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Evaluation of the Properties of Rubberized Asphalt Binders and Mixtures

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EVALUATION OF THE PROPERTIES OF RUBBERIZED ASPHALT BINDERS AND MIXTURES

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Abstract

Rubber modified binder samples are tested and evaluated based on SHRP requirements. Best rubber content is suggested for modifying binder. Rubber modified asphalt mixtures were manufactured and tested. Based on Hveem stability and volumetric properties of asphalt mixtures, optimum binder content is evaluated and reported. Performance properties of asphalt mixtures made with various rubber size and method were analyzed and compared. An ultrasound measurement performed on asphalt mixture samples and the results were analyzed. It is discovered that rubber improves asphalt viscosity and resistance to rutting deformation. Rubber also increases asphalt's dynamic modulus.

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Chapter 1
Introduction

1.1. Problem Statement

Modifying asphalt and producing asphalt binders and asphalt mixtures with better performances is necessary. Ground rubber is one of the popular modifiers which is used in several places. Considering the fact that asphalt is used in various places, it is critical to discover the influence of local materials on rubber modified asphalt.

The introduction of asphalt rubber goes back to the late 1930s as a sealing material. However, its use as a pavement material is increasing in many states. In Nevada this kind of modifier is not studied widely. Making rubberized asphalt with binder manufactured in Nevada and carrying out equivalent tests based on NDOT requirements on rubberized binder is the first step of this study. Afterwards, making rubberized asphalt mix samples based on selected rubber content is the second step in order to find and recommend best rubberized asphalt mix for Nevada based on different types of aggregates and binders which are used in this state for pavement.

Strategic Highway Research Program (SHRP) recommended required tests to evaluate asphalt binder and asphalt mixture. Tests carried out on asphalt mixture are expensive and require time.

Ultrasound surveying is one of the easy and less expensive methods which is widely used in industry to evaluate the properties of materials. Despite its popularity in other industries such as evaluating steel materials, it is not used considerably for evaluating asphalt materials. Any correlation between ultrasound wave behavior in asphalt mixtures and asphalt mix properties can lead to using this equipment as a preliminary tool to evaluate asphalt properties.

1.2. Objective

In this dissertation, rubber-modified asphalt and rubberized asphalt mixtures are evaluated and tested for different types of asphalt binder and aggregates prepared from various existing sources in Nevada. To start, a literature review will be conducted to produce an initial guideline for various blended rubberized asphalt. Then, rubberized-asphalt binder will be subjected to various tests in order to evaluate properties of samples with different rubber content. Other tests will be conducted to come up with the optimal binder content for mix design. Finally, an extensive testing and evaluation process will be carried out on asphalt mix samples with recommended rubber content mixed with binder and various aggregate sources and grading.

Samples will be tested based on SHRP in order to evaluate rubberized-asphalt binder properties. The results will be presented in graphs and tables for comparison and analysis. This is the first stage of the dissertation.

Around two hundred samples are subjected to be made and evaluated based on different aggregate sources and grades in order to find the properties of rubber modified asphalt mixture containing different rubber and binder content. All tests are carried out based on ASTM or Nevada Department of Transportation recommendation. The results will be demonstrated in graphs and tables as well as figures illustrating the testing process.

Ultrasound surveying will be carried out on asphalt mixtures and the ultrasound wave speed and attenuation will be presented in graphs and tables.

The dissertation is defined to be done in three stages. In the first stage the properties of asphalt binder is evaluated based on SHRP requirements and the results are presented. An optimum rubber content is recommended at the end of this stage to be used in producing rubber modified asphalt mixture. In the second stage rubber modified asphalt mixtures are evaluated to illustrate performance properties of modified asphalt mixture. In order to perform all tests SHRP requirements and Nevada DOT recommendation were used as base standard.

Asphalt mix samples were evaluated using an ultrasound device in third stage. The goal is to discover ultrasound wave behavior in different asphalt mix samples. Wave speed and attenuation in different asphalt mixtures is then compared to asphalt mix performance properties to illustrate any correlation between mix properties and ultrasound behavior. In Chapter four the analysis of the results and findings is presented. Sample graphs and tables are demonstrated in chapter three and four and the other graphs are displayed in appendixes.

1.3. Background

With the growing concerns regarding climate change worldwide, tendency towards using green products is increasing. The abundance of waste is a serious concern. Consequently, numerous agencies are trying to find and improve methods in order to re-use these materials in different sectors as recycled material. Based on the EPA's latest report, 89 million out of 258 million tons of waste was recycled in the USA in 2014. On the other hand, approximately 34.6 percent of waste material was recycled this year [1]. Around 300 million scrap tires are produced annually in the United States while 185 million are already stockpiled based on EPA estimations. This number will be 1.5 billion globally in 2035 [2].

It must be mentioned that the country severely lacks landfills for stockpiling scrap tires. Thus, any effort in increasing or improving scrap tire recycling is to be welcomed. EPA evaluations demonstrate that currently around 45 percent of scrap tires are being recycled [1]. Almost 54 percent of scrap tire is used for tire-derived fuel and 24 percent as ground rubber, while less than 5 percent used in civil engineering related areas [3].

One of the applications of recycled tire is rubberized asphalt binder. The rubber is used as a modifier to increase asphalt's elasticity, flexibility and durability against aging. Tire, due to its anti-oxidant content, can also be used to maintain asphalt. The method of modifying asphalt binder with ground scrap tire is called crumb rubber modifier (CRM) which is broadly used in hot-mix asphalt in Arizona, California, Florida, and Texas. According to the ASTM, the virgin binder must have by weight at least 15 percent of CRM in order to call asphalt "asphalt rubber." [4].

1.4. Rubberized asphalt, materials and properties

1.4.1. CRM Binder

Using rubber as a modifier in asphalt pavement dates back to 1960s when Charles McDonald introduced method for modifying asphalt mixtures by adding elastic materials such as crumb rubber [5]. Arizona Department of Transportation (ADOT) used rubberized hot mix asphalt as paving material by 1975 for the first time [6]. Since then Arizona has become the leading state in using rubber modified asphalt to paving its roads and highways. Based on ADOT, around 1,500 tires are recycled in construction of every lane-mile pavement [7]. In 1975 several experimental tests carried out by Caltrans on asphalt rubber chips which leaded to the construction of first rubberized asphalt pavement in California by 1978 [8]. It has to be mentioned that for the first time, in 2011 rubberized asphalt was used in Nevada [9]. There are two methods for processing binders: wet process, otherwise known as asphalt rubber and dry process, also known as rubber modified. The dry process is not used in the United States.

1.4.2. Tire Composition

The three main components of tires are rubber, steel and fiber. Rubber makes up to 60 percent of a tire's weight, thereby making it the main component in tires. The rubber component in both passenger and truck tires is typically made of natural isoprene. Figure 1 and Table 1 illustrates the components and composition of a typical tire [10, 11].

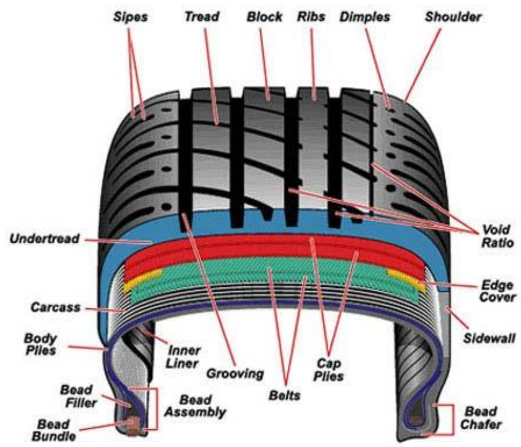


Figure 1. Components of tire

Table 1. Passenger and Truck Tires Composition

Materials	Passenger Car (%)	Truck (%)
Rubber/ Elastomer	48	43
Carbon Black	22	21
Metal	15	27
Textile	5	---
Zinc Oxide	1	2
Sulphur	1	1
Additives	8	6

Chapter 2

Literature Review

In order to develop models for predicting fatigue performance of Rubberized Asphalt Concrete (RAC), Xiao carried out a research in Clemson University. For this reason, various samples were made with two aggregate sources and tested to perform fatigue analysis and modeling. The objectives of this dissertation was conducting laboratory tests in order to evaluate the performance of the rubberized asphalt concrete, measuring the fatigue life of the samples and developing a predictive mathematical model to predict the fatigue life of the samples. He summarized that using crumb rubber in asphalt improves aging resistance in rubberized asphalt concrete [12].

Shatnawi performed laboratory tests to determine the effect of CRM on reducing the noise on highways. This research was subject of a dissertation in Clemson University. For this reason mix samples were made using binders with and without rubber modifier in order to compare their performance against noise. Based on this research, energy absorption property of crumb rubber does not have significant impact on noise reduction. But the volumetric increase property of crumb rubber in asphalt mix was found to have influence in noise reduction. In addition, the research demonstrated that, permeability and binder content have significant effect on noise reduction which means crumb rubber has an indirect influence in reducing noise. Another indication in this research was the relation between noise reduction and different type of porous and dense mixtures. The results showed that pavements with optimum thickness will demonstrate the highest sound absorption [13].

In 2002 Qin presented his presentation about determining rubberized hot mix asphalt performance under Accelerated Loading Facility. The author used a 2-D finite element analytical model to predict the performance of the ALF test lanes based on material properties data which were collected from laboratory tests. The overall purpose of the study was comparing the performance of hot mix asphalt containing CRM with similar samples with no CRM under ALF loading. In this study the lane with CRM-HMA demonstrated significantly smaller rut depth compared to lane containing conventional mix, while their performance in laboratory were similar [14].

The effect of aging on asphalt rubber pavements was the purpose behind conducting theses by Reed. In first step, rubberized asphalt binder samples were subjected to different aging condition and then tested for viscosity. Based on viscosity analysis, he suggested that asphalt rubber binders exhibit less long-term aging. Second stage was evaluating binder samples aging in laboratory under accelerated oxidative aging and also aging that occurs because of long term storage. For evaluation of results, he used dynamic modulus of samples and demonstrated that aging in asphalt rubber is highly relevant to temperature and samples showed more stiffening in higher temperatures. In final phase, he collected samples from a pavement which was under service for seven years and conducted dynamic modulus test and beam fatigue test. Similar to the laboratory results, the dynamic modulus of the samples showed less stiffening for samples at low temperature while fatigue test presented both stiffening and brittle behavior for samples [15].

R. G. Hicks, summarized the benefits of rubberized asphalt mixtures are as follows [16]:

- Higher binder contents lead to improved resistance to surface cracking as well as fatigue and reflection cracking
- Improved resistance to aging and oxidation

- Less rutting due to higher viscosity
- Better night-time visibility
- Reduction in tire noise and decreased splash and spray in the event of rain
- Construction time is decreased and less maintenance cost are required because of the improved performance
- Energy and resources are conserved due to the use of recycled material [17]

2.1. Binder Properties

2.1.1. Strategic Highway Research Program (SHRP)

In the early 1980's several issues happened relevant to highways and bridges in the United States raised concerns about safety and durability of these main infrastructures. As a result in 1987 a five-year long research program was developed and carried out by Federal Highway Administration to investigate and improve transportation productivity and safety on highways. One of the main objectives of this program was investigating asphalt and long-term performance of pavement. In order to better understanding the physical and chemical properties of asphalt several testing equipment were introduced with new testing methods.

2.1.2. Performance Grade (PG)

Performance Grade (PG) which developed after SHRP is a grading system related to the climate and environmental condition of the area that asphalt will be used with the regard to aging concerns of asphalt pavement. On the other hand, because of the fact that climate conditions in Nevada are different compared to Alaska, therefore the type of asphalt used in Nevada is other than the one which is suitable for Alaska. In this method two numbers are reported with each binder sample. First number is the average of seven-day maximum pavement temperature and second number is the least temperature which pavement will experience both in Celsius. For instance PG 76-16 is suitable for area in which pavement's maximum seven-day temperature will be less than 76 Celsius and minimum temperature will be over -16 Celsius. Figure 2 illustrates different types of asphalt binder based on PG.

Temperature C °	52	58	64	70	76
-16	52 -16	58 -16	64 -16	70 -16	76 -16
-22	52 -22	58 -22	64 -22	70 -22	76 -22
-28	52 -28	58 -28	64 -28	70 -28	76 -28
-34	52 -34	58 -34	64 -34	70 -34	76 -34
-40	52 -40	58 -40	64 -40	70 -40	76 -40

(green)	*Crude Oil*
(yellow)	*High Quality Crude Oil*
(red)	*Modifier Required*

Figure 2. Performance Grade system for grading binder

Test methods were added to traditional test procedures to simulate aging properties of asphalt binder. The following tests were added by SHRP research group [18]:

High Temperature Viscosity Test

Bending Beam Rheometer

Low Temperature Direct Tension Test

Direct Shear Rheometer

2.1.3. Viscosity

Asphalt binder viscosity controls the pump-ability, mix-ability and workability of the binder. On the other hand with specific binder viscosity magnitude it is possible to pump the binder into mix manufacturing plant and mix it with aggregates and at the end use the mixture as a pavement with reasonable effort. Rotational Viscometer is one of the most common ways of measuring the viscosity of asphalt binder. The result of this test which is measured in Pa.s is dynamic viscosity [19]. Figure 3 illustrates a model of instrument used for evaluating binder viscosity. For unaged binder it is recommended to have viscosity less than 3 Pa.s. This value satisfies the workability of asphalt binder during pavement construction.

Figure 3. Rotational viscometer

2.1.4. Bending Beam Rheometer

Low-temperature cracking is one of the most-frequent faults in asphalt pavements, specifically in old asphalt. SHRP research program requested adding test method for evaluating asphalt binder's resistance to low temperature. Bending Beam Rheometer is designed to measure binder's stiffness and relaxation in low-temperature. The result of this test is binder's creep stiffness over the time which can be converted to the modulus of stress relaxation [19]. A sample of bending beam is illustrated in figure 4 and 5.

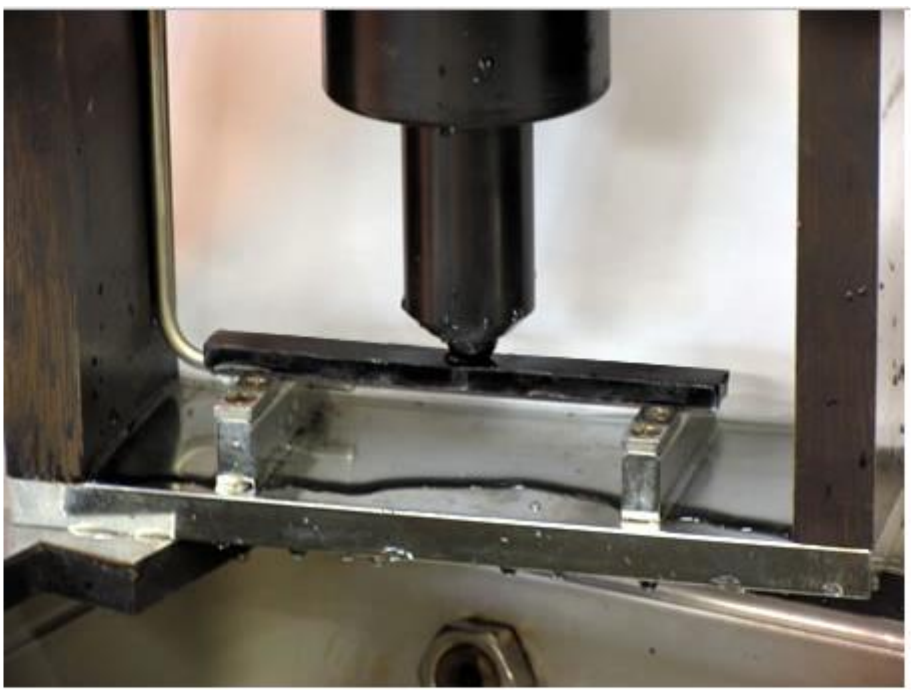


Figure 4. Bending beam rheometer

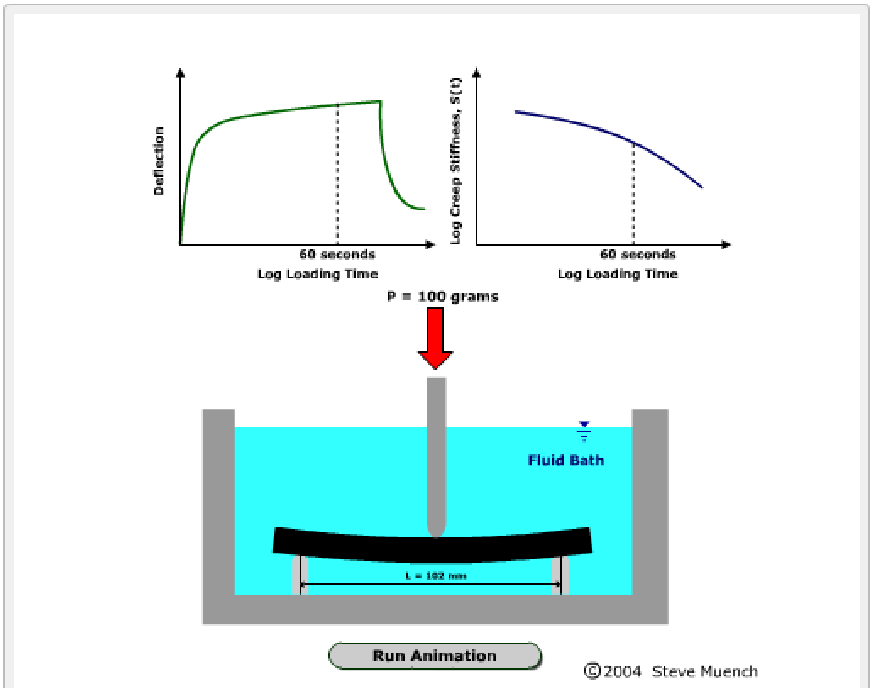


Figure 5. Bending beam schematic test configuration

2.1.5. Direct Tension Test

Based on SHRP requirements in order to evaluate binder performance in low temperature Direct Tension Test (DTT) is developed. The results of this test present the stiffness and relaxation properties of asphalt binder which are used to estimate binder ability to withstand low-temperature cracking. The combination of DTT and BBR provides PG grade low-temperature properties [19].

By 1994 T.J. Lougheed and T.A Papagiannakis indicated that adding rubber to binder increases the amount of binder viscosity. According to their experiment, adding more rubber lead to higher viscosity value [20]. W. Hainian and Z. You performed tests on binder with different rubber content to evaluate viscosity and low-temperature stiffness of the asphalt binder. Their experiments demonstrated that binder viscosity improves by adding crumb rubber. They also indicated that rubber modified binder shows lower creep stiffness at low temperature [21]. Figure 6 illustrates an example graph of stiffness and rubber content relationship. J. Shen and S.N. Amirkhanian carried out tests on rubber mixed binder samples and concluded that ambient CRM binder resulted in viscosity 1.16 to 1.58 times higher than cryogenic CRM binders. They also summarized the surface area of the ambient CRM binder to be 2.5 times of the cryogenic CRM binders [22].

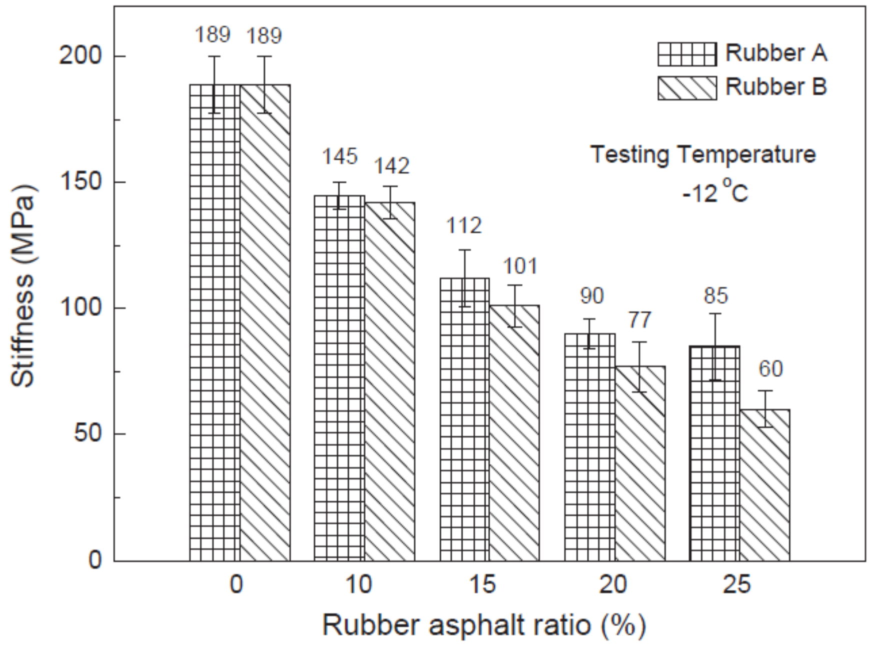


Figure 6. Stiffness versus rubber content

2.1.6. Direct Shear Rheometer

Direct Shear Rheometer (DSR) is part of Superpave Performance Grade characterization by finding the elastic and viscous properties of binder at specific temperature. In order to find the shear properties of the asphalt binder, this test is carried out on unaged binder as well as RTFO-aged and PAV-aged asphalt binder. The results of this test is complex shear modulus (G*) which controls the rutting properties of the asphalt and phase angle (δ) that is related to the viscosity of binder sample. The more viscose binder samples will lead to higher angle phase. In order to prevent the asphalt pavement from rutting the binder should have larger complex shear modulus [19].

Figure 7 presents correlation between binder shear modulus and phase angle which are results of direct shear rheometer test.

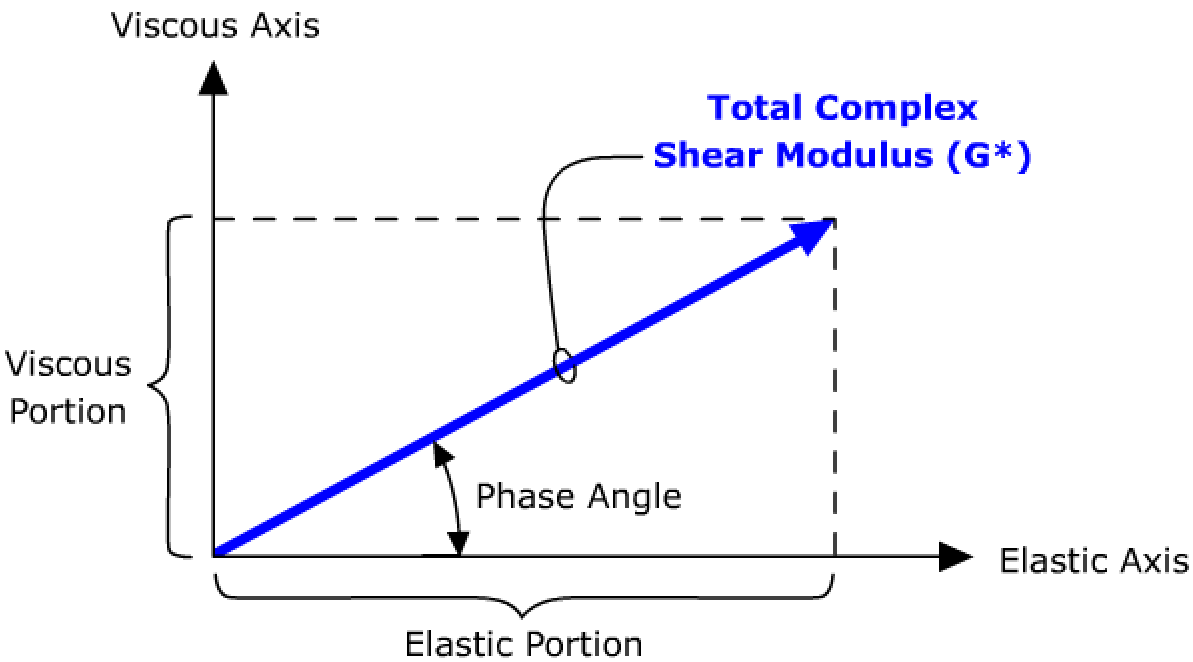


Figure 7. Binder complex shear modulus and phase angle

2.1.7. Ductility

This test is based on stretching the binder inside a water bath at 4 or 25 degree Celsius until the sample tears apart. The range of stretching demonstrates binder resistance to cracking under repeated loading and during the cold weather.

2.1.8. Flash Point

In this test, binder sample is subjected to heating in an open cup while a small flame is on top of it. The temperature in which a burning flash or spark appears on binder is measured as flash point. This temperature is also used as the temperature at which binder ignites and starts burning.

2.1.9. Rolling Thin Film Oven State (RTFO)

Rolling Thin-Film Oven test is used for simulating the short-term aging aspect of asphalt binder. Binder samples are poured in cylindrical glasses. These bottles are placed in a rotating unit inside an oven. Combination of heating and rotating creates an environment in which asphalt binder ages and is used to estimate the short term changes in binder behavior. The result of this test is used to determine binder resistance to fatigue and rutting. It is important to mention that the short- term aged binder then undergoes performance tests such as Dynamic Shear Rheometer (DSR), Ductility, Bending Beam Rheometer (BBR) and other required experiments [19].

2.1.10. Pressure Aging Vessel (PAV)

Pressure Aging Vessel (PAV) as a test method is part of Superpave Performance Grade (PG) requirements which is used for evaluating the long-term aging properties of asphalt binder. The basic philosophy of this test is similar to RTFO. Asphalt binder is subjected to heat and pressure for the specific time period and the resulted sample simulates binder which aged seven to ten years. In order to estimate the fatigue and low temperature cracking of the asphalt it is necessary to perform aging test on binder samples. It has to be mentioned that aging is usually because of the oxidation that happens in asphalt binder. Binder oxidation happens during the mixing process and placement as well as over the service time [19].

Set of experiments carried out by S. Lee, C. K. Akisetty and S.N Amirkhanian illustrated that addition of more CRM to binder caused an increase in viscosity as it is demonstrated in figure 8. Based on their experiments, ambient CRM binders show higher viscosity compared to cryogenic CRM binders. CRM improved rutting and fatigue cracking properties of the binder while the stiffness decreased with the increase of the CRM percentage [23]. H. H. Kim and S. Lee added wax to rubberized binder and evaluated the effect of crumb rubber on viscosity of the mix. Their experiment summary showed direct correlation between rubber content and binder viscosity. With the increase of rubber percentage in modified binder significant improvement is observed in viscosity. In contrast, adding wax to rubberized binder decreased the amount of viscosity [24].

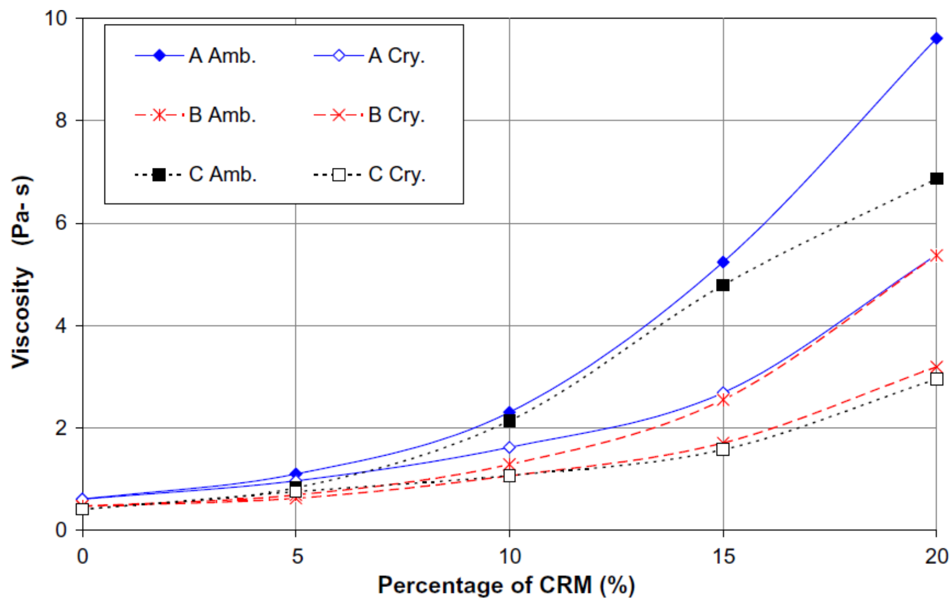


Figure 8. Correlation between rubber content and viscosity

N. Mashan and colleagues carried out experiments on binder with different rubber content to investigate the influence of the rubber on binder properties. The results showed that, adding rubber decreased the amount of ductility and penetration. They also indicated that adding rubber enhanced the rutting resistance of the rubberized binder [25]. A. Rodriguez and J. Gallego conducted tests on warm mix binder modified with 15 percent rubber and indicated increase in dynamic viscosity in rubberized binder [26]. The results of a set of experiments performed on rubberized asphalt binder by H. Wang and colleagues demonstrated improvement in binder viscosity and decrement in creep stiffness by adding rubber in binder [27]. Based on research carried out by K. Jeong, S. Lee and S. Amirkhanian to find out the interaction effects of CRM on binders, adding crumb rubber on asphalt binder increases viscosity and G*/sinδ significantly while the increase in LSM values is slight. Figure 9 exhibits relation between dynamic shear modulus and rubber content [28].

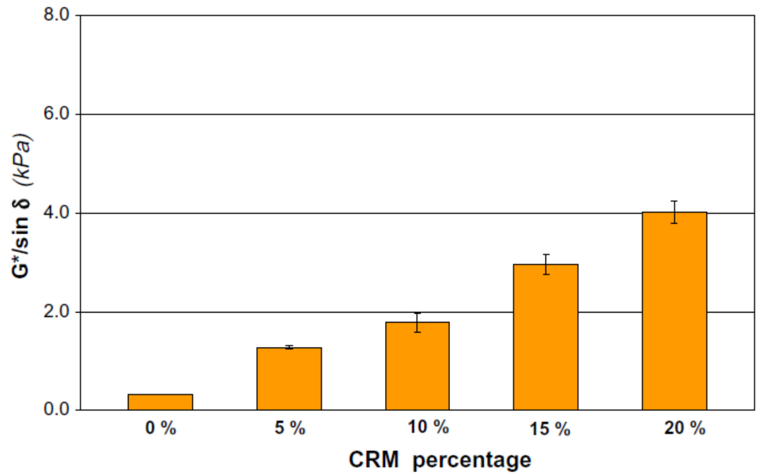


Figure 9. Dynamic shear modulus versus rubber content

A set of experiments performed by P. Cong and co-workers on binder mixed with various rubber content. They concluded that by adding crumb rubber in binder, the softening point, elastic recovery, viscosity, complex modulus (G*) and rutting parameter increase while the amount of ductility, penetration and phase angle (δ) decreases [29]. Other experiments indicated that rubber increases fatigue resistance of the binder significantly while decreases the dynamic flexure stiffness of the virgin binder [30]. A sample result is showed in figure 10.

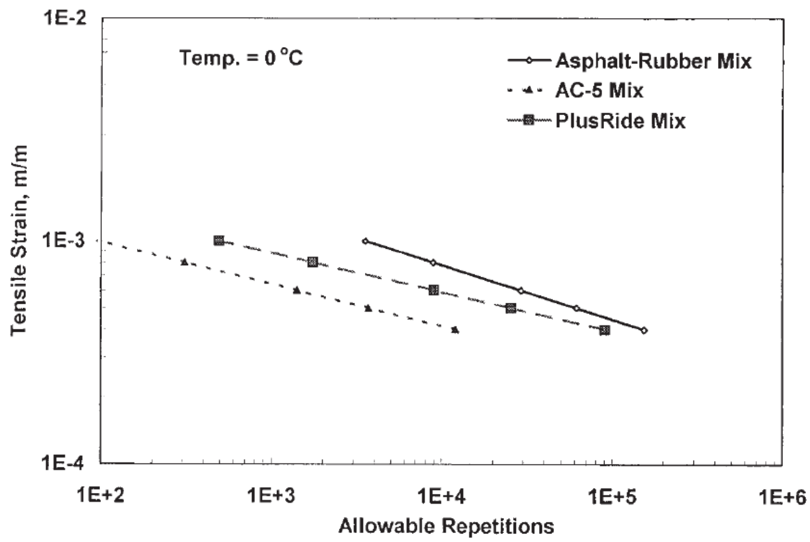


Figure 10. Fatigue resistance of different binders

Investigation carried out by N. Mashaan et al. revealed the opposite influence of rubber in binder ductility. With the increase of the rubber content in rubberized binder the ductility decreases significantly. In contrast, the elastic recovery and rutting factors improve with the increase in rubber percent in binder [31].

2.1.11. Toughness and Tenacity

Toughness and Tenacity provides a test method in order to evaluate the elastic properties of asphalt binder. These two parameters are related to the adhesion properties of asphalt binder. Binders which have been modified with elastomeric additives such as polymers have the capability of experiencing long stretches and at the same time having resistance to further stretches. The results of this test represent the two parameters toughness and tenacity [32]. An investigation performed by F. Zhang and J. Yu illustrated improvement in binder toughness and tenacity by adding Styrene-Butadiene Rubber (SBR) to the virgin binder [33].

2.2. Grinding Process and its Influence and CRM Asphalt

There are different methods in order to grind the scrap tire and produce ground tire rubber. R. West et al. investigated the effect of various rubber grinding methods which included Crackermill, Granulator, Micromill and Cryogenic Process on rubberized asphalt binder. Based on this investigation, grinding process has a significant influence on the shape, texture and physical properties of the rubber particles as well as on rubberized binder properties [34].

Based on process temperature, grinding is categorized under two main procedures. First method is called Ambient in which the grinding is carried out in room temperature. Sharp cutting blades are used to cut tires to smaller pieces and shredded into tiny particles. The particle sizes are between 75 µm to 5 mm. due to tearing process result of ambient processing is a rough texture with higher surface area. Second procedure is Cryogenic method in which nitrogen or other liquids are used to freeze the tire scraps and then a hammer to crash the cooled tire to particles between ¼ inch and mesh #30. The rubber particles produces with cryogenic procedure have usually cubic shapes [35].

C. Thodesen et al. performed experimental research to discover the influence of rubber characteristics on rubberized binder viscosity. The results indicated that binder modified with ambient ground rubber has higher viscosity compared to binder modified by cryogenic ground rubber [36]. In another investigation, J. Shen et al. illustrated ambient CRM particles have significantly more surface area compared to cryogenically ground rubber and consequently, ambient-rubber-modified binder demonstrated higher phase angle. They also discovered that binder modified with larger rubber particles shows larger complex modulus which is a benefit for rutting resistance [37].

Studies have shown that microstructure for rubber produced by ambient method has a porous appearances while the result of cryogenic process is more angular shape as the differences illustrated in figure 11. Having porous texture leads to having interaction with binder and absorbing more fine binder particles and consequently to having better rutting resistance [21]. Based on studies carried out by J. Shem and S. Amirkhanian, adding 10 percent of rubber to binder adds one high temperature to the original binder PG grade and mixing binder with 15 percent of rubber increases the virgin binder PG grade at least two high temperature. This increase in high temperature is regardless to the grinding process. They also declared the mixing time has no influence on failure temperature of the rubberized binder [38].

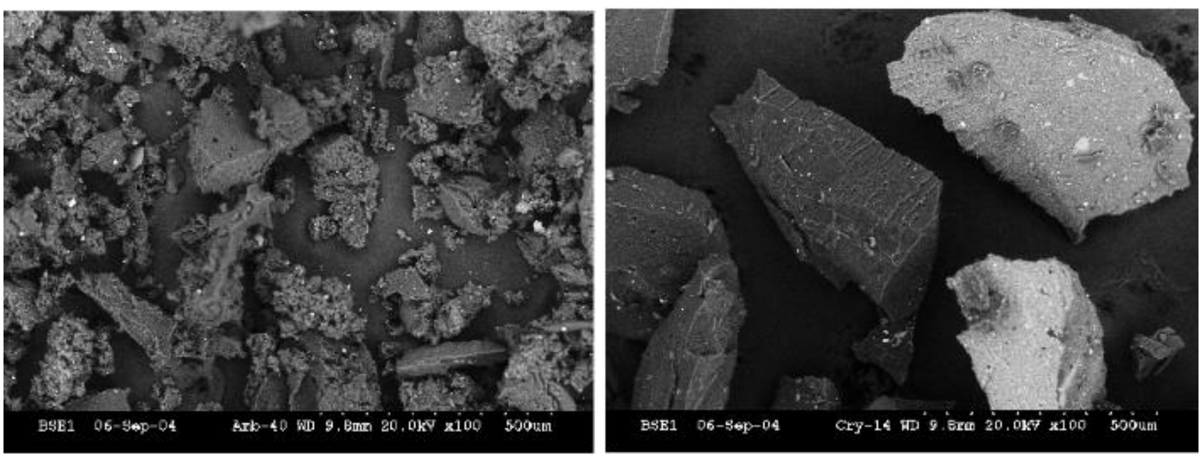


Figure 11. Rubber microstructure; a) ambient; b) cryogenic

Experimental study carried out by P. Cong et al. on asphalt binder modified with both ambient and cryogenic rubber demonstrated better pavement performance for cryogenic ground rubber. Based on this study regardless of grinding process, rubber increases the amount of softening point, elastic recovery, viscosity, complex modulus and rutting factors of the asphalt binder and reduces the magnitude of penetration, ductility and phase angle. Rubber additives have better improving influence on high and low temperature performance properties of softer asphalt binder [39]. Z. Lei et al. declared that, rubber fineness, virgin asphalt grade, stress level and also temperature have significant influence on high temperature performance of the binder modified with rubber. In this research, lower rubber fineness as well as lower virgin binder grade has result of improving the permanent deformation of the asphalt. This study confirms the positive influence of the rubber additives on performance grade and rutting properties of the virgin binder [40].

N. Kebaili et al. performed penetration test to evaluate the effect of rubber powder size on the modified binder penetration rate. The results indicated that modified binder with finer powder has less penetration rate as well as softening point. The reduction in penetrability has also direct correlation with the rubber content. On the other hand increment of the rubber content leads to decrease on penetration rate [41].

2.3. Optimum Rubber Content

G. W. Maupin studied the influence of different rubber content on binder performance in Virginia. He made rubberized binder samples containing 5, 10 and 15 percent of rubber. The results demonstrated better performance for asphalt having 10 percent or less rubber [42]. T. C. Billiter et al. performed tests to evaluate the effect of rubber content and size on binder properties. They used binder from two different sources to make rubberized binder samples. The results indicated with the increase of rubber content the temperature susceptibility improves and complex viscosity at rutting temperature increases. In addition, complex viscosity is relevant to the source binder for samples having same rubber content and particle size. Their experiments demonstrated that rubber particle size is more dependent on the source binder and has lower influence in the performance of the rubberized binder [43].

D. Yousefi et al. carried out performance tests on binders containing 4, 8, 12, 16 and 20 percent crumb rubber. The aim of this study was evaluating optimum binder content additives based on conventional and SHRP performance tests. Based on their experience adding 4 percent of rubber has no influence in binder properties while rubber modified with 20 percent did not perform well with traditional tests. They suggested 16 percent of rubber is the optimized rubber content for modifying virgin binder. Furthermore, they discovered that viscosity increases significantly with increasing the rubber content from 16 percent to 20 percent [44].

In a study by B. Celauro et al. rheological tests were carried out on binder samples containing various rubber content between 3 to 24 percent. At the end they suggested using 18 percent as an optimized rubber content to modify binder [45]. In addition to processing method, CRM rubber content, particle size, tire type as it is demonstrated in figure 12 and surface area have direct influence on viscosity of rubber modified asphalt binder [36]. H. Wang et al. compared viscosity-temperature correlation, RTFO aging, creep stiffness and economical parameters for binder samples containing various rubber content and proposed 15 to 20 percent to be the optimum rubber content for modifying binder [27].

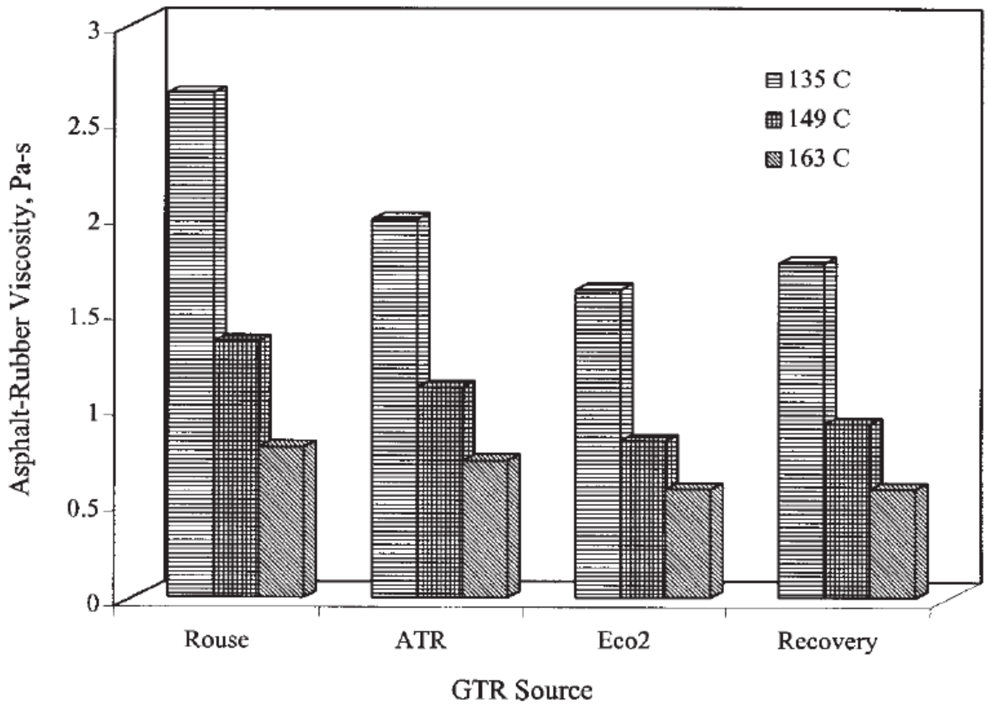


Figure 12. Influence of rubber source on modified binder viscosity

Based on a research carried out by V. Gopal et al. optimum rubber content is relevant to the source binder and crumb rubber size. For each rubber size an optimum rubber content has to be evaluated depending on the asphalt binder. The influence of the rubber size to the performance of the asphalt binder is relevant to the temperature and source binder [46].

2.4. Asphalt Mix Types

Hot Mix Asphalt (HMA) is the most common type of flexible pavement. HMA or Asphalt Concrete (AC) is made with the mix of aggregate, binder or bitumen and air. Generally, HMA is classified based on production method. Three main types of asphalt concrete include Dense-Grade Mix, Stone Matrix Asphalt (SMA) and Open-Graded Mix. Dense-Graded Mix which is the traditional method and most common type of HMA will be used in this investigation for making asphalt mix samples. Mix design for pavement means evaluating volumetric relation of asphalt binder and aggregates. In order to find volume for each ingredients of asphalt mix, weight is measured and then converted to volume. Following paragraphs include definitions about mix's main weight and volume parameters [47].

2.5. Density or Specific Gravity

Density or Specific Gravity is the unit mass of material. In a compacted asphalt sample several different terms of specific gravities are calculated and used.

In defining aggregates, Apparent Specific Gravity (G_{sa}) is the mass of aggregate without permeable water divided to solid volume. In practice G_{sa} is calculated by dividing the mass of impermeable portion of aggregate to the mass of gas-free distilled water which has the same volume. Bulk Specific Gravity is evaluated by dividing the mass of permeable aggregate in air to the mass of gas-free distilled water which has equal volume. Bulk Specific Gravity is divided to two categories which include Bulk Dry Specific Gravity (G_{sb}) and Bulk Saturated Surface Specific Gravity (SSD).

For asphalt, Bulk Specific Gravity for a compacted mix sample (G_{mb}) is the mass of material which includes both permeable and impermeable airs to the volume of gas-free distilled water. The use of Bulk Specific Gravity is to calculate the weight per unit volume of compacted mix sample. Following equation (1) is used for calculating G_{mb} on test specimens which are carried out based on AASHTO T 166:

Equation (1):

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}}$$

In which:

W_D: Dry Weight

W_{SSD}: Saturated Surface Dry (SSD) Weight

W_{sub}: Weight Submerged in Water

Theoretical Maximum Specific Gravity (G_{mm}) for a bituminous mix sample is measured by dividing the mass of void less HMA to the mass of gas-free distilled water with equal volume. This specific gravity also is called Rice Specific Gravity and is calculated using equation (2).

Equation (2):

$$G_{mm} = \frac{W_{agg} + W_b}{V_{eff} + V_b}$$

In which:

W_{agg}: Weight of Aggregates

W_b: Weight of Absorbed Asphalt

V_{eff}: Effective Volume of Aggregates

V_b: Volume of Asphalt Binder

2.6. Void related parameters

2.6.1. Air Voids (V_a)

Air Voids present the cumulative volume of small air pockets between binder coated aggregates during the compaction. It is measured as the ratio of air volume to the total balk volume of the compacted sample and is expressed as percent. Air Void is one of the most dominant parameters in mix design because it is directly related to the pavement stability as well as durability. Equation (3) is used to calculate voids (V_a)

Equation (3):

$$\left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$$

Where:

G_{mb}: Bulk Specific Gravity of the compacted mixture

G_{mm}: Maximum Theoretical Specific Gravity of the mixture

2.6.2. Voids in the Mineral Aggregates (VMA)

The volume of the void trapped between aggregate particles is called Voids in the Mineral Aggregates (VMA) which includes both air voids and effective asphalt content. This parameter is also presented in percent of the total volume. In samples with lower VMA values, lack of room for mixture will result in coating aggregates with insufficient binder. Mixtures with higher amount of VMA are considered to be unstable. Therefore it is important to design a mix with appropriate amount of VMA. In order to calculate VMA equation (4) is used.

Equation (4):

$$VMA = (1 - \frac{G_{mb}\,(1 - P_b}{G_{sb}}) \times 100$$

G_{mb}: Bulk Specific Gravity of the compacted mixture

G_{sb}: Bulk Specific Gravity of Aggregate

P_b: Asphalt Content by mix weight

2.6.3. Voids Filled with Air (VFA)

Voids filled with Asphalt (VFA) is another important parameter presenting the portion of asphalt content filling the voids between aggregates on the other hand effective portion of asphalt content. It is relevant to air voids and is expressed in percentage (equation 5).

Equation (5):

$$VFA = \frac{VMA - Va}{VMA} \times 100$$

In which:

V_a: Volume of Air Voids

Figure 13 demonstrates a sketch of volumetric parameters in asphalt mix sample (19).

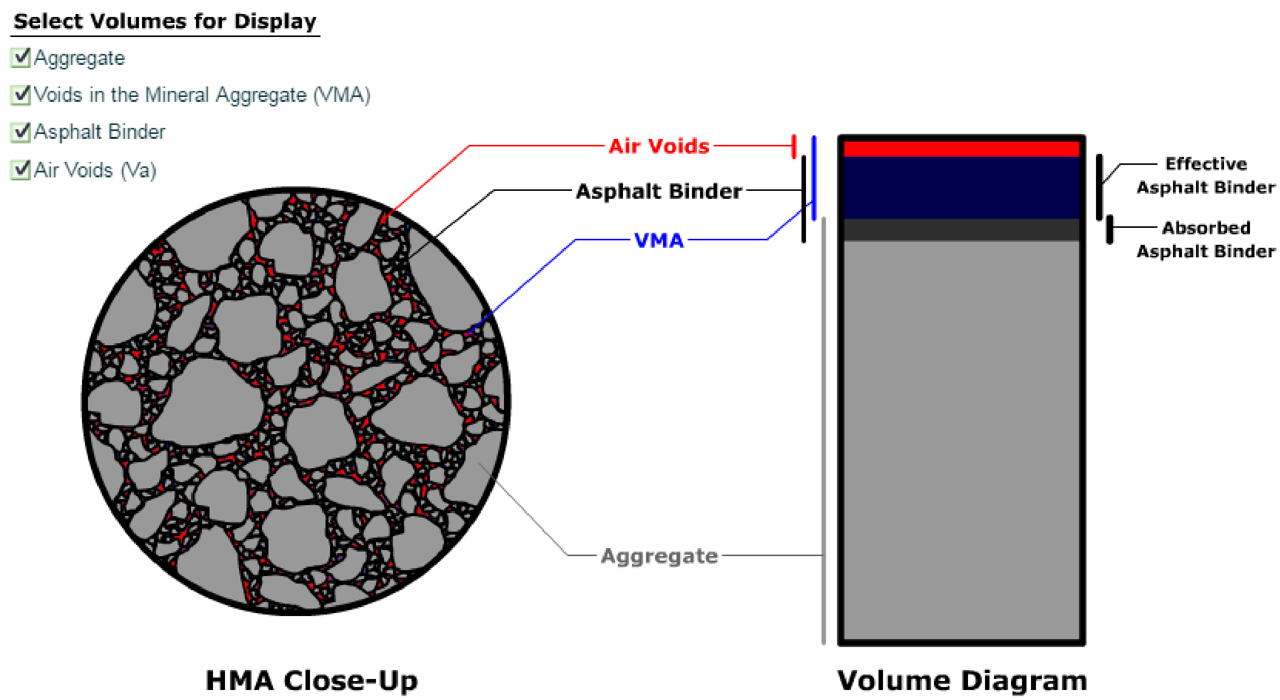


Figure 13. Volumetric properties of asphalt mix

2.7. Asphalt Mix Design

Asphalt mix design typically refers to the process of evaluating aggregate and binder type and their optimum combination. In order to do this task several methods are available. These methods include Marshal Mix design, Hveem and Superpave mix design. The last one is developed after SHRP program. Variables which are important for a mix design are:

- Source, gradation, texture and shape, toughness, durability and abrasion resistance of aggregates
- Type, durability, rheology and additives of binder
- Binder to aggregate ratio which is expressed in percent.

2.7.1. Hveem Mix Design

Hveem mix design developed in 1920s in California but it is still one of the common methods of designing asphalt mix especially in western states like Nevada. Major steps in designing based on Hveem mix method include [19]:

1. Selecting aggregate
   1.1. Performing tests on aggregate
   1.2. Evaluating other properties of asphalt such as gradation, size and specific gravity
   1.3. Selecting best aggregate blend and gradation
2. Selecting appropriate asphalt binder
3. Making trial asphalt mix samples
4. Compacting the samples with California Kneading Compactor to produce cylindrical samples with dimensions (diameter equal to 102 mm and height approximately 64 mm)

2.7.2. Aggregate

Aggregate is a term used to describe sand, gravel and crushed stone which typically accounts for 92 to 96 percent of hot mix asphalt volume. Both natural materials which are extracted from large rocks and minerals and manufactured materials such as industries byproducts are used to provide aggregate. Igneous, sedimentary and metamorphic rock are the main source for stone-crushed aggregates. Type tests that are recommended to be carried out on aggregates in order to confirm its quality to be used in pavement are as follow: [19]

- Gradation and Size
- Toughness and Abrasion Resistance
- Durability and Soundness
- Particle Shape and surface texture
- Specific Gravity
- Cleanliness and Deleterious Materials
- Moisture Content

2.7.3. Marshal Mix Design

Marshal Mix design dates back to 1939 and its main design procedures is similar to Hveem mix process. The main difference is the compaction method. In this method Marshal Hammer is used to compact the mix and produce cylindrical samples. Graphs demonstrated in figure 14 are used to select the optimum binder content in this method. Selected optimum binder content must satisfy all six properties shown in these graphs [19].

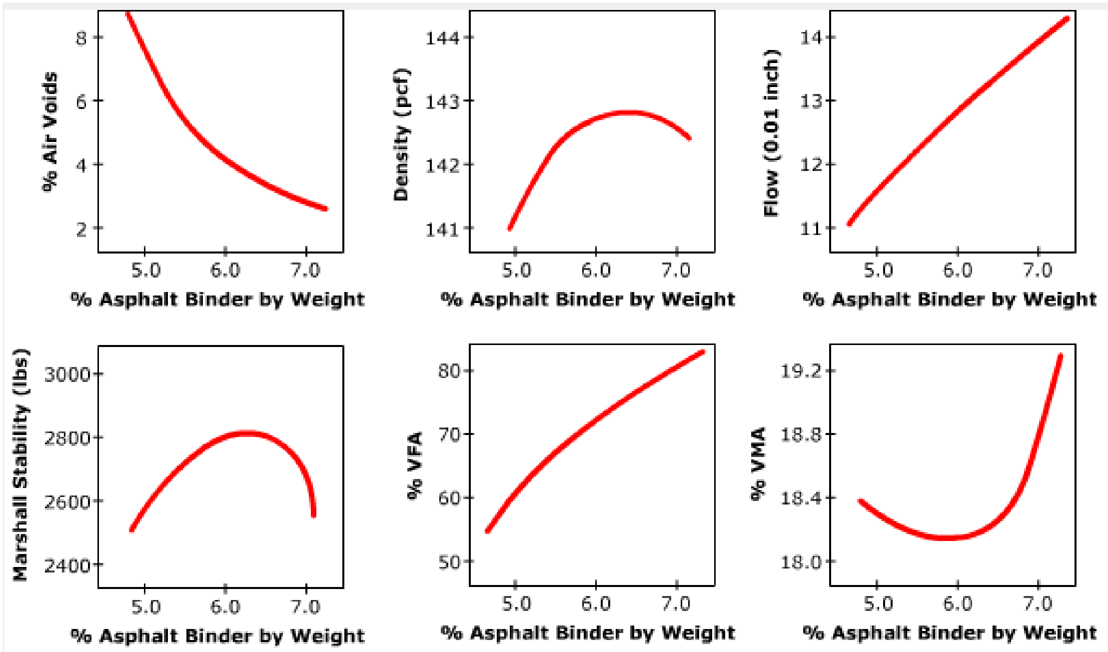


Figure 14. An example of selecting optimum binder content

2.7.4. Superpave Mix Design

Superpave mix design method is a new method which developed after SHRP in 1993. This procedure includes seven major steps that are:

1. Selecting aggregates
2. Selecting appropriate binder
3. Producing samples
4. Carrying out performance tests on binder
5. Calculating density and air void
6. Evaluating optimum binder content
7. Evaluating moisture susceptibility of samples

Superpave gyrator compactor is used to compact and produce mix samples. In this method samples have 150 mm diameter and 115 mm height. Optimum binder content is selected based on a process related to gyrator compacting numbers.

2.8. Objectives of mix design

In order to achieve the required quality in pavement the following parameters should be taken into account in designing a proper asphalt mix [19]:

- By selecting appropriate aggregate and binder content and viscosity, designed mix should have sufficient resistance against rutting and deformation.
- HMA should have enough fatigue resistance to withstand repeated loading. This parameter is related to binder content and stiffness.
- Asphalt mix must be designed to have sufficient resistance against low temperature cracking.
- Asphalt mixture should be designed to withstand and not degrade under moisture condition.
- Skid resistance for asphalt mix is confirmed with selecting appropriate amount of asphalt binder.
- Asphalt mix should have appropriate workability for placing and compacting.

2.9. Rubber Modified Asphalt Mix

Arizona and particularly Phoenix is leading in terms of using rubber modified asphalt. As mentioned in previous sections for the first time they invented and developed using rubberized asphalt in 1960s. Over the period of twenty years between 1971 and 199, about 3.6 million waste tires were used in this state to pave the streets in Phoenix. Rubber modified asphalt overlay shows more resistance to cracking. Rubber did not illustrate any influence on skid resistance but it improved riding surface and decreased traffic noise significantly [48].

A set of experiments carried out by L. Raad et al. on aged asphalt concrete revealed that while aging reduces fatigue life of conventional asphalt, it does not have significant influence on rubber modified asphalt. Moreover, rubber modified asphalt demonstrated lower stiffness compared to traditional asphalt [49]. Crumb rubber modified asphalt mixes demonstrated improved fatigue behavior and elastic recovery compared to non-modified samples in an investigation carried out by S. Palit et al. CRM asphalt samples also exhibited lower temperature and moisture damage susceptibility as well as lower permanent deformation in comparison to traditional mixes. Based on rutting and fatigue properties of asphalt mixes, superpave aggregate gradation demonstrated better results compared to gap-graded mix samples [50].

R. Liang and S. Lee investigated short-term and long-term properties of rubber modified asphalt binder and mix and concluded rubber modified asphalt demonstrated more elastic response which means rubberized asphalt pavement will have better rutting resistance as well as improved resistance against permanent deformation. They also indicated based on indirect tensile strength, for traditional HMA samples, behavior changed significantly from short-term aging to long-term aging compared to CRM modified asphalt [51]. An investigation carried out in Louisiana illustrated similar or lower fatigue cracks and rutting depth compared to control traditional mix section after 5 to 7 years [52].

H. Wang et al. studied fatigue behavior of rubber modified asphalt mixtures. Samples with various rubber content were tested and at the end they summarized asphalt mix with 20 percent rubber content to have the best anti-fatigue property with lowest crack growth signs. Comparing the size of rubber particles, smaller sizes lead to slower crack growth. They also concluded that temperature has a significant influence on fatigue life of rubber modified asphalt mixtures [53]. B. V. Kok and H. Colak revealed asphalt mixture with 8 percent rubber has 50 percent higher stiffness compared to regular asphalt mix. Based on their investigation on both binder and mixtures modified with rubber, 8 percent was the optimum rubber content with highest quality achievements [54]. Figure 15 display the accumulated deformation versus loading cycles.

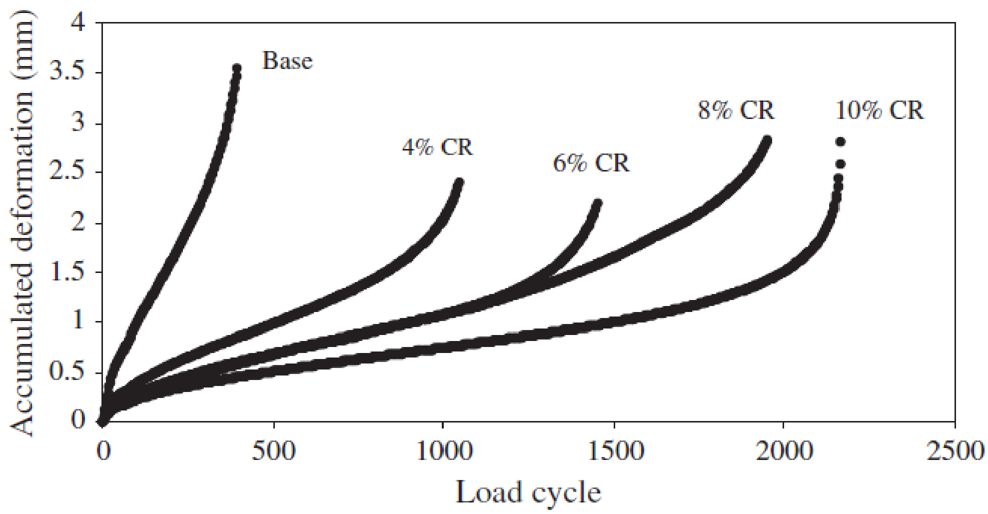


Figure 15. Accumulated deformation versus loading cycle

Rubber additive improved the asphalt mix permanent deformation properties based on a study carried out by L. Fontes et al. while mixtures made with gap-grade aggregate demonstrated the best results [55]. In a literature review conducted by D. Presti on Recycled Tire Rubber (RTR) asphalt exhibiting higher binder content is required to coat the aggregates in rubber asphalt mixture manufactured with open-graded aggregates compared to dense-graded samples. Increased binder content leads to better fatigue and crack resistance in mixture [56].

Literature review shows European countries also are interested in investigating and developing rubber modified asphalt. In a study carried out by F. Santagata et al. in Italy, the authors indicated Asphalt Rubber Friction Course (ARFC) shows higher stiffness modulus as well as improved resistance to rutting and permanent deformation which is the result of higher binder viscosity [57]. In another investigation M. Partl et al. demonstrated open-graded asphalt modified with rubberized binder resulted in significantly high value of fatigue resistance and low amount of moisture susceptibility. This is due to the use of rubber in binder and higher content of binder in asphalt mixture to coat the aggregates [58].

F. Navaro et al. performed tests on high modulus asphalt samples with additives such as rubber. The results revealed that while rubber is the most economic modifier it also improves the mix resistance to plastic deformation and reduces its susceptibility to temperature. Similar to other additives, rubber increased the mix resistance to rutting and climate changes. In addition rubberized asphalt mix illustrated higher stiffness compared to normal asphalt mixture. Slight reduction in mechanical resistance was the only negative influence of these additives to asphalt mixture [59]. Similar results were achieved by Xia et al. in their experiment on reclaimed asphalt pavement containing rubber modifier. Rubber improved rutting resistance as well as resistance to deformation while decreasing creep stiffness. Mix resistance to deformation had a direct correlation to rubber content [60].

Modulus resilient increases with the increase of rubber content in HMA but rubber size has a negative influence on modified mix resilient modulus. In this regard the influence of ambient rubber has slightly better influence on mix resilience compared to cryogenic rubber. Rubber additives improve mix fatigue resistance regardless of the type and size of the rubber [61]. Moreno et al. conducted experiments on modified mix resistance to plastic deformation. Adding rubber improved the mix resistance to plastic deformation which lead to lower permanent deformation values. Higher CRM content indicated better creep modulus. Improved stiffness modulus was another benefit of using rubber modifier. They suggested using 20 percent rubber as the optimum rubber content to obtain the highest improvement in modified mixture [62].

A field investigation carried out in Taiwan on gap-graded and open-graded asphalt mix illustrated better density and smoothness for rubberized asphalt in comparison to regular asphalt pavement. Gap-graded asphalt resulted to lower deflection compared to open-graded asphalt mixture. At the end mesh #30 was suggested to be used for producing ground rubber [63].

Other research on stone matrix asphalt modified with rubber exhibited no significant influence on moisture susceptibility for rubberized asphalt compared to traditional asphalt while rubber modified stone matrix asphalt showed improved rutting properties [64].

Tortum et al. carried out a comprehensive experiment on rubber modified mix samples produced with Marshal Mix method and suggested Mesh # 40 for rubber size with optimum rubber content of 10 percent and 5.5 percent as optimum binder content. In order to achieve the required quality mixing temperature was recommended to be 150 degree Celsius and 15 minutes for compacting time [65]. H. Katman et al. revealed asphalt mix produced by continuous blending method has lower viscosity but higher deformation resistance in comparison to terminal blended mixture [66].

G. Shafabakhsh et al. demonstrated asphalt mix modified with 10 percent waste rubber has lower rutting depth and better performance compared to regular asphalt. Rubber also increases asphalt sensitivity to temperature leading to better performance against permanent deformation [67]. Experiments carried out by A. Ameli et al. indicated slight increment in Marshal Stability by the use of 20 percent rubber in reclaimed asphalt pavement. The mix resistance to the rutting is directly related to the amount of rubber [68].

Stone Matrix Asphalt (SMA) containing 20 percent ground tire rubber size #30 exhibited optimum volumetric requirements based on research performed by Chiu and Lu. In this study, SMA mixtures demonstrated better rutting resistance compared to traditional asphalt mixes while rubber modified SMA asphalt mixes illustrated the highest rutting resistance. Rubberized SMA did not improve mixture susceptibility to moisture [69].

C. Akisetty et al. declared aggregated source (as it demonstrated in figure 16) and its physical and mechanical properties of aggregate particles have significant influence on Indirect Tensile Strength (ITS), rutting depth and resilient modulus of rubberized warm mix asphalt [70]. Modulus of elasticity is a key parameter in designing pavement. On the other hand pavement performance and response to traffic load are relevant to asphalt mix stiffness. Factors influencing stiffness are asphalt mix variables, asphalt and aggregate type and source, air void percentage and temperature [71].

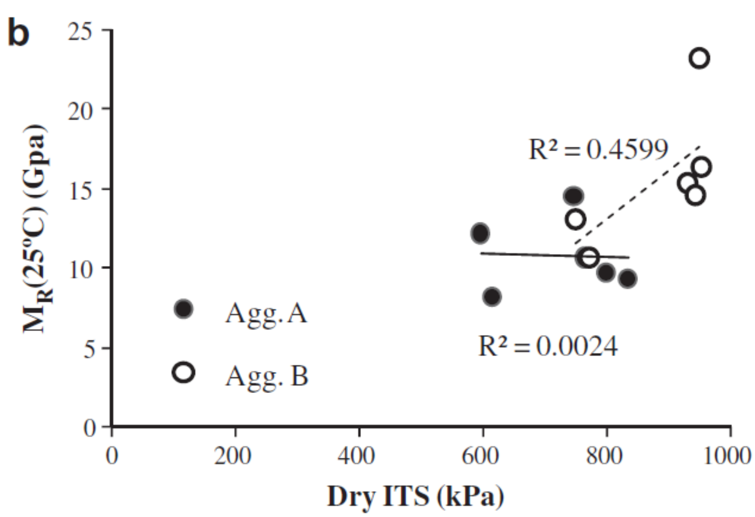


Figure 16. Effect of aggregate source on aged asphalt modulus

2.10. Non-Destructive Testing (NDT)

Nondestructive testing (NDT) is a method in which the test does not influence or change the object or material. In this method, material properties and conditions are evaluated and inspected without causing any damage on the material itself. Being nondestructive makes this testing method a cost-effective technique for inspecting engineering materials. Several different procedures that are classified as nondestructive testing are as follow [72]:

- Visual Testing (VT)
- Radiography (RT)
- Magnetic Particle Testing (MT)
- Ultrasound Testing (UT)
- Penetrant Testing (PT)
- Ground Penetrating Radar (GPR)
- Electromagnetic Testing (ET)
- Acoustic Emission Testing (AT)

2.11. Ultrasound Testing

Using ultrasound techniques for detecting and evaluating material properties dates back to 1930s. In order to measure object's dimension, properties and flaw energy from high frequency sound is used. Typically, an ultrasonic system includes pulser/receiver, transducer and monitor. Transducer produces high frequency ultrasound energy. This energy passes through material in wave form. Reflected wave shape illustrates cracks or flaws in object as well as any change in material type. A schematic view of how an ultrasonic test works is demonstrated in figure 17. Based on the wave shape it is possible to evaluate the size and position of the crack or flaw. Other electronic tools can be used to produce detailed images. Longitudinal waves (parallel to wave direction) and transverse waves (perpendicular to wave direction) are most commonly used in ultrasound test method [72].

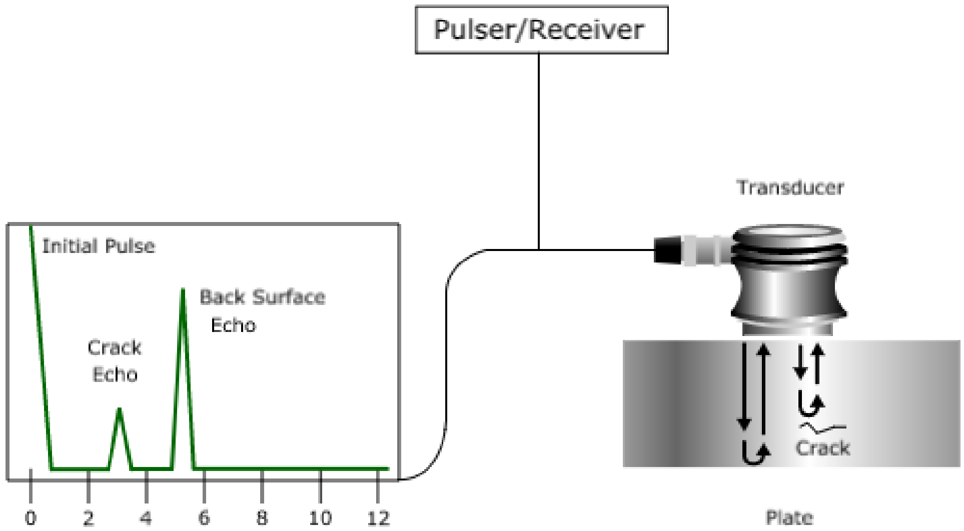


Figure 17. Schematic demonstration of ultrasonic test

2.11.1. Wave Properties

Terms of direction, velocity, energy, period and frequency, amplitude, wavelength and etc. are among several parameters used to describe wave properties. Figure 18 illustrate a graphical view of wave motion over time. Period, T, is the time required for a complete vibration while frequency, *f*, refers to the number of vibrations per second which is calculated in Hertz. On the other hand period is equal to $T = 1/f$. Wavelength, λ, is referred to the distance between two consecutive crests in a vibration. Wavelength is relevant to wave speed and period or frequency. This relation is exhibited in equation 10 [73]:

Equation 10: $$\lambda = \frac{v}{f}$$

Where:

λ = wavelength

v = wave speed

f = frequency

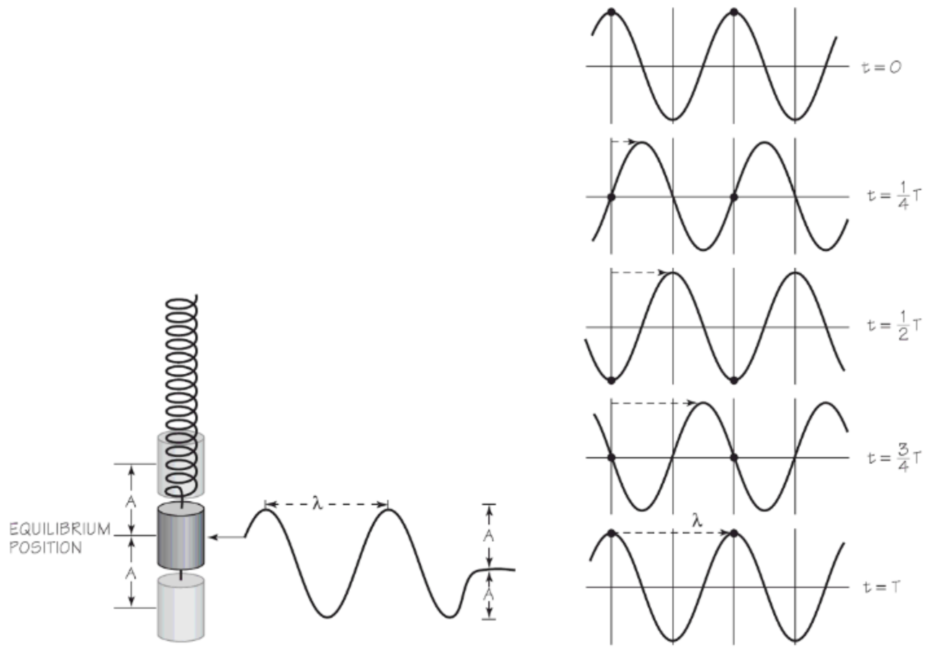


Figure 18. Periodic motion of a wave

Another parameter which is used in defining wave parameters is angular wave number, *k*, which is demonstrated in radian per unit distance. On the other hand the number of cycles in a given wavelength is called wave number. Wavelength is a complete cycle wave. Therefore wave number can be calculated using equation 11 [74].

Equation 11: $$k = \frac{2\pi}{\lambda}$$

Where:

k = wave number

λ = wavelength

2.11.2. Wave Velocity

There are several velocities in wave definition. Plane velocity, angular velocity, and phase velocity are among these definitions. Angular velocity or frequency is one of the most used parameters which equation 12 is used for calculating [74].

Equation 12:

$$\omega = \sqrt{\frac{K}{m}} = 2\pi f$$

Where:

ω = angular velocity (angular frequency)

K = spring constant

m = mass

In a travelling wave the speed in which a wave moves on a string is called phase velocity. The phase velocity is calculated based on equation 13 [74].

Equation 13:

$$V_{\phi} = \frac{\omega}{k}$$

Where:

V_{ϕ} = phase speed

ω = angular frequency

k = number of waves

2.11.3. General Wave Equation

Based on wave differential equation a general solution for vibrating motion is:

Equation 14:

$$x(t) = a\ cos\omega t + bsin\omega t$$

Where:

a and b = constants

For a uniform singular motion with radius equal to R and in time t, x and y coordinates of the motion will be as follows [74]:

Equation 15:

$$x(t) = R\cos(\omega t - \phi)$$

Equation 16:

$$y(t) = -Rsin(\omega t - \phi)$$

Where:

ϕ = clockwise angle in radian

2.11.4. Attenuation

As a wave spreads in distance its intensity and amplitude decreases. Attenuation is related to material and is caused by combination of absorption and scattering. In other words, sound reflects in directions other than its original direction by changing to the other forms of energy. For a plane wave equation 17 is used to express attenuation [72]:

Equation 17:

$$A = A_0 e^{-\alpha z}$$

Where:

A = attenuated amplitude

A_0 = un-attenuated amplitude

α = attenuation coefficient

z = travel distance from original location

e = Napier’s constant = 2.71828

In order to determine the value of attenuation in Nepers per meter (Np/m) the number of decibels is counted between two signals. By dividing decibels to time interval between these signals attenuation coefficient is calculated using equation 18. Figure 19 displays wave attenuation [72]. Figure 20 illustrates a chirp signal [75].

Equation 17:

$$\alpha = \frac{0.1151}{v} U_t$$

Where:

α = attenuation coefficient

U_t = decibels per seconds

v = velocity

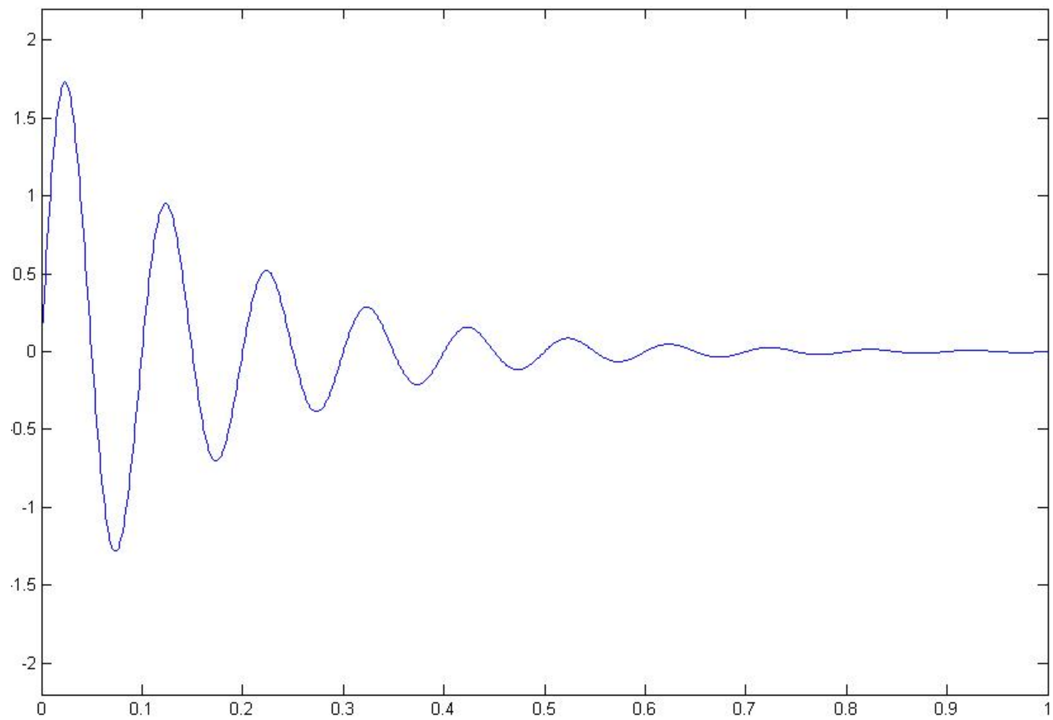


Figure 19. wave attenuation

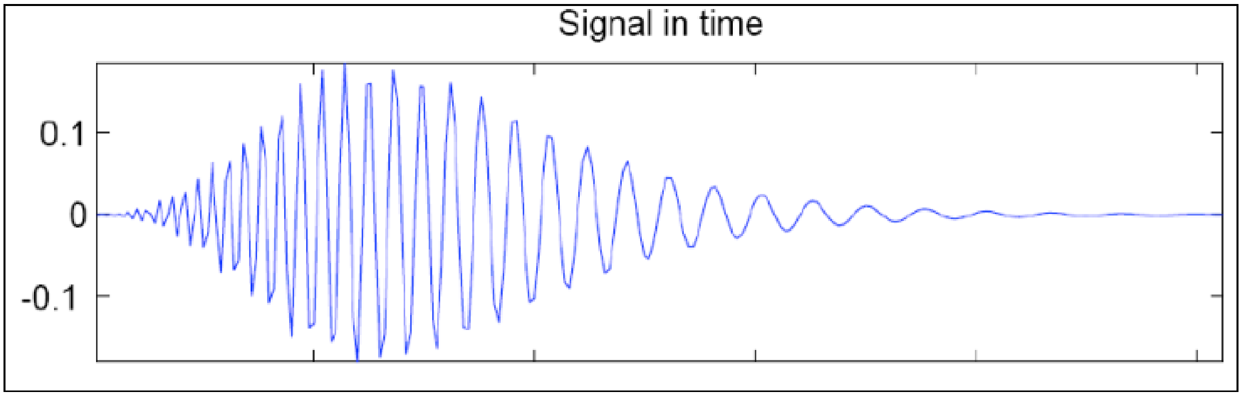


Figure 20. Example of a Chirp signal

2.11.5. Transmission and Reflection

In any boundary where acoustic impedance, Z, changes due to the change in material type, part of wave reflects and the rest transmits. The term mismatch is used to describe difference in acoustic impedance. Larger Z will lead to reflecting higher amount of wave in boundary. Coefficient of reflection can be calculated using equation 18. Figure 21 display transmission and reflection process from water to steel material [72].

Equation 18:

$$R = [\frac{Z_2 - Z_1}{Z_2 + Z_1}]^2$$

Where:

R = coefficient of reflection

Z_1 = acoustic impedance for first material

Z_2 = acoustic impedance for second material

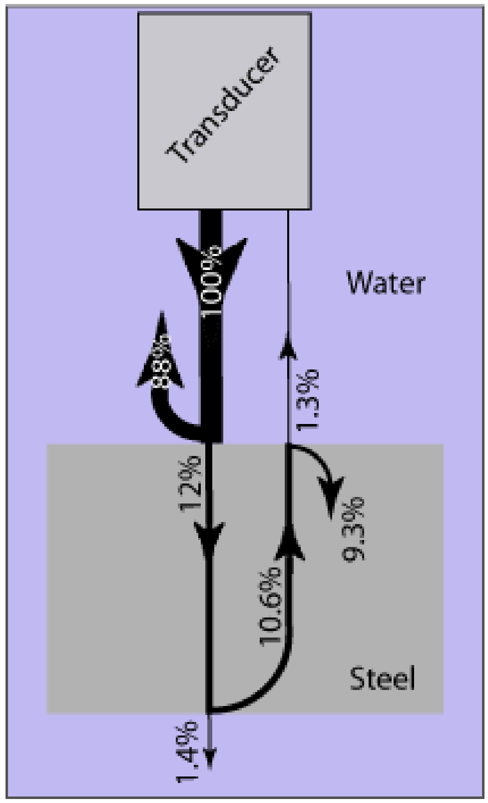
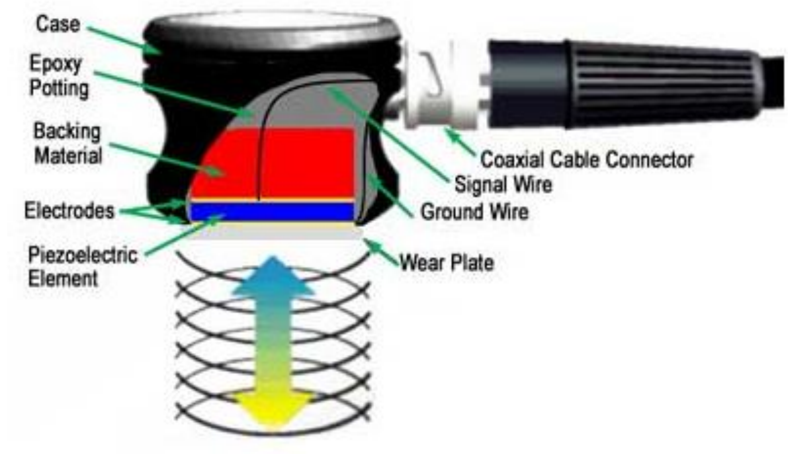


Figure 21. Transmission and reflection process

2.11.6. Piezoelectric Transducers

In order to convert electrical pulses to mechanical vibration and returning vibration back to electrical energy in ultrasound system a unit called piezoelectric transducer is used. There is a piece made with polarized material and two electrodes in opposite sides in the center of transducer which makes the conversion process possible. Figure 22 illustrates transducer and schematic current excitation around a transducer [72].

a: 

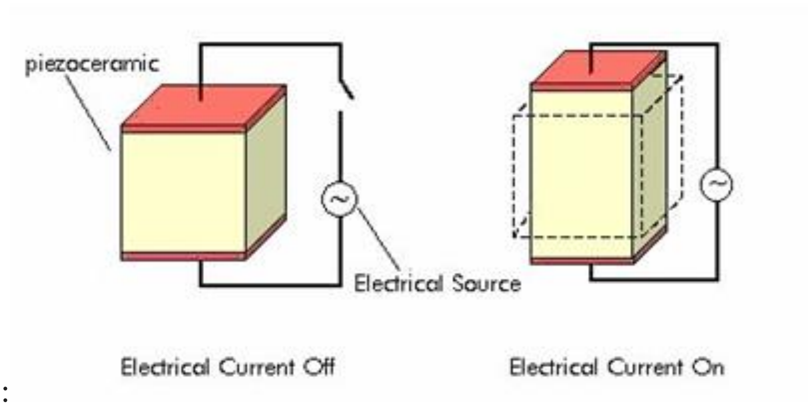
b: 

Figure 22. Transducer components, b: Piezometric process

It is very important to select an appropriate piezometer. Transducer's respond to signals depends on various parameters such as material, mechanical and electrical construction, electrical and mechanical loading condition, radiation surface, mechanical damping, type of connector, etc. It is important to mention that some transducers are transmitters while the other ones are good receivers. On the other hand an efficient transmitter is not a good receiver and vice versa. For instance in order to detect smaller cracks with ultrasound testing it is necessary to have efficient transmitter and receiver as well as high resolution.

Bandwidth which means the range of frequency is another parameter related to transducer. In order to have high resolving power, a transducer with broad frequency range is required. While transducers with lower frequencies produce higher energy and penetration, high frequency produce higher sensitivity with lower penetration rate [72].

2.11.7. Types of Transducer

In general the classification of transducers are as follow. Figure 23 display a sample of both transducers [72].

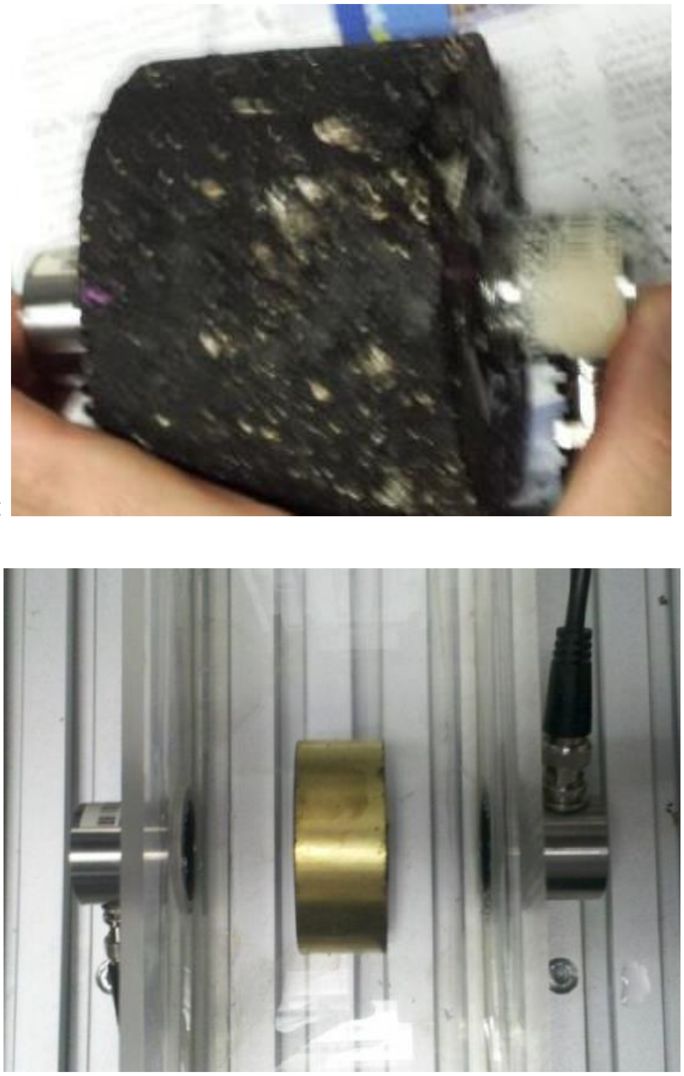
- **Contact transducers**

  This type of transducer is dependent on the user and works by contact to the object. Their ergonomic design gives them possibility to be gripped and moved over the surface of the object while being protected in a resilient casing.

- **Immersion transducers**

  This type of transducer is not contact-based transducer and is designed waterproof to be used inside a liquid. It has the capability of concentrating sound signal in a small point to increase sensitivity and axial resolution.

a:



b:

Figure 23. Transducer during the measurement, a: contact, b: immersion

2.12. Ultrasound Measuring Methods

There are two major measuring methods with ultrasound systems:

- Pulse-Echo measuring method
- Pulse-receiver measuring method

In pulse-echo method the same transducer which creates and sends the signal, receives the returned signal that is reflected from other end of the object or from cracks inside that object. By measuring the time of flight that takes for a signal to reflect, it is possible to find any fault or discontinuity inside material. An example is displayed in figure 24. Because of the fact that measured time includes both radiation and reflection, velocity of sound wave will be calculated based on equation 19.

Equation 19 [72]:

$$v = \frac{2d}{t}$$

Where:

v = velocity

d = distance from surface to crack or to edges

t = time of flight

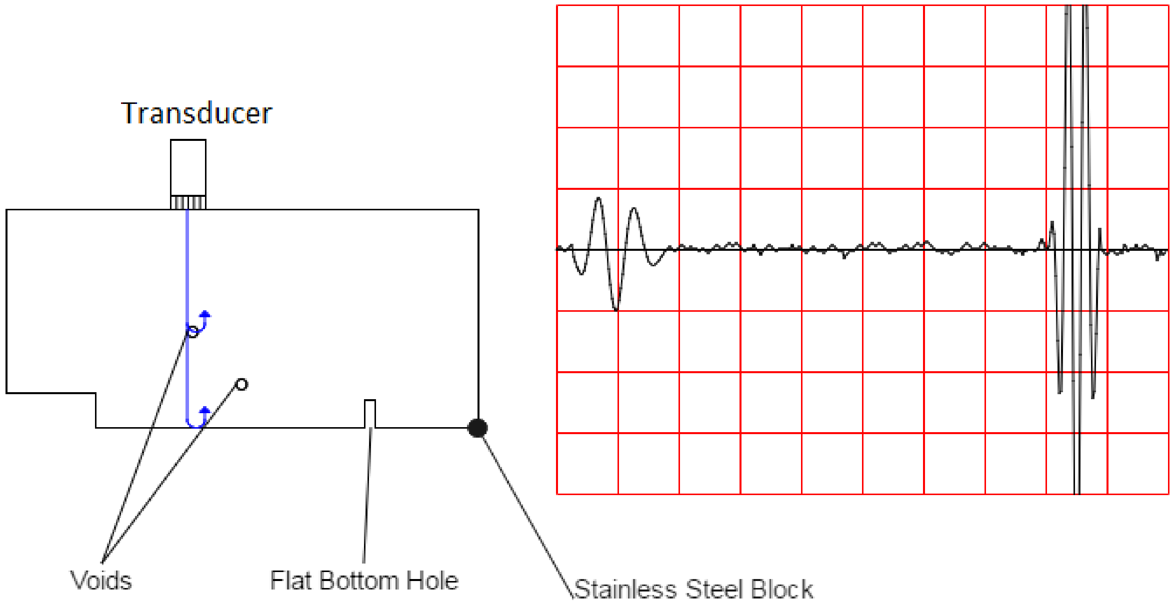


Figure 24. Pulse- Echo method for detecting voids and discontinuity

In second method one transducer produces signal while another transducer receives it on the other side or with angle from the first one. Velocity of sound wave depends on the density and elastic properties of the object. By measuring flight time between two transducers it is possible to calculate the wave velocity inside that object. A schematic is exhibited in figure 25 [77].

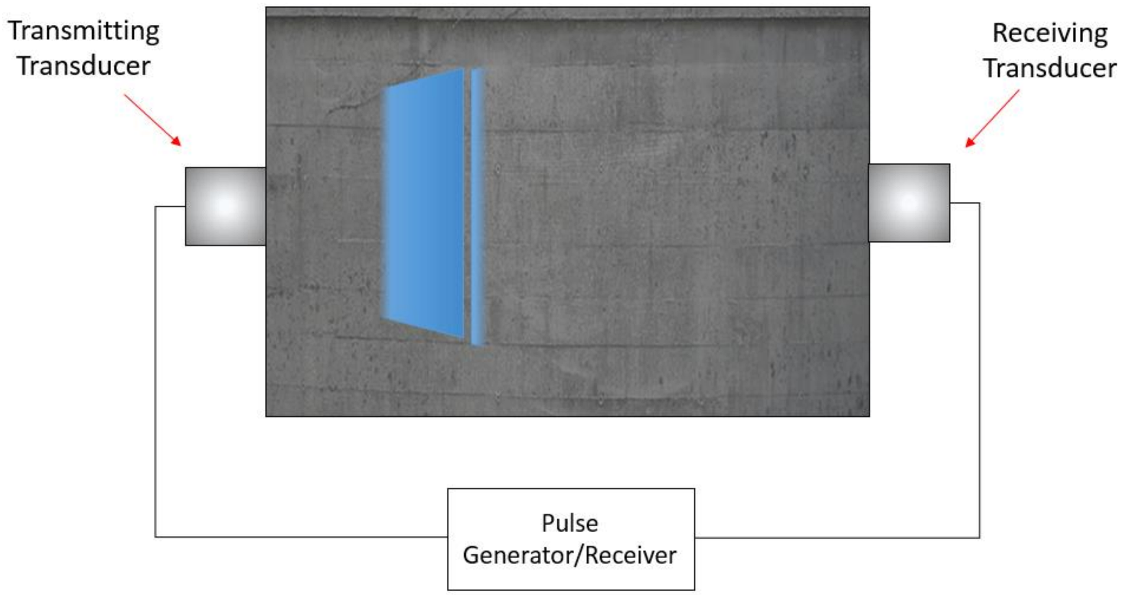


Figure 25. Pulse - receive method for measurement

2.13. Testing asphalt with ultrasound

Beside industrial use of ultrasound testing technique for evaluating the properties of construction materials, several research projects also have been performed to reveal any reasonable correlation between ultrasound results with regular property tests. A. Krishnan studied characterizing asphalt binder with non-contact ultrasound testing [77]. M. Khalili performed ultrasound measurements to correlate the results with rheological properties of asphalt binder. He indicated ultrasound velocity decrement with the increase in temperature. Solid aged samples illustrated higher velocity while modified binders resulted in lower velocity [76]. The trend of change in IR with temperature is illustrated in figure 26.

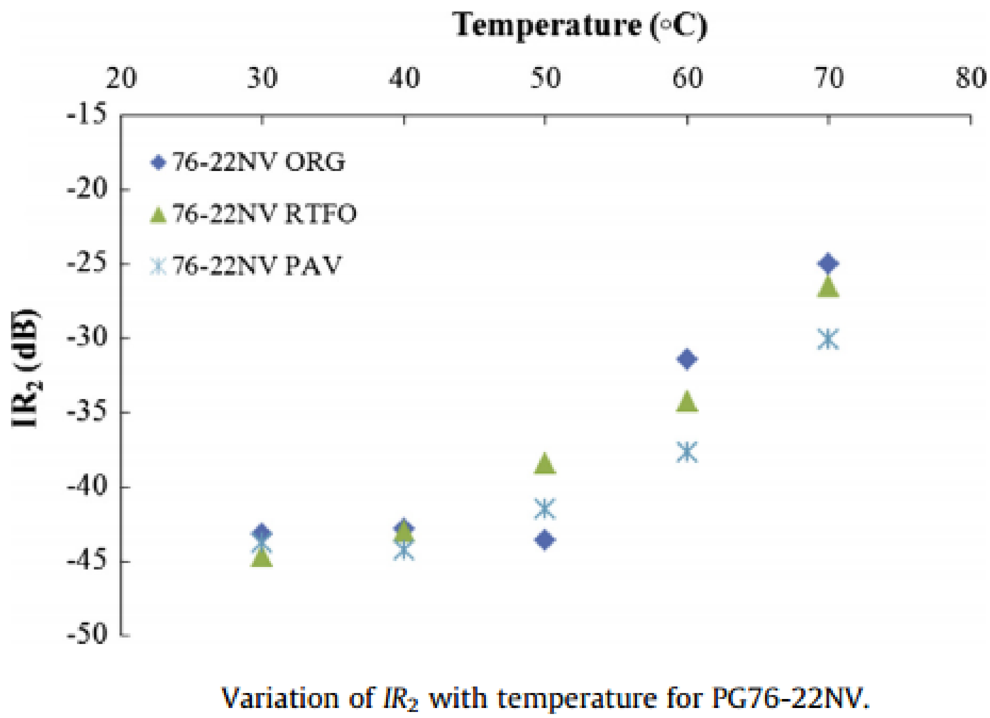


Figure 26. Correlation between IR2 and temperature

M. Tigdemir et al. used ultrasound test to evaluate the fatigue properties asphalt pavement. For this reason seismic properties of asphalt samples were measured and the results were compared to the results of repeated-loading test with indirect tensile equipment. Figure 27 exhibits a correlation between predicted data obtained from seismic model and experimental data resulted from fatigue loading test [78]. They approached the possibility of predicting fatigue properties of asphalt pavement using non-destructive ultrasound technics.

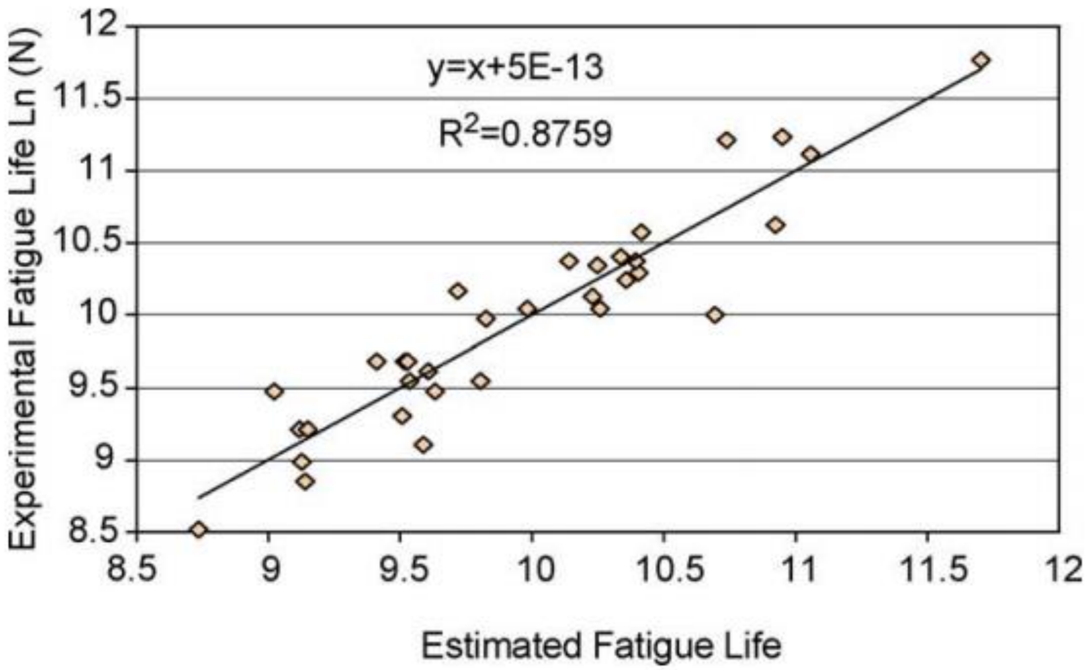


Figure 27. Correlation between ultrasound measurements with fatigue test results

In 1988 R. Sztukiewicz used ultrasound measuring technique to evaluate the properties of asphalt samples in laboratory as well as in-situ properties of asphalt pavement. He used non-contact transmission method on asphalt samples and contact echo method for in-situ evaluation of the pavement. Figure 28 demonstrate the correlation between bulk specific gravity of samples and wave velocity measured with ultrasonic equipment. The results indicated that wave velocity increases with the increase of bulk specific gravity [79].

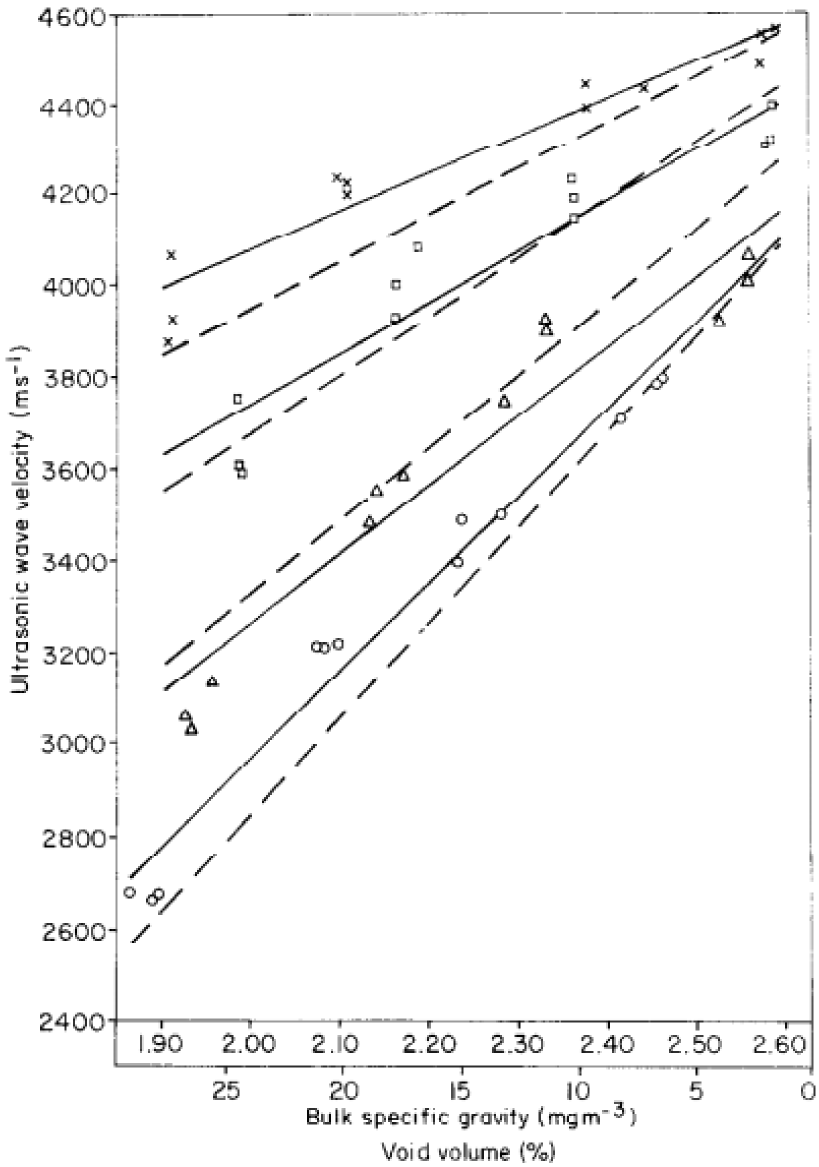


Figure 28. Bulk specific gravity versus wave velocity in different asphalt samples

M. Dunning performed non-contact ultrasound test on asphalt mix samples and exhibited correlations between wave velocity and Integrated Response (IR) with asphalt mix properties. There is direct relation between IR with various specific gravity measurements. Integrated Response increases with the increase of bulk specific gravity for samples made with different binder content. Figure 29 display correlation between IR and bulk specific gravity for a sample made with 5 percent binder [75]. He plotted the results of all measurements in one graph and revealed the relationship between Integrated Response (IR) with specific gravity which is presented in figure 30.

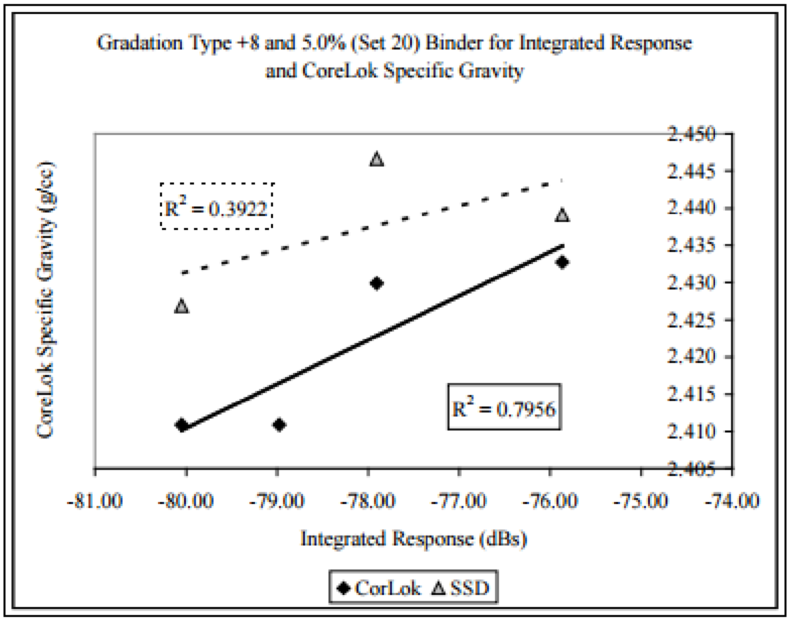


Figure 29. Bulk specific gravity versus Integrated Response

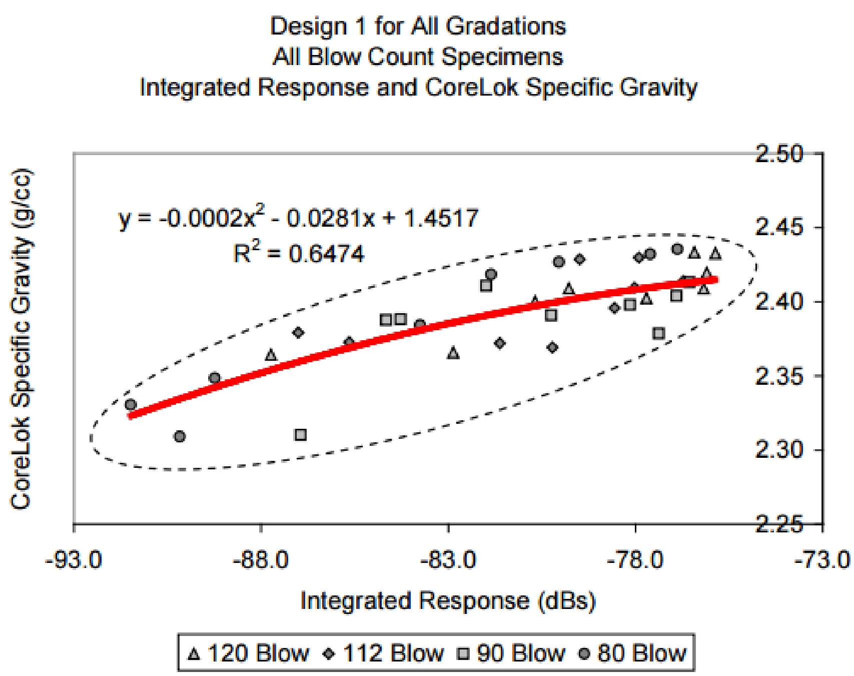


Figure 30. Correlation between Bulk specific gravity and Integrated Response

J. Velsor et al. investigated using ultrasonic testing system for evaluating asphalt complex modulus. Both indirect tensile test (IDT) and ultrasonic measuring were used in measuring dynamic and shear modulus on two samples in four different temperature. They observed 7 to 22 percent difference between dynamic modulus resulted from IDT and ultrasound test. The results also presented 5 to 18 percent difference for shear modulus [80]. J. Contreras et al. presented the use of ultrasonic direct test in measuring asphalt mix dynamic modulus. The results from which an example is illustrated in figure 31 shows dynamic modulus measured by ultrasound test is higher than the result of standard dynamic test [81].

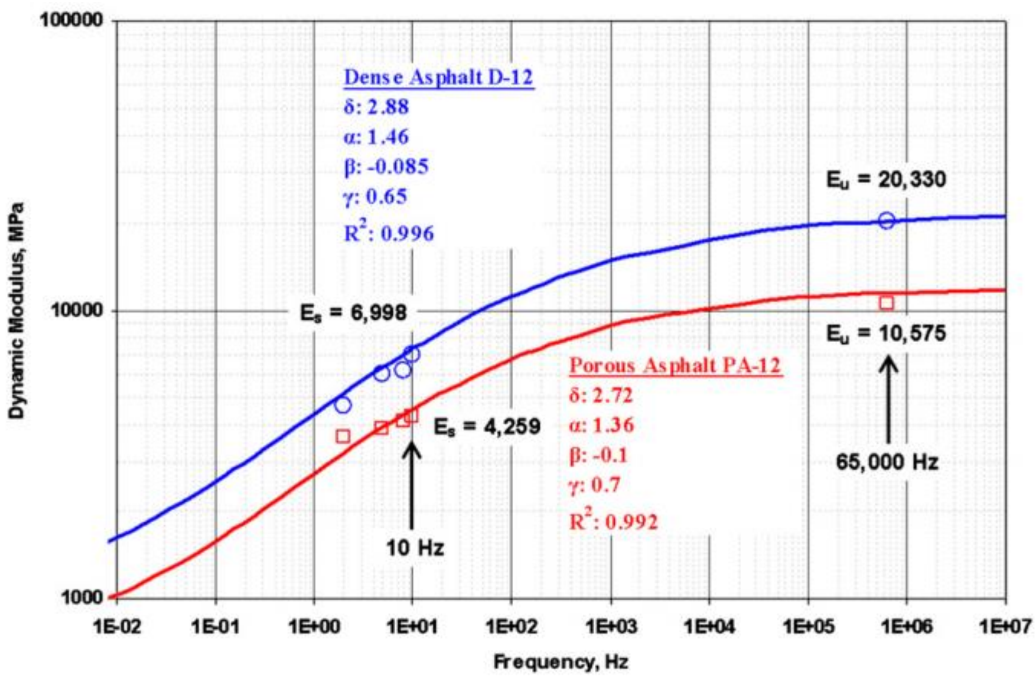


Figure 31. Magnitude of dynamic modulus, measured by standard (Es) and ultrasonic (Eu) test

D. Mounier et al. measured linear properties of asphalt mixture with ultrasound equipment and concluded that determining complex modulus of asphalt mix sample is possible by measuring wave flight time and IR with an error below 20 percent. It is important to select an appropriate loading frequency to obtain correct results [82].

Chapter 3
Methodology and Testing

The main goal in this study is to investigate and correlate the results of ultrasound measurements with performance properties of rubber modified asphalt mixture. On the other hand it is necessary to determine performance properties of each sample to be able to compare them with the ultrasound test results. Considering to the fact that there is no investigation in Nevada about best combination of rubber content with local asphalt binder, determining best rubber percent for modifying asphalt binder was also added to this research. In order to achieve its aforementioned goals, the study is divided into three sections.

3.1. Section one: Rheological properties of rubber modified asphalt binder

Section one includes determining the optimum content of rubber in asphalt binder. For this reason, several tests should be carried out on various binders from different sources and with different rubber content. These tests are selected based on SHRP requirements for evaluating binder performance. Binder from different local sources as well as different grades are subjected to be tested. Each sample will be mixed with various rubber content.

3.1.1. Sample Preparation

In order to be practical, each binder sample is mixed with three rubber content which are 10 percent, 15 and 20 percent. Two rubber size including mesh number 20 and mesh number 40 also were selected to take into consideration the influence of rubber particles in modified binder.

Performance tests were carried out on both rubber modified asphalt binder and original non-modified asphalt to have a comparison of the results. Flowchart presented in figure 32 displays the methodology and experiments carried out on each sample. At the end rubber size and content which lead to the best rubber modified binder performance is selected. Both rubber size and content are prominent factors in evaluating rubber modified binder properties.

Figure 33 demonstrates the sources which binders were obtained as well as the type of binder and modifying. Rubber was ground using two methods which include cryogenic and ambient. For each method rubber was ground into two sizes which are sieve #20 and #40. In order to make modified samples each binder was modified with three different percentages which are 10, 15 and 20 percent.

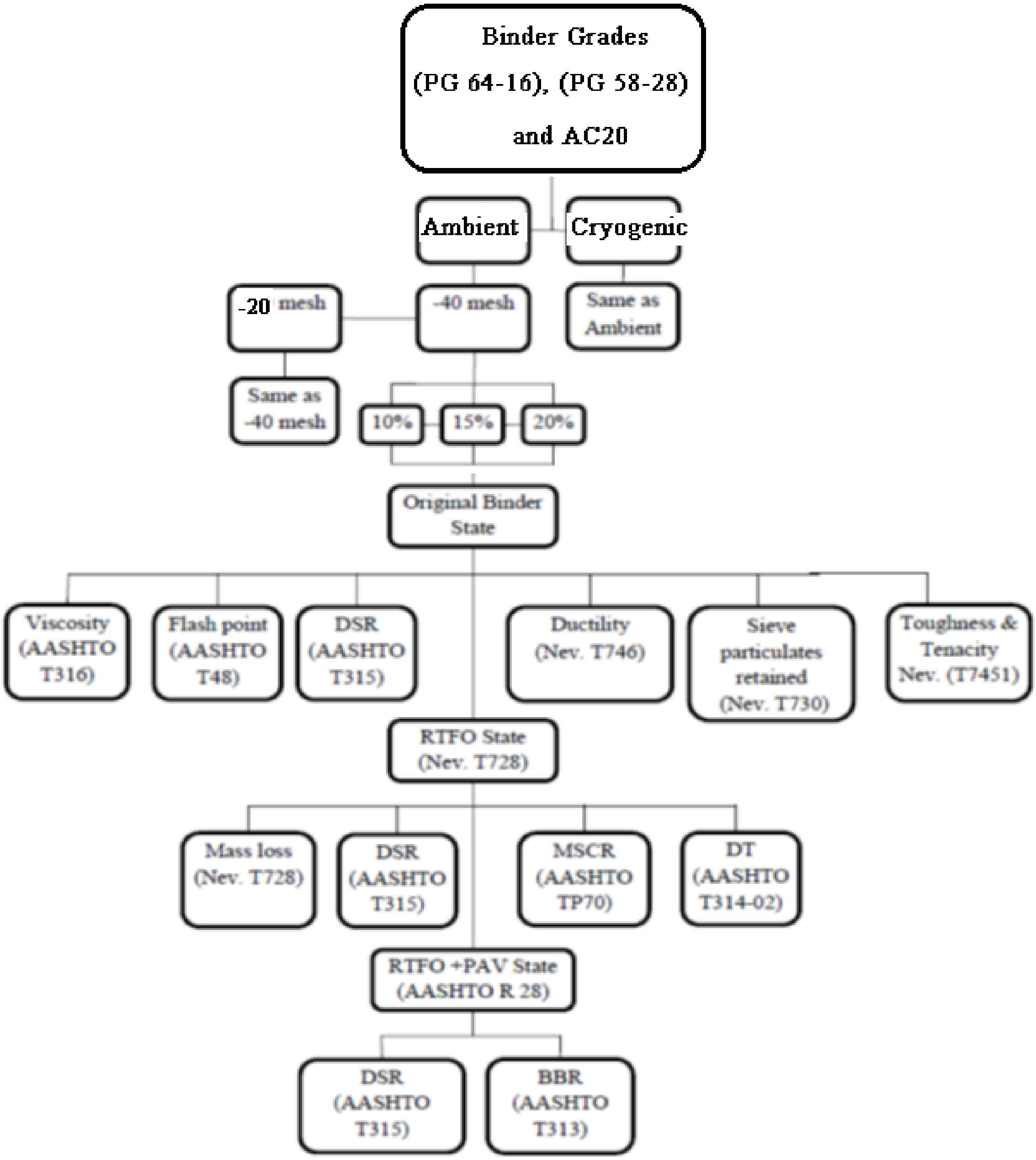


Figure 32. Methodology of evaluating properties of rubber modified binder

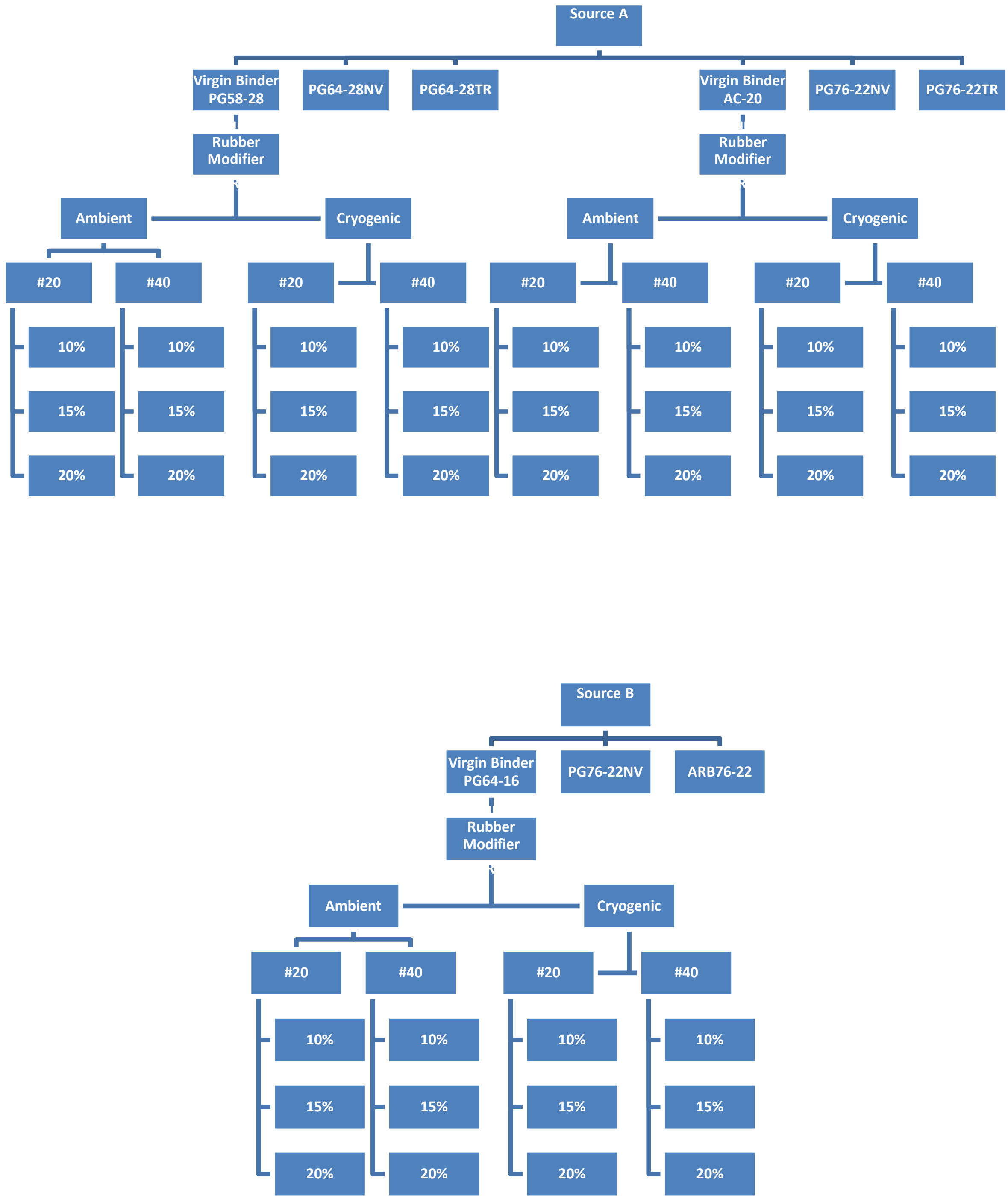


Figure 33. Asphalt binder samples obtained from sources A and B and modified in lab

Asphalt binder was provided from local manufacturers and mixed with rubber to produce rubberized asphalt binder. Binder with two different PG grades and one viscosity grade were provided in this section. These grades are PG 64 – 16, PG 58 – 28 and AC20. Binders from different sources are classified with letters A and B. In order to take the influence of binder source into consideration, binders from two sources were provided.

Following experiments were carried out on samples based on SHRP requirements. For each sample three tests were conducted on every category. It gives the opportunity to disregard any test with marginal results and take the average of the results for each sample. It has to be mentioned that there is acceptance limit for each test based on ASTM and or Nevada requirements. In this research all tests were carried out considering their acceptance limit.

3.1.2. Asphalt binder Viscosity

Binder viscosity is a dominant parameter which determines the possibility of pumping to or from asphalt plants when its temperature is between 149°C and 177°C with regards to its grade and viscosity [15]. AASHTO T 316 provides the required procedure and specifications based on SHRP requirements. It must be mentioned that because the project's binder contains crumb rubber, specifications will be more difficult to fulfill due to crumb rubber being more viscous. The summary of the results of viscosity measured during the experiment is presented in figure 34.

Considering the fact that various binder type is used to make rubber modified samples the horizontal axis demonstrates the binder type. In addition, crumb rubber is produced with different grinding process as well as particle size. Therefore the horizontal axis also displays this dominant factor. Moreover, the percent of rubber in each sample is presented in the graph. Therefore it is possible to compare the influence of each parameter in the properties of the modified asphalt binder. This procedure will continue in comparing the results of the other experiments.

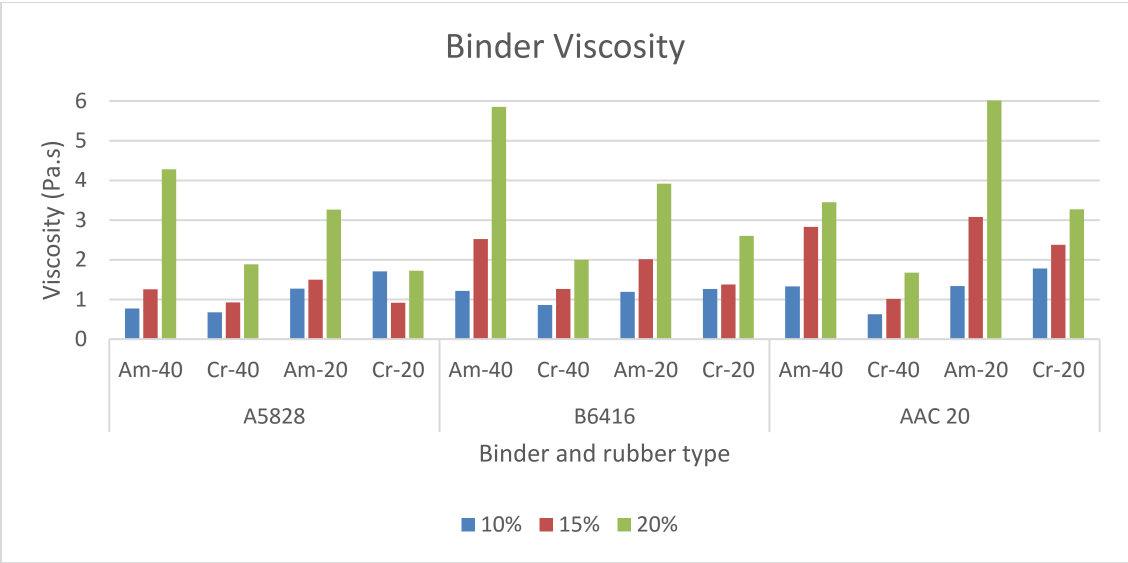


Figure 34. Viscosity of binders mixed with CRM

3.1.3. Flash Point

Requirements and procedures for this test is provided by AASHTO T48 and it shows the minimum temperature at which the test flame ignites the sample's vapor. The results of flash point test on samples are demonstrated in figure 35.

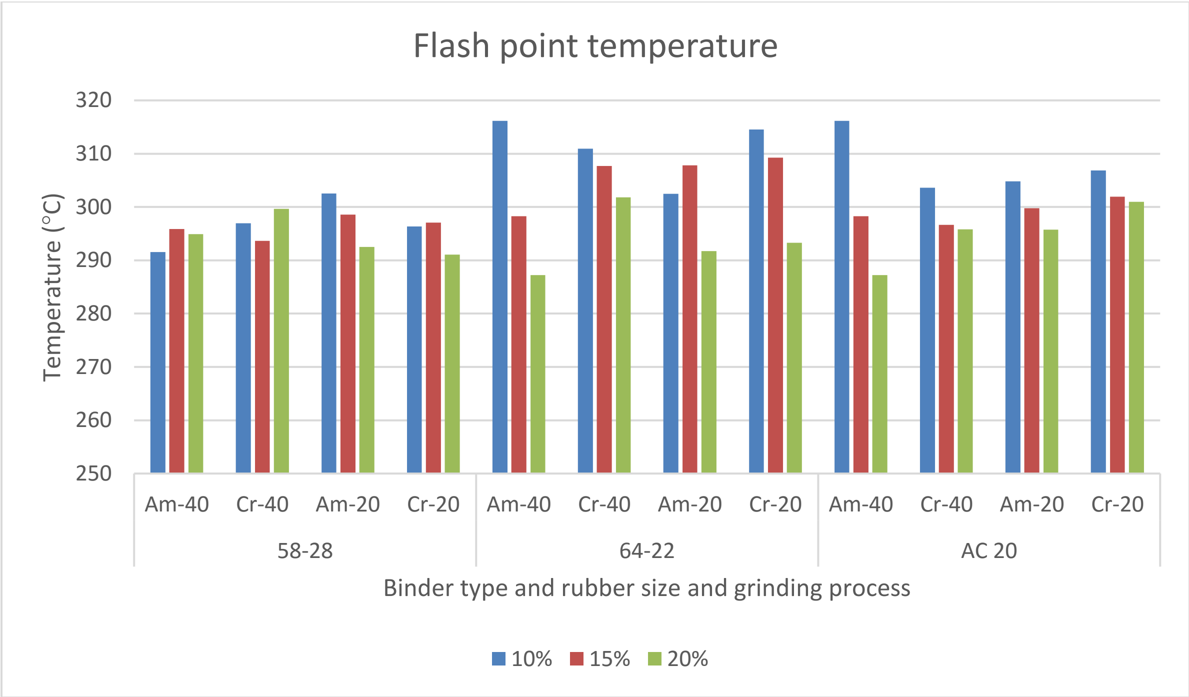


Figure 35. Flash point of binders mixed with CRM

3.1.4. Direct Shear Rheometer (DSR)

Based on SHRP, the Dynamic Shear Rheometer test should be used to determine the value for failure temperature, phase angle and G*/sinδ. These parameters are crucial for evaluating the performance of the pavement in terms of its resistance to rutting. In order to do that, test procedure and specifications requirements provided by AASHTO TP 315 are used to carry out this experiment. A sample of failure temperature which resulted from DSR is illustrated in figure 36. Phase angle and G*/sinδ are measured in different temperatures.

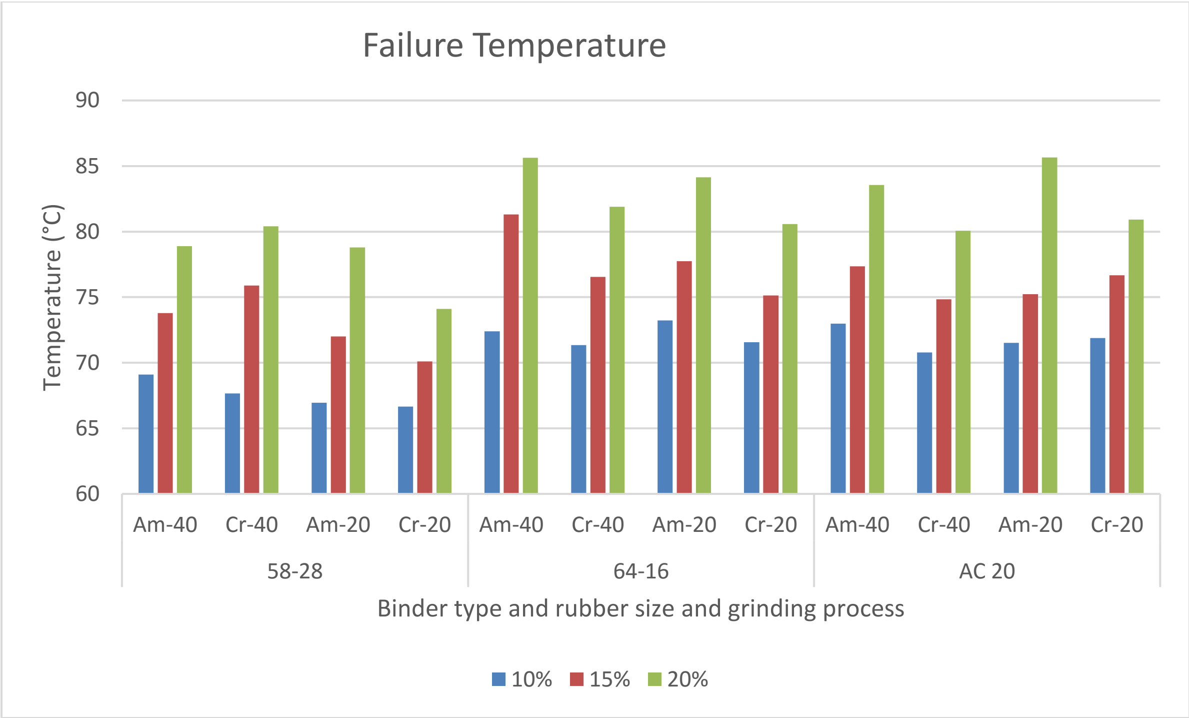


Figure 36. Failure temperature for samples mixed and mixed with CRM

3.1.5. Ductility

This test was conducted according to Nevada requirements which is provided at NEV. T746E. This test demonstrates the tensile properties of the binder. Figure 37 demonstrates ductility test on a sample of rubber modified asphalt binders. It has to be mentioned that this test was carried out in a water tank which had 4°C temperature in accordance with Nevada requirements.

It this test binder is placed in the mold and stretched from both sides until it tears apart. Binders with higher stretch rate will show better performance in cold weather. On the other hand in cold weather they will show lower amount of surface cracks.

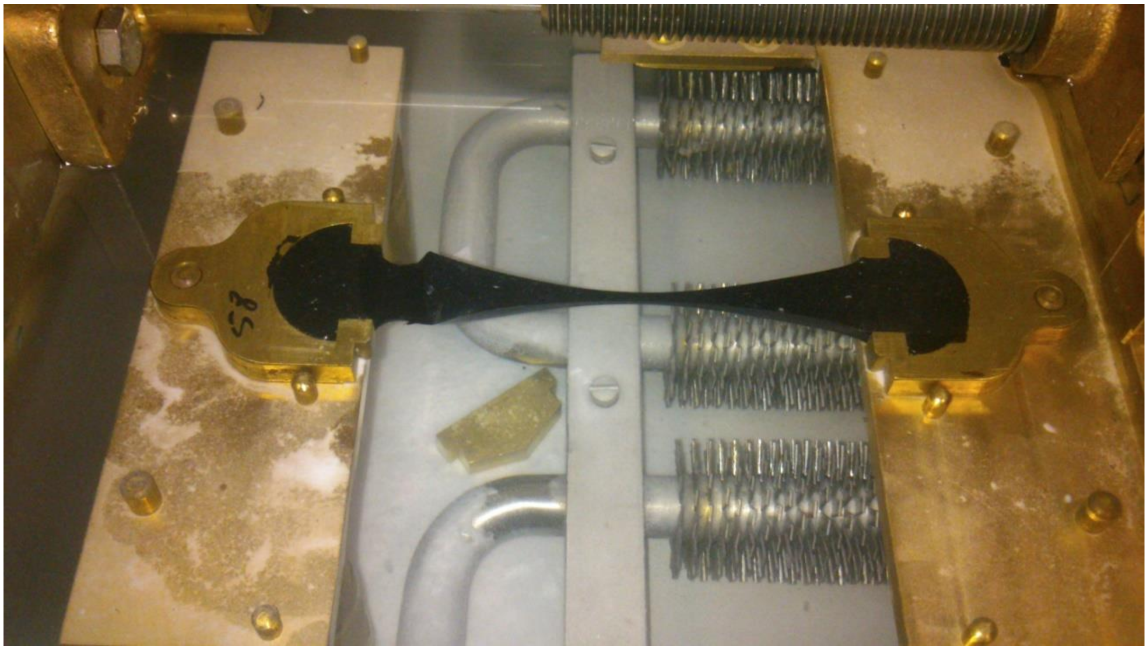


Figure 37. Ductility of binder PG 58-28 mixed with CRM

3.1.6. Toughness and Tenacity

In order to carry out this test, the specifications provided by Nev. 7451 is used. The area under the curve made between force and elongation is called toughness and is an indicator of the strength of the asphalt binder as well as its elasticity. Tenacity is represented by the curve area between force and elongation after the initial strength has been overcome. This parameter is an indicator for stretching capability of asphalt binder after initial strength. Figure 38 exhibits the result of the test on a sample which is the mix of binder type PG 64-16 and rubber ambient size mesh #20. This figure shows row result of the test on sample. The horizontal axis display the amount of force in pounds and the vertical axis shows the magnitude of elongation relevant to the force.

The results of this graph is converted to toughness and tenacity which are the goal of this experiment. Similar to the other experiments, the influence of the binder and rubber on these parameters will be presented and discussed in the next chapter.

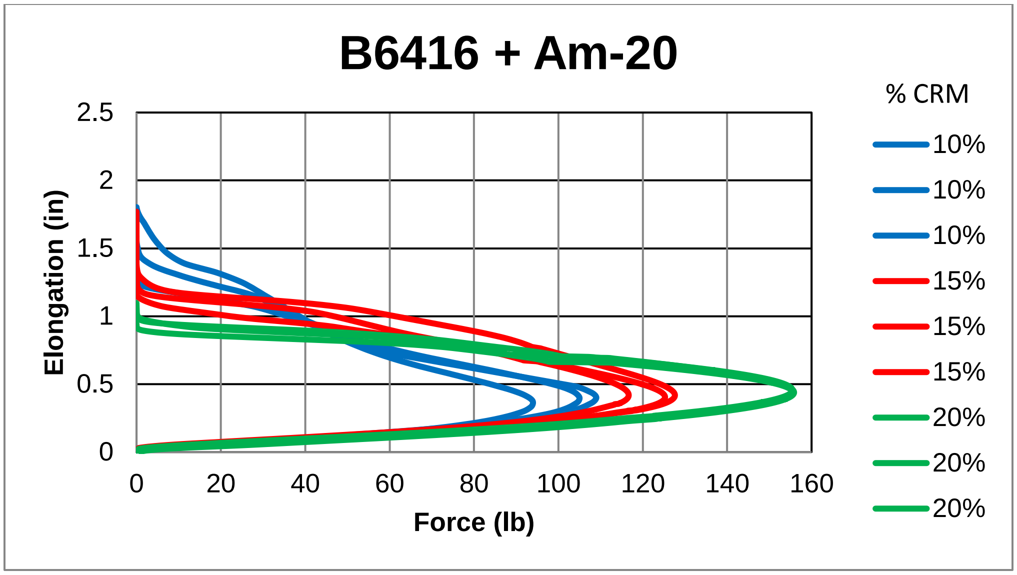


Figure 38. The result of Toughness & Tenacity test on PG64-16 binder sample mixed with CRM

3.1.7. RTFO aged binder

In order to compare the short-term aged behavior of rubber modified asphalt binder, RTFO aged process was conducted on samples. The aged samples then were tested again under DSR, ductility and creep recovery test processes to evaluate the short-term aged properties of them. Comparing each parameter between original and aged sample will give a perspective about the trend of the change in binder behavior. Figure 39 demonstrates a sample of phase angle on aged sample.

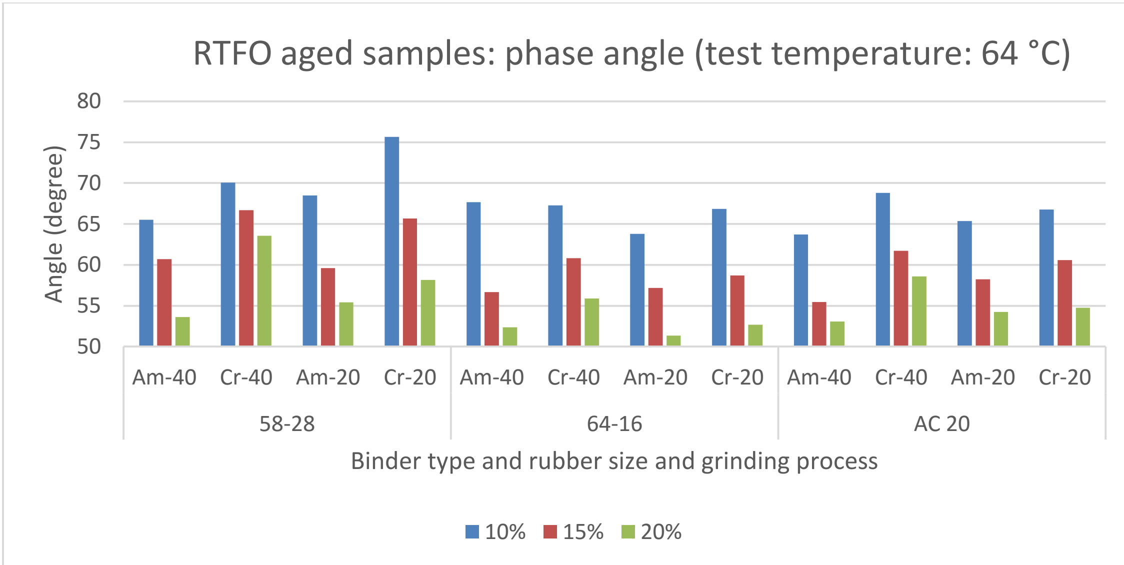


Figure 39. Phase angle for aged samples mixed and mixed with CRM

3.2. Section two: rubber modified asphalt mixture

Besides analyzing the properties of asphalt binder it is necessary to select an appropriate combination for rubber to be mixed with binder as a modifier. In this research ambient process was used as grinding process to generate required rubber. Scrap tire was ground to produce both size #20 and #40 ambient rubber. In regard to rubber content in binder, 15 percent was used to manufacture rubber modified asphalt binder. All three binder sources which were tested in section one were also used in this section to produce asphalt mix samples. The procedure utilized for selecting this combination was an experimental process based on the results of experiments presented above on binder samples.

3.2.1. Aggregate properties

In second phase of this research, based on the selected rubber size and properties, mix samples were made and evaluated in order to find and suggest the best mix design for Nevada. For this reason two sources of aggregates were used; source one: aggregates from southern Nevada and source two: aggregates from northern Nevada. In order to make the samples, specifications provided by Nevada Department of Transportation were used. The results also contain some suggestion for best mix design for Nevada with regard to compatibility with binder and aggregate sources that is used for pavement in this state.

In order to take into consideration the influence of aggregate on modified asphalt mix behavior, two different aggregate type were used. Asphalt mixtures were made with both aggregate and subjected to Hveem stability and air void analysis. It is necessary to achieve air void below the maximum acceptable range. Otherwise the gradation and or temperature have to be modified. It is important to notice that there was obvious difference in shape and color of the aggregate provided from these different sources. On the other hand evaluating mixtures made with various aggregate is important. Table 2 demonstrates the properties of aggregate received from southern Nevada.

Table 2. Properties of Aggregate from southern Nevada

Sieve		**Type2C**		Specification	Range
Size	**mm**	**range**	**Mid pt.**		
1 in	25	100	100		
3/4 in	19	88-95	91.5	Coarse S.G	2.63
1/2 in	12.5	70-85	77.5	Fine S.G	2.51
3/8 in	9.5	60-78	69	Cali. S.G.	2.65
No.4	4.75	43-60	51.5	Water Abs. +#4	3/4#" : 0.9, ½" : 1.3
No.10	2	30-44	37	Sand Equivalent	81
No.40	0.425	12-22	17	LA Abrasion	15.7
No.200	0.075	3-8	5.5	Frac. Face Count	3/4#" : 100 , ½" : 98

3.2.2. Hveem stability

According to standard practice of Nev. T760C which provides specifications for mix design in Nevada DOT, Hveem mix design method was used on this research. In order to compact the sample and run the stability test, the method provided by Test Method Nev. T303 was used. Cylindrical samples with approximately 100 mm diameter and 64 mm height which were made using stabilometer in Nevada department of transportation.

After selecting the best combination of rubber type, size and content, next step is evaluating the properties of asphalt mixture. In order to do that, rubber modified asphalt mix samples were produced and tested in accordance to SHRP and ASTM as well as Nevada department of transportation requirements. In this regard, modified asphalt mix samples with various binder content were generated and subjected to weight volume texts. The goal of these experiments were to determine the optimum binder content.

Because of the fact that Hveem procedure is used in this research, the results of Hveem stability experiment on samples with different binder content were analyzed to extract the sample with highest stability. A sample is demonstrated in figure 40. The horizontal axis is binder content while the vertical axis shows Hveem stability for each sample. As it can be seen in this figure, Hveem stability are carried out on modified asphalt mix samples with binder content 3.5 percent to 6 percent. In this example asphalt mix with 4.5 percent of binder displays the highest stability. It is important to notice that the ratio of binder to aggregate dry weight is called binder content in a mix sample. Generally 5 samples with half percent intervals are made and undergo under stability test. Then the results are evaluated based on stability test requirements. The percentage of the sample with highest stability is recorded and used in selecting optimum binder content.

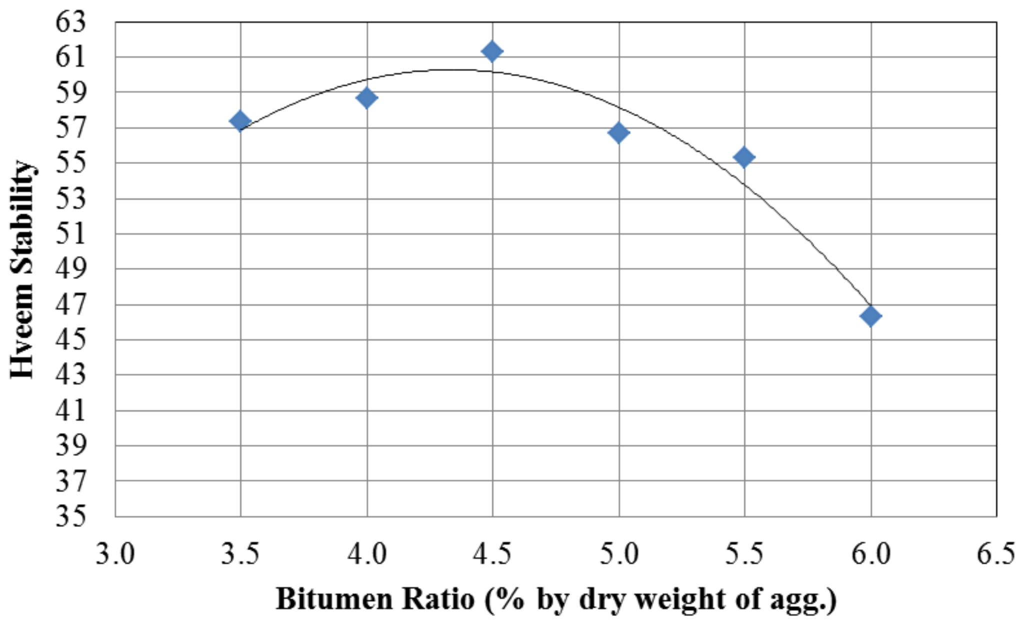


Figure 40. A sample of Hveem stability on modified asphalt mix

3.2.3. Volumetric properties of rubber modified asphalt mixtures

In order to select the optimum binder content, volumetric properties of mix samples were measured concurrent to Hveem stability tests. The combination of the results gathered from stability test and sample's volumetric properties lead to selecting optimum binder content. Volumetric properties of asphalt mix samples mean various density measurements as well as air void content based on test method Nev. T760C. Figure 41 illustrates an instrument used for measuring specific gravity next to a pack of compacted cylindrical samples ready for experiment.

Similar to Hveem stability, the results of measurements were graphed and analyzed to determine the best binder percentage. These graphs include density, air void and void mineral aggregate which is abbreviated as VMA. The combination of volumetric properties and stability leads to a pavement with adequate stability and durability as well as workability. It is necessary for asphalt mix to have appropriate volumetric properties because it controls the space required for binder and aggregate to be mixed. The process of selecting binder content in general is called asphalt mix design. This procedure is an experimental process which is recommended by both industrial and research based agencies.

Figure 41. Pack of compacted samples next to density measuring tool

3.2.4. Dynamic modulus of asphalt mixture and moisture induced damage

Dynamic modulus of modified asphalt mix samples made with optimum binder content were then measured and analyzed. Measuring dynamic modulus properties of modified asphalt mixes was performed at three different temperatures which are 4°C, 20°C and 40°C. For each temperature, phase angle of the samples also were measured. In addition, samples were subjected to moisture to evaluate the magnitude of damage caused by moisture. Disc shape compact tension test (DCT) as well as semi-circular bend geometry (SCB) were used to determine the fracture energy (GF) for each mix samples. Figure 42 displays equipment required for measuring dynamic modulus. Cylindrical samples with 100 mm in diameter and 150 mm in height were used in this experiment.

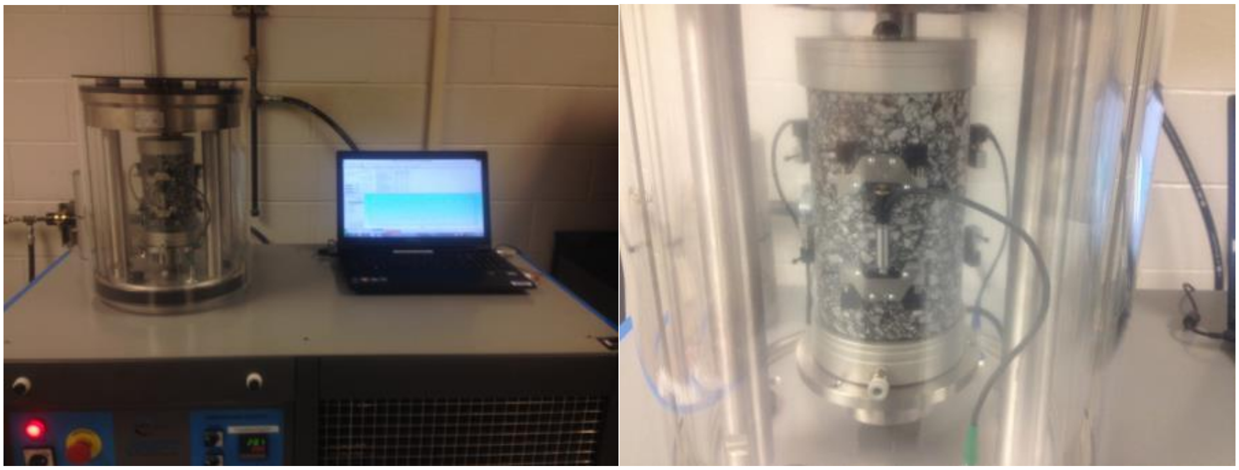


Figure 42. Required equipment for measuring dynamic modulus

In order to measure the rutting properties of asphalt concrete mixtures, the flow number were used. Flow number is the load pulses number at minimum rate of changes in permanent strain under repeated load experiment. This number is determined by differentiation of the permanent strain and number of load cycles. An unconfined repeated load test with 600 KPa as deviatoric stress was carried out at test temperature of 59°C. In order to achieve the goals, all samples were conditioned overnight to ensure an equilibrium temperature. The test process includes applying continuous haversine axial compressive load on cored cylindrical samples. AASHTO T269 test method was used to evaluate the air voids of each sample prior to dynamic modulus testing. Teste specimens had air void 7 ± 1%.

3.2.5. Disk shaped compact tension test

In order to determine the fracture energy (Gf) of asphalt mixture a test procedure called disk shaped compact tension test which is developed at the University of Illinois, is used. Single notched edge circular samples are used in this test method which is illustrated in figure 43. The fracture energy resulted in this experiment is used to determine the fracture resistance behavior of the asphalt pavement. Samples with higher fracture energy values would have better resistance to fracture under thermal cracking as asphalt concrete pavement. ASTM D7313 is used for preparing samples which include sawing and coring of the samples.

In general, all samples failed after around 5 minutes of testing time with 1 to 6 mm crack mouth opening displacement (CMOD) while the control mode rate was 1 mm/min. The area under the load versus CMOD curve indicates the fracture energy.

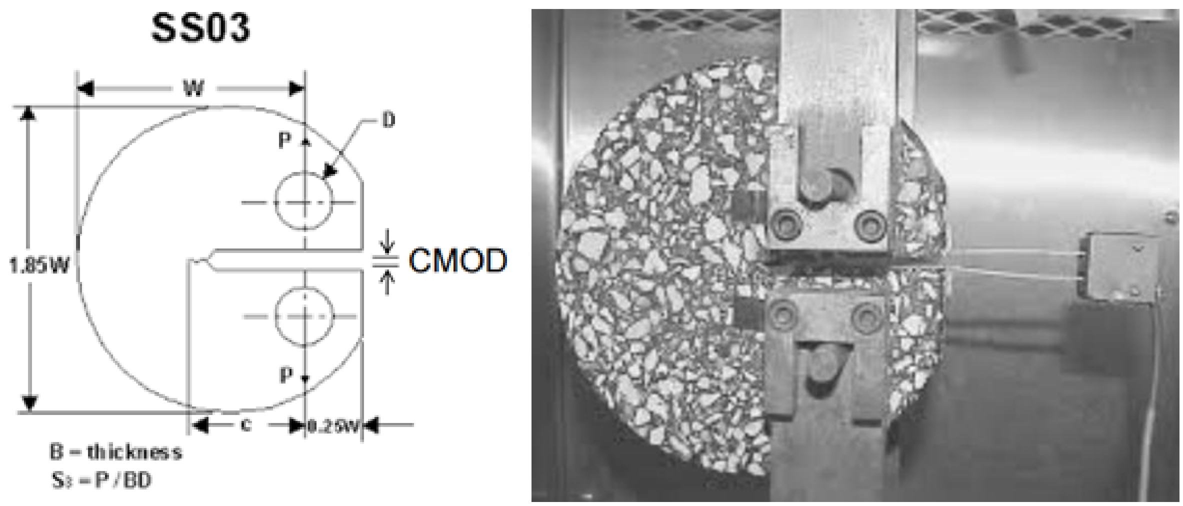


Figure 43. Disk shaped compact tension test

3.2.6. Semi-circular bending (SCB) test

The semi-circular bending test was carried out in accordance to AASHTO T312 at temperature -12°C on samples with 7 ± 1 air void. Specimens with 115 ± 5 mm height produced by Superpave gyrator are used to obtain a cylindrical slice with 25 mm ± 2 mm thickness. A schematic view of the specimen is displayed in figure 44. Then each slide was subject to be cut to almost two half slices. A notch is then cut in each slide along the symmetry axis which is 15 ± 0.5 mm long and less than 1.5 mm width. The result of this experiment is presented as crack mouth opening displacement (CMOD) versus applied simple load.

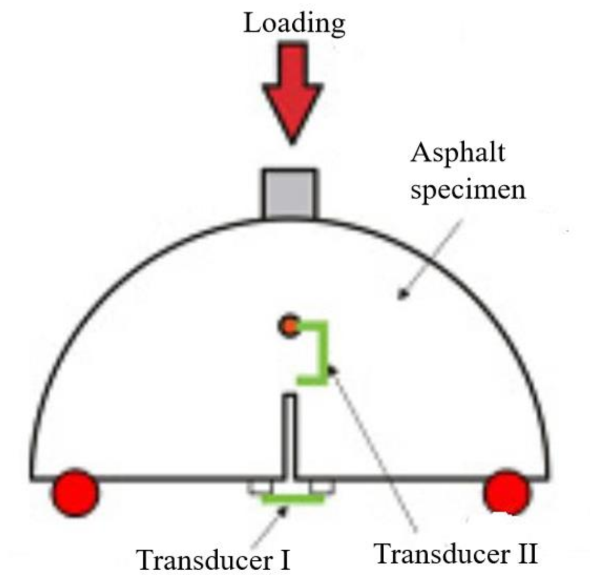


Figure 44. Schematic view of SCB test

3.3. Section three: ultrasound survey on samples

3.3.1. Selecting best ultrasound method for testing

In this section the best method for running the test must be selected. It means the following steps should be followed to receive the required results:

- The type of transducer for performing the test should be selected
- Selected and fixed apparatus such as transducer, pulser and receiver should be checked with different mixes and samples to see if any changes in mix affect the results or not and to find out if the adjustments made on the testing equipment are working properly.
- Selecting the best scanning method for correlating ultrasonic measurements with HMA properties.

For this reason cylindrical samples made with different binder content and different rubber size and mix are used. The samples have around 75 mm height which are appropriate for laboratory testing. The ultrasonic method is based on measuring the wave velocity inside the material in order to find a term called Integrated Response (IR) related to the tested sample. A pulser and receiver system with two transducers is used in a direct-based transmission method. In order to find the best frequency for testing several tries should be carried out to find the best configuration and frequency. For this reason different types of transducers which propagate wave with various frequencies were tested. In the beginning a transducer with 900 kHz frequency was used based on previous studies. Transducers with 900 kHz frequency did not produced an appropriate wave in response as it is demonstrated it figure 45.

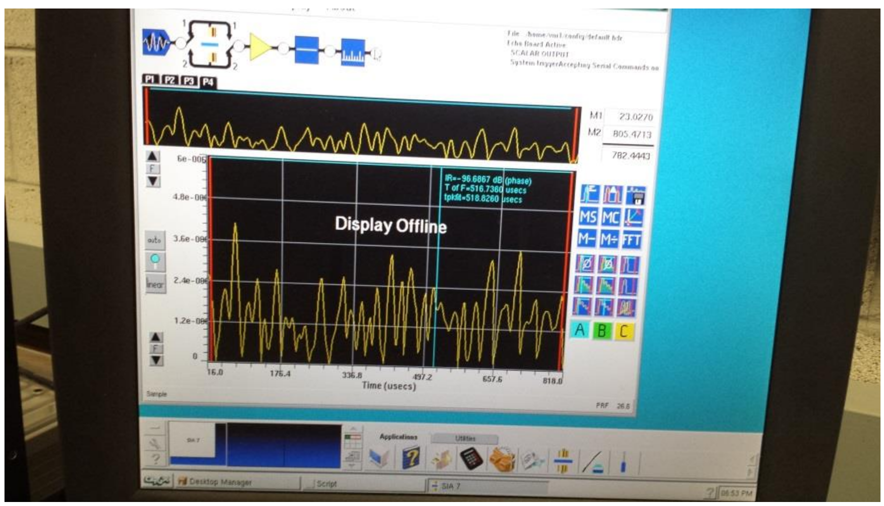


Figure 45. Defective wave propagation

Transducer, type Ultra ZRD 100-2 NCA 1000 which propagates longitudinal waves with 125 kHz frequency, created an appropriate wave in contact test method. A sample of propagated wave is demonstrated in figure 46.

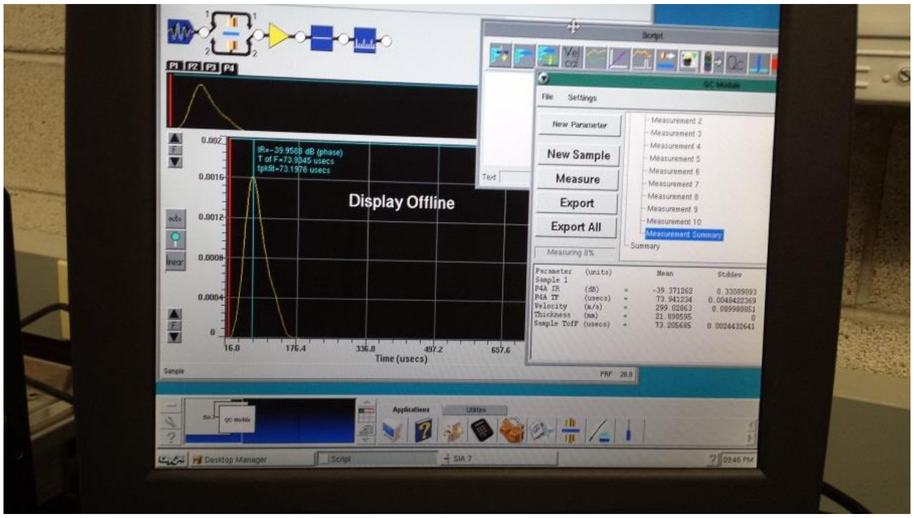


Figure 46. Appropriate wave propagation

In table 3, required settings for pulser-receiver of the mentioned transducer are illustrated.

Table 3. Required settings for transducer, longitudinal method

Item	Unit	setting
type	-	Ultran ZRD 100-2 NCA 1000
Frequency	kHz	225
Bandwidth	kHz	56
Duration	µsec	150
Amplitude	%	75
Chirp step - A	%	45
Chirp step – B	%	45

Transducers should be installed and fixed on both sample sides while the sample is rested on a table. Figure 47 demonstrates the testing apparatus. There are three different types of waves propagated by ultrasonic testing devices. These three waves are longitudinal, shear and surface waves. In this experiment the longitudinal testing method is used. In order to run the contact test in both methods a Vaseline gel also is used to diminish the amount of scatter and irregularity on the sample's surface.

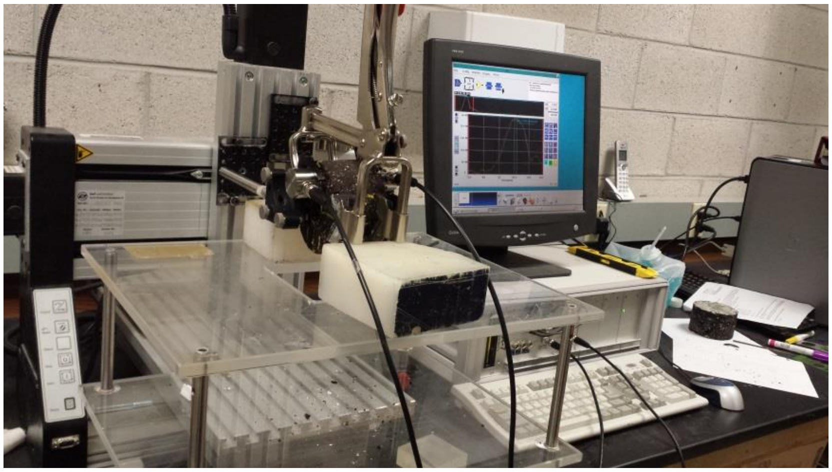


Figure 47. Ultrasonic testing apparatus

For this reason, the cylindrical samples with 100 mm diameter and 75 mm height were used. The samples were fixed on the table as is shown in figure 48 and then the transducers connected to the sample from both sides. For each sample reading was carried out in 10 different points on the surface of the sample to find the average of each reading. It is important to mention that there are several factors affecting the test results. These factors include the properties and behavior of asphalt samples and technical errors which are relevant to the testing instrument. These errors are misalignment in transducers during measuring, using inappropriate transducer, applying unequal and various pressures on the two transducers, placing the transducers on a rough surface, etc.

Figure 48. Sample fixed between two transducers

In order to find the properties of asphalt using ultrasonic instrument, the velocity of wave inside the sample should be calculated. The wave velocity is one of the most common methods in ultrasonic tests. For this reason the time of wave flight inside the sample is measured by instrument as well as the thickness of the sample. Then the velocity can be calculated based on the time and thickness. For measuring the thickness of the sample caliper is used.

Chapter 4

Analysis and Discussion

4.1. Properties of rubber modified binder

The results of experiments carried out on asphalt binder will be discussed in this chapter. Results of experiments on both un- aged and aged will be presented, compared and discussed to reveal the influence of each individual parameter on the behavior of modified binder. As mentioned in the literature review, viscosity is one of the most addressed parameters in analyzing binder properties. Various binder types as well as rubber size and type were used to produce rubber modified asphalt samples. The results of viscosity test are presented again in figure 49 with different order.

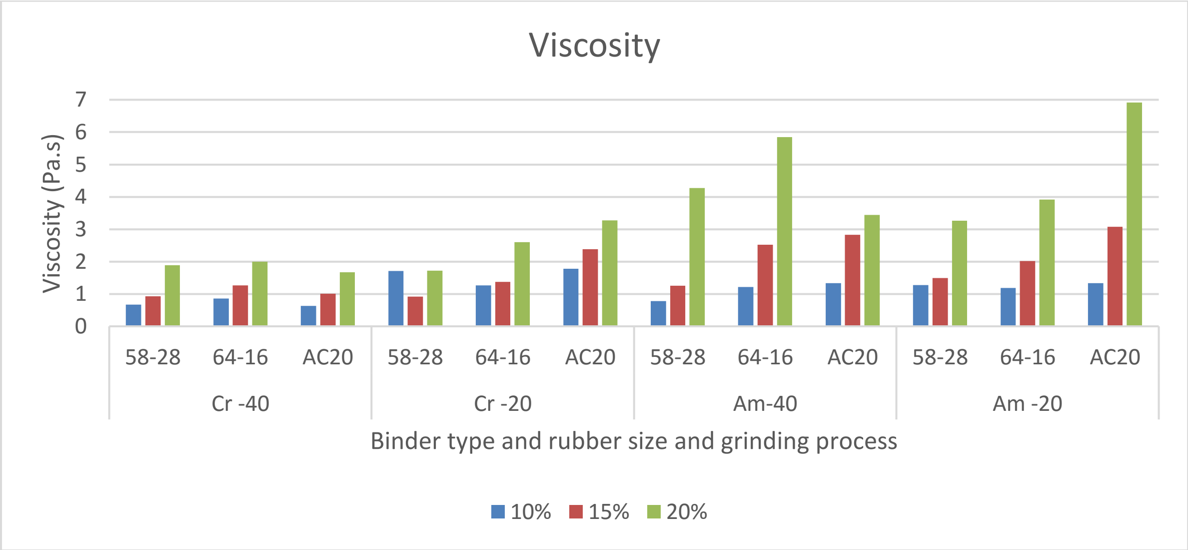


Figure 49. Viscosity of binders mixed with CRM with regard to rubber type

There is direct correlation between rubber content and viscosity. It is obvious that viscosity increases with the increase of rubber percentage. This is in conformity to the results of other research which is presented in literature review.

Moreover, there is a distinguished relationship between rubber grinding process and viscosity. Samples mixed with rubber ground with cryogenic grinding method demonstrates lower viscosity compared to rubber modified binder samples mixed with rubber manufactured based on ambient procedure. The viscosity of ambient samples are almost twice the viscosity of similar samples mixed with cryogenic rubber. Rubber content has higher influence on the properties of ambient samples in comparison to cryogenic ones.

For ambient samples there is sharp increase in viscosity relevant to rubber content. Samples with 10 percent rubber content exhibit viscosity significantly lower than the samples mixed with 20 percent ambient rubber. This trend is lower for cryogenic samples. Rubber size has relatively lower impact on viscosity. Binder mixed with small particle size rubber shows slightly lower viscosity. The rate of growth in viscosity is the same for binders from various sources.

The trend-line demonstrates the rate of growth in viscosity for samples mixed with 15 percent rubber content. It can be seen that there is a slight increase from cryogenic #40 to ambient #20. This growth is relatively higher between ambient #40 and ambient #20.

As it is illustrated in this figure, viscosity of almost all samples made with cryogenic grinding process are less than 3 Pa.s which is required for a sample to pass this test based on SHRP. For ambient samples on the other hand viscosity is higher than SHRP limit for samples containing 20 percent rubber. In selecting best rubber content for modifying asphalt binder this parameter has to be taken into consideration.

In general, flash point temperature decreases as rubber content increases. That is probably because rubber ignites in lower temperature compared to binder. This decline is relatively low and all samples displayed flash points higher than the minimum limitation of SHRP requirements. There is no distinguishable correlation between rubber size and type and flash point properties of modified binder samples.

4.2. Elastic and tensile properties of the samples

Analyzing the results of ductility and toughness and tenacity tests on samples are necessary to reveal the elastic properties of rubber modified asphalt binder as well as tensile behavior of them. Figure 50 illustrates the summary of ductility test on samples. Presented graph is for un-aged samples and is ordered regarding to the type and size of rubber as well as binder source.

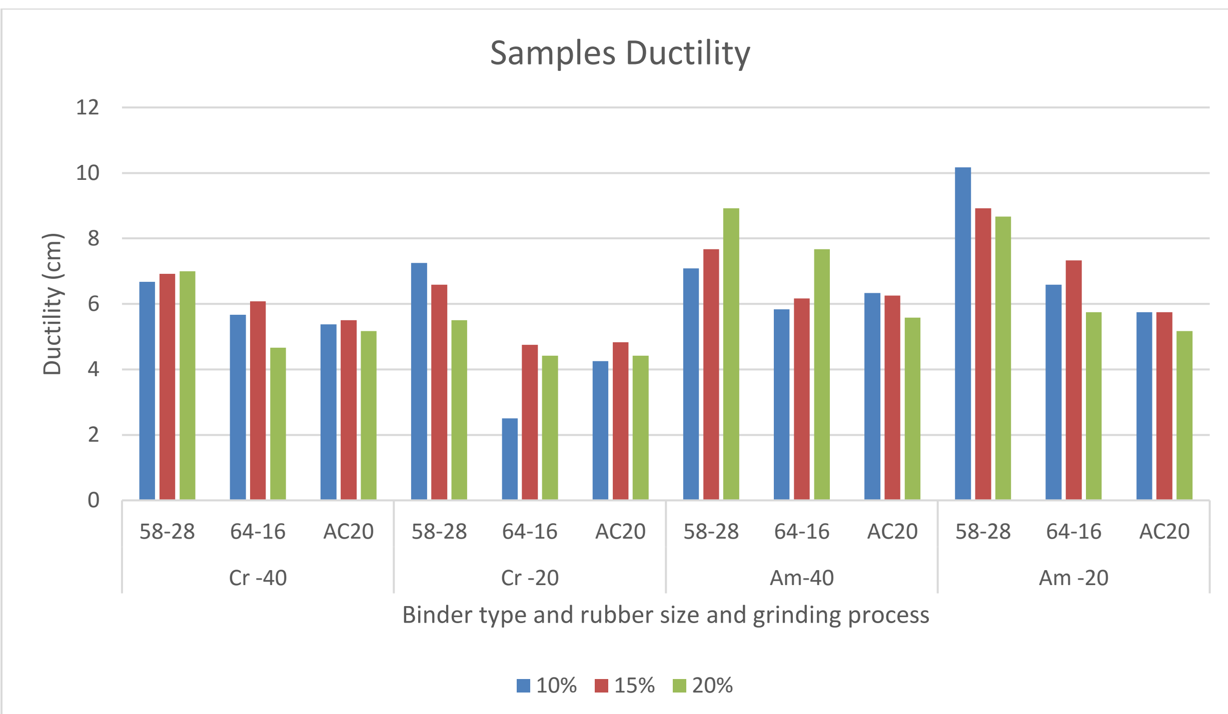


Figure 50. Ductility of binders mixed with CRM with regard to rubber type

The vertical axis displays the amount of elongation in centimeter while the horizontal axis shows binder type and rubber size and grinding process. On average binder grade PG 58-28 shows higher results which means modified asphalt binder has higher elasticity. For samples made with rubber ambient #40 the rate of ductility improves with the addition of rubber while in general, adding more rubber leads to a decline in ductility properties of rubber modified asphalt.

It has to be mentioned that on average the magnitude of ductility is lower than original binder ductility which is almost 40 centimeter. It is important to mix the rubber modified asphalt well before carrying out test on samples to make sure there is adequate coherence and unity between rubber particles and binder.

On average binder samples with 15 percent rubber demonstrates slightly higher ductility. This is true for samples made with binder AC20 and PG 64-16 while for modified binder PG 58-28 it is absolutely relevant to the grinding process. On the other hand while for cryogenic samples ductility increases with rubber content for ambient samples there is an obvious decline in ductility with the increase of rubber percent.

For RTFO aged representatives the same modified binders the ductility behavior shows some changes as it is illustrated in figure 51. The order of binder sources is changed to make it easy to analyze the results.

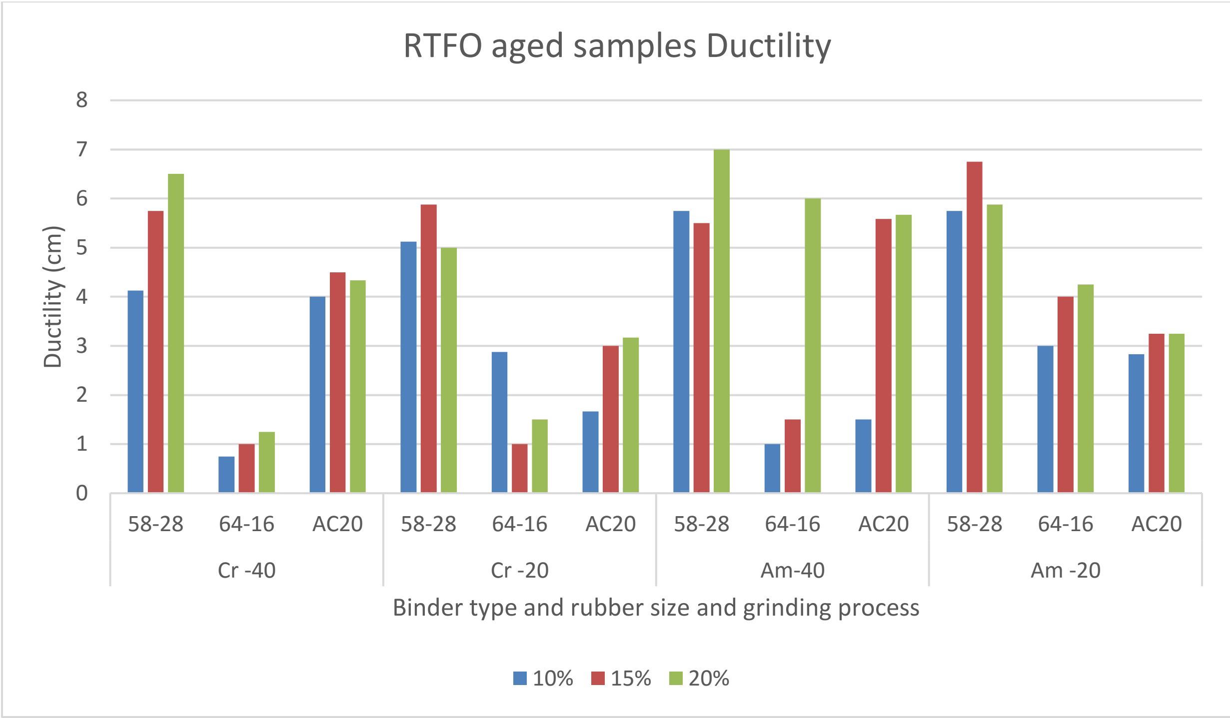


Figure 51. Ductility of binders mixed with CRM for RTFO aged specimens

It sounds like samples made with source binder PG 64-16 loos ductility properties more than other binder sources. Again modified binder PG 58-28 displays the highest ductility in comparison to other binder sources. For this binder source, rubber size and grinding type does not show significant impact on binder behavior. Binder AC20 modified with smaller rubber particles exhibits rather higher ductility in average.

For most samples the magnitude of ductility improved for RTFO aged representatives relevant to rubber content. Binders modified with 10 percent rubber demonstrate lower ductility on average compared to samples with higher rubber percentage. This is an interesting approach because it shows rubber improves the ductility properties of aged asphalt. On the other hand for pavements made with rubber modified asphalt, higher binder content will lead to better short-term aged ductility behavior.

Another important factor is the rate of change between unaged and RTFO aged behavior of the samples. In comparison between figure 48 and 49 it can be seen that except binder source PG 64-16 the other two sources do not show significant decline in ductility properties. It means that short-term aging does not lead to any reduction in ductility which is a positive point.

The results of toughness and tenacity test also illustrate the elasticity properties of modified binders. Therefore it is important to analyze these parameters. It has to be mentioned that this test was carried out just on unaged samples. The results of toughness which are related to the elasticity of modified binder are presented in figure 52. The results of tenacity are not presented here because there was not any obvious trend.

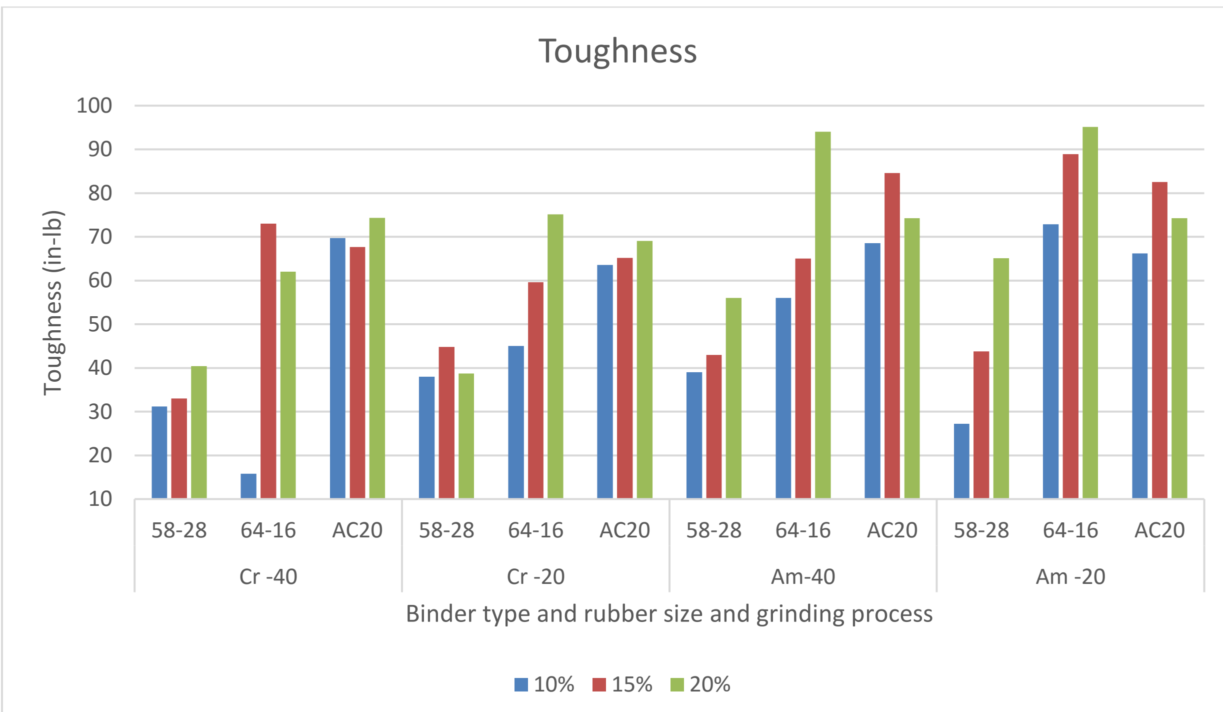


Figure 52. Toughness for binders mixed with CRM

Despite ductility, modified binder source AC20 and PG 64-16 display higher toughness compared to PG 58-28. While for PG grade samples the amount of toughness improves with the increase of rubber content for AC20 specimens, binder modified with 15 percent rubber exhibit higher toughness. In general for AC20 the difference of tenacity between 10 and 20 percent rubber is significantly low and avoidable. The size and type of rubber does not show any impact on the behavior of the modified asphalt. On the other hand the elasticity of modified asphalt binder is irrelevant to rubber size and grinding process.

Maximum initial strength of the samples is another result of toughness and tenacity test which is exhibited in figure 53. Similar to the toughness, the higher initial strength was observed for modified specimens made with binder source AC 20 and PG 64-22. There is a direct relation between rubber content and initial strength for most samples that means adding more rubber improves the initial strength of modified binder. For each binder source rubber type and size does not indicate any influence.

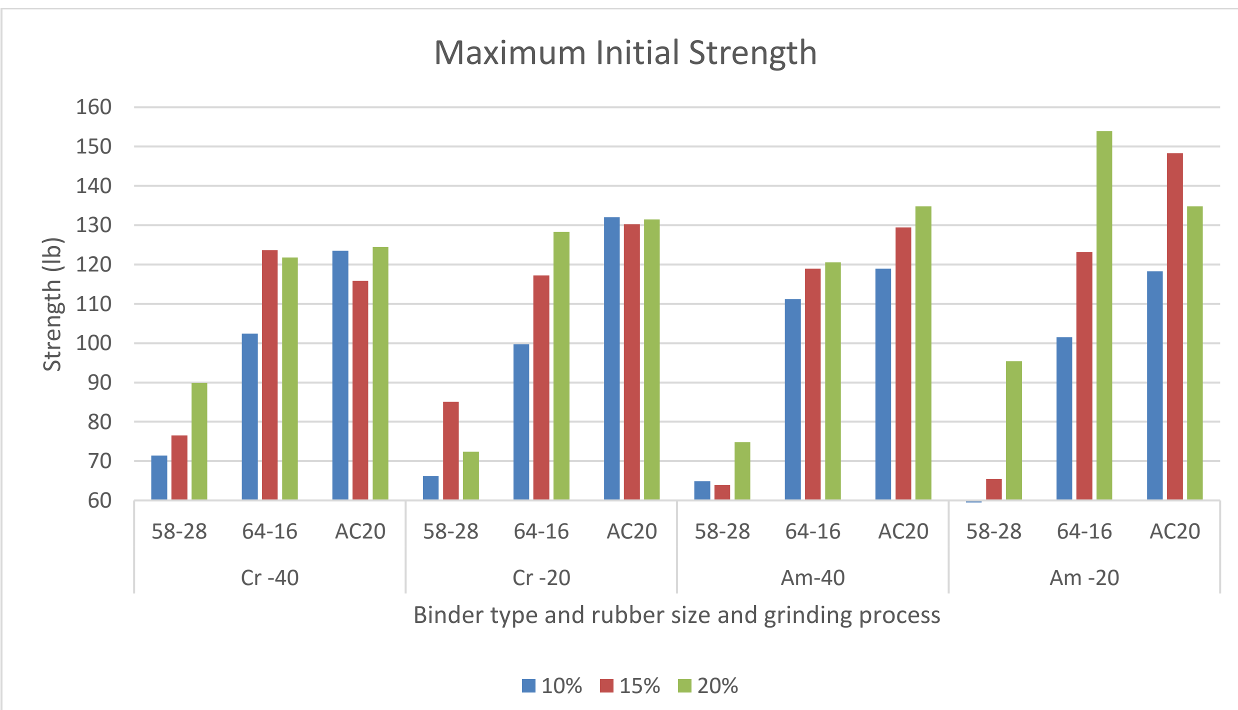


Figure 53. Maximum initial strength for binders mixed with CRM

With respect to the above paragraphs it is clear that there is not any unique trend repeating for all specimens in all experiments. In contrast, it can be observed that each parameter is different. While several parameters are relevant to binder source, the others are more affected by rubber grinding type and size. In general, it is obvious that elastic properties of modified binder increase with addition of more rubber while their ductility declines.

4.3. Rutting properties of modified binder

Direct shear rheometer test was carried out on modified binder samples in different temperatures. A sample of the results is presented in figure 54 which is $G^*/\sin\delta$ in different binder samples at 70°C. As it can be seen, binder made with ambient rubber demonstrates higher $G^*/\sin\delta$ compared to cryogenic representatives. In this regard while binders made with cryogenic #20 rubber resulted in slightly higher $G^*/\sin\delta$ in comparison to cryogenic #40, the trend is opposite for ambient sample.

There is a direct relation between rubber content and $G^*/\sin\delta$ and this parameter increases significantly with the addition of rubber. The highest $G^*/\sin\delta$ observed for samples that are made with 20 percent of rubber ambient #40 while the lowest magnitude belongs to binders modified with 10 percent rubber. Considering the fact that G* is indicator for complex shear modulus, any increment in this parameter will lead to improvement in rutting properties of the asphalt pavement.

On the other hand, with adding more rubber to binder the rutting properties of the asphalt binder increases which is an important factor in pavement. Binder samples with 20 percent rubber content should have 3 times higher complex modulus compared to samples having 10 percent rubber. The results of the test in different temperatures which are presented in appendix A also show similar behavior. It is observed that $G^*/\sin\delta$ declines as temperature increases. At 64 °C, samples show the highest magnitude for G*/sin δ while it is dramatically lower at 76 °C. This increase in complex shear modulus is in conformity to other investigations indicated in chapter 2.

Meanwhile, it sounds like, this parameter also is relevant to binder source. Samples made with binder PG 64-16 and AC20 demonstrated higher G*/sin δ compared to PG 58-28 source binder.

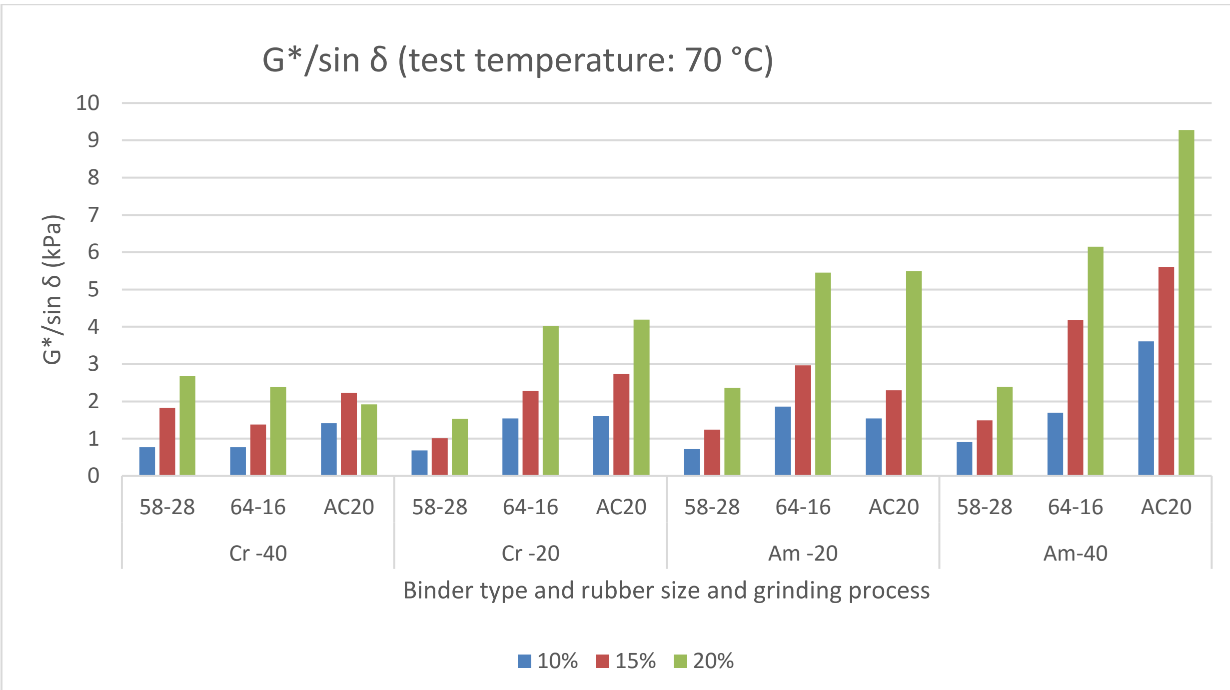


Figure 54. G/sin δ for binders mixed with CRM*

Phase angle which is another parameter evaluated based on DSR test decreases as rubber content increases. In other words, modified binder mixed with 20 percent rubber has inevitably lower phase angle compared to samples that have 10 percent rubber. Not a significant difference was observed between various grinding process and rubber size. Based on literature review other researchers also observed similar results.

Moreover, failure temperature improves with increasing rubber content. The rate of change in temperature is similar for various samples. Modified samples made with binder PG 58-28 resulted in slightly lower failure temperature. In comparison between different rubber size and type also, cryogenic samples have rather lower failure temperature though the difference is not significant.

The results of DSR test on RTFO aged samples exhibit similar behavior. The rate of change between cryogenic and ambient is different. For RTFO aged samples, cryogenic #20 resulted in higher $G^*/\sin \delta$ compared to other rubber types. Similar to un-aged samples, modified binder source PG 58-28 demonstrated lower $G^*/\sin \delta$ in comparison to the other sources. In general $G^*/\sin \delta$ increases with rubber content while phase angle diminishes. A direct relation also was observed between failure temperature and rubber content.

4.4. Long term aged properties of modified binder

Long-term properties of modified binder were evaluated based on PAV aging test procedure. Sample stiffness is presented in figure 55 which is the result of bending beam rheometer (BBR) test. It is evident that long-term stiffness decreases with the increase of rubber content. Modified samples made with binder PG 64-16 demonstrated lower stiffness compared to the other sources. The rate of decline in stiffness for this source also is relatively low between 10 and 20 percent rubber content. It has to mention that higher creep stiffness leads to higher thermal stress. Based on ASTM requirements stiffness must be less than 300 MPa.

Moreover, results of DSR test on long-term aged modified samples which are exhibited in appendix A indicate that $G^*/\sin \delta$ decreases with the increase of rubber percentage. This is in contrast with results of the test on unaged and short-term aged samples. Modified samples made with binder PG 64-16 illustrated higher results. Master stiffness curve (M-value) on the other hand did not show remarkable differences for various rubber percentage as well as rubber type and size. All the values are less than 0.3 which is required based on ASTM.

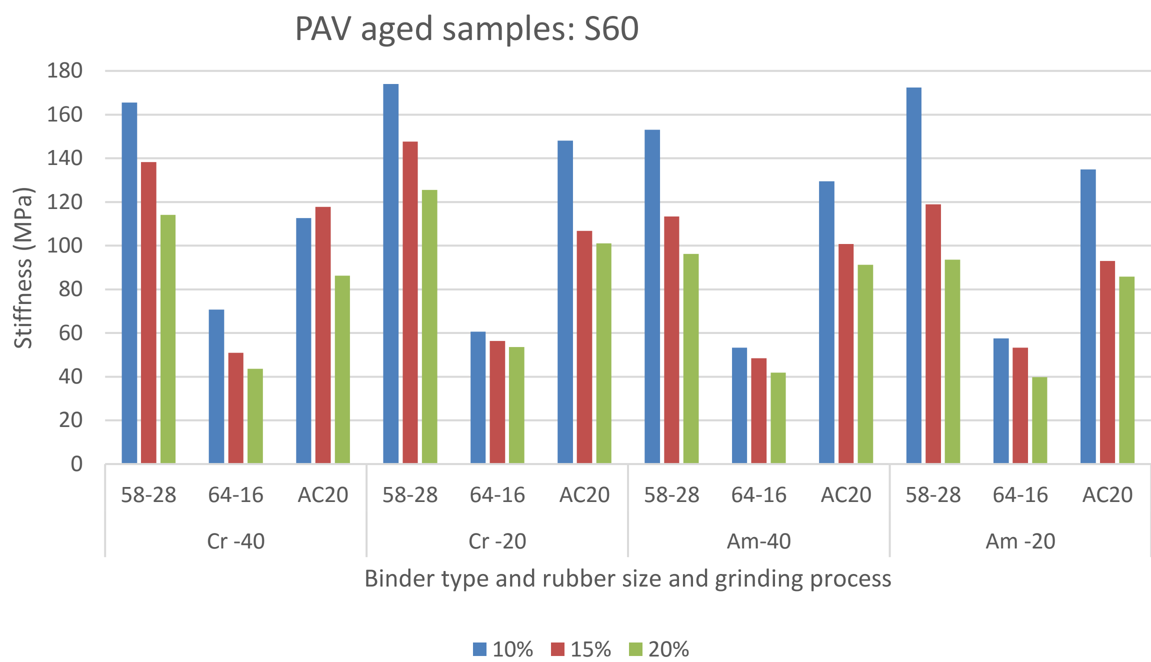


Figure 55. Stiffness for PAV aged CRM modified binders

4.5. Recommended best rubber type, size and content

Basically it is important to find an optimum content for rubber to be mixed with binder as a modifier. This optimum or best rubber content should satisfy the requirements of each test presented in above paragraphs. Considering the fact that the behavior of modified binder varies with rubber size, type and percentage, finding an appropriate regression model between all parameters is necessary.

There are samples which have failed in satisfying requirements for one or several tests. While adding more rubber improves several properties, it has negative influence on some other parameters. The same is true about the process which is used in manufacturing rubber. On the other hand, while cryogenic samples exhibited better results for some tests, it was ambient which showed improved results for other experiments. Rubber size also displayed effects on several parameters. Based on some experiments it is better to use smaller particles while other experiments demonstrated improvements in using larger particle size.

4.6. Analytic Hierarchy Process (AHP) Method

The type of binder also plays remarkable role in responding several experiments. In other words, it is necessary to take into consideration type of binder in analyzing modified binder. Therefore the question is which type of rubber, with which size and percentage is considered to be an improving additive for binder.

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making approach and was introduced by Saaty (1977 and 1994). It has particular application in group decision making, and is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, shipbuilding and education. The AHP has attracted the interest of many researchers mainly due to the nice mathematical properties of the method and the fact that the required input data are rather easy to obtain. The selection of one alternative from a given set of alternatives, usually where there is multiple decision criteria involved, is one of the application of AHP.

For the purpose of this study, the twelve combination of CRM with each virgin binder are considered as alternatives and the following properties are considered as criteria; Ductility of original sample, Ductility of RTFO-aged sample, Failure temperature of original sample, Failure temperature of RTFO-aged sample, Flashpoint, Tenacity, Toughness, and Viscosity.

All twelve alternatives are ranked in each criteria based on the test results. The alternative that its property is closest to the average of polymer modified and terminal blend is rank as the highest, and so on. Tables 4 through 6 show the rank of each alternative in each criterion for virgin binders of PG58-28, PG64-16, and AC-20, respectively.

Table 4. Rank of each alternative in each criterion for A5828

rank	DU-ORG	DU-RTFO	FT-DSR-ORG	FT-DSR-RTFO	Toughness	Tenacity	Viscousity	Flashpoint
1	Am-20-10	Am-40-20	Am-40-10	Cr-20-10	Am-20-20	Am-40-10	Cr-20-15	Am-20-10
2	Am-20-15	Am-20-15	Cr-40-10	Cr-40-10	Am-40-20	Am-20-10	Cr-40-15	Cr-40-20
3	Am-40-20	Cr-40-20	Cr-20-15	Am-20-10	Cr-20-15	Am-20-15	Am-40-10	Am-20-15
4	Am-20-20	Am-20-20	Am-20-10	Am-40-10	Am-20-15	Cr-20-10	Cr-40-10	Cr-20-15
5	Am-40-15	Cr-20-15	Cr-20-10	Cr-40-15	Am-40-15	Am-20-20	Am-40-15	Cr-40-10
6	Cr-20-10	Am-20-10	Am-20-15	Cr-20-15	Cr-40-20	Am-40-15	Am-20-10	Cr-20-10
7	Am-40-10	Am-40-10	Am-40-15	Am-40-15	Am-40-10	Am-40-20	Am-20-15	Am-40-15
8	Cr-40-20	Cr-40-15	Cr-20-20	Am-20-15	Cr-20-20	Cr-40-15	Cr-20-10	Am-40-20
9	Cr-40-15	Am-40-15	Cr-40-15	Cr-40-20	Cr-20-10	Cr-20-15	Cr-20-20	Cr-40-15
10	Cr-40-10	Cr-20-10	Am-20-20	Cr-20-20	Cr-40-15	Cr-40-10	Cr-40-20	Am-20-20
11	Cr-20-15	Cr-20-20	Am-40-20	Am-20-20	Cr-40-10	Cr-40-20	Am-20-20	Am-40-10
12	Cr-20-20	Cr-40-10	Cr-40-20	Am-40-20	Am-20-10	Cr-20-20	Am-40-20	Cr-20-20

Table 5. Rank of each alternative in each criterion for B6416

rank	DU-ORG	DU-RTFO	FT-DSR-ORG	FT-DSR-RTFO	Toughness	Tenacity	Viscousity	Flashpoint
1	A-40-20	A-40-20	A-20-15	A-20-10	A-20-20	A-20-10	C-20-20	A-20-10
2	A-20-15	A-20-20	C-40-15	C-20-10	A-40-20	A-40-10	A-40-15	C-20-10
3	A-20-10	A-20-15	C-20-15	C-40-10	A-20-15	C-20-10	A-20-15	C-40-10
4	A-40-15	A-20-10	C-20-20	A-40-10	C-20-20	C-40-15	C-40-20	C-20-15
5	C-40-15	C-20-10	A-20-10	C-40-15	A-20-10	C-40-10	A-20-20	A-20-15
6	A-40-10	A-40-15	A-40-15	C-20-15	C-40-15	A-20-15	C-20-15	C-40-15
7	A-20-20	C-20-20	C-40-20	A-20-15	A-40-15	C-20-15	C-20-10	A-20-10
8	C-40-10	C-40-20	A-40-10	A-40-15	C-40-20	A-20-20	C-40-15	C-40-20
9	C-40-20	A-40-10	C-20-10	C-40-20	C-20-15	A-40-20	A-40-10	A-40-15
10	C-20-15	C-20-15	C-40-10	C-20-20	A-40-10	C-20-20	A-20-10	C-20-20
11	C-20-20	C-40-15	A-20-20	A-40-20	C-20-10	C-40-20	C-40-10	A-20-20
12	C-20-10	C-40-10	A--40-20	A-20-20	C-40-10	A-40-15	A-40-40	A-40-20

Table 6. Rank of each alternative in each criterion for B6416

rank	DU-ORG	DU-RTFO	FT-DSR-ORG	FT-DSR-RTFO	Toughness	Tenacity	Viscousity	Flashpoint
1	A-40-10	A-40-20	A-20-15	C-20-10	A-40-15	A-40-10	C-40-20	C-20-10
2	A-40-15	A-40-15	C-20-15	A-20-10	A-20-15	A-20-10	C-20-10	A-20-10
3	A-20-10	C-40-15	C-40-15	A-40-10	C-40-20	C-40-10	A-20-10	C-40-10
4	A-20-15	C-40-20	A-40-15	C-40-10	A-40-20	C-40-15	A-40-10	C-20-15
5	A-40-20	C-40-10	A-40-10	C-40-15	A-20-20	A-40-15	C-40-15	C-20-20
6	C-40-15	A-20-15	C-40-20	C-20-15	C-40-10	C-40-20	C-20-15	A-20-15
7	C-40-10	A-20-20	C-20-10	C-40-20	C-20-20	A-20-15	A-40-10	A-40-15
8	C-40-20	C-20-20	A-20-10	A-20-15	A-40-10	A-40-20	A-40-15	A-40-10
9	A-20-20	C-20-15	C-20-20	A-20-20	C-40-15	C-20-15	A-20-15	C-40-15
10	C-20-15	A-20-10	C-40-10	A-40-15	A-20-10	A-20-20	C-20-20	C-40-20
11	C-20-20	C-20-10	A-40-20	A-40-20	C-20-15	C-20-20	A-40-20	A-20-20
12	C-20-10	A-40-10	A-20-20	C-20-20	C-20-10	C-20-15	A-20-20	A-40-20

At this point each alternative is weighed based on its rank. Since there are twelve alternative the weight of 12 is assigned to the highest rank and 11 to the second highest and so on. Criteria are also weight based on their importance for that grade of asphalt binder. Table 7 shows the weight of each property (criterion) for different grades.

Table 7. Weight of each criterion (property)

Weight	A5828	B6416 and AC20
8	FT-ORG	FT-ORG
7	Tenacity	Ductility-RTFO
6	Viscousity	Viscousity
5	Ductility-ORG	Ductility-ORG
4	FT-RTFO	Ductility-RTFO
3	Toughness	Toughness
2	Ductility-RTFO	Tenacity
1	Flash point	Flash point

Figures 56, 57 and 58 present the results of analysis which leads to selecting best combination of rubber size, type and content for modifying asphalt binder.

Based on these figures asphalt binder produced with 15 percent rubber AM#20 has the highest rank among the others and is selected for modifying asphalt binder 64-16.

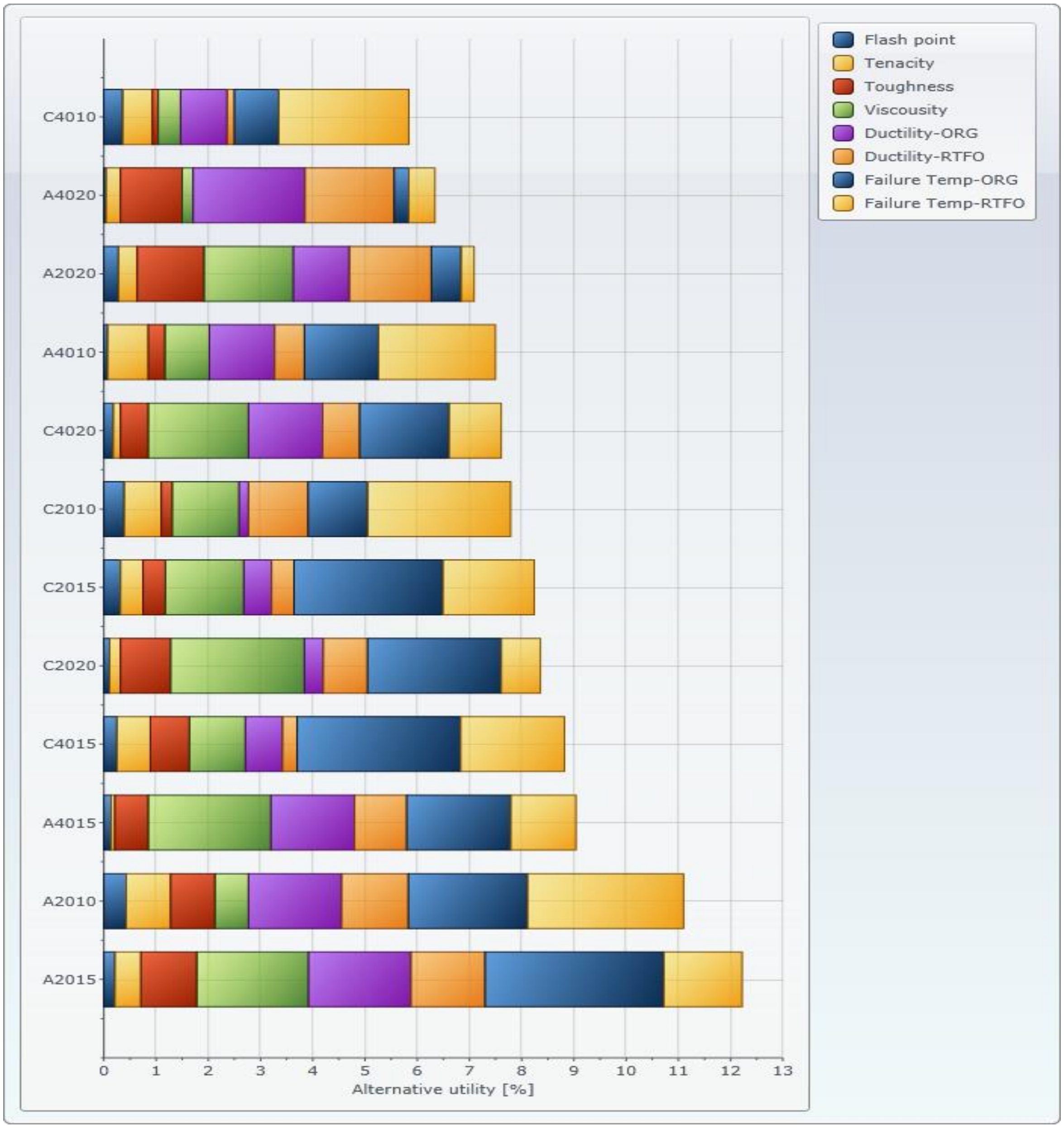


Figure 56. Selecting best rubber type and percentage for binder 64-16

10 percent rubber type AM#40 illustrated the highest rank for binder 58-28 and AC-20 which are presented in figure 57 and 58.

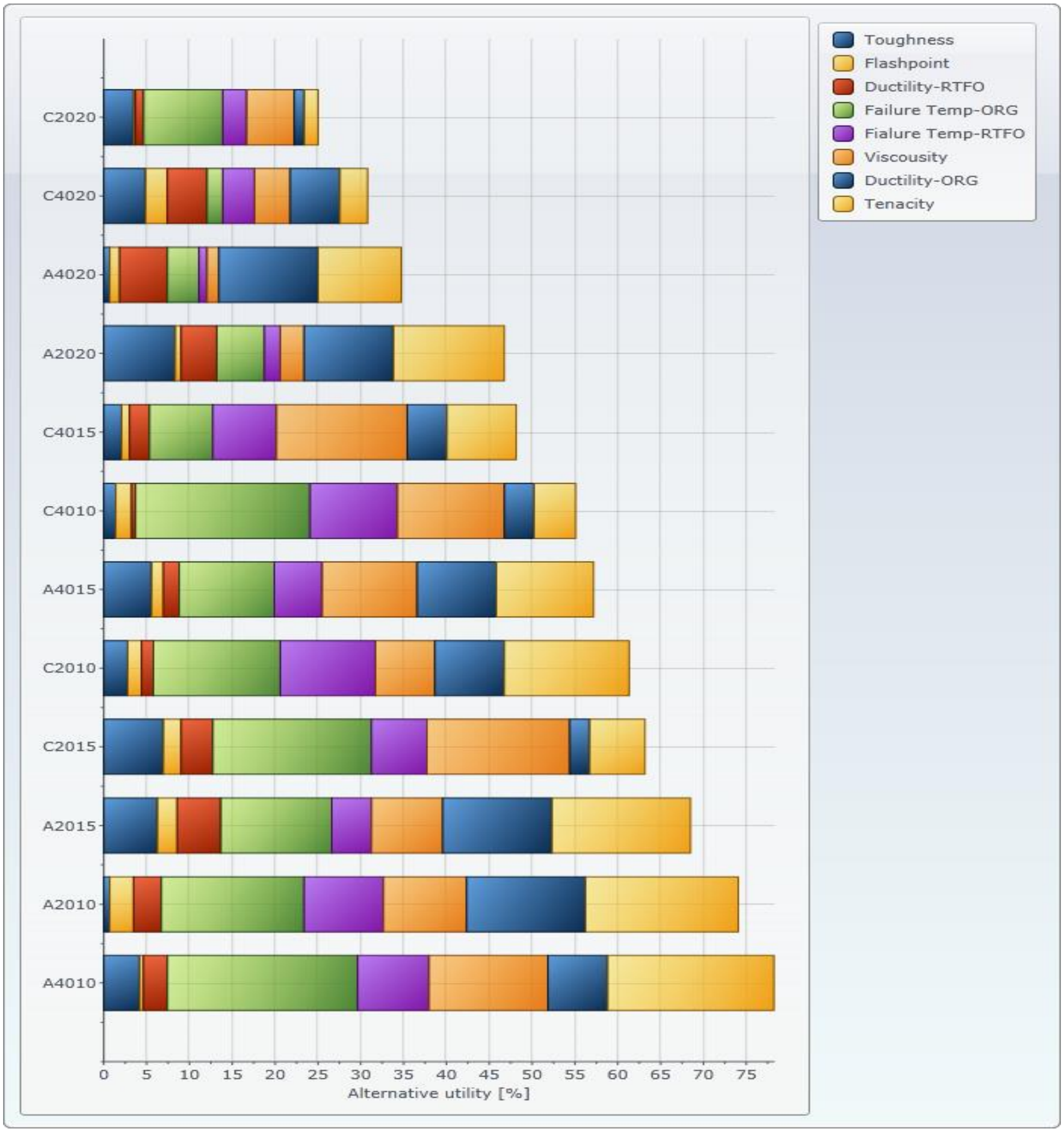


Figure 57. Selecting best rubber type and percentage for binder 58-28

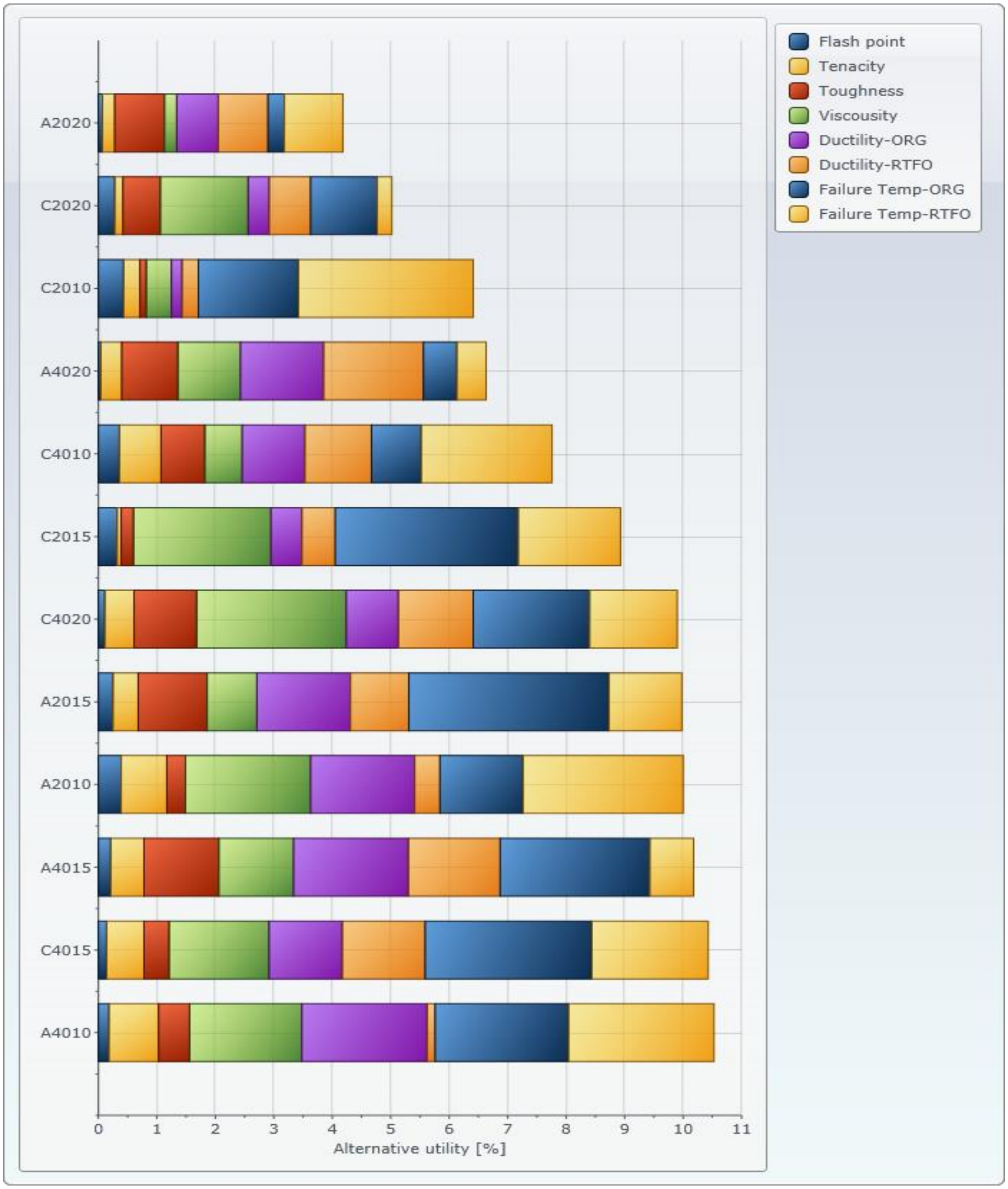


Figure 58. Selecting best rubber type and percentage for binder AC-20

4.7. Modified asphalt mixture: density and air voids

Analyzing density and air void properties of asphalt mix samples presents the behavior of mixture related to binder content. It is a necessary step in evaluating and defining optimum binder content. The rate of changes in the amount of density, air void and VMA (Void Mineral Aggregate) with binder percentage is presented in figure 59 for asphalt mix manufactured with binder PG 58- 28 and 15 percent rubber ambient # 40.

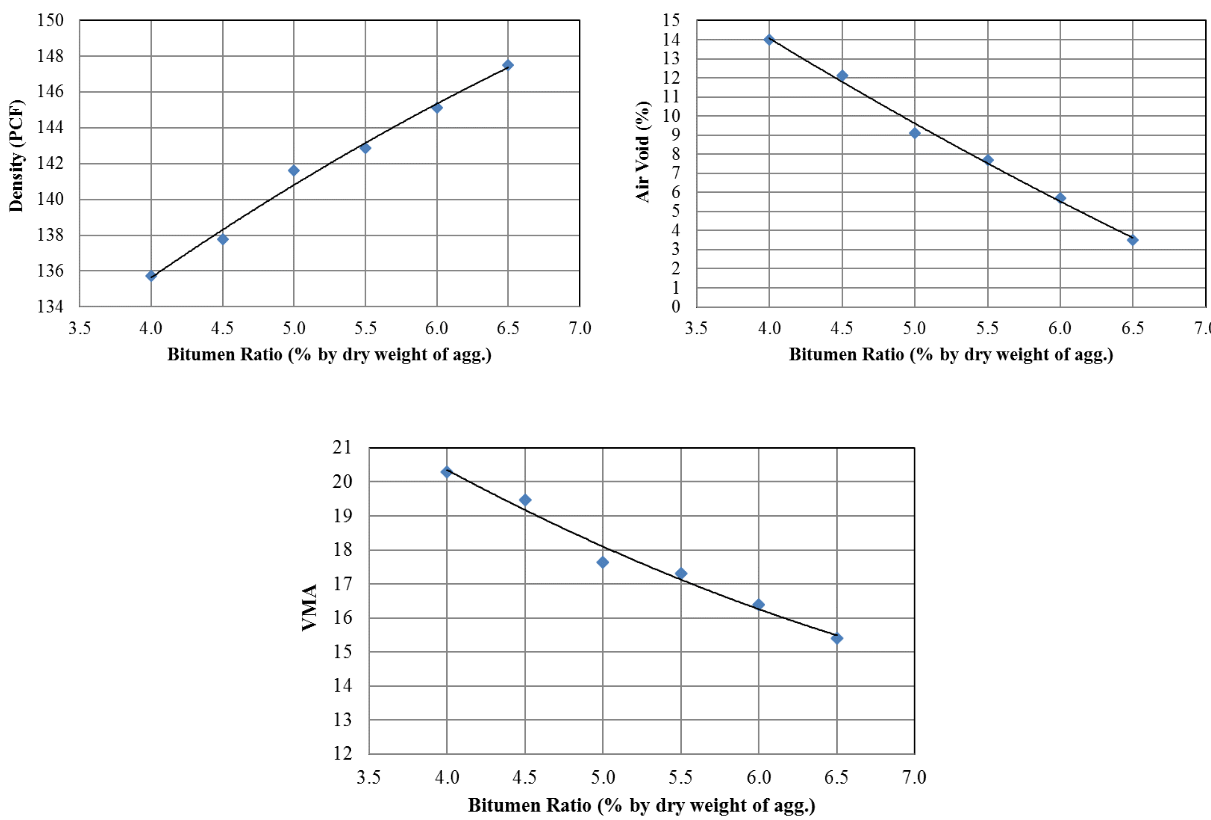


Figure 59. Density, air void and VMA (binder PG58-28, rubber am. #40, 15 %)

For the presented sample the rate of change of air void and VMA are declining with the increase of binder content while the density is improving. Five different specimens are made in this pack with binder content rating between 4 percent and 6.5 percent. Increasing trend for density indicates that the asphalt mixture still has the capacity for more binder to be added. In general, asphalt mixture density increases with binder for lower binder contents but by adding more binder this trend changes and tendency for density is declining for higher binder content.

Generally, asphalt mixtures made with non-modified asphalt lead to a bell shape graph for binder content between 4 to 6 percent. Considering the fact that in this research rubber modified asphalt binder is used, it sounds like rubber has improved the capability of asphalt to be mixed with higher binder content. This is probably because rubber has higher absorption rate and absorbs part of the binder. It is due to the surface area of the rubber particles, especially for ambient ground rubber. The other reason can be related to surface of the aggregates and the way rubber modified bitumen fills the voids between aggregates.

Air void and VMA both demonstrate diminishing trend which is typical for asphalt mixture. This trend indicates that binder is filling the voids between aggregates and creates a coherent environment for aggregates to stick together and are compacted. It is necessary to indicate that increasing binder content can have an opposite influence on mixture air void if binder content exceeds certain limits. The results of volumetric properties of asphalt mixture are presented in appendix B.

4.8. Stability properties of asphalt mixture

It is mentioned in previous chapters that in order to select optimum binder content combination of volumetric properties with stability of mix samples have to be analyzed together. The results of stability test which are obtained from Hveem stability equipment are illustrated in figure 60 for the same sample mentioned above.

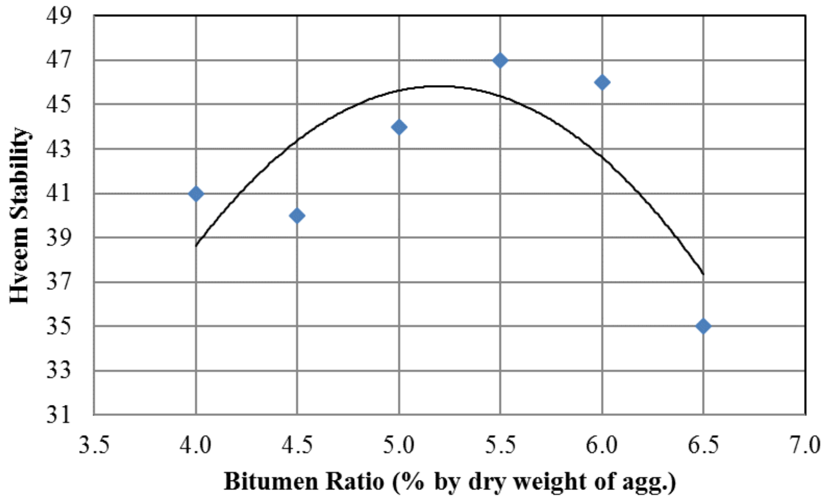


Figure 60. Hveem stability of rubber modified asphalt (Binder PG58-28, rubber am. #40, 15 %)

The bell shape graph indicates that sample's stability improves with the increase of rubber modified binder but suddenly declines as binder content reaches to a certain percentage. For asphalt mixtures made with binder PG 58 -28 modified with 15 percent ambient # 40 rubber, 5.2 percent sounds to be the best or optimum binder content. On the other hand, representatives generated with 5.2 percent rubber modified binder should have the highest stability.

But as mentioned, stability is not the only parameter which needs to be satisfied in order to find the optimum binder content. It is the combination of all four graphs that reveals the best binder content. Both air void and VMA have to be less than certain value to satisfy the requirements of standard which in this research is standards accepted by Nevada department of Transportation. Meanwhile the analysis of volumetric and stability behavior of asphalt mix samples revealed that rubber modified binder content presented in table 8 is the optimum binder content for each binder type and rubber size and type.

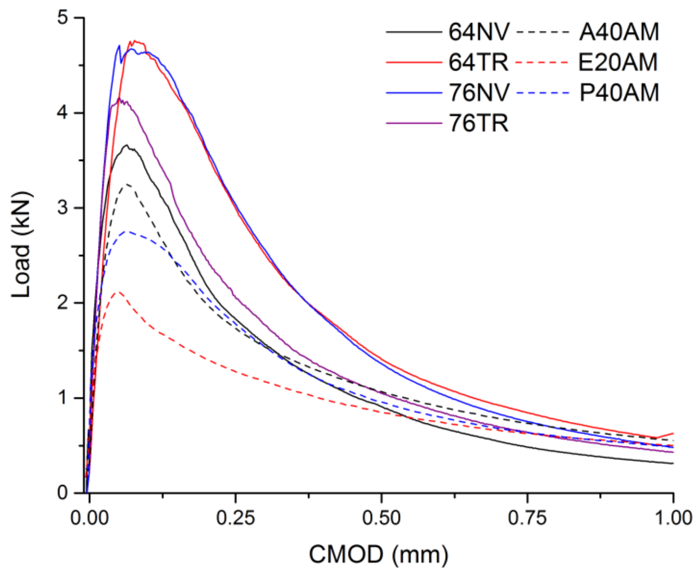
Table 8. Optimum binder content

Binder (type)	Rubber (percent/type/size)	Optimum binder content (%)
PG 64-16	+15% Am #20	6.7
AC 20	+15% Am #40	6.6
PG 58-28	+15% Am #40	6.4
PG 76-22 NV	-	5.8
PG 76-22 NV	Terminal Blend	6.0
PG 64-28 NV	-	5.0
PG 64-28NV	Terminal Blend	5.0

Modifying asphalt with rubber leads to relatively higher optimum binder content compared to traditional asphalt mixtures made with non-modified binder, as it is illustrated in table. This increase in binder content can lead to more durability but also higher cost.

4.9. Performance properties of asphalt mixture

The average values of loading response resulted from semicircular bending test on asphalt mix samples are presented in figure 61. All experiments were carried out in -12°C. From this graph it is clear that asphalt mix made with terminal blend rubberized asphalt grade PG 64-16 has the highest value, followed by mix samples made with virgin binder PG 76-22. Samples made with rubberized asphalt display lower values which means rubber modified asphalt mix has lower resistance to loading. Based on this results it can be concluded that rubber modified asphalt could not resist higher loads in cold temperatures in comparison to pavement made with virgin rubber.



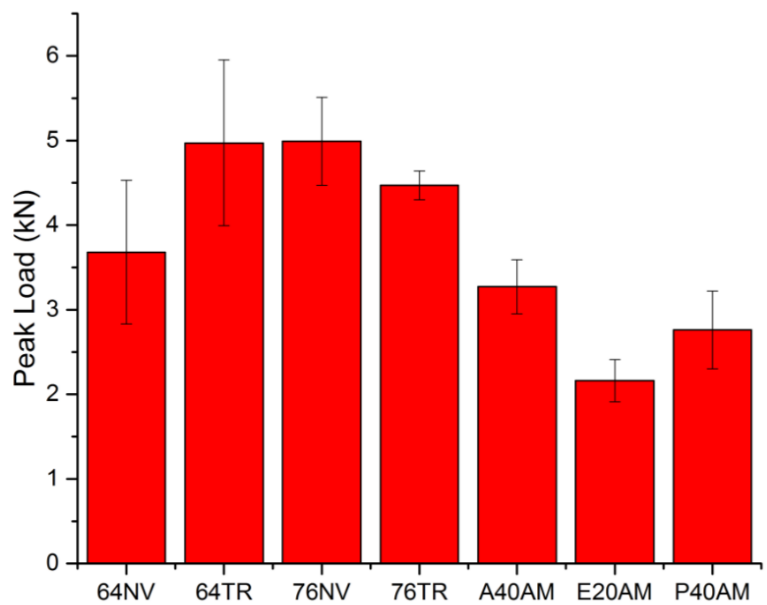


Figure 61. The average values of loading response under SCB test

The average total fracture energy for each sample then was calculated based on the results of SCB test which is illustrated in figure 62. Fracture energy results are used to determine the sensitivity of various mix samples. The observations indicate similarity between fracture energy and loading response. Moreover, asphalt mixture produced with binder PG76-22 has the highest value while for PG64-28 and PG64-16-AM -20-15 the value of fracture energy are almost similar and indicate the lowest values. Besides, it can be observed that asphalt mixtures manufactured with PG76-22TR, AC20-AM-40-15 and PG58-28 –AM-40-15 resulted in similar values for fracture energy.

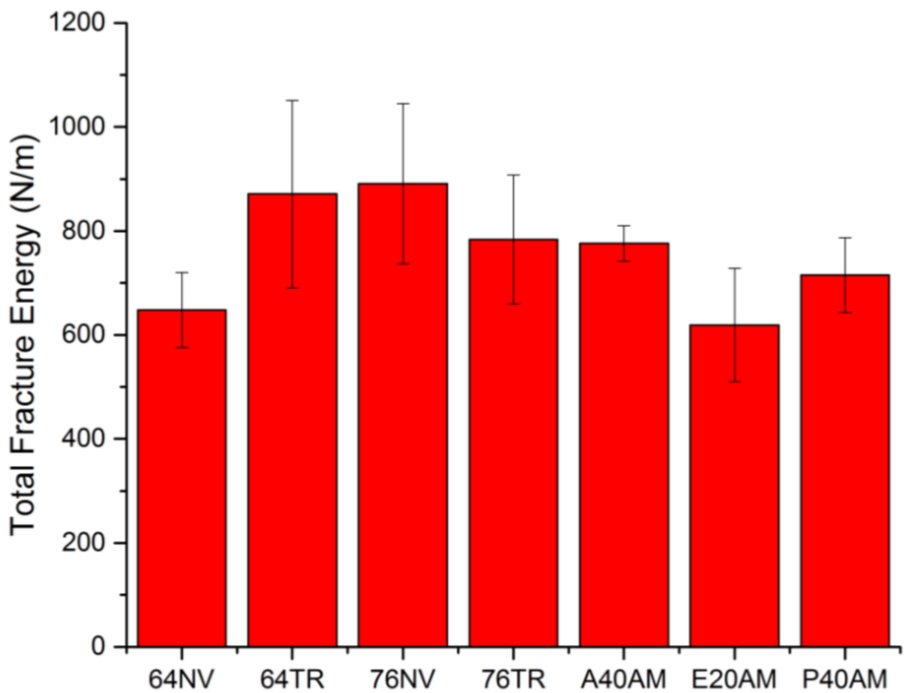
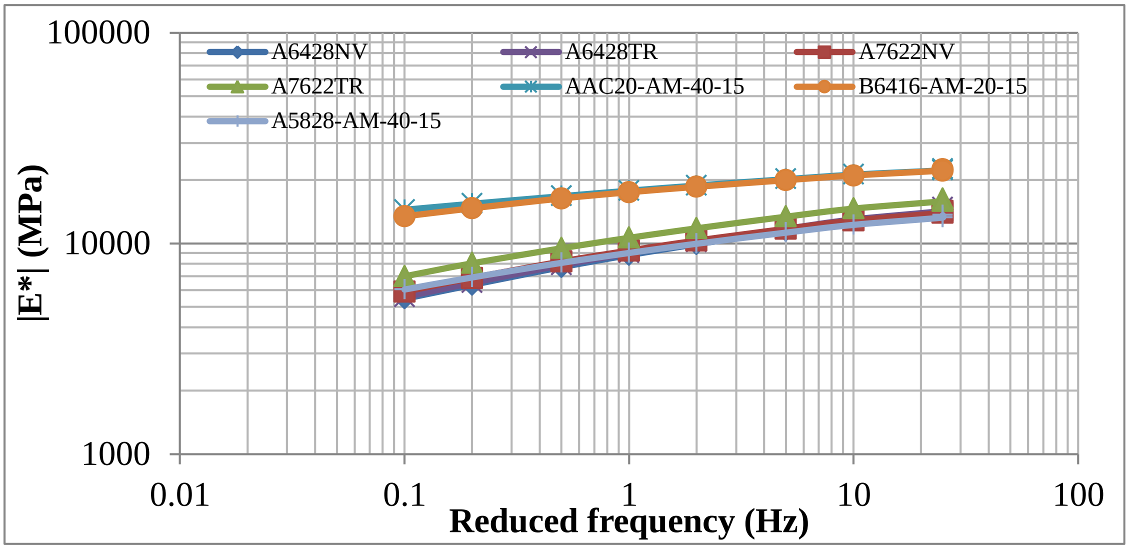


Figure 62. The average fracture energy values under SCB test

To conclude the results of SCB test it has to be indicated that rubber modified asphalt mixtures could have lower resistance to peak loads compared to traditional non-modified asphalt mixtures. But based on fracture energy results, both rubber modified asphalt and non-modified asphalt have similar resistance to low temperature cracking. In addition, this experiment demonstrated the importance of binder source and its influence on determining fracture energy.

Based on the results of dynamic modulus test it is observed that samples made with modified binder AC20-Am-40-15 has the highest dynamic modulus followed by mixtures produced with

B64-16-Am-20-15. This is regardless of the test temperature. Also as it is illustrated in figure 63, mixtures made with 64-28 TR and 76-22NV have the lowest dynamic modulus regardless of tests temperature. Rubber modified samples demonstrated higher dynamic modulus values except 58-28-Am-40-15 which has lower dynamic modulus.



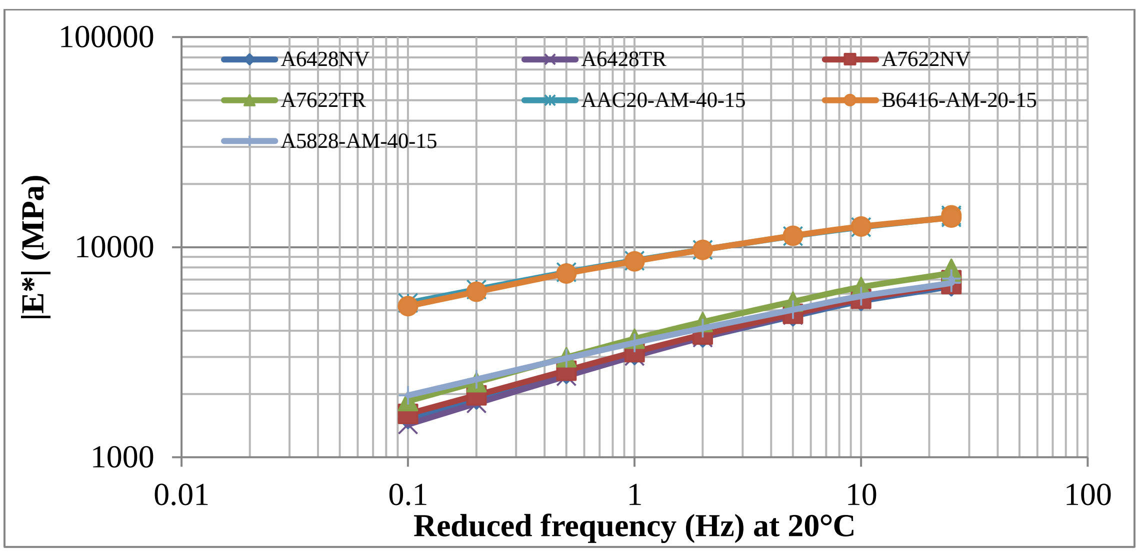


Figure 63. Dynamic modulus of the samples at 4 °C and 20° C

In regard to flow number, it is which has the highest value. In general samples made with 15 percent rubber have higher values except 58-28-Am-15 which has the lowest flow number. The results are displayed in figure 64. In general having higher flow number and dynamic modulus means having better performance in terms of resistance to rutting. On the other hand because of the fact that rubber modified samples demonstrated higher dynamic modulus, they will show more resistance to rutting as pavement.

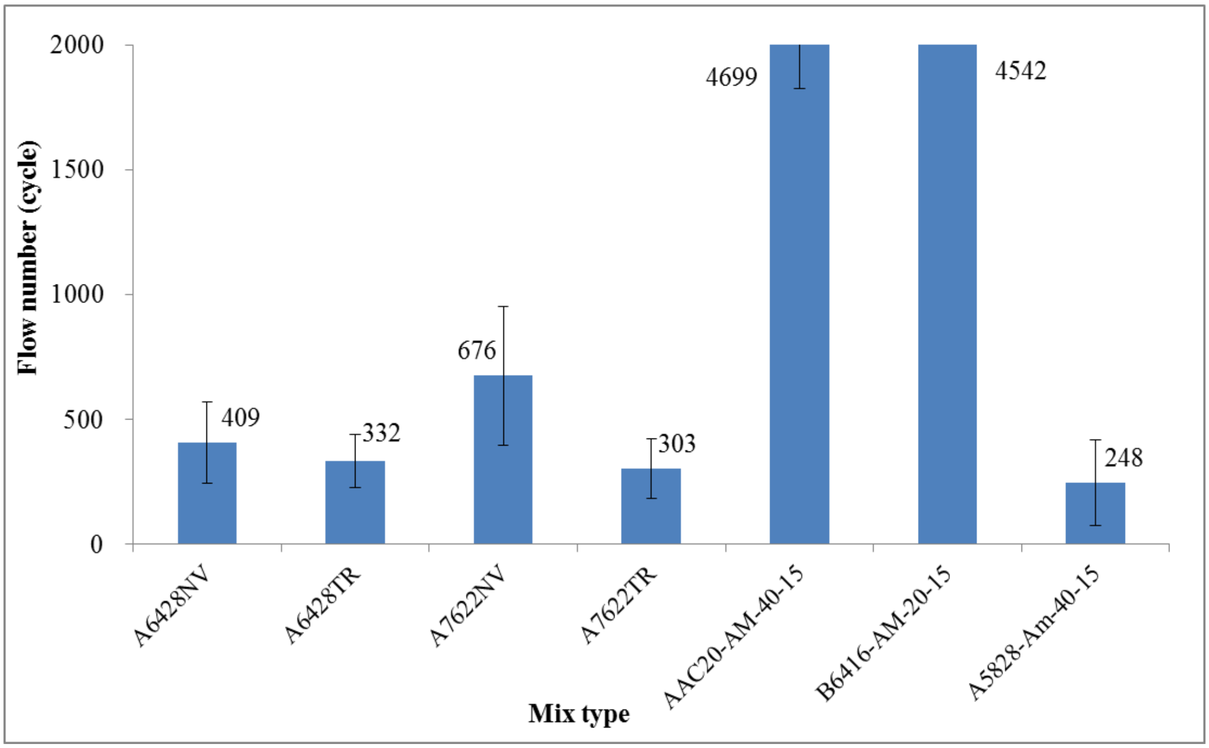


Figure 64. Sampls flow number at 59°C

One the main reasons behind conducting this study was performing tests with local materials. Based on the results it can be seen that material type has inevitable influence on the performance of the asphalt. It is obvious that source binder plays a key role in determining values for flow number and dynamic modulus as well as other parameters. The results of the test at 40°C is in appendix B.

4.10. Analyzing ultrasound test results

The goal of conducting ultrasound measurements on asphalt mix samples were finding any correlation between wave velocities or integrated response (IR) with asphalt performance resulting from other experiments. Considering the fact that there were sufficient samples made with various binder types, aggregate sources and rubber content it was expected to investigate and discover the influence of these parameters on ultrasound measurements.

In order to achieve the expected goals, it is necessary to use the same ultrasound transducer probes and fix all other properties such as frequency and bandwidth for all mix samples. During the investigation it was observed that some of the samples did not respond properly to the ultrasound wave, especially samples made with higher rubber content. On the other hand the wave propagation was highly defective and not reliable to record time of flight and integrated response. Therefore eliminating packs made from several sources was inevitable.

It is assumed that, the defective wave propagation in rubber modified samples was due to flexibility of the mixture as well as having uneven surface area. Sample pack presented in figure 65 illustrate specimens which no wave propagation observed with selected ultrasound properties.

Figure 65. Pack of samples leaded to defective wave propagation

By changing the wave properties like using different frequency it was observed that it is possible to get a relatively better wave shape in response but it was in contrast with other packs. On the other hand, in order to measure ultrasound properties of rubber modified asphalt mixtures other transducer probe with different propagating wave properties are required. In this experiment, contact transducers were used. It is possible to get another results with the use of non-contact method for flexible rubber modified asphalt mixtures.

4.10.1. Wave Velocity

Meanwhile, the research on other packs demonstrated some correlation between wave speed in asphalt mix sample and binder content. In the beginning the assumption was measuring the ultrasound wave response in five points of the surface, but after performing measurements on several samples, this idea changed to finding wave response in the middle of each sample which showed more reliable wave shape. It is necessary to mention that there were three specimens for each binder content in each pack. Several representatives were highly damaged or had uneven surfaces which it was impossible to get a reliable wave respond. These samples also were illuminated. Figure 66 exhibits the results of measurements on all samples. In this graph the average of wave speed is calculated and used.

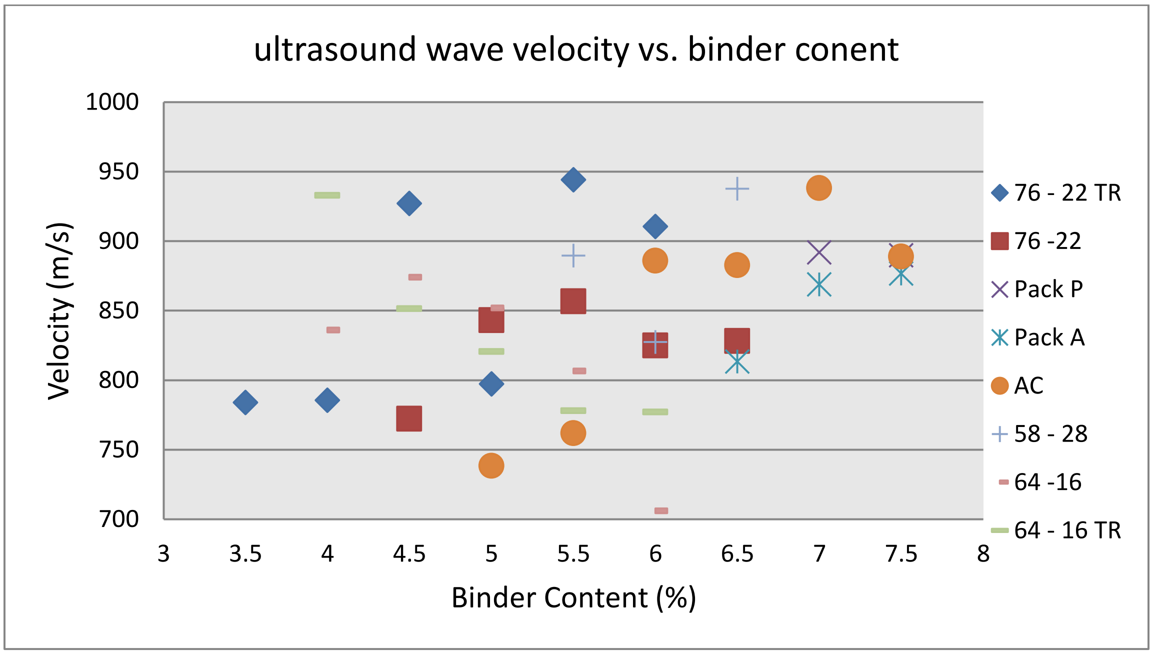


Figure 66. Ultrasound wave velocity on asphalt mix samples

Taking a close look at this graph reveals that wave speed is increasing with the increase of binder content for most packs while increase in binder content has negative influence on wave speed propagated in several other packs. This difference in wave speed trend possibly demonstrates the influence of binder type and aggregate source on ultrasound properties of asphalt mixture. For some specimens though this trend is increasing at the beginning and declining when higher binder content is used. Figure 67 illustrates ultrasound wave speed in samples made with terminally blended rubber modified binder. In this pack binder grade is PG 76-22 and three specimens were made with every binder content.

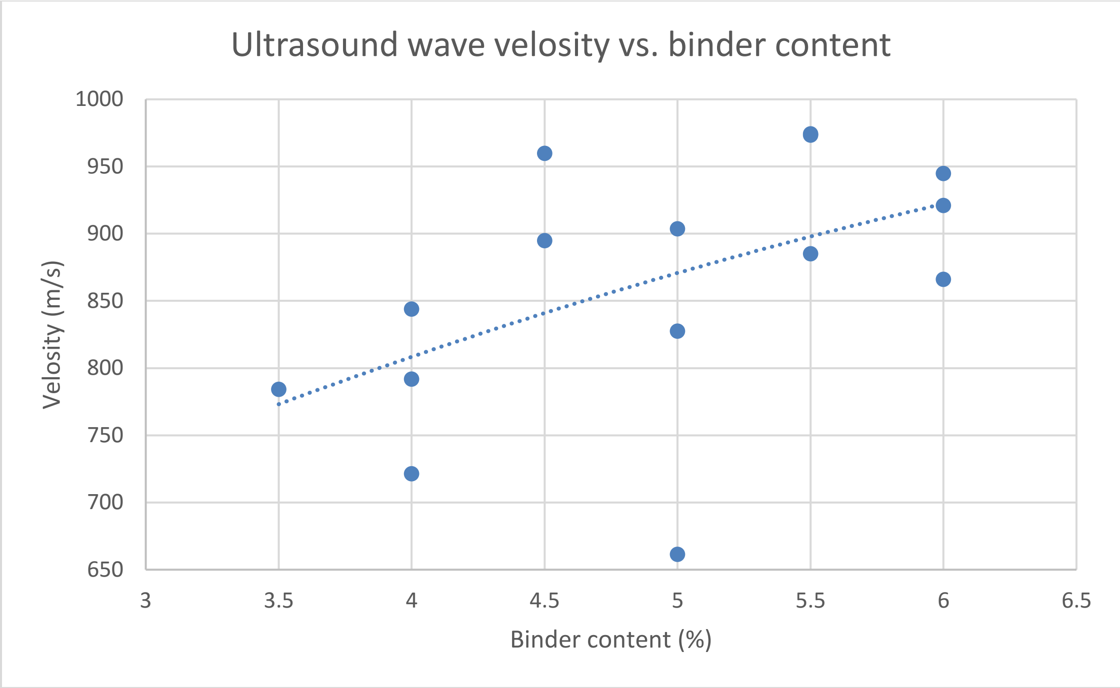


Figure 67. Ultrasound wave velocity on asphalt mix sample PG 76-22 TR

As it can be seen in this graph, in general, wave speed in asphalt mix samples is increasing relevant to binder content in this pack. The increase in wave speed sounds to be steady with adding more binder in asphalt mixture, though specimens produced with 4.5 percent binder displayed higher wave speed. For mixtures made with 3.5 percent binder, two samples and for mixture made with 4.5 percent binder, one specimen were highly damaged and just wave response for one sample out of three was recorded.

The trend of wave speed increases for some packs and then decreases as the binder content rises more. An example is presented in figure 68 which is for a pack of specimens manufactured with non-modified binder grade PG76-22. There is an obvious increase in wave speed with binder content in the beginning, then this trend changes and wave speed decline. The highest wave speed is observed in mixture sample made with 5.5 percent of binder. The point is, for this pack also asphalt mixture with 6.5 percent binder shows higher wave speed in comparison to specimen with 4.5 percent of binder content.

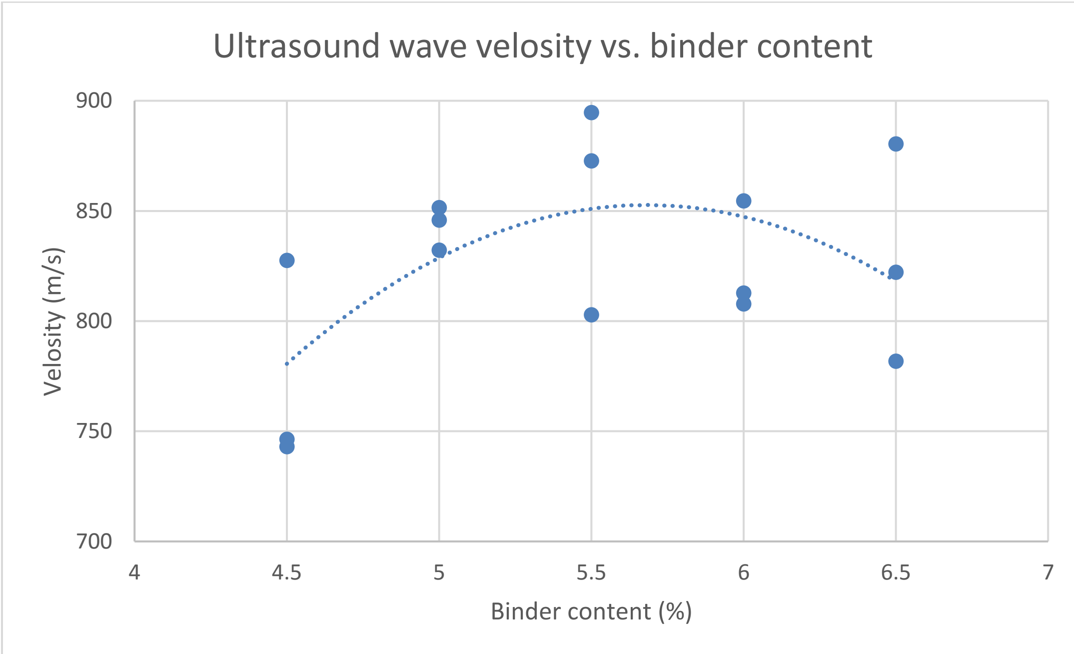


Figure 68. Ultrasound wave velocity on asphalt mix sample PG 76-22

Samples generated with binder type 64-16 the trend for wave speed is the opposite of what mentioned in above paragraphs. As a sample is presented in figure 69, wave speed diminish as binder content increases. The trend of decreases in wave speed for this pack is relatively sharp for lower binder content while for samples with higher binder content this trend is smooth. It has to mention that the number of specimens for each binder content in this pack was just one.

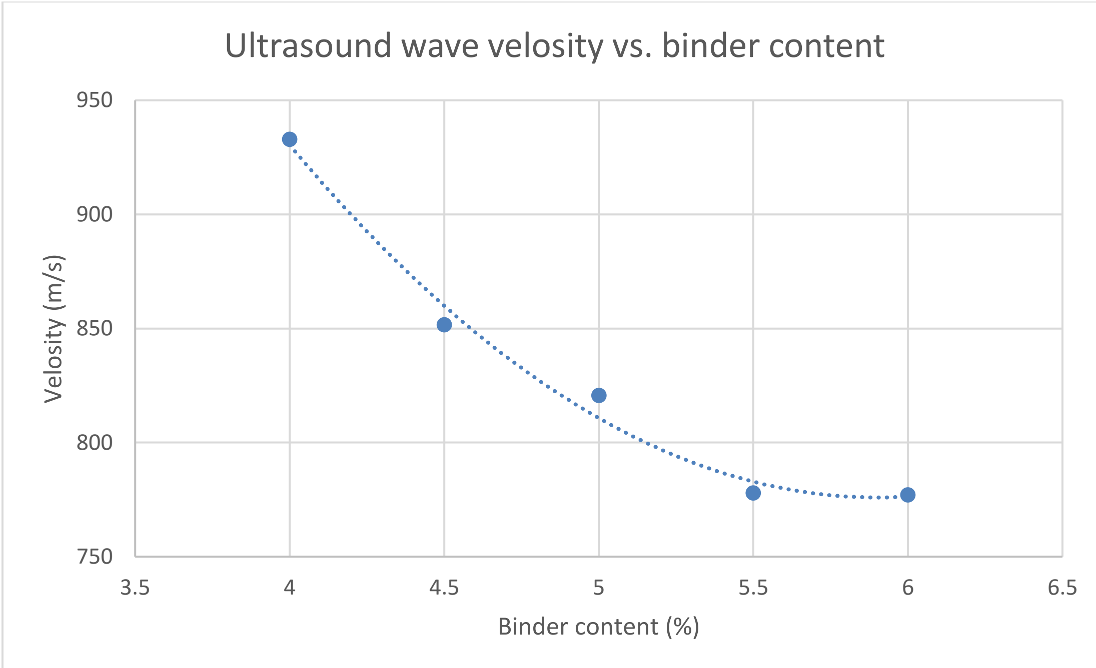


Figure 69. Ultrasound wave velocity on asphalt mix sample PG 64-16

4.10.2. Integrated Response (IR)

In contrast with wave speed, integrated response (IR) for all samples displays an increasing trend with the increase of binder content. Regardless of aggregate source or binder type this decline in IR is observed in all packs. For some packs the decline rate in absolute IR is smooth while for other packs a significant decline is observable. In general specimens demonstrated IR magnitude between -20 (db.) and -80 (db.). For some representatives the trend is sharp for asphalt mix samples made with lower binder content and smoothen as binder content increases while for other packs the decline rate is steady in relevant to binder content.

Figure 70 exhibits correlation between IR with binder content for all samples. The declining trend in integrated response is obvious in this graph. Figure 71 illustrates a sample with sharp decline in the beginning and then slow decrease for samples with higher binder content.

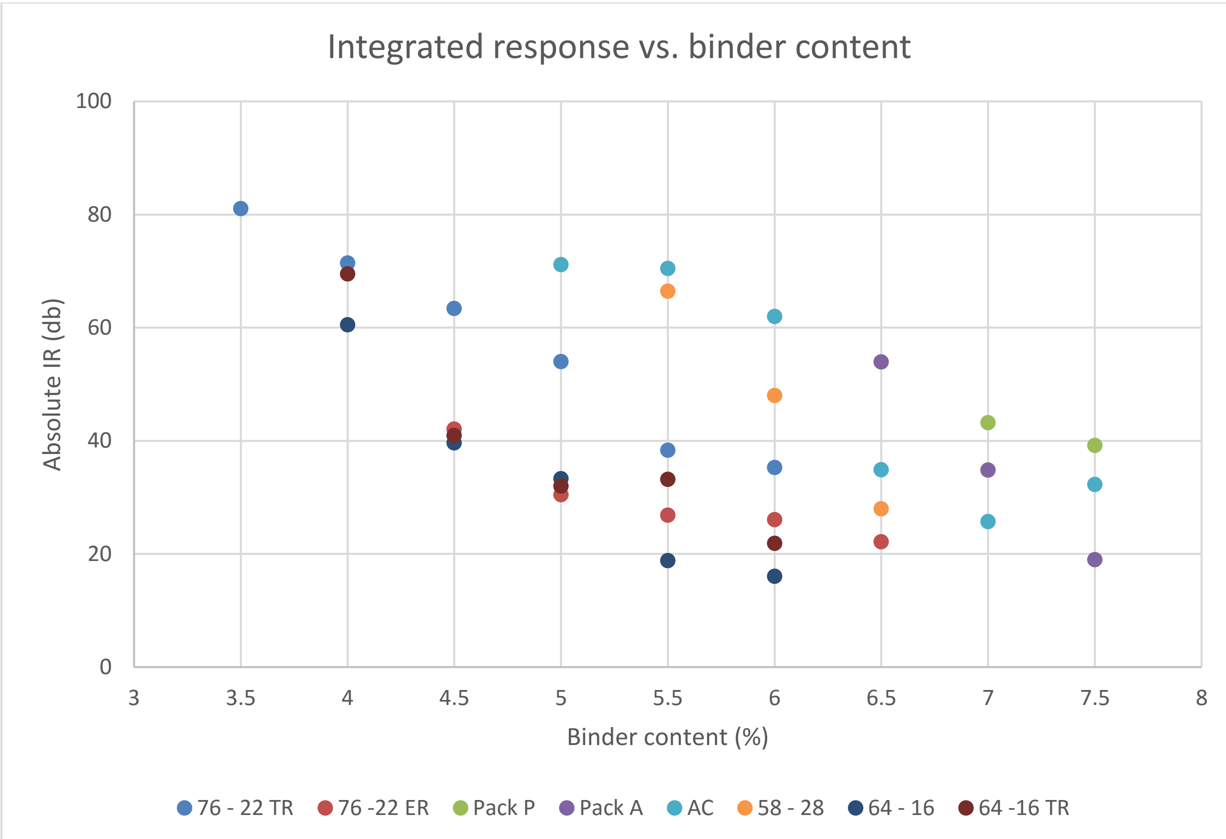


Figure 70. Ultrasound wave absolute IR on asphalt mix samples

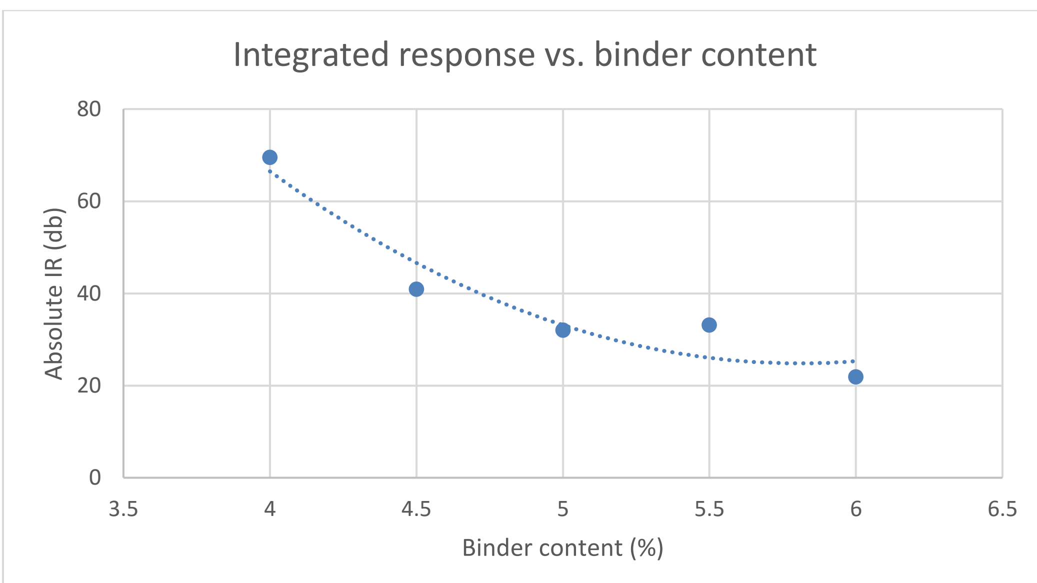


Figure 71. Ultrasound wave absolute IR on asphalt mix sample PG 64 - 16

4.11. Conclusion

Extensive testing and evaluations were carried out on various binder samples with different amounts of crumb rubber in order to find the best and optimum rubber content regarding to the binder source and type. In the second phase, various trial mix samples were made and evaluated. The results demonstrated a significant compatibility for crumb rubber modified asphalt binder with aggregate and binder sources as well as optimum binder content for each content. Ultrasound tests were carried out on samples to determine the variation of wave through each sample and the results were presented graphically. In addition, the survey will include evaluating graphs and finding any correlation between ultrasound results and other parameters as well as dynamic modulus and other properties of asphalt mix and binder.

4.12. Future Work

A possible future work can include the further analysis on compacted samples in order to find parameters such as aging resistance, durability, elasticity and flexibility. Because Nevada is in a hot and dry area, carrying full scale tests by installing trial pavement in order to find the influence of hot and dry weather on pavement can be subject of future works.

Appendix A

Full Tests Results on Asphalt Binder Samples

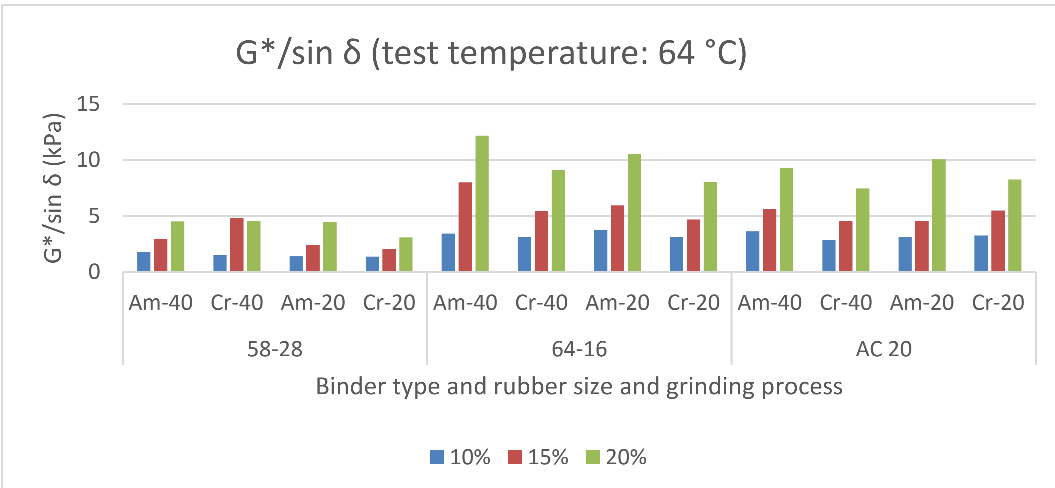


Figure A1. G/sin δ (test temperature: 64 °C)*

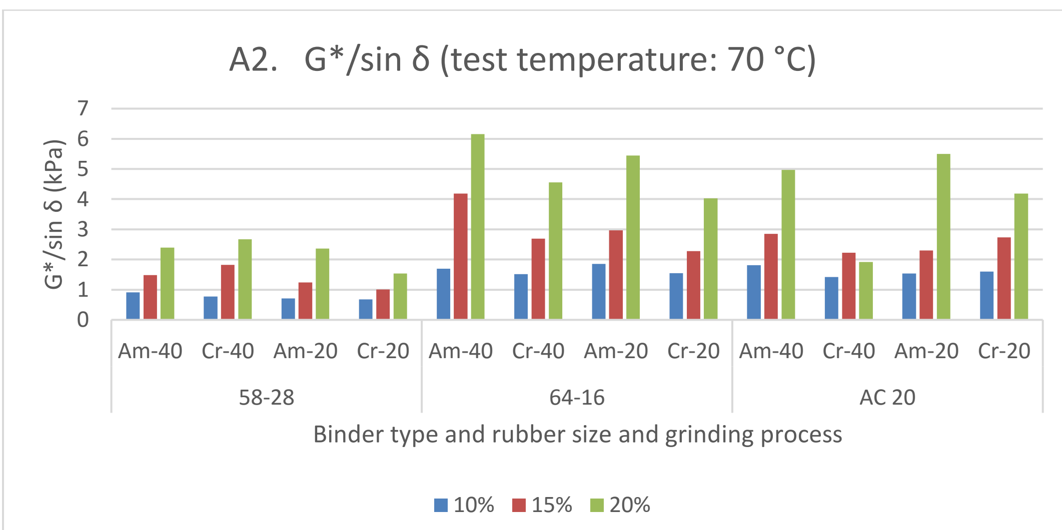


Figure A2. G/sin δ (test temperature: 70 °C)*

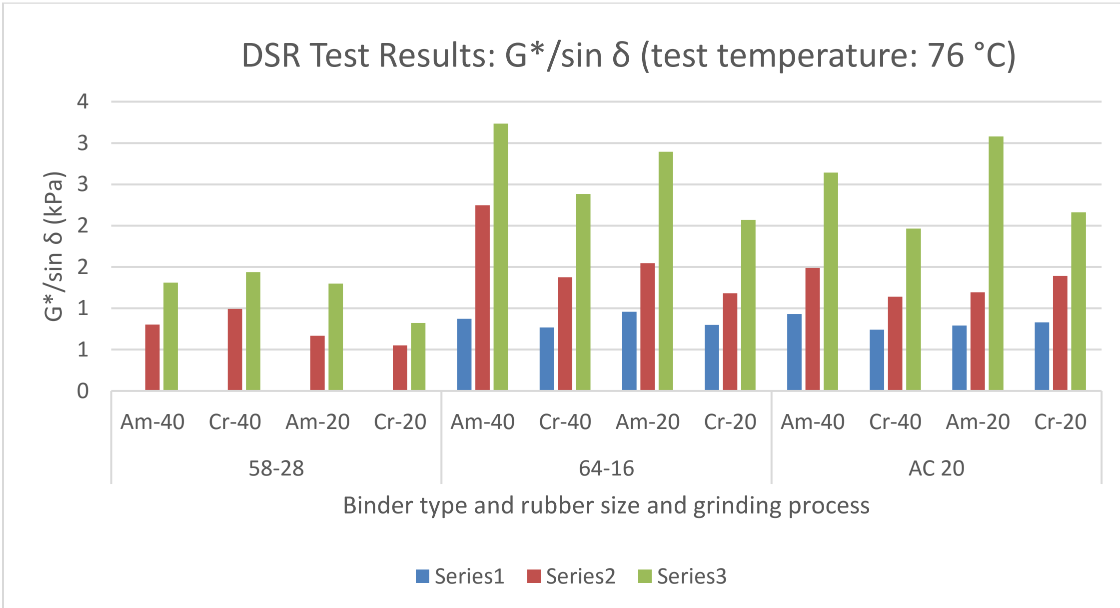


Figure A3. G*/sin δ (test temperature: 76 °C)

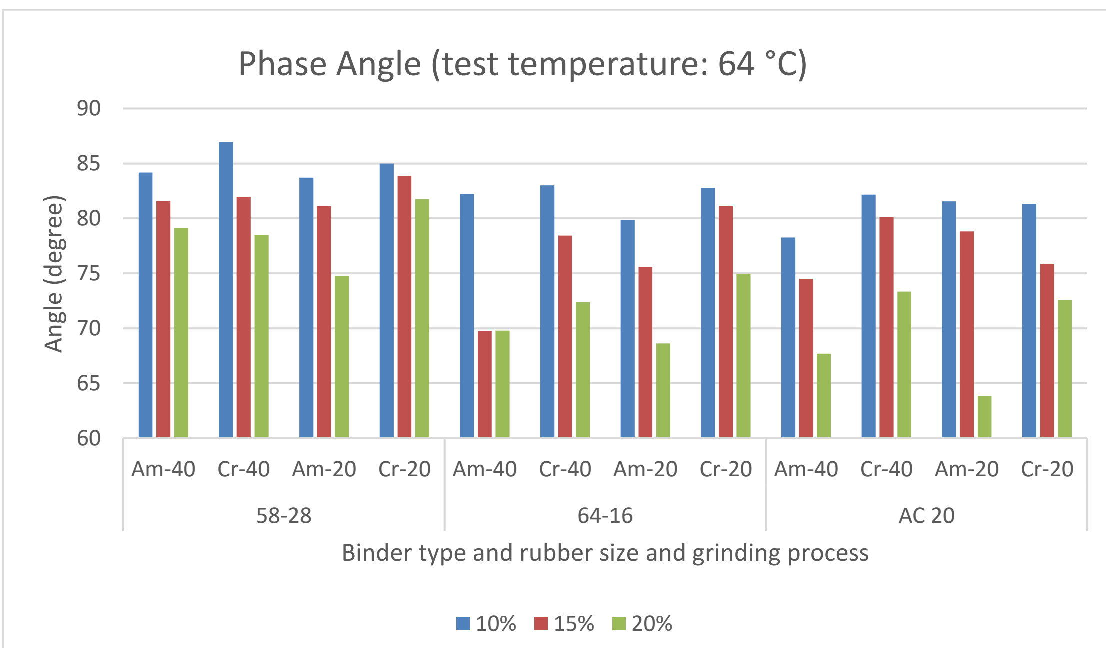


Figure A4. Phase Angle (test temperature: 64 °C)

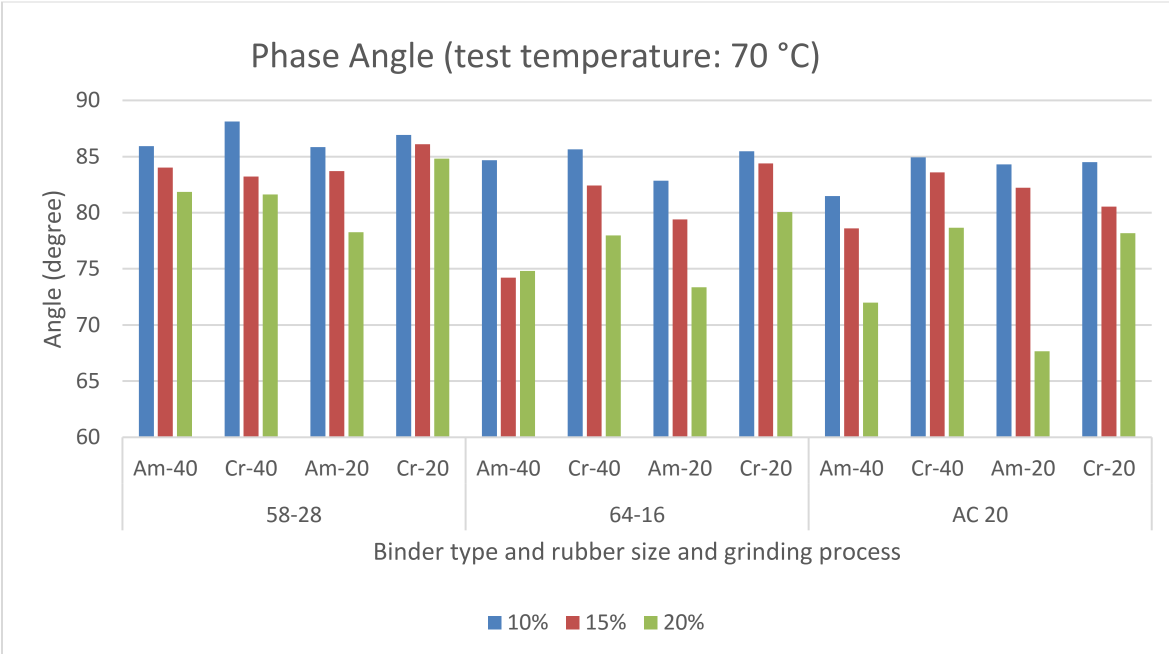


Figure A5. Phase Angle (test temperature: 70 °C)

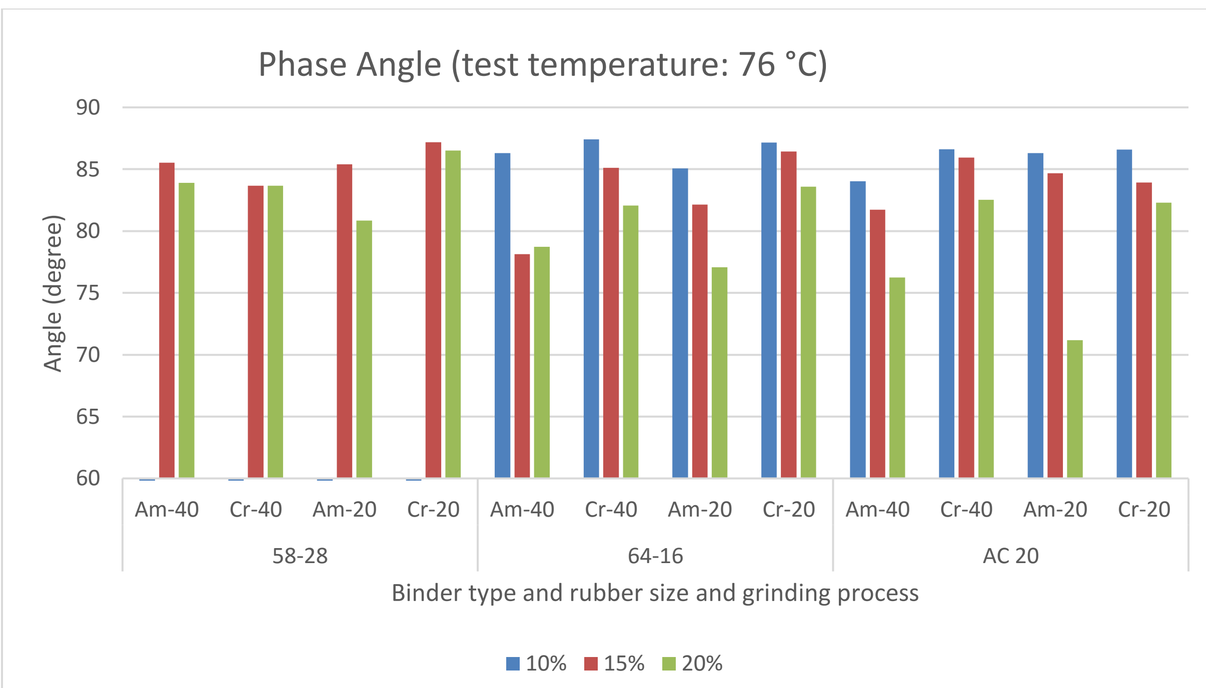


Figure A6. Phase Angle (test temperature: 76 °C)

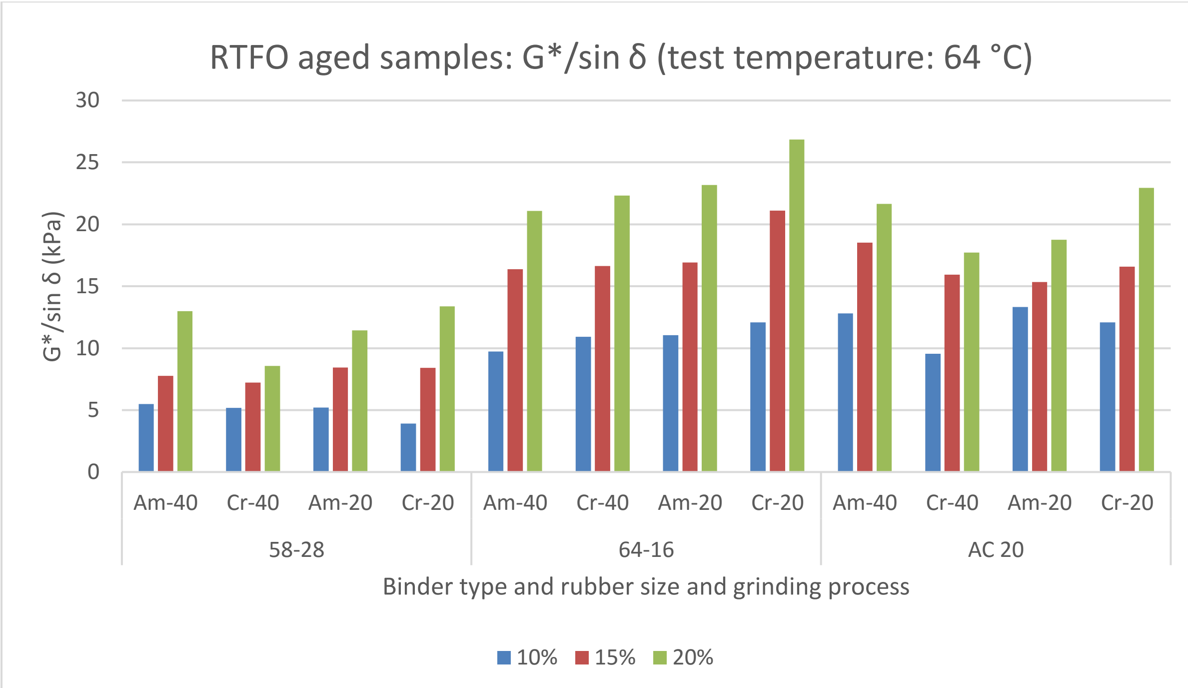


Figure A7. RTFO-aged. G/sin δ (test temperature: 64 °C)*

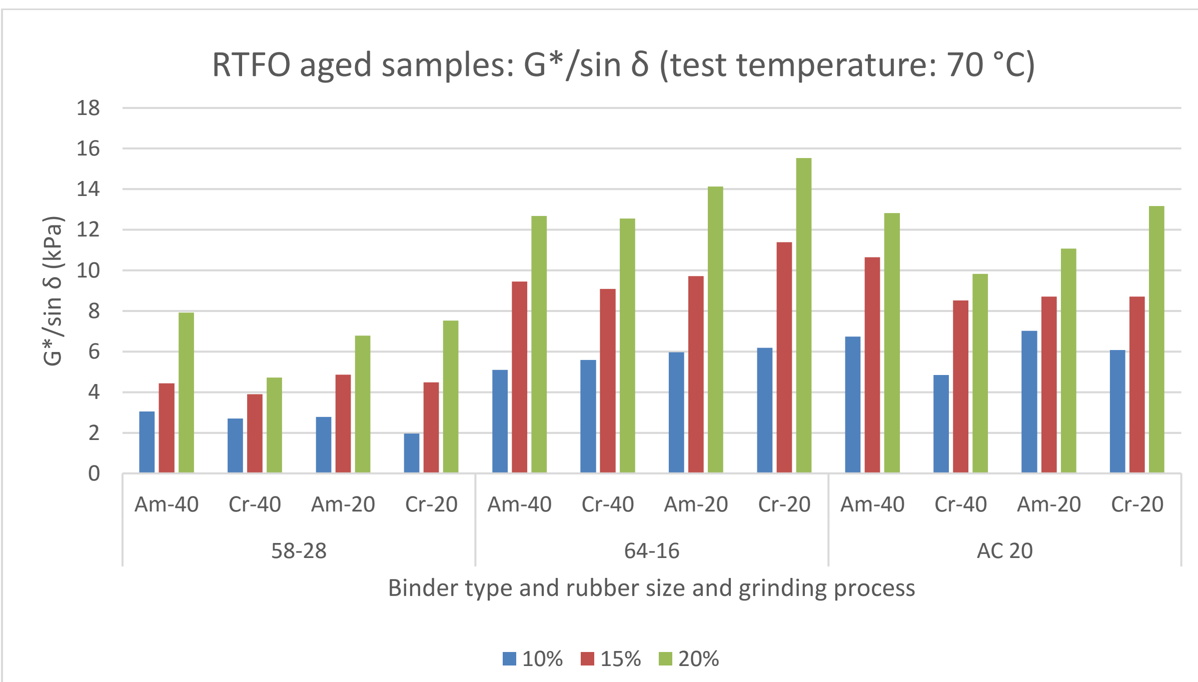


Figure A8. RTFO-aged. G/sin δ (test temperature: 70 °C)*

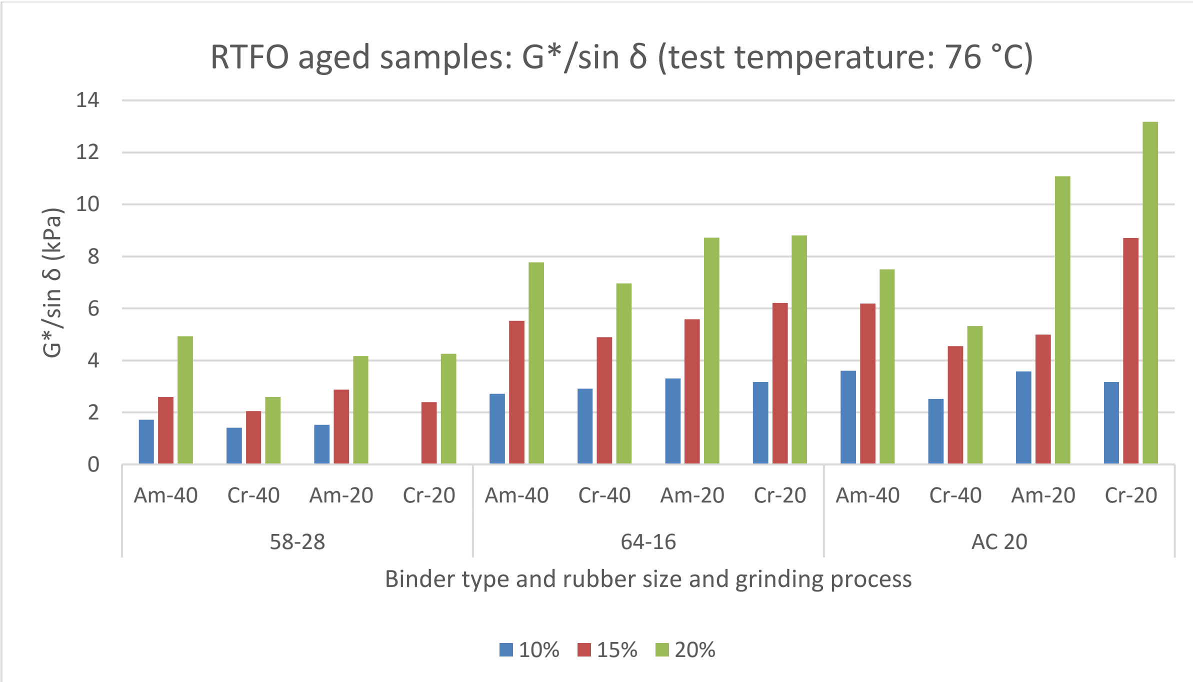


Figure A9. RTFO-aged. G*/sin δ (test temperature: 76 °C)

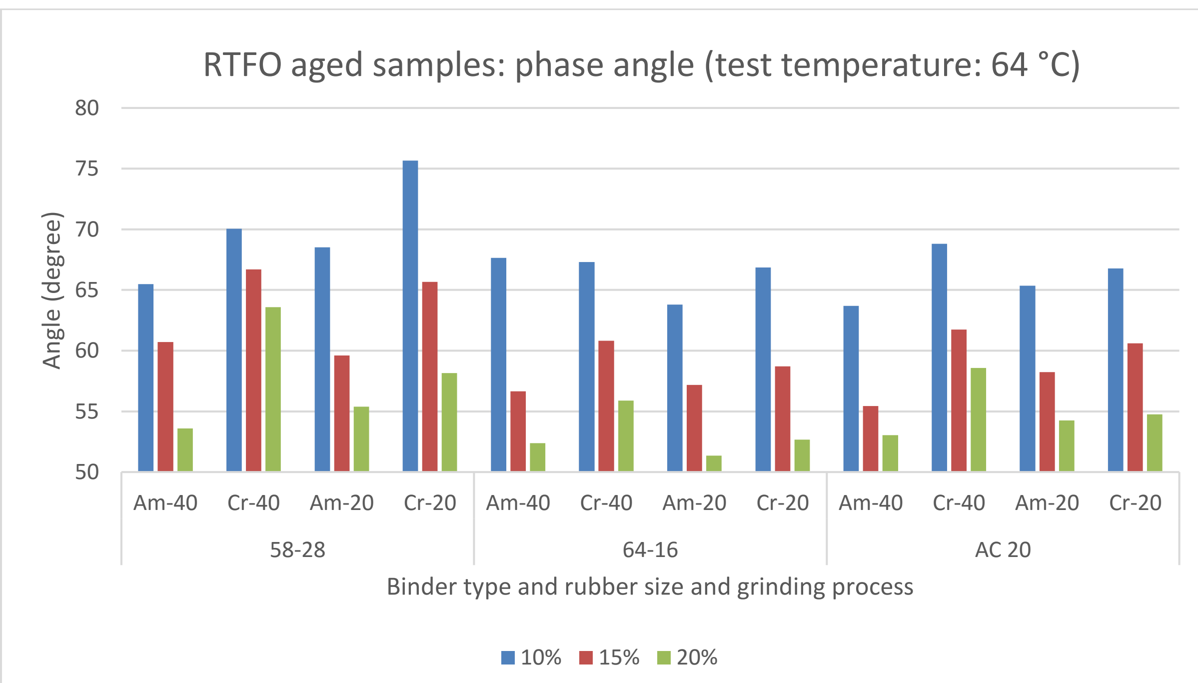


Figure A10. RTFO-aged. Phase Angle (test temperature: 64 °C)

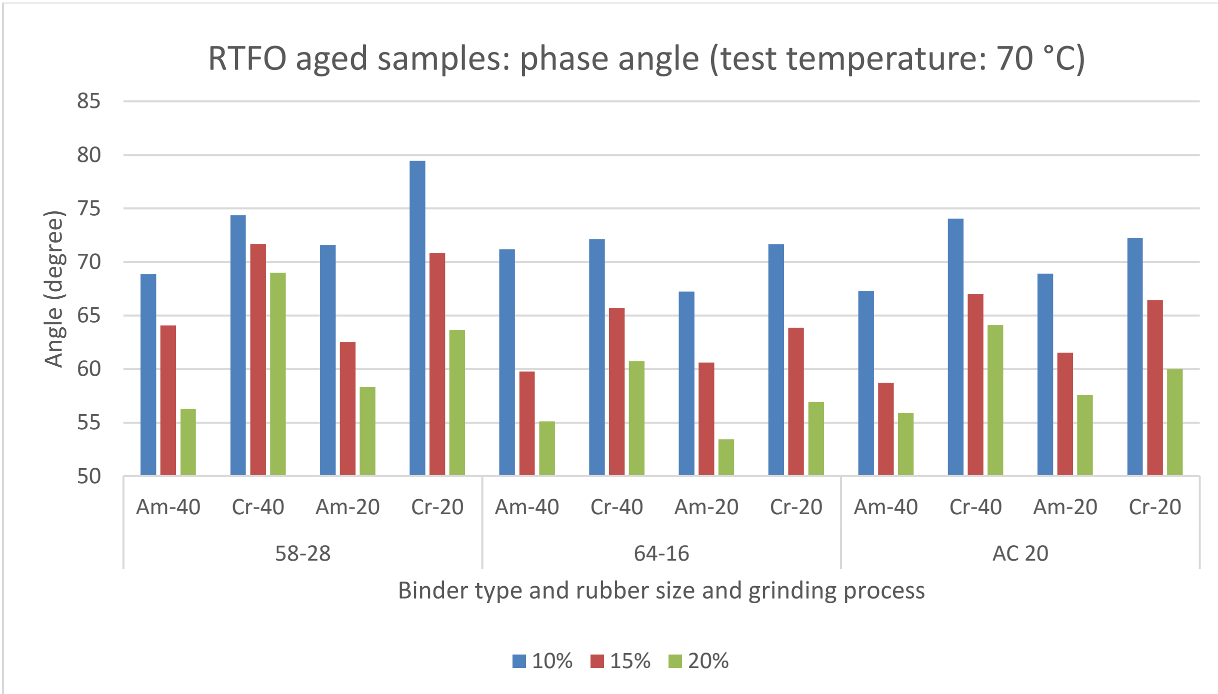


Figure A11. RTFO-aged. Phase Angle (test temperature: 70 °C)

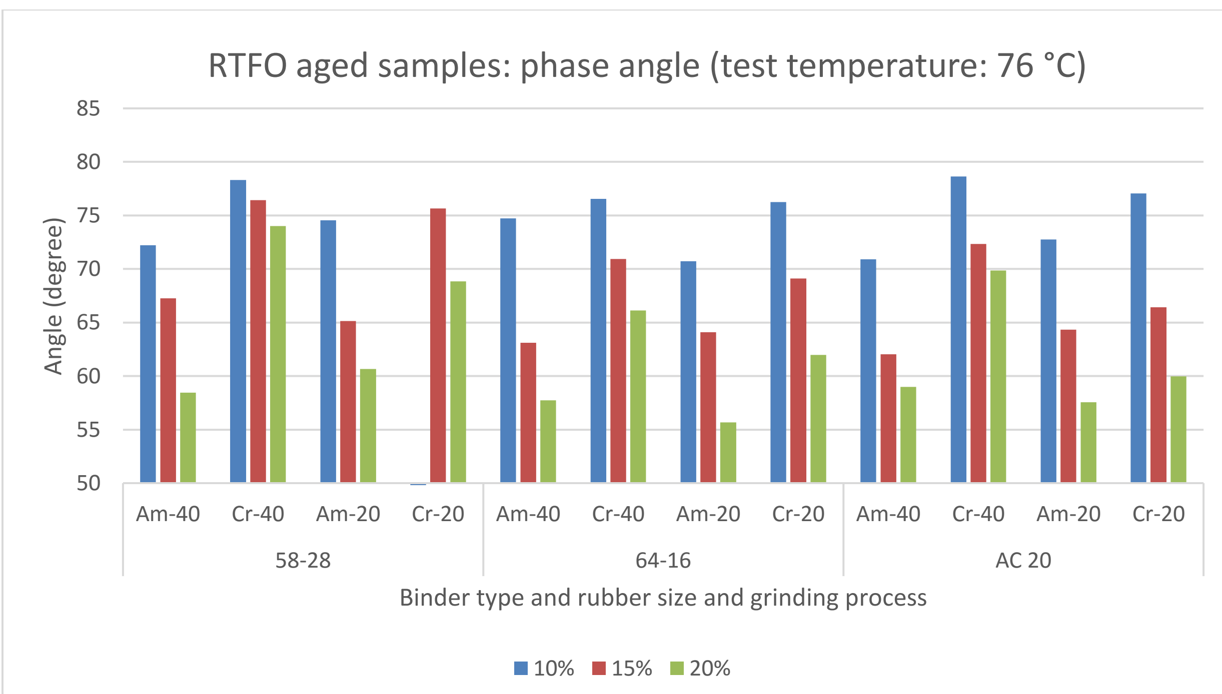


Figure A12. RTFO-aged. Phase Angle (test temperature: 76 °C)

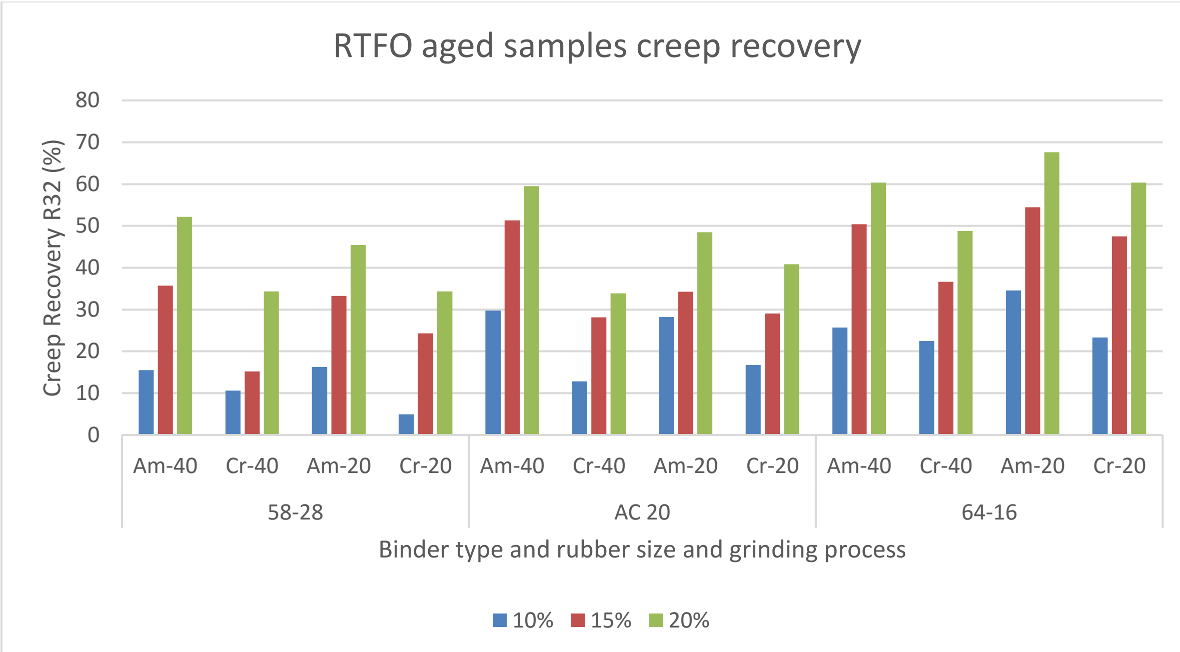


Figure A13. RTFO-aged. Creep recovery

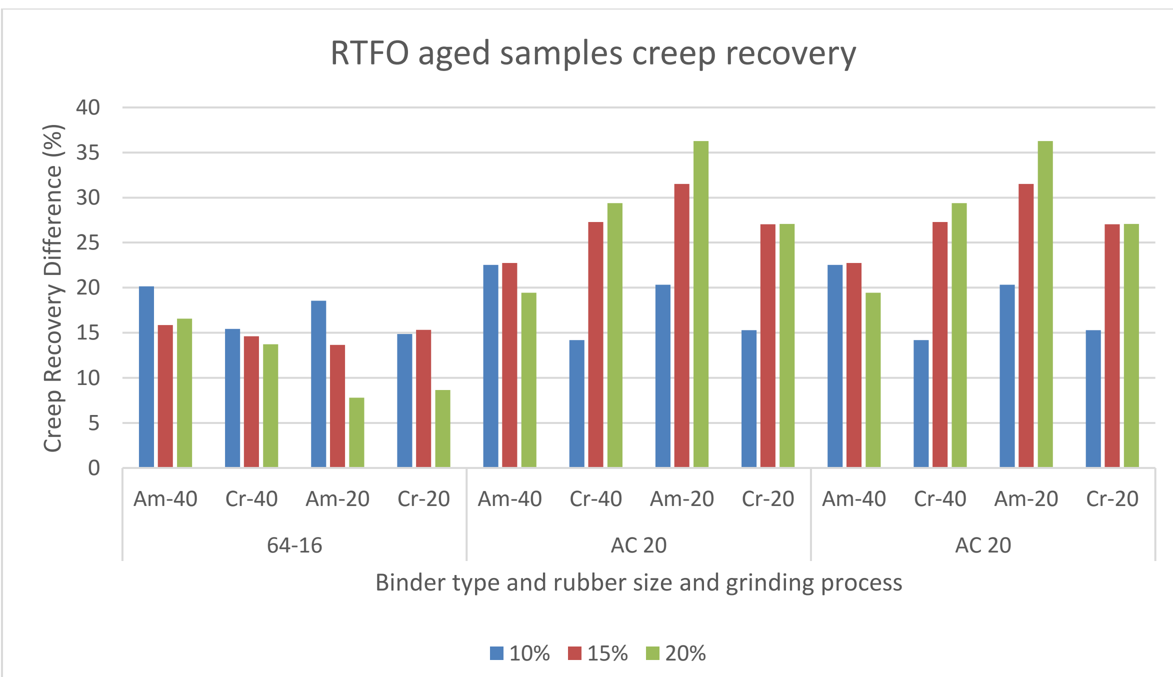


Figure A14. RTFO-aged. Creep difference

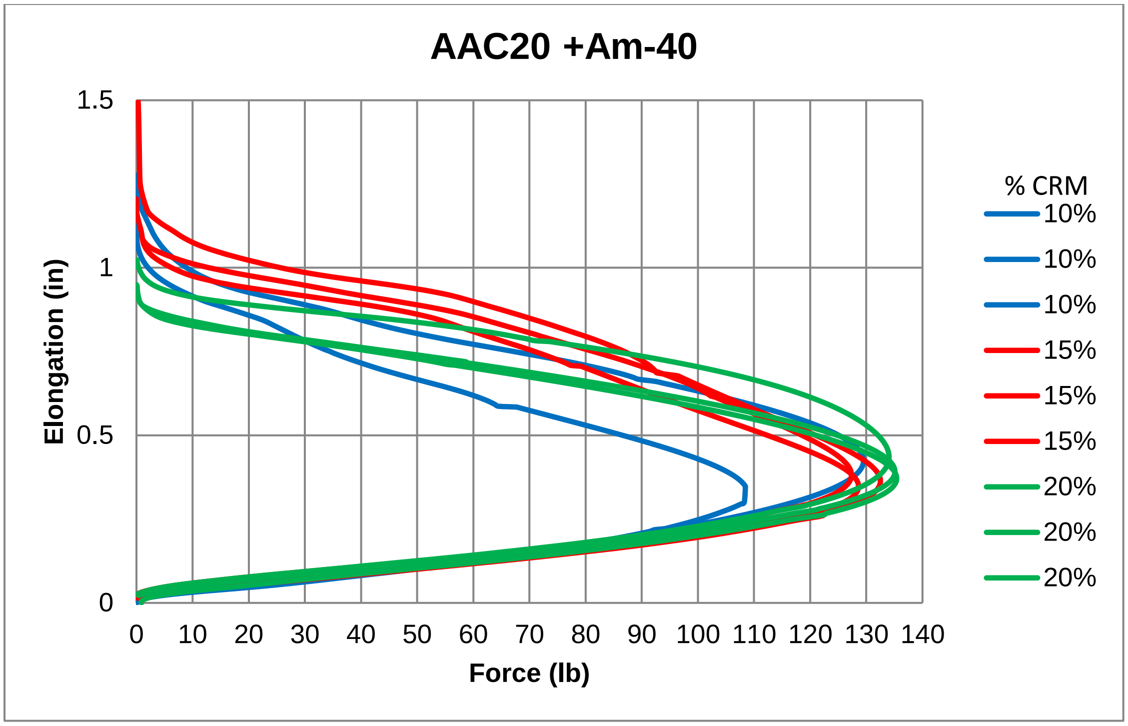


Figure A15. Toughness and Tenacity AC 20 – Am 40

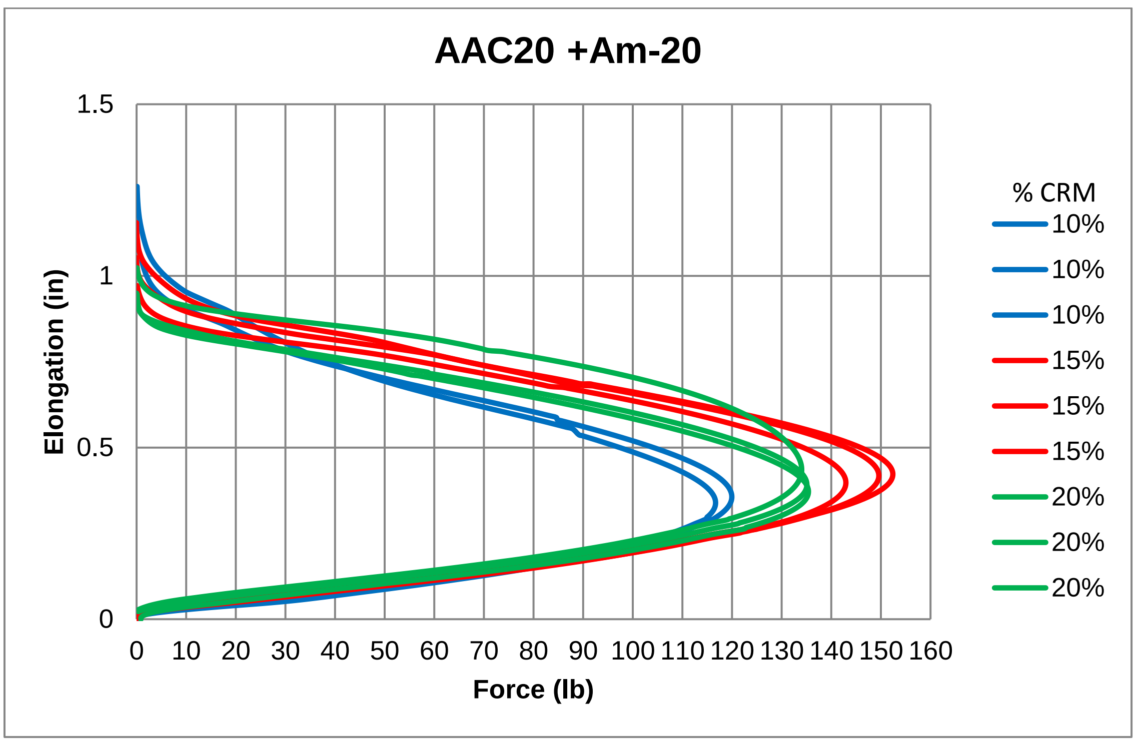


Figure A16. Toughness and Tenacity AC 20 – Am 20

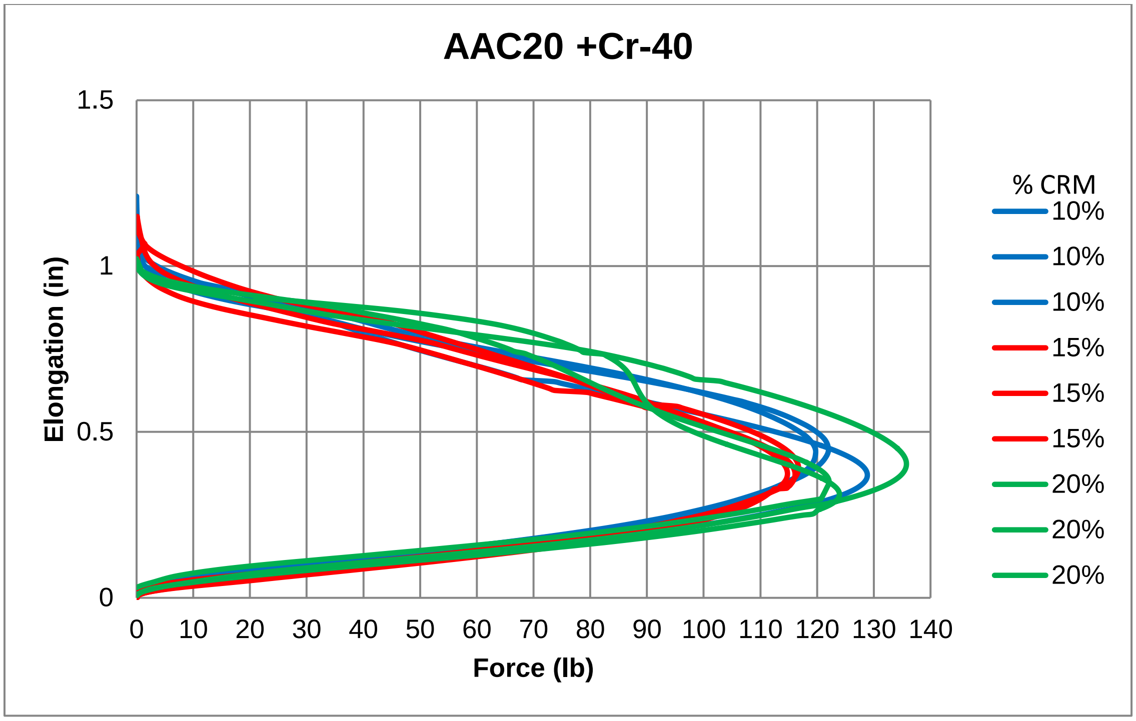


Figure A17. Toughness and Tenacity AC 20 – Cr 40

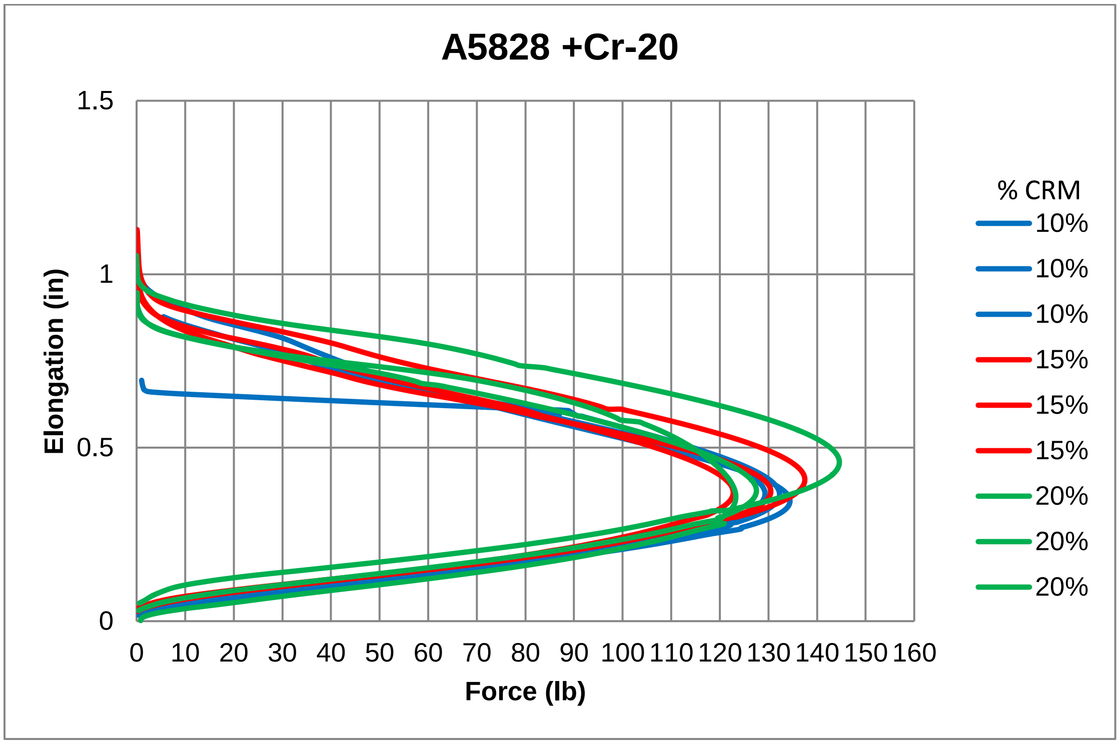


Figure A18. Toughness and Tenacity AC 20 – Cr 20

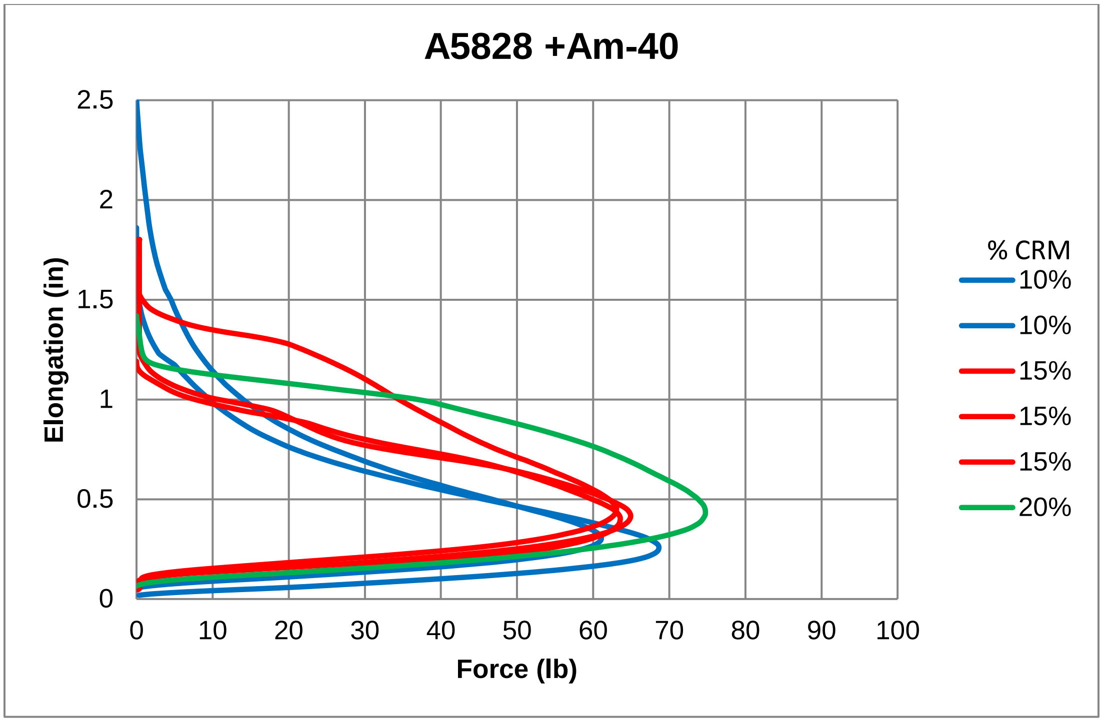


Figure A19. Toughness and Tenacity 58-28 – Am 40

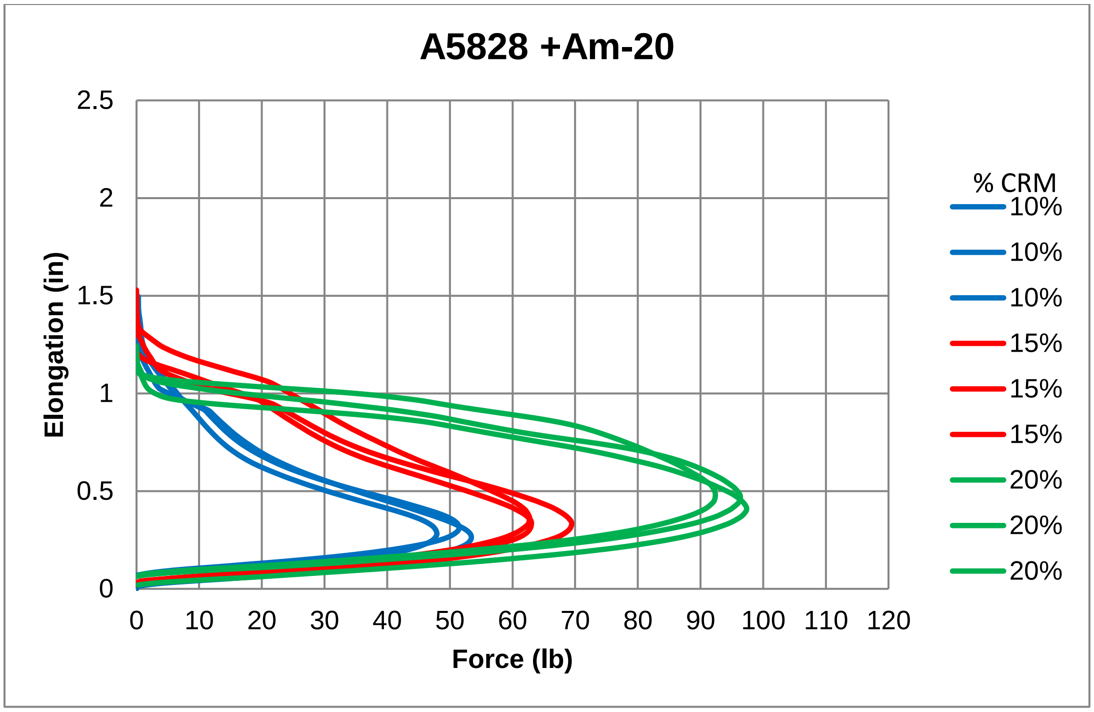


Figure A20. Toughness and Tenacity 58-28 – Am 20

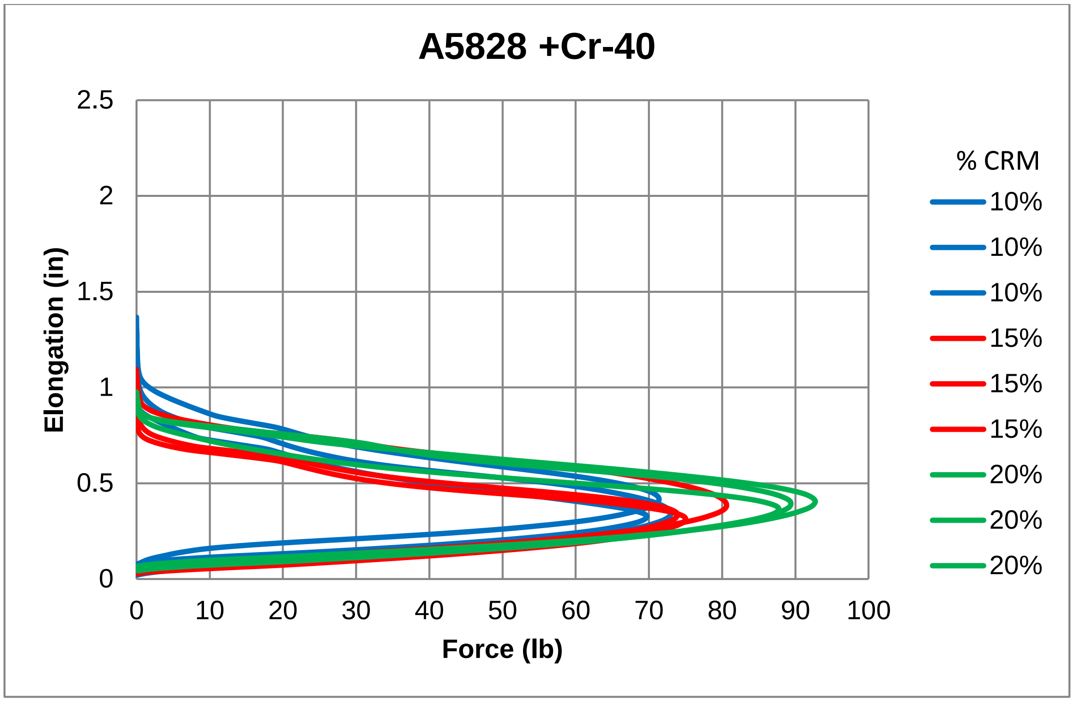


Figure A21. Toughness and Tenacity 58-28 – Cr - 40

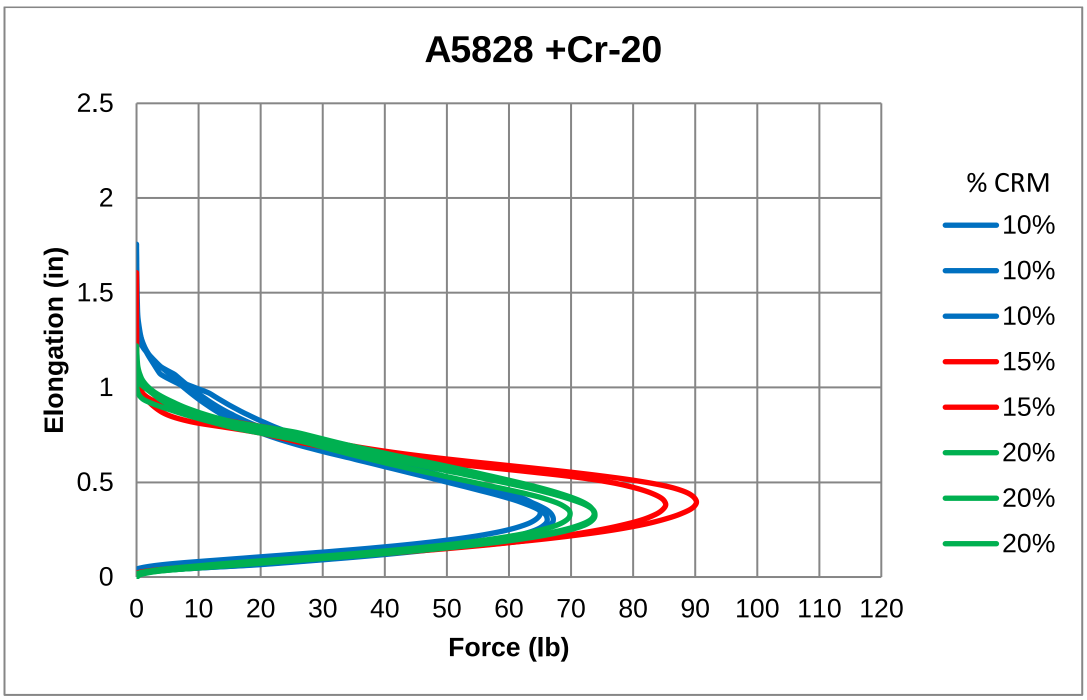


Figure A22. Toughness and Tenacity 58-28 – Cr - 20

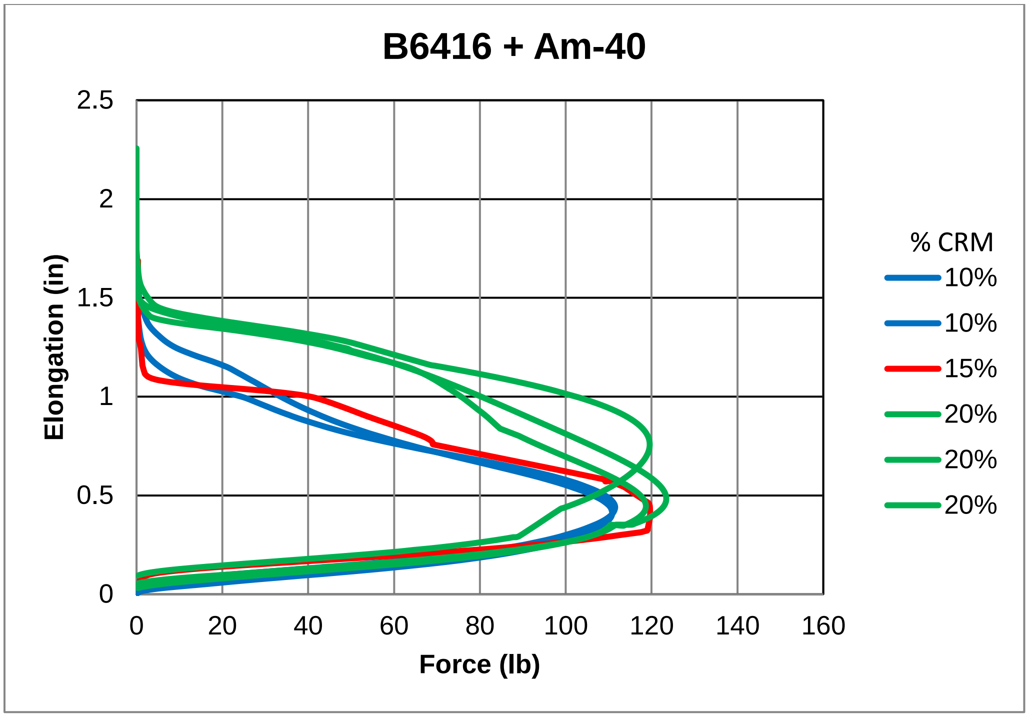


Figure A23. Toughness and Tenacity 58-28 – Am - 40

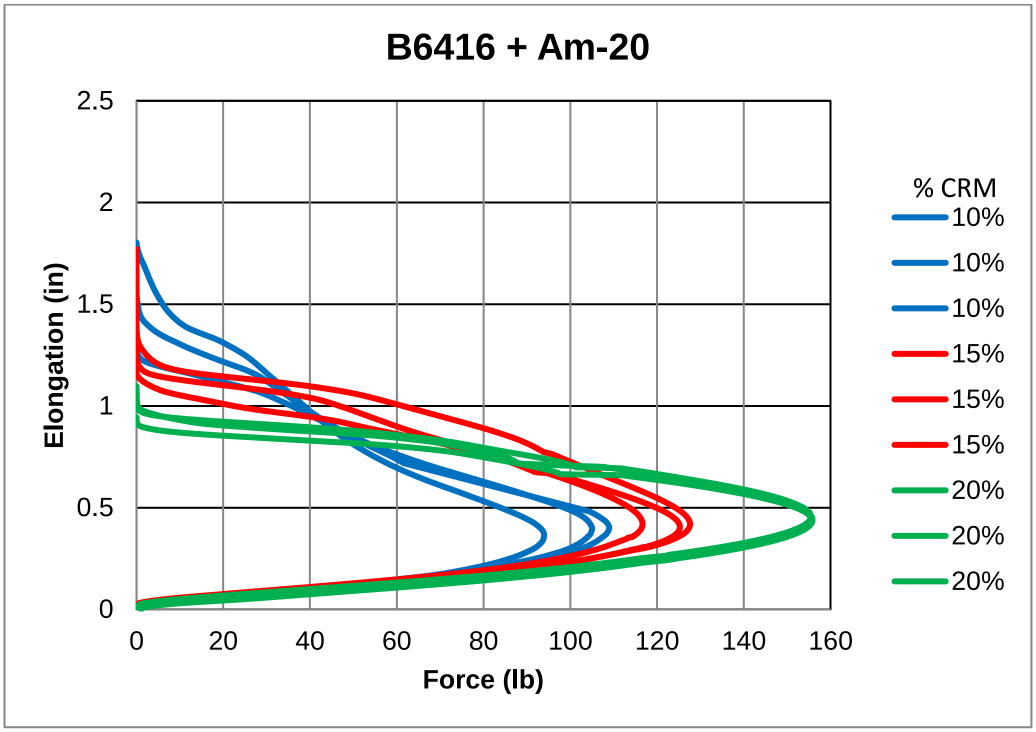


Figure A24. Toughness and Tenacity 58-28 – Am - 20

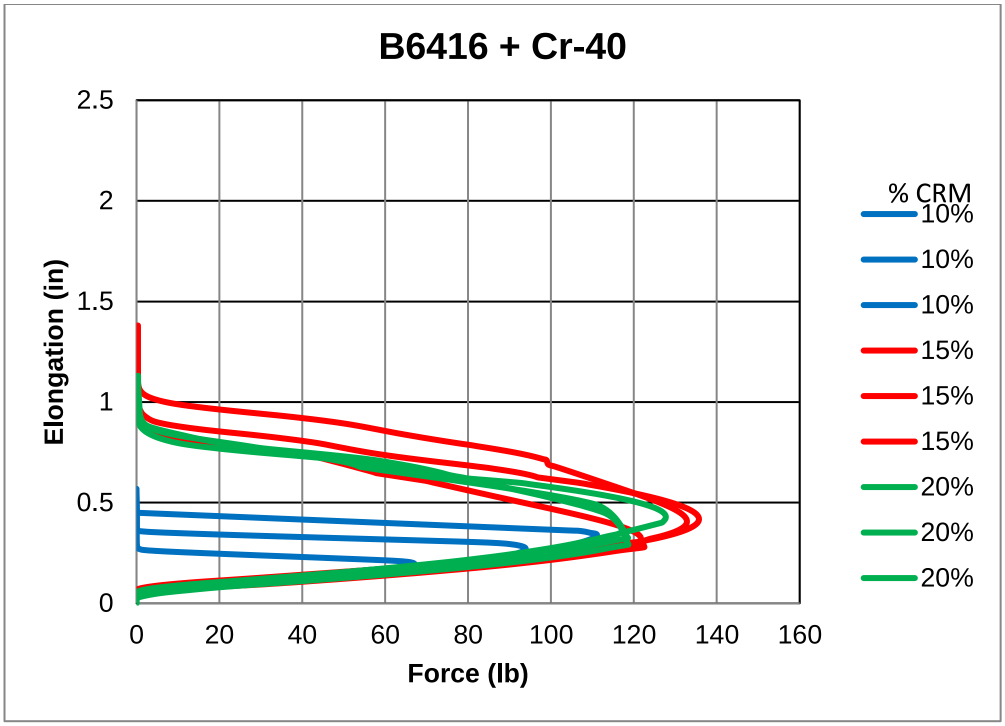


Figure A25. Toughness and Tenacity 64-16 – Cr - 40

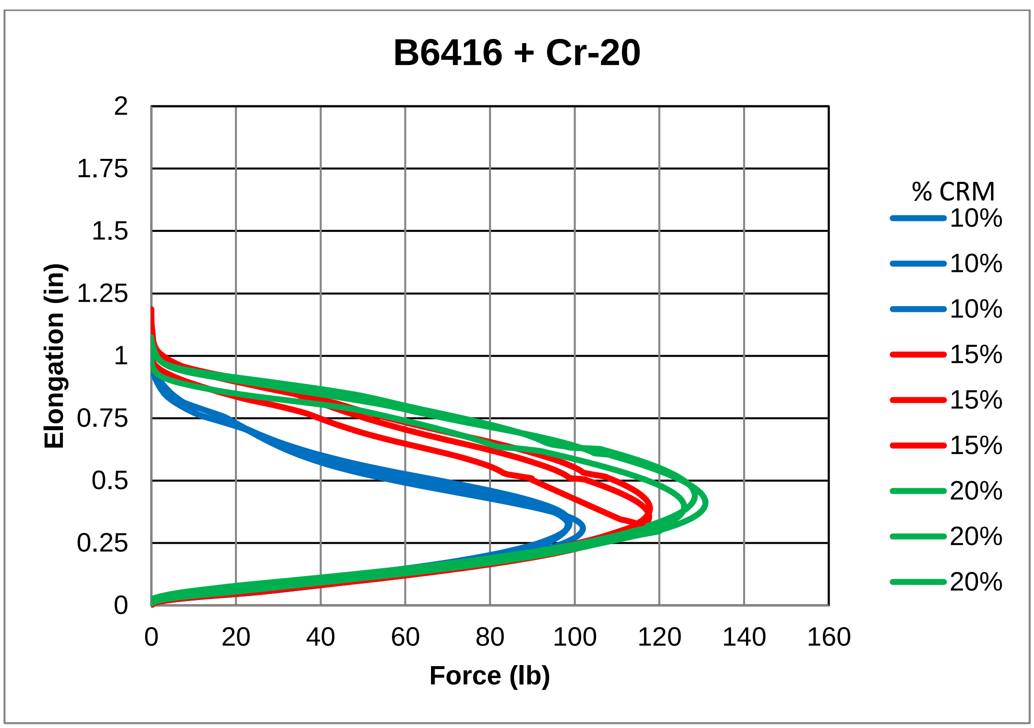


Figure A26. Toughness and Tenacity 64-16 – Cr - 20

Figure A27. Sieve analysis, 58-28, Cr-40

Figure A28. Sieve analysis, AC 20, Am-40

Appendix B

Full Tests Results on Asphalt Mixture Samples

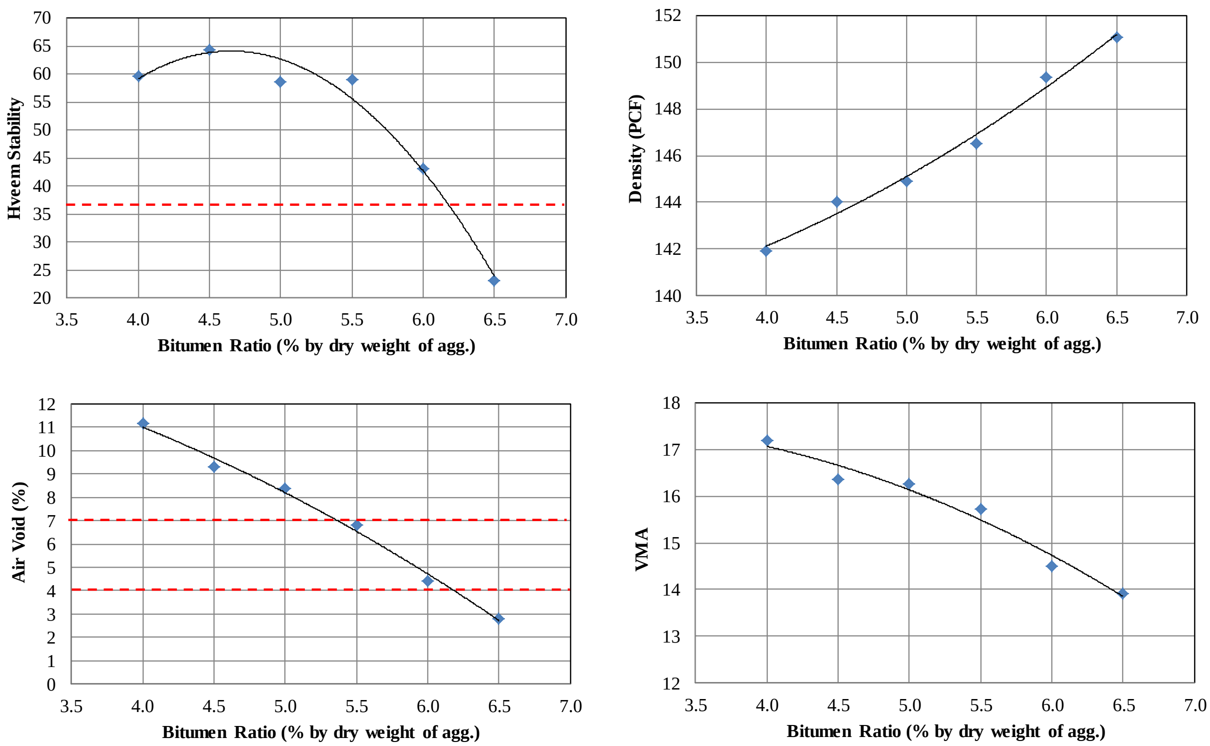


Figure B1. Mix design properties for various binder types (binder 76-22 NV)

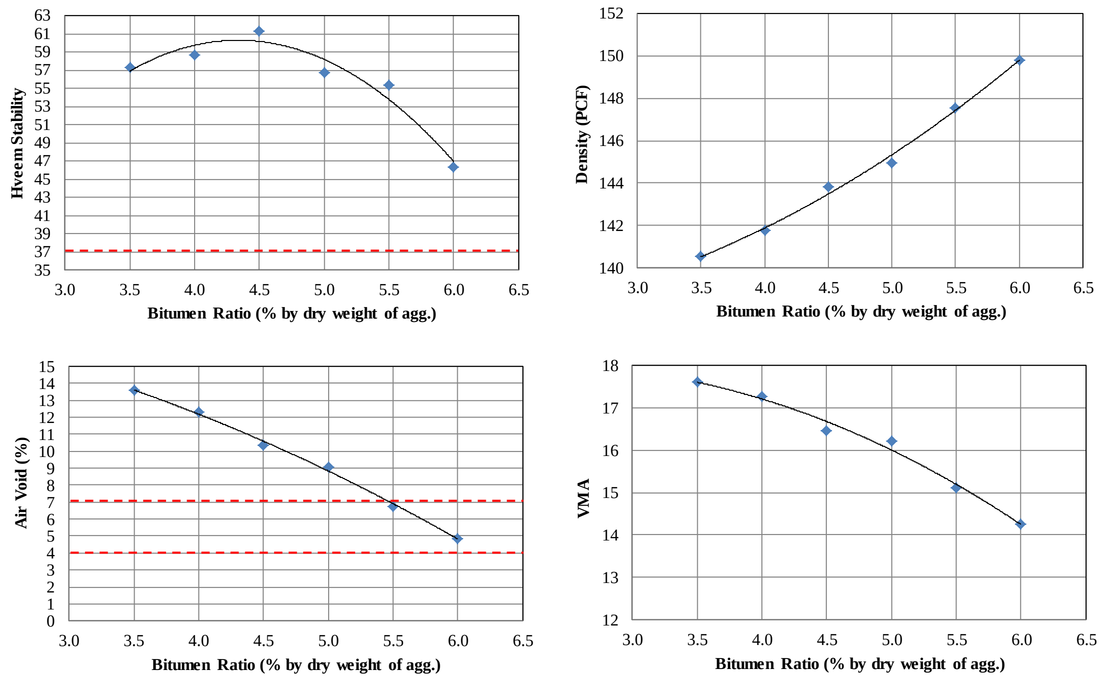


Figure B2. Mix design properties with for various binder types (binder 76-22 NV TR)

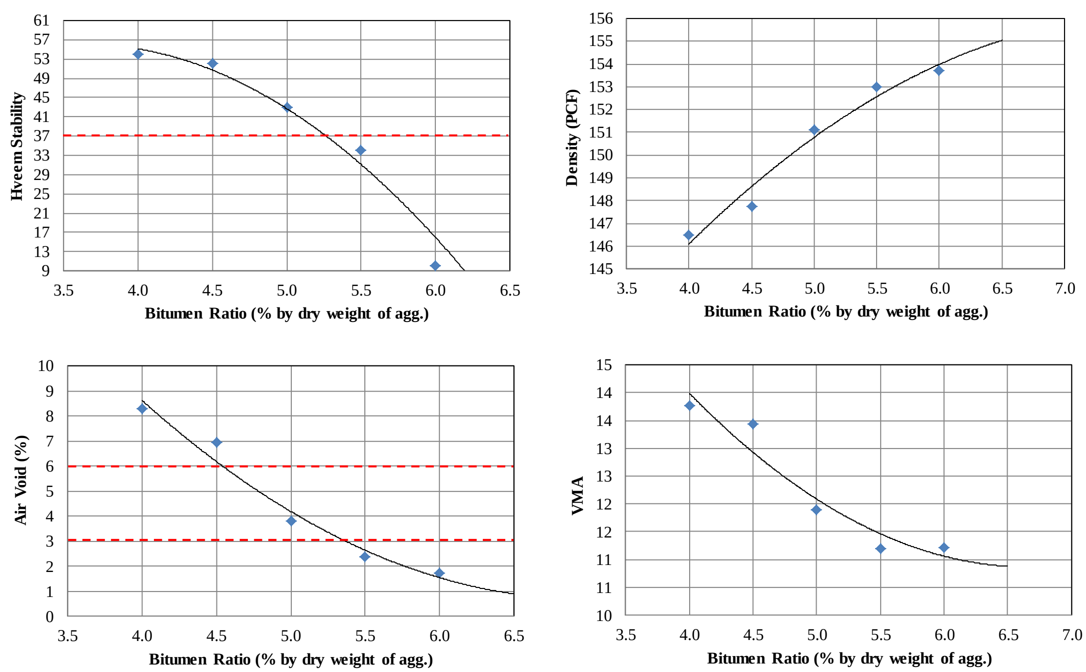


Figure B3. Mix design properties with for various binder types (binder 64-22 NV)

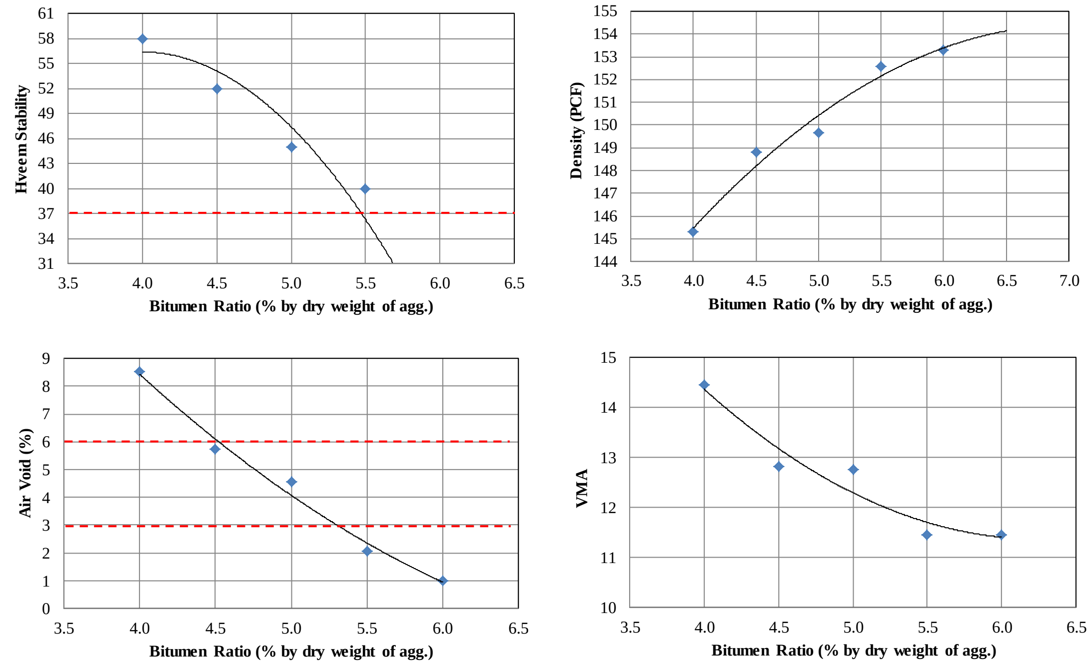


Figure B4. Mix design properties with for various binder types (binder 64-22 NV TR)

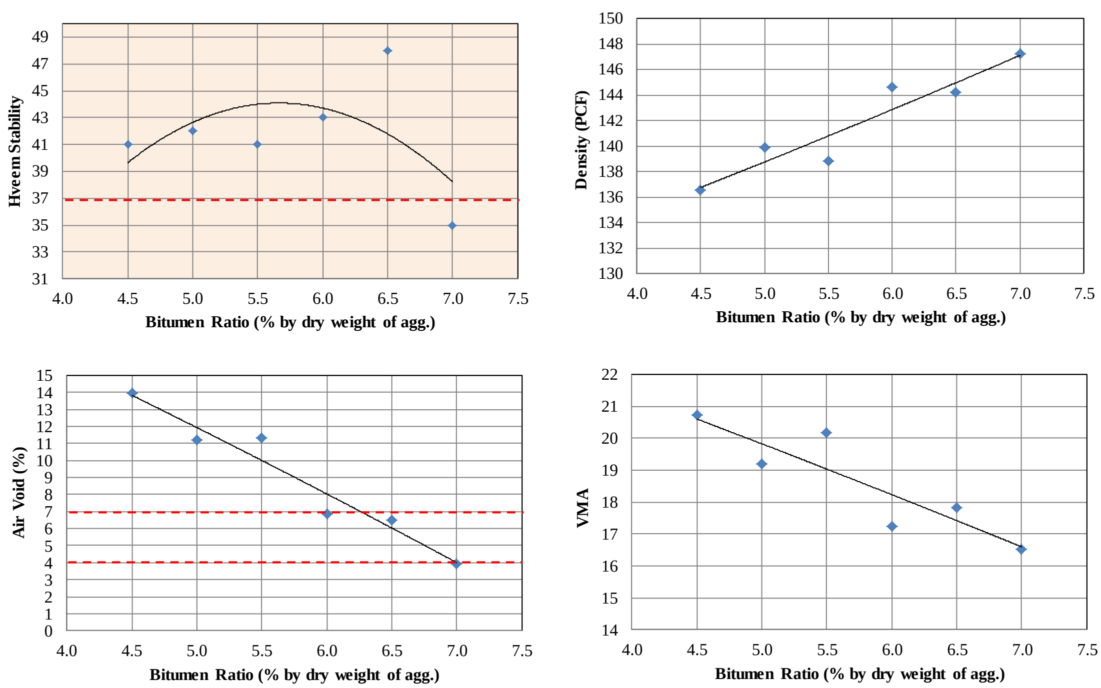


Figure B5. Mix design properties with for various binder types (binder 64-22, 15% Am-20)

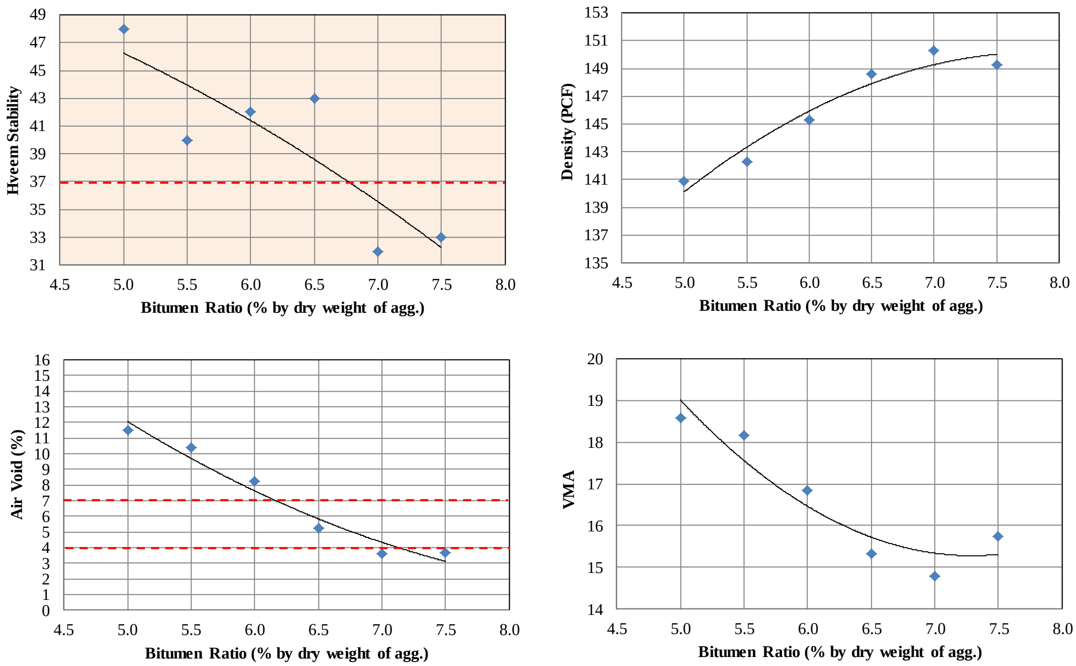


Figure B6. Mix design properties with for various binder types (binder AC 20, 15% Am-40)

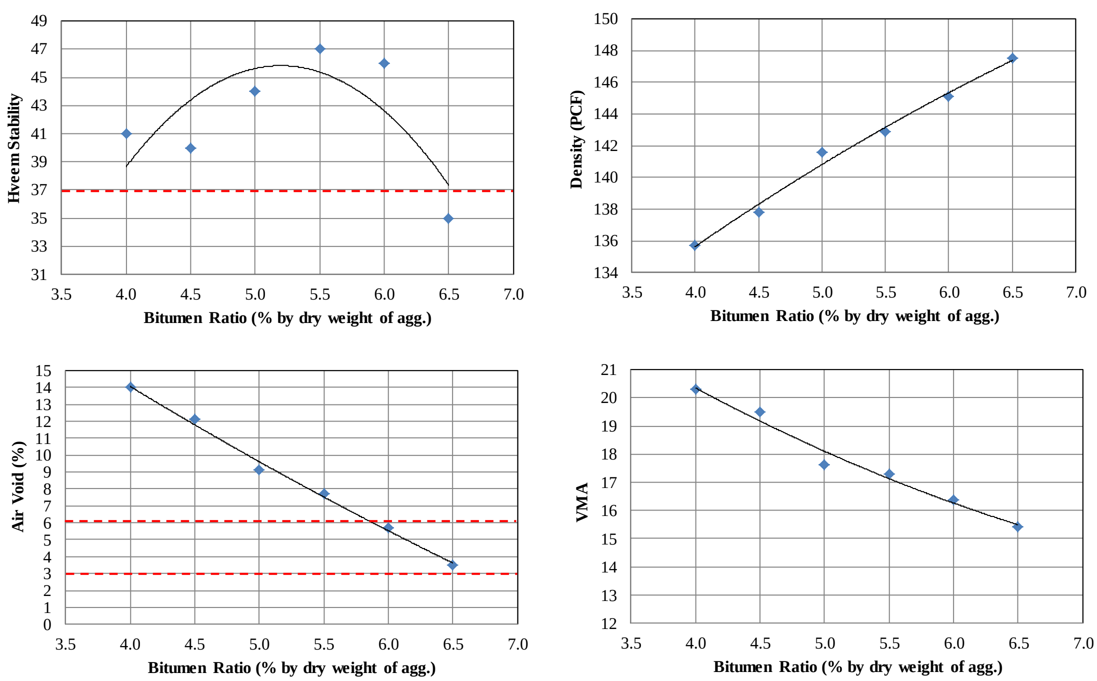


Figure B7. Mix design properties with for various binder types (binder 58-28, 15% Am-40)

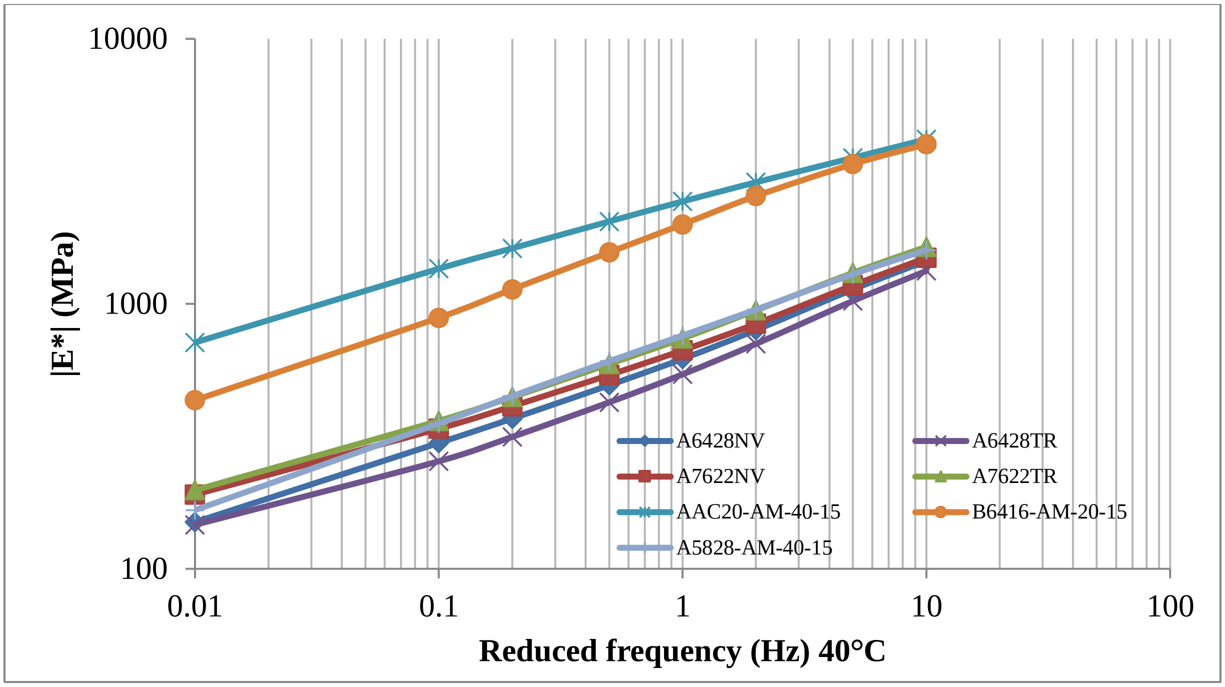


Figure B8. Dynamic modulus of various mixtures at 40° C

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Curriculum Vitae

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Education

- PhD in Civil Engineering (2013 - 2017)
  University of Nevada Las Vegas (UNLV)

- Master's in Civil Engineering (December 2009)
  Iran University of Science and Technology (IUST)

- B.Sc. Civil Engineering (May 2002)
  Iran University of Science and Technology (IUST)

Work Experience

- UNLV Soil and environmental Laboratory (2015 – 2017)
  Performing Tests on Soil samples, Part of team, making Soil columns and Cleaning Soil
- NOVA Geotechnical & Inspection Services – (April 2016 – June 2016)
  Special Inspector – Summer Internship
- Gostaresh Ahan Rah (GAR Co.) General Contractor, Iran. (2007 – 2013)

Railroad Bridges and Structures Construction and Maintenance Project Manager – Estimator

- Metra Consulting Company, Iran. (2002 – 2007)
  Staff Engineer-Special Inspector

  Geotechnical Engineering, Transportation Engineering (High Speed Railway)

Lab Experience

- Geotechnical and Asphalt Research Coordinator (2013 – 2017)
  Conducting Tests on Rubber Asphalt Binder based on Nevada accepted Standards and ASTM
  Making Asphalt Mix Samples and Conducting Tests on Mix Samples
  Performing Ultrasound survey on Asphalt Mix Samples

- Soils and Environmental Laboratory Coordinator (2015 – 2017)
  Conducting Tests on Soil Samples based on ASTM
  Member of the Team Performing Cleaning Tests on Contaminated Soil Columns

Teaching Experience

- Teacher Assistant (2013 – 2017)
  CEE 110 L Introductions to Civil Engineering Design Lab
  CEE 334 L Soil Mechanics Lab

Certificates and Licenses

- OSHA 10 Safety and Health Certificate
- Engineer in Training – EIT No.0T7544
- Clark County Approved Special Inspector (G-A)
- Nuke Soil Density/Moisture Gauge Certificate

Awards

- Third Place as Outstanding Teaching Assistant within UNLV (2016 -2017)
- Scholarship from ASME-Joint Rail Conference 2015

Publications & Conference Presentations

- M. Esmaeili, S. Amiri, K. Jadidi, "An Investigation into the Behavior of Asphalt Underlays in Railway Track" Rail and Rapid Transit Feb. 2014, 228: 182-193, First Published online on Dec. 12, 2012.
- K. Jadidirendi, J. Zakeri, H. Teng, "Field Investigation for Identifying the Effects of DTS Operation on Track Geometry", ASME, Joint Rail, San Jose CA, 2015.
- K. Jadidirendi, J. Zakeri, "Effect of Outsourcing on Railway Track Maintenance and Repair", 11th International Conference, Railway Engineering, Westminster - England, 2011.
- K. Jadidirendi, J. Zakeri, "Design and Manufacturing of an Intelligent System for Ballast Compaction Estimation", 10th International Conference, Railway Engineering, Westminster, England, 2009.
- Member of Authors, "Railway track installation inspection guideline, Management and Planning Organization Office of Deputy for Technical Affairs, Technical, and Criteria Codification (Bulletin No. 355)".
- Member of Authors, "High Speed Railway Track Design and Installation Guideline Management and Planning Organization Office of Deputy for Technical Affairs, Technical, Criteria Codification (Bulletin No. 394)".
- Editor and Main author, "Guideline for Railway Track Maintenance and Repair".

Software

- Microsoft Office
- AutoCAD
- SketchUP
- Tensar Software
- Reinforced Wall Design Software
- Sab
- Kentrack

Languages

- English
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