of road (V) = 1000m*7*0.05m=35m^3
  - Density of asphalt (D) =2400kg/ m^3
  - Quantity of asphalt=D*V= 2400kg/ m^3 *350m^3=840,000kg
  - Quantity of bitumen per km=0.05*840000kg=42000kg
  - Cost of bitumen per km=42000kg*154.32Birr= 6,481,440 ETB
- **Material cost analysis of partially replaced bitumen**

For this study 3.5%CR and 10% kaolin additives were used for bitumen modification to partially replace the material. This implies that a total of 13.5% bitumen by weight is replaced by crumb rubber and kaolin additives.

Total Quantity of bitumen needed for 1km road is 42000kg from this 13.5% weight of bitumen is replaced by CR and kaolin content. The remaining net bitumen content becomes 86.5% of 42000kg.

- **Quantity of material**
  - Net quantity of bitumen (86.5% of bitumen) =42000*0.865=36330kg
  - Quantity of CR =42000*0.035=1470kg
  - Quantity of kaolin=42000*0.1=4200kg
- **Material cost**
  - Cost of bitumen=36330*154.32 ETB=5,606,445.6 ETB
  - Cost of kaolin per kg= 15 ETB
  - Cost of kaolin = 4200*15=63000ETB
  - Cost of crumb rubber (CR) per kg = 11 ETB
  - Cost of crumb rubber (CR)= 1470*11= 16170 ETB
  - Total material cost =5,606,445.6+63000+16170=5,685,615.6 ETB

- **Cost of bitumen reduction**
  - Cost of bitumen reduction= cost of bitumen before replacement- cost of bitumen after replacement
  - Cost of bitumen reduction= 6,481,440 ETB-5,685,615.6 ETB
  - Cost of bitumen reduction=795,524.4 ETB

Based on this cost analysis replacing 13.5% of bitumen by crumb rubber and kaolin reduce the cost of bitumen from 6,481,440 ETB to 5,685,615.6 ETB for road per km. This indicates that the partially replacement or modification of bituminous material provides 795,524.4 ETB material costs saving per km. This study achieves the goal of the research by 12.3% reducing the cost of material for asphalt. The use of crumb rubber and kaolin for asphalt modification can reduce the need for original bitumen. Modification of bitumen with alternative materials including crumb rubber and kaolin clay has a vital role to improve performance and cost effectiveness asphalt.

4.14 Practical implementation

Practical implementation of crumb rubber with kaolin modified asphalt involves integrating of these materials for asphalt pavement construction to improve performance of asphalt and reducing bitumen cost. Crumb rubber powder is blended with bitumen using wet process to improve rutting and deformation resistance and overall durability of asphalt concrete. Kaolin is added to bitumen and crumb rubber mix to strengthen bonding between CR and bitumen. The addition of kaolin increase aggregate and binder bonding can make the mix workable, increase flexibility of asphalt mixture and improve performance of asphalt. In practice the modified binder can be produced at asphalt plants using standard mixing equipments where the additives are uniformly dispersed by optimizing temperature and mixing time. The modified asphalt mixture can be lay using conventional asphalt paving equipments. Implement quality controls by performing tests to monitor the performance of asphalt under traffic loading and environmental condition.

Chapter Five

5. Conclusion and Recommendation

5.1 Conclusion

One potential solution to the asphalt industries sustainability and performance is the inclusion of crumb rubber and kaolin into asphalt pavements. For this study performance of crumb rubber with kaolin modified binder and asphalt were evaluated through experimental testing methods including various testes. Through the outcomes of the result it was found that optimum content of crumb rubber (CR) and kaolin is 3.5% and 10% by weight of binder respectively. For this optimum level all criteria were met the standard specification. The optimum combination of CR with kaolin for binder and asphalt modification was evaluated by adding kaolin in to CR and bitumen mix.

Crumb rubber, kaolin and their optimum mix combination improves asphalt binders physical and rheological properties. It increases softening point, flash and fire point while decreasing penetration and ductility values. Based on DSR test result both crumb rubber, kaolin and their combination increases complex modules (G*), rutting parameter and decrease the phase angle compared to the control mix. This indicates that the improvement of the stiffness, elasticity and rutting resistance of binders property. 3.5% CRMA, 10% KNMA and their combined mix improve rutting resistance of asphalt mixture by 52.2%, 52.1% and 73.9% respectively. This indicates that with a small amount of CR can achieve high performance improvement of asphalt pavement. These materials also improve moisture resistance; load associated cracking (fatigue performance) and durability of asphalt. This is due to the potential ability of materials to resist high temperature susceptibility and moisture damage effect. Based on material cost analysis the use of crumb rubber and kaolin additive for partial replacement of bitumen reduce the cost of material by 12.3%.

Based on overall assessment of the finding the optimum combination of CR and kaolin modified mix provides superior performance of asphalt as compared to control, crumb rubber and kaolin modified mix alone. This is due to the addition of kaolin in to CR and bitumen mix increase the bonding between binders and aggregate. It also filling voids and improves mixing cohesion, workability and flexibility. By utilising these materials, improve pavement durability, quality and economic sustainability in asphalt industry.

5.2 Recommendation

Crumb rubber with kaolin modified asphalt should be adopting and test practically in pavement industry for sustainable solution of pavement materials. It helps to assess the actual performance, durability and economic feasibility under actual traffic and environmental situations.

It is recommended that further studies are needed to investigate the effect of crumb rubber and kaolin on different asphalt binder penetration grade other than 80/100.To evaluate the effectiveness and potential of additives on a different bitumen grade used for bitumen and asphalt modification.

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APPENDIX

Appendix A

All conducted laboratory tests for Binder

A.1 Sample preparation

Figure A.1 sample and mix preparation for kaolin modification of binder

FigureA.2 sample and mix preparation for crumb rubber (CR) modification of binder

A.2 **Penetration testing**

Figure A.3 Penetration testing

A.3 Ductility testing

Figure A.4 ductility test

A.4 softening point testing

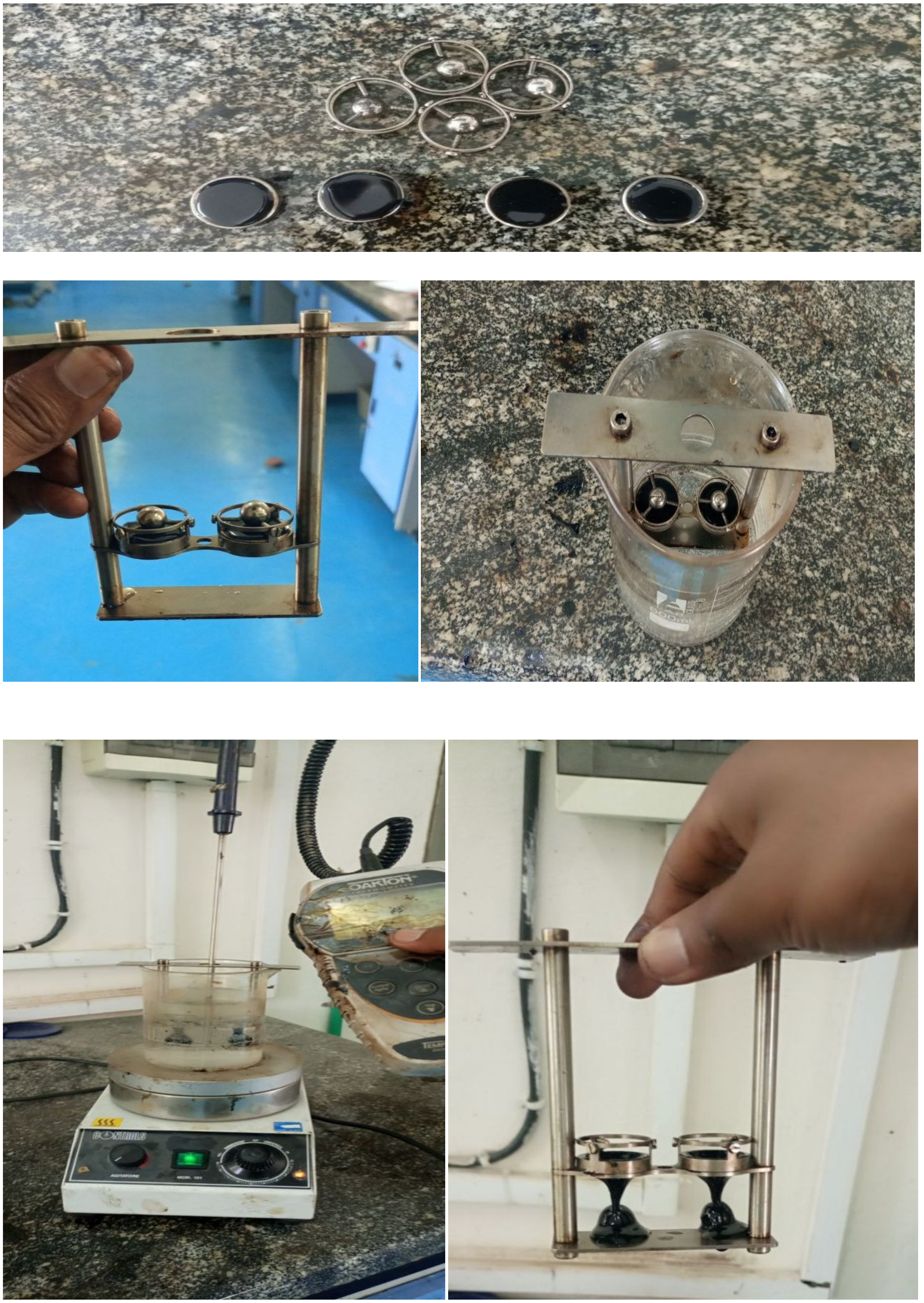


Figure A.5 softening point ring and ball test

A.5 Flash and fire point testing

Figure A.6 Flash and Fire point test

A.6 DSR Test

Figure A.7 DSR test

A.7 Rolling thin film oven test (RTFOT)

Figure A.8 RTFOT testing

Appendix B

Physical Test results of Binders

B.1 Physical Test results for original bitumen (OB)

Table B-1 Penetration test result

Original Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading(1/10mm)	0.6	0.5	0.2	0.6	0.5	0.4	0.7	0.5	1.4
Final reading(1/10mm)	91	92	91.5	92	91.8	91.2	92	91.4	92.6
Difference (1/10mm)	90.4	91.5	91.3	91.4	91.3	90.8	91.3	90.9	91.2
Average(1/10mm)	91.06			91.16			91.13		
Overall average(1/10mm)	91.12								

Table B -2 Ductility test result

Sample	Original Bitumen (OB)		
Trials	1	2	3
Ductility (cm)	146	144	145
Average (cm)	145		

Table C -3 Softening point test result

Original Bitumen						
Trials	T-1		T-2		T-3	
sample	1	2	1	2	1	2
T °C	45.6	45.9	44.3	44.8	45.1	45.8
average T °C	45.75		44.55		45.45	
average T °C	45.25					

Table B -4 Flash and fire point test result

original Bitumen						
Test	**flash point**			**fire point**		
Trials	1	2	3	1	2	3
T °C	265	265	266	276	276	275
Average T °C	265.33			275.66		

B.2 Physical Test results for crumb rubber modified binder (CRMB)

Table B -5 Penetration test result

2% CR + 98%Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading(1/10mm)	0.8	0.3	0.2	0.3	1	0.6	0.4	0.2	0.6
Final reading(1/10mm)	79	81.2	79.8	79.3	79	79.5	79.4	79.8	79.9
Difference (1/10mm)	78.2	80.9	79.6	79	78	78.9	79	79.6	79.3
Average(1/10mm)	79.56			78.63			79.3		
Overall average(1/10mm)	79.16								

3.5% CR + 96.5%Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading (1/10mm)	0.8	0.3	0.2	0.3	1	0.6	0.4	0.2	0.6
Final reading 1/10mm)	72.3	72.5	72.6	73.1	72.9	72.8	72.8	72.7	72.9
Difference (1/10mm)	71.5	72.2	72.4	72.8	71.9	72.2	72.4	72.5	72.3
Average 1/10mm)	72.03			72.3			72.4		
Overall average (1/10mm)	72.24								

5% CR + 95% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading (1/10mm)	0.6	0.4	0.9	0.4	0.2	0.6	0.3	0.4	0.2
Final reading (1/10mm)	65.1	64.9	64.8	65.2	65.1	65.3	65.7	65.8	65.6
Difference (1/10mm)	64.5	64.5	63.9	64.8	64.9	64.7	65.4	65.4	65.4
Average (1/10mm)	64.3			64.8			65.4		
Overall average (1/10mm)	64.83								

6.5%CR + 93.5% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading (1/10mm)	0.3	0.4	0.6	0.4	0.2	0.4	0.3	0.5	0.2
Final reading (1/10mm)	55.1	55.3	55.3	55.5	55.4	55.7	55.6	54.9	55.3
Difference (1/10mm)	54.8	54.9	54.7	55.1	55.2	55.3	55.3	54.4	55.1
Average (1/10mm)	54.8			55.2			54.93		
Overall average (1/10mm)	54.97								

8% CR + 92% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading (1/10mm)	0.8	0.5	0.9	0.3	0.6	0.4	0.6	0.4	0.5
Final reading (1/10mm)	48.3	48.5	48.2	47.6	47.7	47.8	47.9	48.1	48.2
Difference (1/10mm)	47.5	48	47.3	47.3	47.1	47.4	47.3	47.7	47.7
Average (1/10mm)	47.6			47.26			47.56		
Overall average (1/10mm)	47.47								

9.5% CR + 90.5% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Initial reading (1/10mm)	0.4	0.3	0.2	0.4	0.5	0.2	0.3	0.2	0.5
Final reading (1/10mm)	42.2	42.1	41.8	42.1	42.5	42.3	42.9	42.1	42.3
Difference (1/10mm)	41.8	41.8	41.6	41.7	42	42.1	42.6	41.9	41.8
Average (1/10mm)	41.73			41.93			42.1		
Overall average (1/10mm)	41.92								

Table B -6 Ductility test result

Sample	2% CR+ 98% B			3.5%CR+96.5%B			5%CR+95%B		
Trials	1	2	3	1	2	3	1	2	3
Ductility (cm)	122	121	120	108	107	105	90	92	89
Average (cm)	121			106.67			90.33		

Sample	6.5%CR+93.5%B			8%CR+92%B			9.5%CR+90.5%B		
Trials	1	2	3	1	2	3	1	2	3
Ductility (cm)	73	79	75	59	62	56	47	49	44
Average (cm)	75.67			59			46.67		

Table B -7 softening point test result

	2% CR + 98% Bitumen						**3.5% CR + 96.5% Bitumen**					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
Sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	47.9	47.9	47.7	47.5	47.9	47.8	48.9	49.1	49.1	49	48.8	49.1
Average T °C	47.9		47.6		47.85		49		49.05		48.95	
Average T °C	47.78333333						49					

	5% CR +95% Bitumen						**6.5% CR + 93.5% Bitumen**					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
Sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	50.1	50.3	50	50	50.3	51	51.9	51.8	51.7	51.9	51.8	52
Average T °C	50.2		50		50.4		51.85		51.8		51.9	
Average T °C	50.2						51.85					

	8% CR + 92% Bitumen						**9.5% CR + 90.5% Bitumen**					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
Sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	53.5	53.2	53.4	53.5	53.3	53.5	54.8	54.9	54.7	54.8	54.7	54.9
Av. T °C	53.35		53.45		53.4		54.85		54.75		54.8	
Av. T °C	53.4						54.8					

Table B -8 Flash and fire point test result

	2% CR + 98% Bitumen						**3.5% CR + 96.5% Bitumen**					
Test	**flash point**			**fire point**			**flash point**			**fire point**		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	270	271	269	281	280	279	275	276	277	285	286	286
Av. T °C	270			280			276			285.66		

	5% CR + 95% Bitumen						6.5% CR + 93.5% Bitumen					
Test	flash point			fire point			flash point			fire point		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	281	279	282	288	290	291	284	286	287	297	295	299
Average T °C	280.66			289.66			285.66			297		

	8% CR + 92% Bitumen						9.5% CR + 90.5% Bitumen					
Test	flash point			fire point			flash point			fire point		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	290	289	291	302	301	303	298	294	296	308	307	309
Average T °C	290			302			296			308		

B.3 Physical Test results for kaolin modified binder (KMB)

Table B -9 Penetration test result

5% Kaolin + 95%Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	0.8	0.3	0.2	0.3	1	0.6	0.4	0.2	0.6
Fin. reading(1/10mm)	82.7	82.8	81.9	82.3	83.1	82.5	83.3	82.3	82.5
Difference (1/10mm)	81.9	82.5	81.7	82	82.1	81.9	82.9	82.1	81.9
Average(1/10mm)	82.03			82			82.3		
Overall average(1/10mm)	82.11								

7.5% Kaolin + 92.5%Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	0.8	0.3	0.2	0.3	1	0.6	0.4	0.2	0.6
Fin. reading(1/10mm)	73.3	74.2	73.5	73.4	73.7	73.9	74.2	73.4	73.3
Difference (1/10mm)	72.5	73.9	73.3	73.1	72.7	73.3	73.8	73.2	72.7
Average(1/10mm)	73.23			73.03			73.23		
Overall average(1/10mm)	73.16								

10% Kaolin + 90% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	0.6	0.4	0.8	0.4	0.2	0.6	0.3	0.4	0.2
Fin.reading(1/10mm)	63.8	63.9	63.5	62.8	63.4	63.8	64.2	63.5	64.3
Difference (1/10mm)	63.2	63.5	62.7	62.4	63.2	63.2	63.9	63.1	64.1
Average(1/10mm)	63.13			62.93			63.7		
Overall average(1/10mm)	63.25								

12.5%Kaolin + 87.5% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	1	0.6	0.5	0.4	0.2	0.4	0.3	0.5	0.2
Fin.reading(1/10mm)	56.4	56.3	57.5	56.9	57.1	57.2	57.1	56.4	57
Difference (1/10mm)	55.4	55.7	57	56.5	56.9	56.8	56.8	55.9	56.8
Average(1/10mm)	56.03			56.73			56.5		
Overall average(1/10mm)	56.42								

15% Kaolin + 85% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	0.8	0.5	0.9	0.3	0.6	0.4	0.6	0.4	0.5
Fin. reading(1/10mm)	49.7	48.8	49.5	49.3	49.7	49.1	49.6	48.9	49.1
Difference (1/10mm)	48.9	48.3	48.6	49	49.1	48.7	49	48.5	48.6
Average(1/10mm)	48.6			48.93			48.7		
Overall average(1/10mm)	48.74								

17.5% Kaolin + 82.5% Bitumen									
Specimen	SP-1			SP-2			SP-3		
Trials	1	2	3	1	2	3	1	2	3
Ini. reading(1/10mm)	0.4	0.3	0.2	0.4	0.5	0.2	0.3	0.2	0.5
Fin.reading(1/10mm)	42.1	41.4	41.5	42.9	42	41.8	41.9	41.2	41.4
Difference (1/10mm)	41.7	41.1	41.3	42.5	41.5	41.6	41.6	41	40.9
Average(1/10mm)	41.36			41.86			41.16		
Overall average(1/10mm)	41.46								

Table B -10 Ductility test result

Sample	5% KN+ 95% B			7.5%KN+92.5%B			10%KN+90%B		
Trials	1	2	3	1	2	3	1	2	3
Ductility (cm)	128	133	132	119	120	118	109	108	111
Average (cm)	131			119			109.33		

Sample	12.5%KN+87.5%B			15%KN+85%B			17.5%KN+82.5%B		
Trials	1	2	3	1	2	3	1	2	3
Ductility (cm)	97	99	95	79	81	83	68	65	67
Average (cm)	97			81			66.66		

Table B -11 softening point test result

	5% Kaolin + 95% Bitumen						7.5% Kaolin + 92.5% Bitumen					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	47.5	47.9	47.2	47.6	47.9	47.5	48.5	48.8	48.6	48.9	48.4	48.7
Av. T °C	47.7		47.4		47.7		48.65		48.75		48.55	
Av.T °C	47.6						48.65					

	10% Kaolin +90% Bitumen						12.5% Kaolin + 87.5% Bitumen					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	50.1	49.8	49.9	49.8	50.1	50.2	51.1	51.3	51.3	51.5	51.5	51.4
Av. T °C	49.95		49.85		50.15		51.2		51.4		51.45	
Av. T °C	49.98						51.35					

	15% Kaolin + 85% Bitumen						17.5% Kaolin + 82.5% Bitumen					
Trials	T-1		T-2		T-3		T-1		T-2		T-3	
sample	1	2	1	2	1	2	1	2	1	2	1	2
T °C	52.3	52.1	52.4	52.6	52.3	52.5	53.5	53.7	53.3	53.6	53.4	53.3
Av. T °C	52.2		52.5		52.4		53.6		53.45		53.35	
Av. T °C	52.36						53.46					

Table B -12 Flash and Fire point test result

	5% Kaolin + 95% Bitumen						7.5% Kaolin + 92.5% Bitumen					
Test	flash point			fire point			flash point			fire point		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	271	273	272	285	284	286	279	281	283	293	292	294
Average T °C	272			285			281			293		

	10% Kaolin +90%Bitumen						12.5% Kaolin +87.5%Bitumen					
Test	flash point			fire point			flash point			fire point		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	289	290	288	299	297	299	296	293	296	304	304	307
Average T °C	289			298.33			295			305		

	15% Kaolin + 85% Bitumen						17.5% Kaolin + 82.5% Bitumen					
Test	flash point			fire point			flash point			fire point		
Trials	1	2	3	1	2	3	1	2	3	1	2	3
T °C	303	302	304	311	313	312	309	307	310	319	317	321
Average T °C	303			312			308.66			319		

Appendix C

DSR Test result

C.1 DSR Test result for Original Bitumen

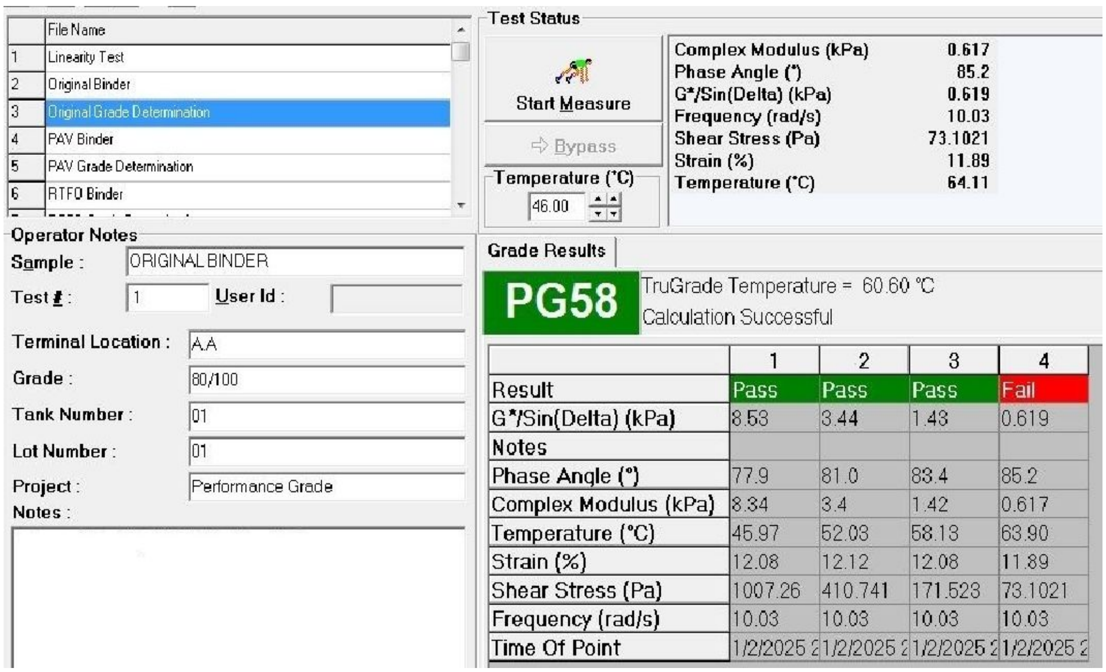


Figure C.1 DSR test result for original bitumen

C.2 DSR Test result for crumb rubber modified binder (CRMB)

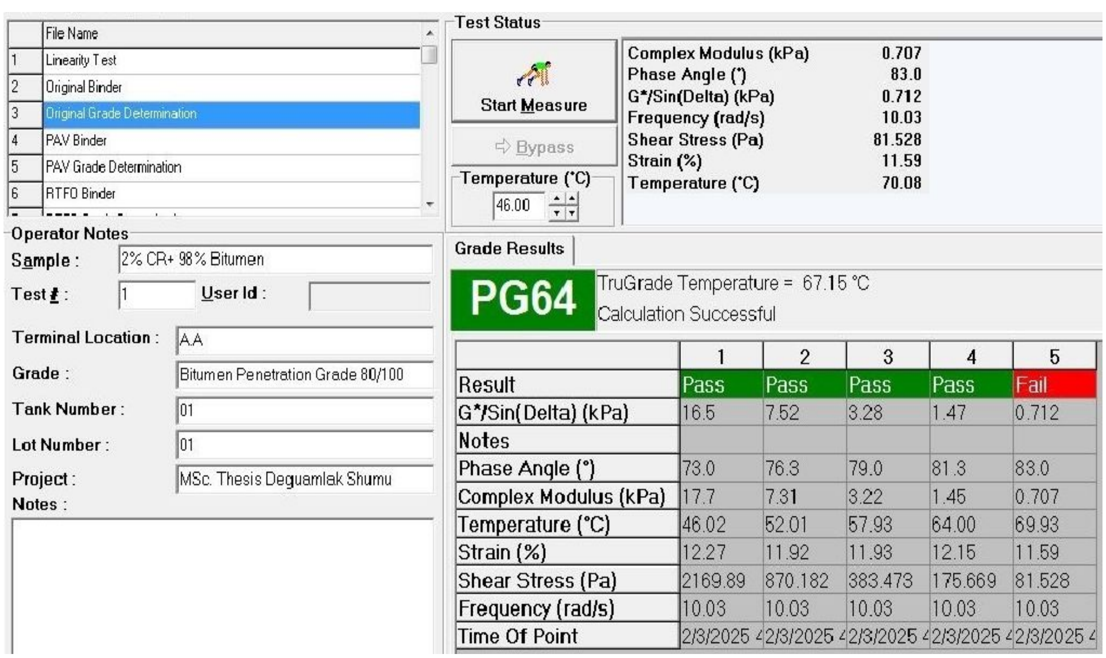


Figure C.2 DSR test result for 2%CRMB

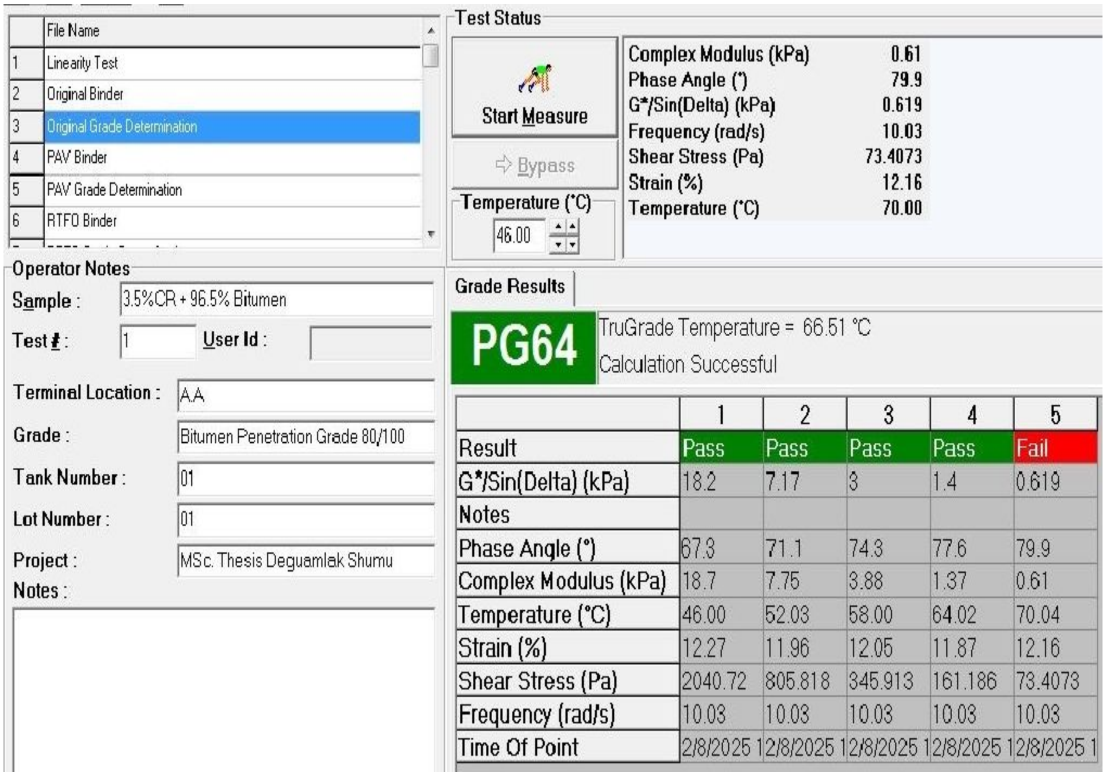


Figure C.3 DSR test result for 3.5%CRMB

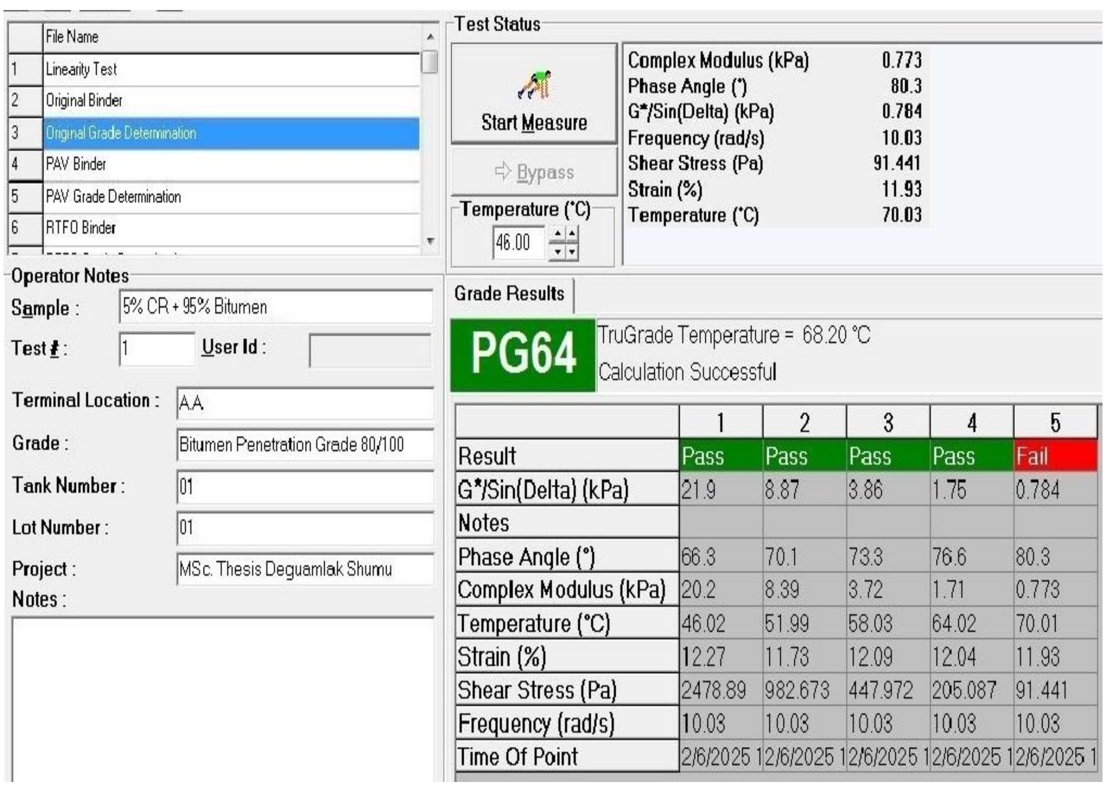
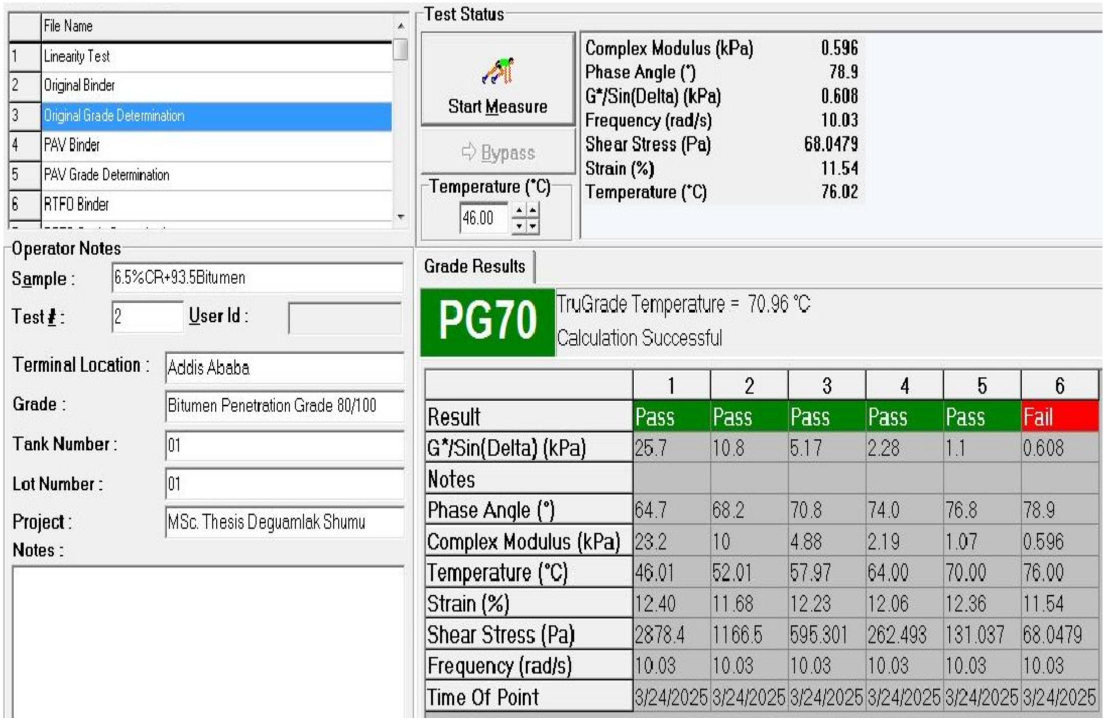
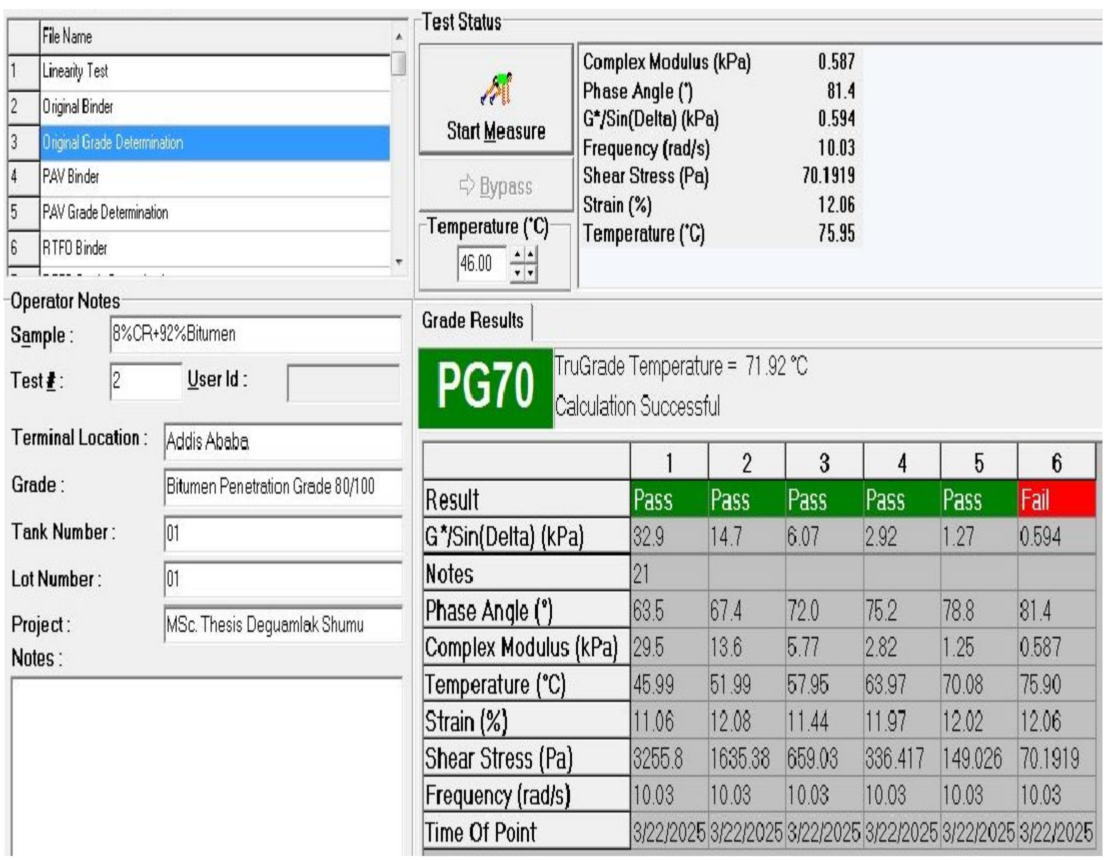


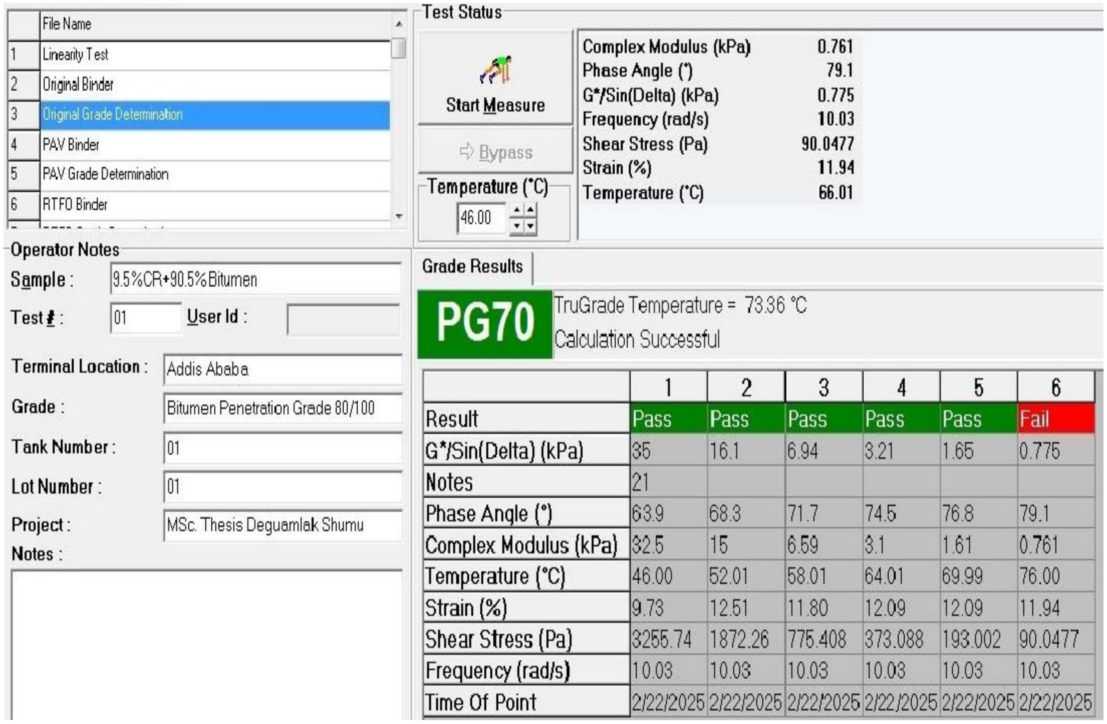
Figure C.4 DSR test result for 5% CRMB



FigureC.5 DSR test result for 6.5% CRMB



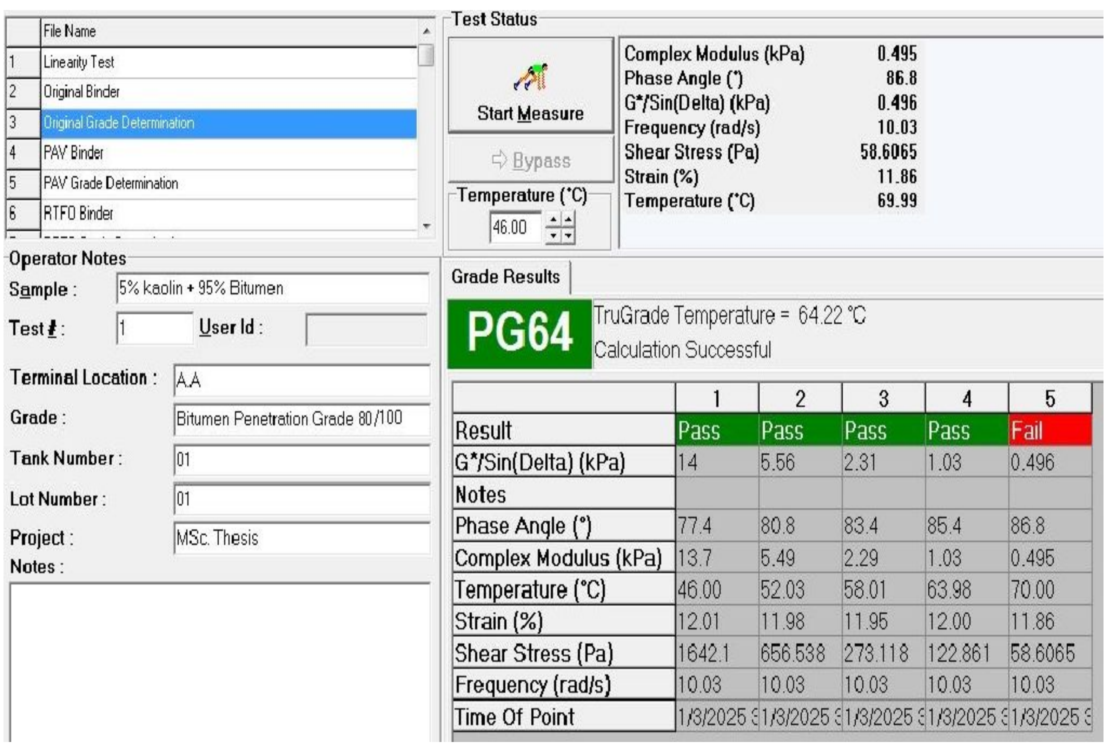
FigureC.6 DSR test result for 8%CRMB



	1	2	3	4	5	6
Result	Pass	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	35	16.1	6.94	3.21	1.65	0.775
Notes	21					
Phase Angle (°)	63.9	68.3	71.7	74.5	76.8	79.1
Complex Modulus (kPa)	32.5	15	6.59	3.1	1.61	0.761
Temperature (°C)	46.00	52.01	58.01	64.01	69.99	76.00
Strain (%)	9.73	12.51	11.80	12.09	12.09	11.94
Shear Stress (Pa)	3255.74	1872.26	775.408	373.088	193.002	90.0477
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03	10.03
Time Of Point	2/22/2025	2/22/2025	2/22/2025	2/22/2025	2/22/2025	2/22/2025

Figure C.7 DSR test result for 9.5% CRMB

C.3 DSR test result for kaolin modified binder (KNMB)



	1	2	3	4	5
Result	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	14	5.56	2.31	1.03	0.496
Notes					
Phase Angle (°)	77.4	80.8	83.4	85.4	86.8
Complex Modulus (kPa)	13.7	5.49	2.29	1.03	0.495
Temperature (°C)	46.00	52.03	58.01	63.98	70.00
Strain (%)	12.01	11.98	11.95	12.00	11.86
Shear Stress (Pa)	1642.1	656.538	273.118	122.861	58.6065
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03
Time Of Point	1/3/2025	1/3/2025	1/3/2025	1/3/2025	1/3/2025

FigureC.8 DSR test result for 5%KNMB

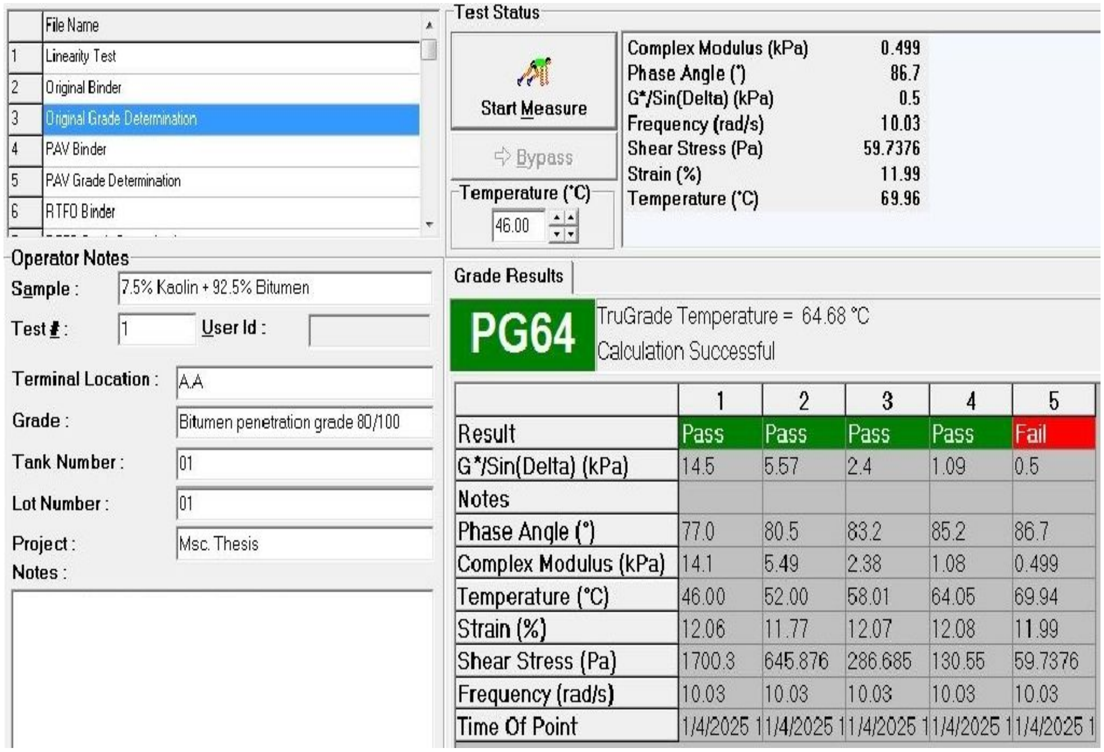


Figure C.9 DSR test result for 7.5% KNMB

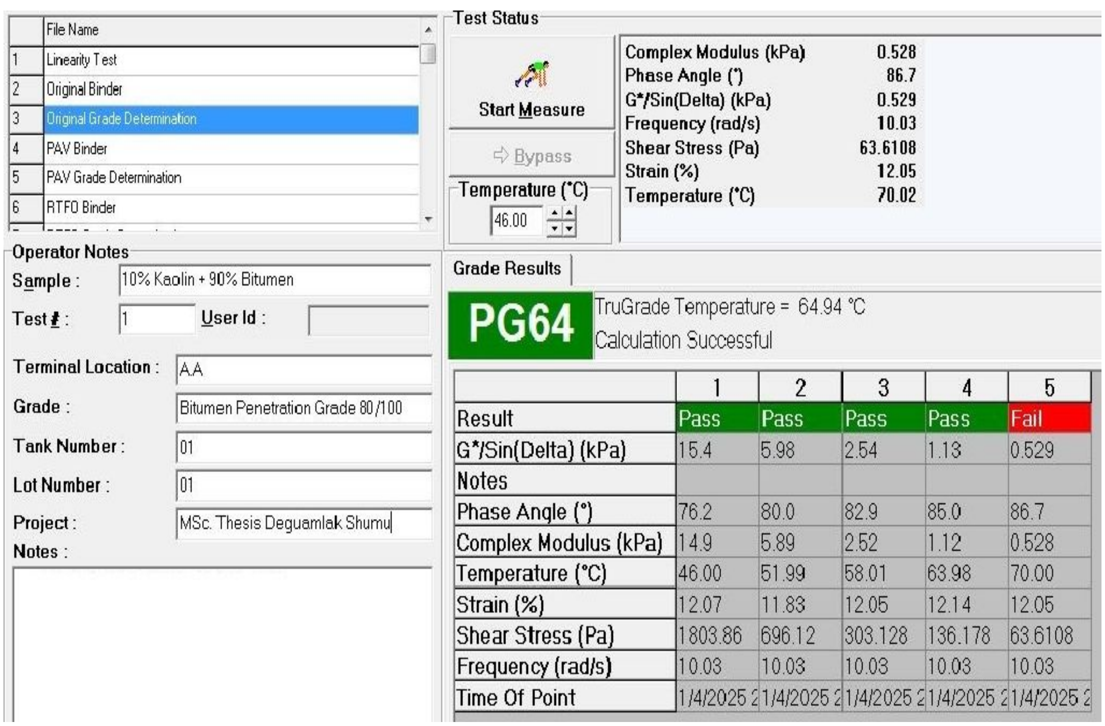
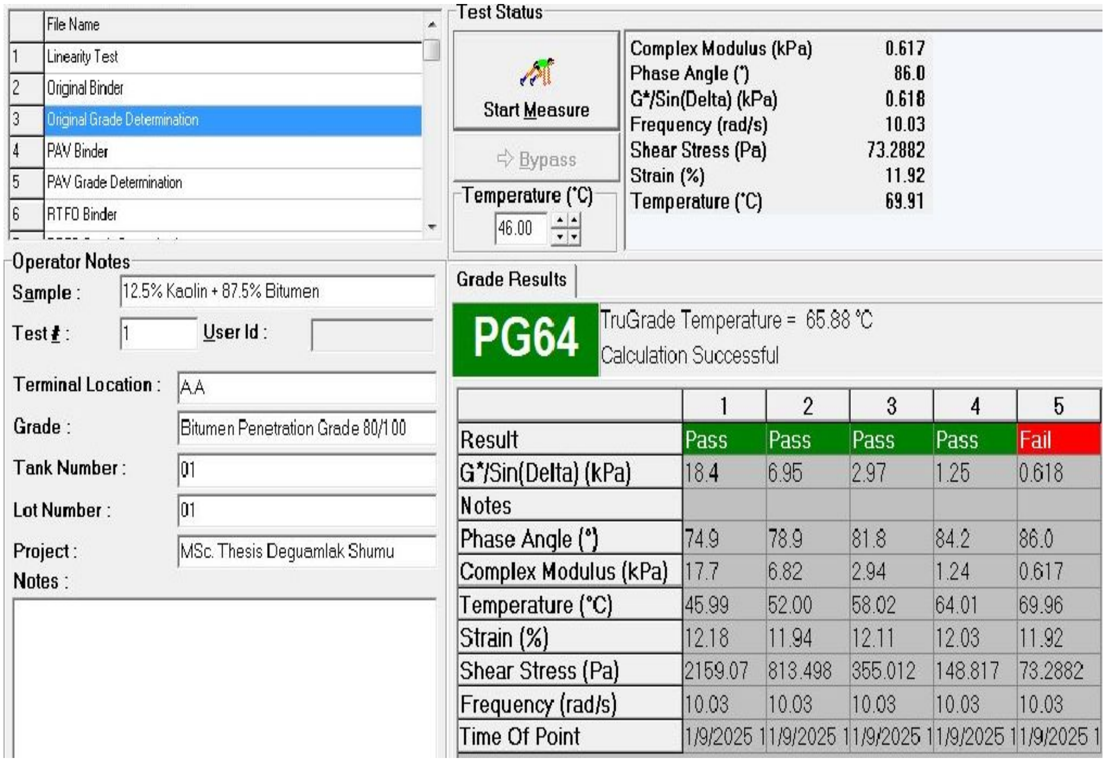
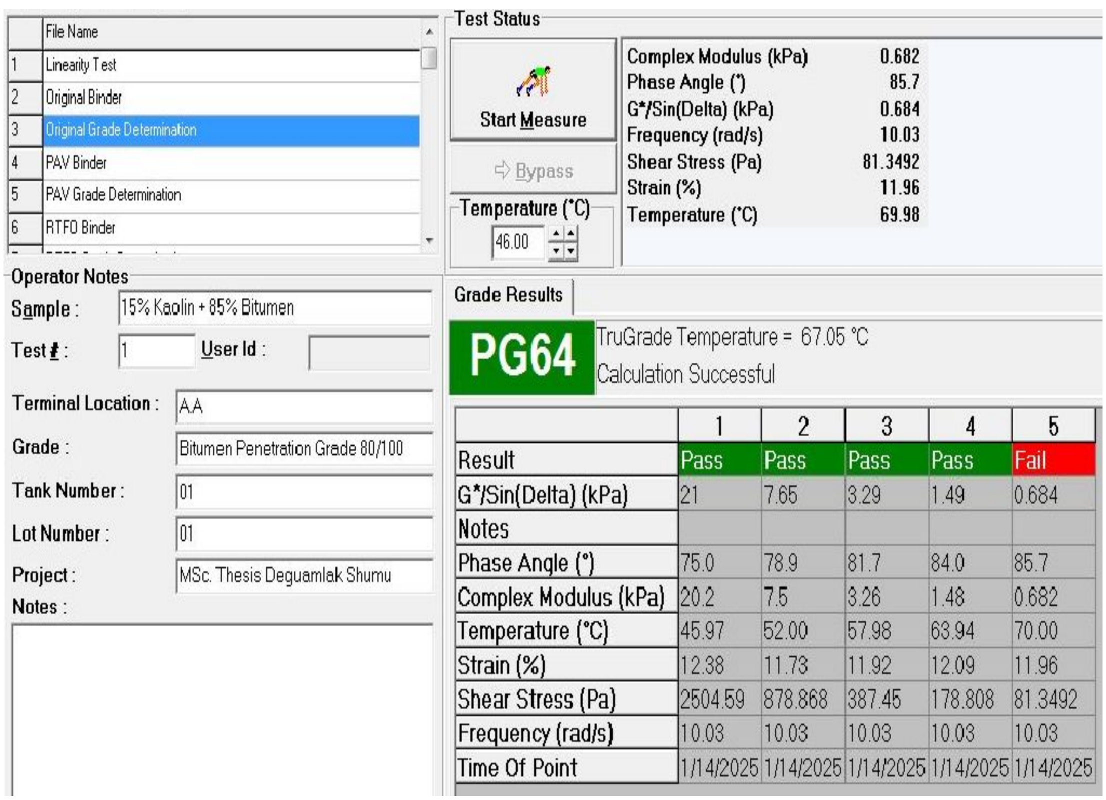


Figure C.10 DSR test result for 10% KNMB



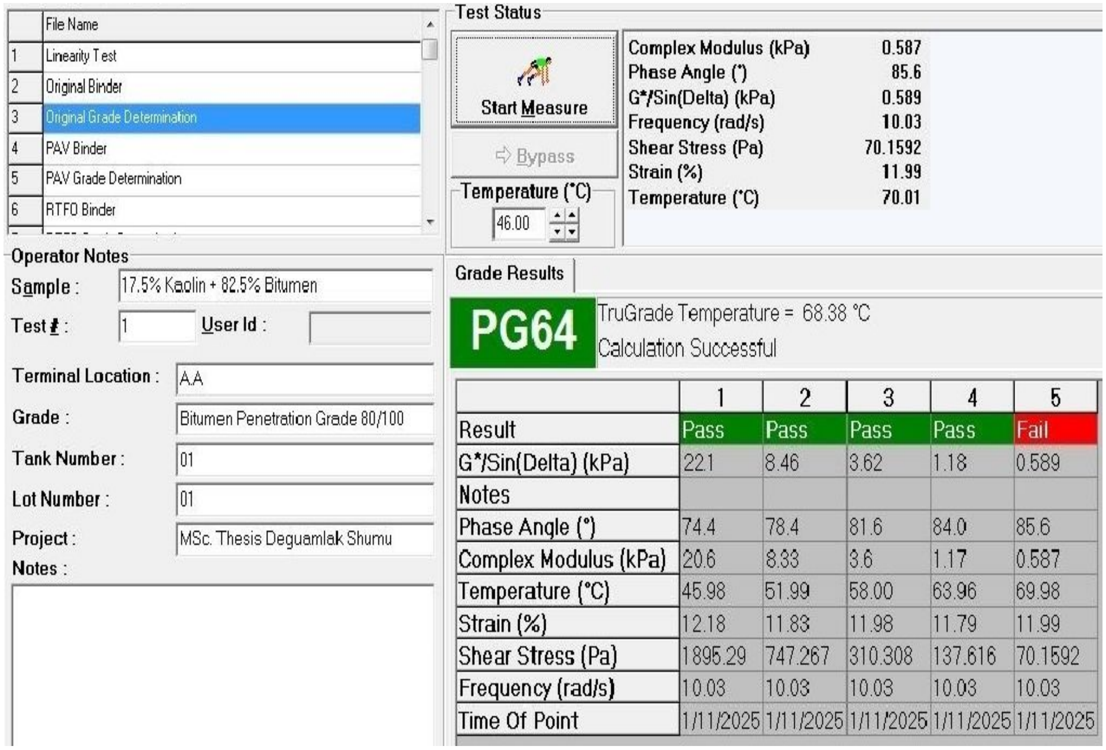
	1	2	3	4	5
Result	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	18.4	6.95	2.97	1.25	0.618
Notes					
Phase Angle (°)	74.9	78.9	81.8	84.2	86.0
Complex Modulus (kPa)	17.7	6.82	2.94	1.24	0.617
Temperature (°C)	45.99	52.00	58.02	64.01	69.96
Strain (%)	12.18	11.94	12.11	12.03	11.92
Shear Stress (Pa)	2159.07	813.498	355.012	148.817	73.2882
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03
Time Of Point	1/9/2025 1	1/9/2025 1	1/9/2025 1	1/9/2025 1	1/9/2025 1

Figure C.11 DSR test result for 12.5% KNMB



	1	2	3	4	5
Result	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	21	7.65	3.29	1.49	0.684
Notes					
Phase Angle (°)	75.0	78.9	81.7	84.0	85.7
Complex Modulus (kPa)	20.2	7.5	3.26	1.48	0.682
Temperature (°C)	45.97	52.00	57.98	63.94	70.00
Strain (%)	12.38	11.73	11.92	12.09	11.96
Shear Stress (Pa)	2504.59	878.868	387.45	178.808	81.3492
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03
Time Of Point	1/14/2025	1/14/2025	1/14/2025	1/14/2025	1/14/2025

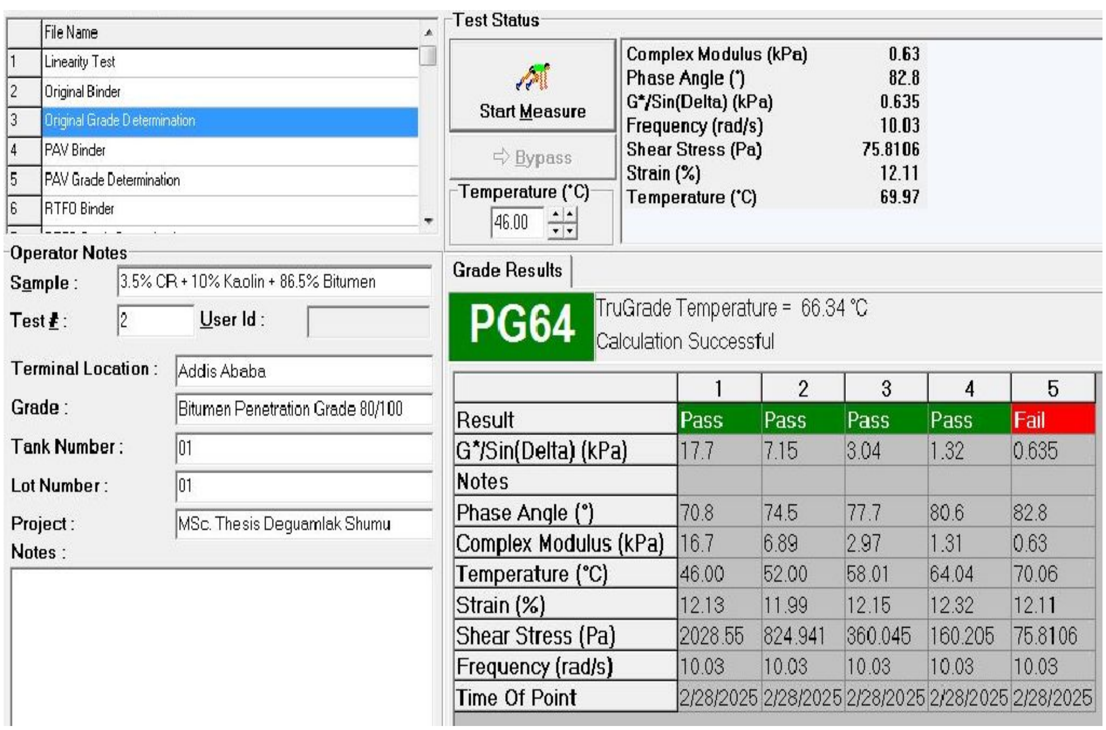
FigureC.12 DSR test result for 15% KNMB



	1	2	3	4	5
Result	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	22.1	8.46	3.62	1.18	0.589
Notes					
Phase Angle (°)	74.4	78.4	81.6	84.0	85.6
Complex Modulus (kPa)	20.6	8.33	3.6	1.17	0.587
Temperature (°C)	45.98	51.99	58.00	63.96	69.98
Strain (%)	12.18	11.83	11.98	11.79	11.99
Shear Stress (Pa)	1895.29	747.267	310.308	137.616	70.1592
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03
Time Of Point	1/11/2025	1/11/2025	1/11/2025	1/11/2025	1/11/2025

Figure C.13 DSR test result for 17.5% KNMB

4. DSR test result for combined modified binder (CMB)



	1	2	3	4	5
Result	Pass	Pass	Pass	Pass	Fail
G*/Sin(Delta) (kPa)	17.7	7.15	3.04	1.32	0.635
Notes					
Phase Angle (°)	70.8	74.5	77.7	80.6	82.8
Complex Modulus (kPa)	16.7	6.89	2.97	1.31	0.63
Temperature (°C)	46.00	52.00	58.01	64.04	70.06
Strain (%)	12.13	11.99	12.15	12.32	12.11
Shear Stress (Pa)	2028.55	824.941	360.045	160.205	75.8106
Frequency (rad/s)	10.03	10.03	10.03	10.03	10.03
Time Of Point	2/28/2025	2/28/2025	2/28/2025	2/28/2025	2/28/2025

Figure C.14 DSR test result for combined modified binder (CMB)

Table C.1 Regression analysis result of original bitumen (OB)

Coefficients					
	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Tempreature	-5.675	1.195	-9.097	-4.749	.001
Tempreature** 2	.047	.011	8.235	4.299	.002
(Constant)	173.278	32.497		5.332	.000

Table C.2 Regression analysis result 3.5% crumb rubber modified binder

Coefficients					
	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Tempreature	-6.178	.813	-7.530	-7.602	.000
Tempreature ** 2	.047	.007	6.643	6.706	.000
(Constant)	203.866	23.202		8.786	.000

Table C.3 Regression analysis result 10% kaolin modified binder

Coefficients					
	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Tempreature	-5.112	.533	-7.831	-9.599	.000
Tempreature ** 2	.039	.005	6.948	8.517	.000
(Constant)	167.652	15.207		11.025	.000

Table C.4 Regression analysis result 3.5% CR+10% kaolin modified binder

Coefficients					
	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
tempreatue	-5.645	.532	-7.628	-10.606	.000
tempreatue ** 2	.043	.005	6.736	9.366	.000
(Constant)	186.067	15.197		12.243	.000

Appendix D

All conducted laboratory tests for asphalt concrete mix

D.1 Material selection

Figure D.1 aggregate

Figure D.2 Filler

Figure D.3 Bitumen

Figure D.4 Waste tire crumb rubber powder

Figure D.5 kaolin powder

D.2 Aggregate testing

Figure D.6 Aggregate gradation test

Figure D.7 specific gravity test for fine aggregate

D.3 Bitumen and aggregate mix preparation and production of asphalt concrete

Figure D.8 Oven drying of aggregate

Figure D.9 Aggregate and bitumen mixing


For Compacting Specimens of HMA
By combining rotary shear action
START
STOP

Figure D.10 Superpave gyratory compaction

Figure D.11 Gyratory compacted asphalt concrete specimens (samples)

D.4 Specific gravity test for asphalt

Figure D.12 Theoretical maximum specific gravity (Gmm) test for asphalt loose mix

Figure D.15 bulk specific gravity (Gmb) test for compacted asphalt concrete mixture

D.5 Rutting test for asphalt

Figure D.16 superpave asphalt concrete slab sample production

Figure D.17 asphalt concrete slab produced samples for rutting test

Figure C.18 Double wheel track rutting test of asphalt concrete

D.6 Indirect tensile strength (ITS) test for Moisture susceptibility of asphalt concrete

Figure D.19 ITS test

D.7 Indirect tensile modules test

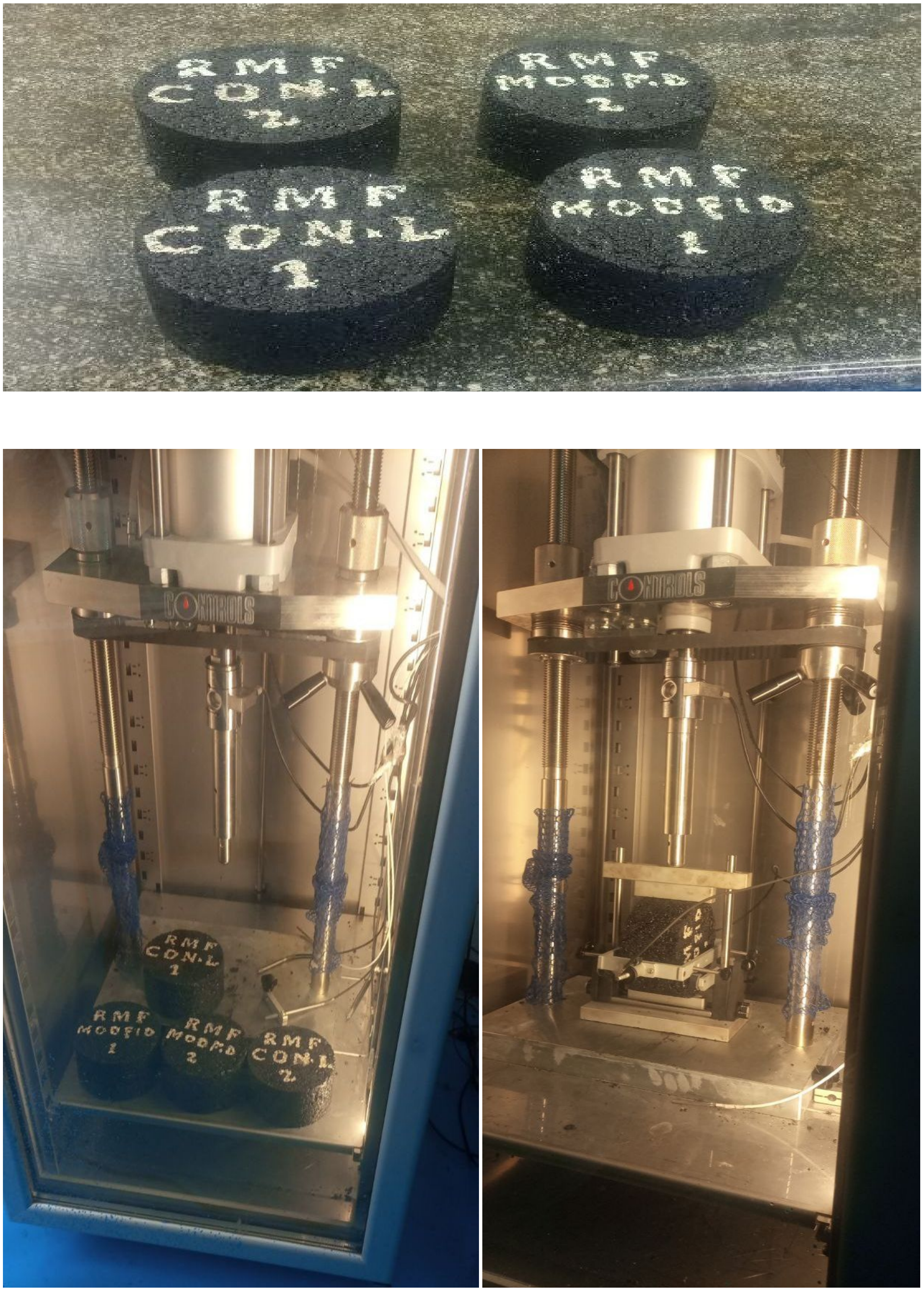


Figure D.20 Indirect tensile modules test

Appendix E

All conduct test result for asphalt mixture

E.1 Specific gravity and water absorption test for fine aggregate

Trial	Weight of SSD sample (g) (S)	Weight of Oven dry Sample (g) (A)	Weight of Pycnometer filled with water (g) (B)	Weight of SSD sample in Pycnometer with water (g) (C)	Bulk Specific Gravity (Gsb)	Bulk SSD Specific Gravity (Gsb SSD)	ApparentSpecific Gravity (Gsa)	Absorption (% Abs)
1	500	498.9	672.9	979.6	2.58	2.58	2.59	0.22
2	500.1	498.8	673.1	980.9	2.59	2.60	2.61	0.25
3	500.5	499.2	672.8	982.3	2.61	2.62	2.63	0.25
	Average				2.59	2.60	2.61	0.24

E.2 Specific gravity and water absorption test for coarse aggregate

	1	nominal maximum size 12.5mm					
Trial	Weight of oven dry specimen(g) (A)	Weight of SSD specimen in Air (g) (B)	Weight of SSD specimen in Water (g) (C)	Bulk Specific Gravity (Gsb)	Bulk SSD Specific Gravity (Gsb SSD)	Apparent Specific Gravity (Gsa)	Absorption (% Abs)
1	1990.4	2000	1238.3	2.61	2.62	2.64	0.48
2	1989.9	2000	1237.5	2.60	2.62	2.64	0.50
3	1989.9	2000	1236.2	2.60	2.61	2.64	0.50
	Average			2.60	2.62	2.64	0.49

	2	nominal maximum size 19mm					
1	2985.5	3000	1864.5	2.62	2.64	2.66	0.48
2	2985.9	3000	1865.5	2.63	2.64	2.66	0.47
3	2985.3	3000	1864.1	2.62	2.64	2.66	0.49
	Average			2.62	2.64	2.66	0.48

Gsb=((Pcoarse+Pfine)/((Pcoarse/Gabcoarse)+(Pfine/Gsbfine)))

Gsb of aggregate=2.61

E.3 Coarse aggregate angularity test result

Aggregate retained sieve (mm)	sample (g)	one or more fractured face sample (g)	two or more fractured face sample (g)	% ≥ 1 fractured face	% ≥ 2 fractured face
4.75	500	491	476	98.2	95.2
12.5	1000	958	911	95.8	91.1

E.4 Los Angeles Abrasion values (LAAV) test

Los Angeles Abrasion values (LAAV) test	Trial 1	Trial 2
weight of dry sample taken passing 19.5 mm and retained on 12.5mm =w1(g)	2500	2500
weight of dry sample taken passing 12.5mm and retained on 9.5mm =w2(g)	2500	2500
total weight of dry aggregate sample =W(g)	5000	5000
weight of aggregate retained 1.7mm sieve=w(g)	4313	4326.3
Los Angeles Abrasion values (LAAV) = ((W-w)/W)*100 (%)	13.74	13.474
Mean aggregate (LAAV) (%)	13.607	

E.5 Aggregate impact values test (ACVT) result

Aggregate impact values test (ACVT)	Trial 1	Trial 2
total weight of dry sample taken =w1	500	500
weight of aggregate passing 2.36mm sieve=w2	32.9	33.7
Aggregate impact value= (w2/w1)*100 (%)	6.58	6.74
Mean aggregate crushing values (%)	6.66	

E.6 Theoretical maximum specific gravity (Gmm) test result for asphalt loose mix

% AC	Sample	Weight of Pyc(g) (W1)	Weight of Pyc+Water(g)(W2)	Weight of Pyc+AC(g) (W3)	Weight of Pyc+AC+ water(g) (W4)	Gmm	Averag Gmm
4.5	Pyc-1	436.2	1699.3	1436.6	2283.0	2.40	2.43
	Pyc-2	395.7	1688.1	1396.3	2282.5	2.47	
5	Pyc-1	436.7	1701	1436.7	2280.9	2.38	2.40
	Pyc-2	395.7	1689.9	1395.7	2276.8	2.42	
5.5	Pyc-1	436.5	1699.5	1436.9	2275.5	2.36	2.36
	Pyc-2	396	1689.2	1396	2266.3	2.36	
6	Pyc-1	436.7	1699	1436.8	2268.7	2.32	2.34
	Pyc-2	396.1	1688.3	1396.1	2265.5	2.37	

E.7 Volumetric properties of asphalt mix

Spe no	%AC by wt of mix	Spec. Height in (mm)	Dry weight (g)	Sub merged weight (g)	Saturated Surface Dry (SSD) Weight (g)	Bulk Specific Gravity of Asphalt (Gmb)	Theoretical Max. Specific Gravity of Loose Mix (Gmm)	Bulk Specific Gravity of Aggregate (Gsa)	(%) Air Void (Va)	% VMA	% VFA
1	4.5	104.32	4018.1	2257.3	4029.4	2.27					
2	4.5	104.72	4020.8	2264	4030.2	2.28					
	Average					2.27	2.43	2.61	6.66	16.94	60.68
1	5	101.84	4018.3	2277.5	4020.8	2.31					
2	5	102.3	4020.1	2276.5	4024.1	2.30					
	Average					2.30	2.4	2.61	4.04	16.17	74.5
1	5.5	100.03	4017.2	2287.8	4021.3	2.32					
2	5.5	100.15	4018	2285.5	4023.3	2.31					
	Average					2.32	2.36	2.61	1.69	16	89.4
1	6	102.96	4019	2262.8	4022.2	2.28					
2	6	102.83	4018.9	2249.5	4023.3	2.27					
	Average					2.28	2.34	2.61	2.56	17.88	85.66

E.8 Rutting test result of compacted asphalt mix

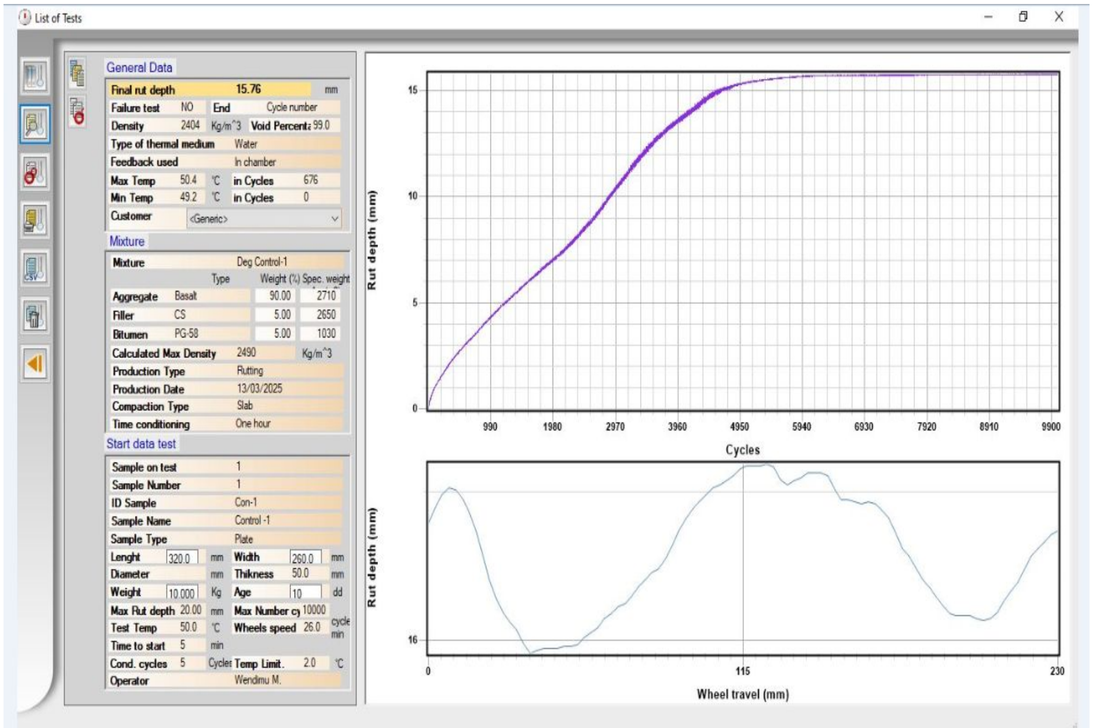


Figure E-1 rutting test result for control mix

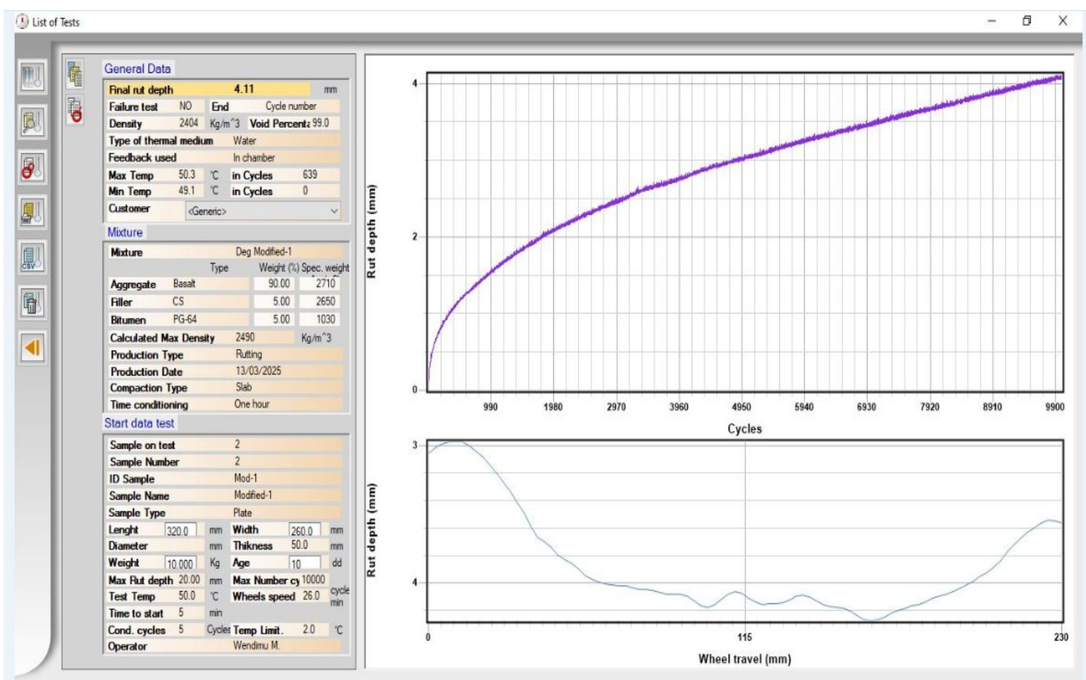


Figure E-2 rutting test result for optimum CR with KN modified mix

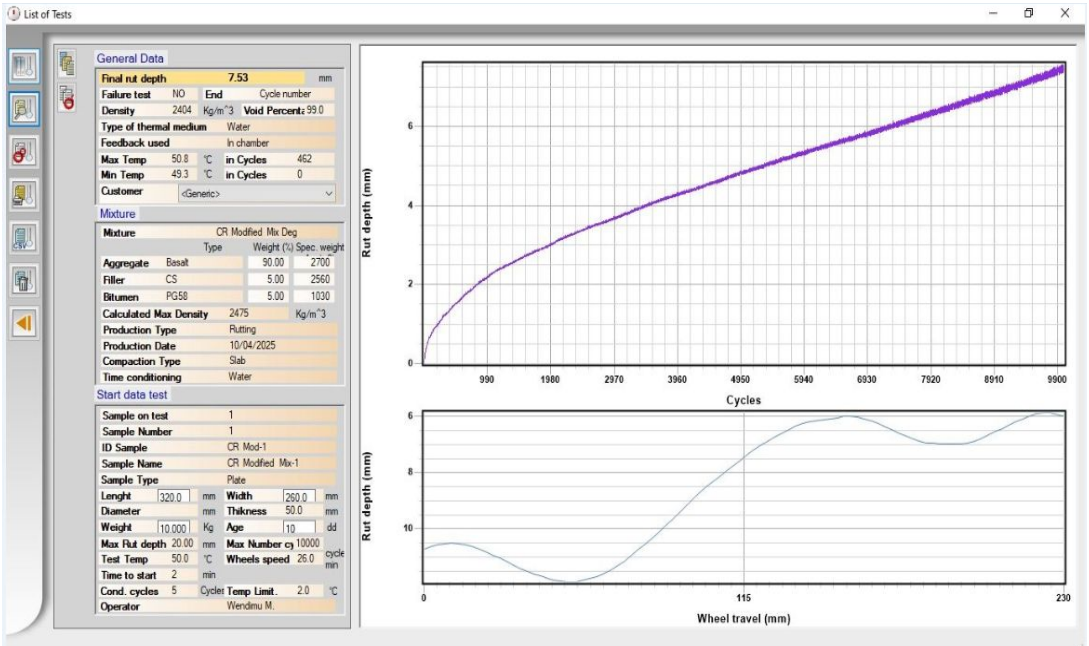


Figure E-3 Rutting test result for CR modified mix

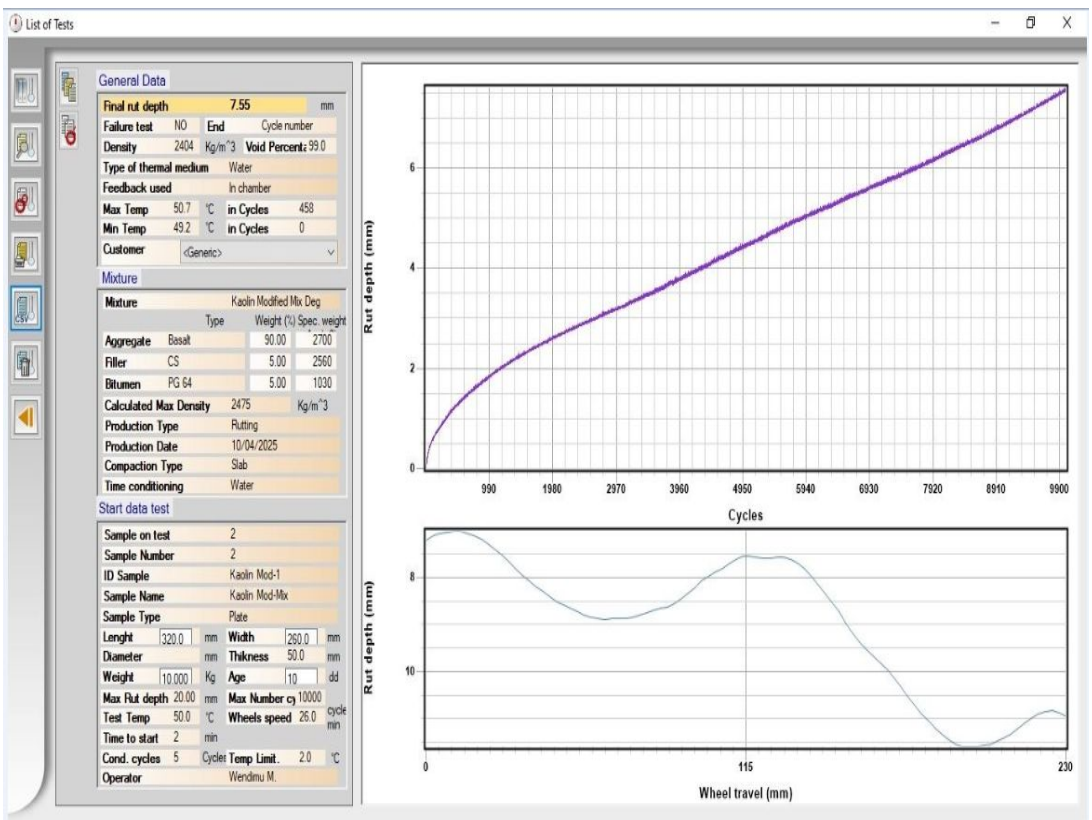


Figure E-4 Rutting test result for Kaolin modified mix

E.9 Indirect tensile modulus test result of compacted asphalt concrete

EN12967 - 26 Annex C Indirect Tensile Modulus Test

Test reference : EN 12967-24 Annex E
Specimen no : 32
Location : AASTU
Operator : Wendimu M.
Comments : ITRM

Template file path : C:\Users\Sotex\Deguamlak ITRM\ITRM Control Mix.tmp
Exported date and time : 22/03/2025 14:32:43

Setup Parameters

Target temperature :	25.0 C	Estimated Poisson's ratio :	0.35
Loading pulse width :	124 ms	Estimated modulus :	500 MPa
Pulse repetition period :	1000 ms	Target deformation :	5 mm
Conditioning pulse count :	5	Contact force :	20 N

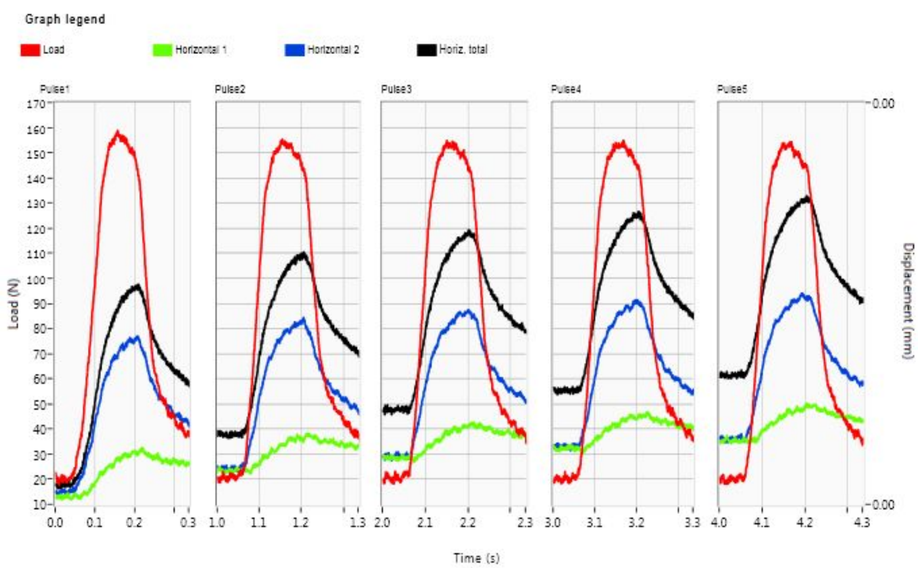
Test Results

Conditioning pulses : 0
Core temperature : 20.0 C
Skin temperature : 26.5 C

Dimension	Ref 1	Ref 2	Ref 3	Ref 4
Length (mm)	84	85	84.5	85
Diameter (mm)	150	150	150	150

Average length 84.62 mm
Average diameter 150.00 mm
Specimen area 17671.46 mm^2

	1	2	3	4	5	Mean	SD	CV%
Stiffness modulus (MPa)	607.2	638.5	643.6	649.0	635.1	634.7	16.2	26316.4
Adjust stiffness modulus (MPa)	582.5	609.5	611.3	627.9	614.2	609.1	16.5	27308.5
Peak horizontal deformation (um)	1.916	1.783	1.763	1.749	1.780	1.798	0.067	0.456
Load area factor	0.47	0.46	0.44	0.50	0.50	0.47	0.02	0.06
Peak loading force (N)	159	155	155	155	154	156	2	329
Load rise time (ms)	156.8	154.4	150.8	168.4	167.6	159.6	8.0	6344.0
Horizontal deformation 1 (um)	0.429	0.338	0.324	0.322	0.362	0.355	0.044	0.196
Horizontal deformation 2 (um)	1.488	1.444	1.439	1.427	1.418	1.443	0.027	0.073
Seating force (N)	22	21	20	19	19	20	1	141



EN12967 - 26 Annex C Indirect Tensile Modulus Test

Test reference : EN 12967-24 Annex E
Specimen no : 2
Location : AASTU
Operator : Wendimu M.
Comments : Combined Mix ITRM

Template file path : C:\Users\Sotex\Deguamlak ITRM\Combined Modified Mix.tmp
Exported date and time : 02/04/2025 11:58:56

Setup Parameters

Target temperature :	25.0 C	Estimated Poisson's ratio :	0.35
Loading pulse width :	125 ms	Estimated modulus :	500 MPa
Pulse repetition period :	1000 ms	Target deformation :	5 mm
Conditioning pulse count :	5	Contact force :	20 N

Test Results

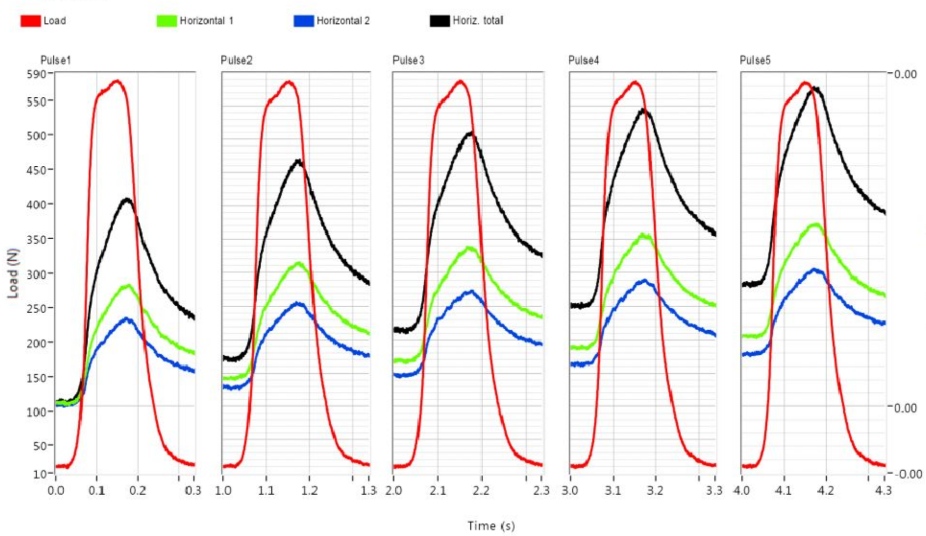
Conditioning pulses : 0
Core temperature : 20.0 C
Skin temperature : 26.5 C

Dimension	Ref 1	Ref 2	Ref 3	Ref 4
Length (mm)	84	85	84.5	85
Diameter (mm)	150	150	150	150

Average length 84.62 mm
Average diameter 150.00 mm
Specimen area 17671.46 mm^2

	1	2	3	4	5	Mean	SD	CV%
Stiffness modulus (MPa)	1444.0	1454.8	1464.7	1450.4	1462.9	1455.4	8.6	7441.8
Adjust stiffness modulus (MPa)	1393.1	1403.7	1407.4	1396.4	1399.4	1400.0	5.7	3238.1
Peak horizontal deformation (um)	2.940	2.911	2.894	2.918	2.889	2.910	0.020	0.041
Load area factor	0.52	0.52	0.51	0.51	0.50	0.51	0.01	0.01
Peak loading force (N)	579	578	579	578	577	578	1	89
Load rise time (ms)	152.0	153.6	151.2	152.4	148.0	151.4	2.1	444.8
Horizontal deformation 1 (um)	1.688	1.672	1.672	1.676	1.644	1.670	0.016	0.026
Horizontal deformation 2 (um)	1.252	1.239	1.222	1.242	1.245	1.240	0.011	0.013
Seating force (N)	21	19	19	19	20	20	1	50

Graph legend



EN12967 - 26 Annex C Indirect Tensile Modulus Test

Test reference : EN 12967-24 Annex E
Specimen no : 3
Location : AASTU
Operator : Wendimu M.
Comments : ITRM CR Modified Mix

Template file path : C:\Users\Sotex\Deguamlak ITRM\Combined Modified Mix.tmp
Exported date and time : 02/04/2025 14:00:09

Setup Parameters

Target temperature :	25.0 C	Estimated Poisson's ratio :	0.35
Loading pulse width :	124 ms	Estimated modulus :	500 MPa
Pulse repetition period :	1000 ms	Target deformation :	5 mm
Conditioning pulse count :	5	Contact force :	20 N

Test Results

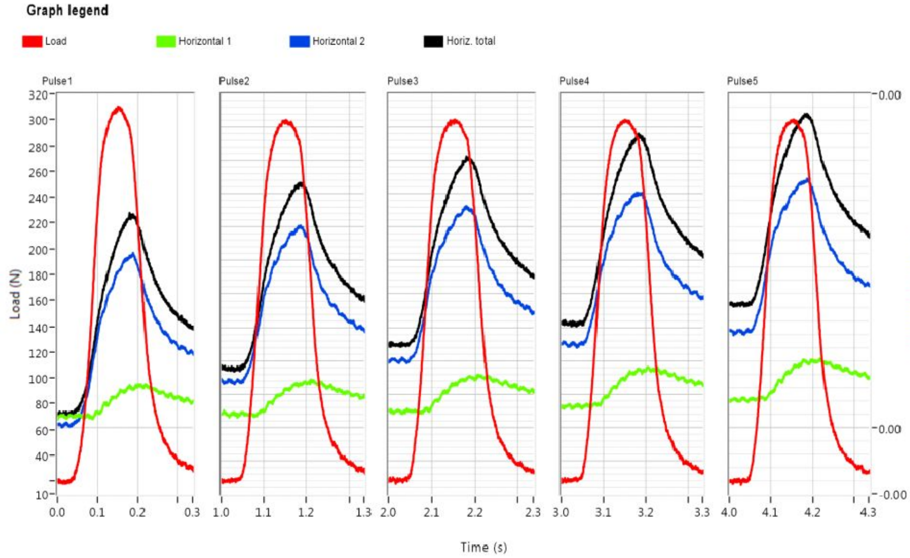
Conditioning pulses : 0
Core temperature : 20.0 C
Skin temperature : 26.5 C

Dimension	Ref 1	Ref 2	Ref 3	Ref 4
Length (mm)	84	85	84.5	85
Diameter (mm)	150	150	150	150

Average length: 84.62 mm
Average diameter: 150.00 mm
Specimen area: 17671.46 mm^2

	1	2	3	4	5	Mean	SD	CV%
Stiffness modulus (MPa)	778.0	795.5	790.7	787.6	778.9	786.1	7.6	5746.2
Adjust stiffness modulus (MPa)	737.8	757.2	754.1	748.5	743.7	748.2	7.8	6061.5
Peak horizontal deformation (um)	2.922	2.761	2.782	2.790	2.824	2.816	0.064	0.405
Load area factor	0.45	0.46	0.47	0.46	0.47	0.46	0.01	0.01
Peak loading force (N)	310	300	300	300	300	302	5	2121
Load rise time (ms)	150.0	152.0	153.6	150.8	154.8	152.2	2.0	388.8
Horizontal deformation 1 (um)	0.495	0.505	0.512	0.567	0.597	0.535	0.045	0.198
Horizontal deformation 2 (um)	2.427	2.256	2.271	2.223	2.227	2.281	0.084	0.712
Seating force (N)	19	20	20	21	18	20	1	112

Graph legend



EN12967 - 26 Annex C Indirect Tensile Modulus Test

Test reference : EN 12967-26 Annex C
Specimen no : 5
Location : AASTU
Operator : Wendimu M.
Comments : ITRM For Kaolin Mix at 25 degree celisius

Template file path : C:\Users\Sotex\Deguamlak ITRM\Combined Modified Mix.tmp
Exported date and time : 11/04/2025 12:42:05

Setup Parameters

Target temperature :	25.0 C	Estimated Poisson's ratio :	0.35
Loading pulse width :	124 ms	Estimated modulus :	500 MPa
Pulse repetition period :	1000 ms	Target deformation :	5 mm
Conditioning pulse count :	5	Contact force :	20 N

Test Results

Conditioning pulses : 0
Core temperature : 20.0 C
Skin temperature : 26.5 C

Dimension	Ref 1	Ref 2	Ref 3	Ref 4
Length (mm)	84	85	84.5	85
Diameter (mm)	150	150	150	150

Average length 84.62 mm
Average diameter 150.00 mm
Specimen area 17671.46 mm^2

	1	2	3	4	5	Mean	SD	CV%
Stiffness modulus (MPa)	1030.7	1021.2	1007.5	996.8	984.0	1008.1	18.6	34761.2
Adjust stiffness modulus (MPa)	933.4	935.4	917.1	904.7	892.5	916.6	18.4	33954.7
Peak horizontal deformation (um)	2.463	2.416	2.441	2.478	2.501	2.460	0.033	0.108
Load area factor	0.35	0.38	0.36	0.36	0.35	0.36	0.01	0.01
Peak loading force (N)	346	337	336	337	336	338	5	2074
Load rise time (ms)	146.8	150.8	146.8	145.6	144.8	147.0	2.3	532.8
Horizontal deformation 1 (um)	0.881	0.949	0.972	1.010	1.025	0.967	0.057	0.323
Horizontal deformation 2 (um)	1.582	1.467	1.469	1.469	1.476	1.492	0.050	0.249
Seating force (N)	21	20	20	20	20	20	1	52