NDOT Research Report

Report No. 513-13-803

Evaluation of New Innovations in Rubber-Modified Asphalt Binders and Rubberized Asphalt Mixes for Nevada DOT

September 2016

Nevada Department of Transportation
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Carson City, NV 89712

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FINAL REPORT

Evaluation of New Innovations in Rubber-Modified Asphalt Binders and Rubberized Asphalt Mixes for Nevada DOT

Prepared for:
Nevada Department of Transportation (NDOT)
Carson City, Nevada

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Introduction

1.1 Problem statement

Nevada DOT, among many other Department of Transportations, has been using polymer modified binders for many years. The feasibility of using other modified binders (e.g., rubberized asphalt) has been investigated for a limited number of modified asphalt binders used in the state. Researchers have shown some promising results for performance of these mixtures. However, factors in selecting and producing the rubber-modified binders have not been studied in detail. These factors affect the rheological properties of the modified binder and performance of the asphalt mixtures. Furthermore, ever since these materials have been used, there have been many new developments in their implementation. For over twenty years, many states around the country have initiated the utilization of some form of rubberized mixtures on a regular basis.

For many years, polymers have been incorporated into asphalt as a way to mitigate many major causes for asphalt pavement failures, including permanent deformation at high temperatures, cracking at low temperatures, fatigue cracking, and stripping damage. These polymer-modified asphalt (PMA) binders have been used successfully at locations of high stress, e.g., interstates and intersections. For several years, PMA binders have proven to be an essential element in the paving process in many parts of the world. Today, several types of polymers are used to modify asphalt binders. Currently in the United States, the most commonly used polymer for asphalt modification – over 80% around the country – is styrene butadiene styrene (SBS), followed ground tire rubber (GTR), styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA), polyethylene, and other such polymers as Titan from Honeywell.

Although they cost more than conventional binders, SBS-modified asphalt binders have been utilized for many years by many state DOTs. The high cost associated with the SBS modification process is mostly due to the unavailability of SBS material. Back in late 2009, the SBS market was hit with a shortage of butadiene; this affected both the supply and cost of SBS modified asphalt binders in the country. Even though the SBS modified binders perform well in many states, including Nevada, for many reasons it is important to have some alternative modifiers, such as GTR, to substitute for SBS in asphalt binders in the future.

Rubberized asphalt mixtures use a type of modified asphalt binder with improved temperature susceptibility and flexibility. This modified binder is formed by the interaction of crumb rubber with the asphalt binder at elevated temperatures for a certain period of time. This type of modified binder has several advantages, including: a) an increase in the binder's elasticity at moderate and high temperatures, and b) an increase in the binder's flexibility at low temperatures. Therefore, the use of a crumb-rubber-modified (CRM) binder in asphalt mixtures improves the resistance to permanent deformation, fatigue, and low-temperature cracking.

Crumb rubber can be produced in almost any particle size, from large aggregate-sized particles to fine powder, by employing several different production methods, i.e., ambient shredding or cryogenic grinding. The percentage of crumb rubber has a significant impact on the properties of CRM binder. The reaction time also is an important factor that might potentially affect the properties of the modified binder. The crumb rubber particles absorb the asphalt binder and swell; the amount is dependent on the nature, temperature, and viscosity of the asphalt binder. The swelling of crumb rubber is a diffusion process, and increases the dimension of the rubber network until the concentration of asphalt uniform and equilibrium swelling is achieved. This complex process affects the performance grade (PG) of the rubberized asphalt binder, especially, since rubber size, type, and blending process vary; therefore, these topics must be investigated with local binders and aggregate sources.

There are many factors that will be investigated in this study, including the effects of the binder source and grade; crumb rubber production types (ambient vs. cryogenic); crumb rubber percentage; and crumb rubber size.

1.2 Background summary

The Nevada Department of Transportation (NDOT) specifies the application of PG 64-28NV base binder and PG 76-22NV polymerized asphalt binder in all dense graded hot mix asphalt (HMA) mixtures placed on highways under its jurisdiction in the northern region and southern region of the state, respectively. In addition, PG 76-22 binder is utilized in stone matrix asphalt (SMA) mixtures and open grade friction course (OGFC) mixtures of NDOT highways to mitigate many major causes for asphalt pavement failures and enhance operation safety.

When a polymer and virgin asphalt are blended, the polymer strands absorb part of the low molecular weight oil fraction of the virgin asphalt and become swollen. When the polymer-rich phase becomes the continuous phase, the swollen strands connect together and form a three dimensional network, providing the physical properties of elasticity, plasticity, and elongation of an asphalt binder. Ultimately, polymerized binders become more viscous and tend to improve the binder coating on aggregates by increasing its film thickness; this holds the aggregate particles together more effectively, resulting in better pavement performance and creating a durable and long-lasting pavement.

The updated NDOT Section 703 (1/28/2013) - Bituminous Materials states that “modified binders shall be blended at the source of supply and delivered as a completed mixture to the job site”. Modified binders must meet the requirements according to NDOT’s specifications. The specifications call for the PG 64-28NV and PG76-22NV to be blended at the source of supply, and delivered as a completed mixture to the job site. Upon request, furnished samples of the base asphalt and polymer are used in the production of PG 76-22NV to test for polymer content.

GTR modifier is a general type of asphalt modifier consisting of crumb rubber produced from scrap tires. Pavement products using a GTR asphalt binder are produced by several techniques, including a wet process and a dry process. These GTR-modified asphalt binders may contain additional additives or modifiers (i.e., rubber polymers, diluents, and aromatic oils) besides scrap tire rubber. The ground tire rubber not only increases the binder’s elasticity but also increases its resistance to aging due to anti-oxidants contained in the tires. It is broadly used as a sustainable material in improving the long-term performance of asphalt pavements of dense-, gap-, and open-graded mixtures. The primary uses of GTR-modified asphalt binders in pavement applications include crack sealants, joint sealants, chip seals, interlayers, hot-mix asphalts (HMA), and membranes.

The use of GTR in hot-mix asphalt increased substantially in the early 1990s due in large part to the mandate imposed in the Intermodal Surface Transportation Efficiency Act (ISTEA). A survey of state highway administrations conducted by the American Association of State Highway and Transportation Officials (AASHTO) in January 1993 indicated that 21 states used CRM in hot mixes in 1992.

However, ever since this mandate was repealed, the use of asphalt rubber has dropped or ceased in many parts of the United States. Since 2000, spikes in oil prices have increased the cost of asphalt more than 250%, from approximately $140 a ton to $500 or more (2014-2015 figures). In recent years, SBS polymers have also been in short supply. There has been a tightening supply of asphalt, and the price of liquid asphalt is now almost double the price of rubber. However, during the same period, because crumb rubber provides a reliable and consistent supply of material, the cost has held steady, remaining between $240 and $340 a ton. Today, rubberized asphalt is gaining wider acceptance by more state DOTs as well as by municipalities and cities.

Crumb rubber can be produced in almost any size, from large aggregate-sized particles to fine powder, by employing several different production methods, such as ambient shredding or cryogenic grinding; the percentage of crumb rubber also has a significant impact on the properties of a GTR binder. Crumb rubber produced from scrap tires consist mainly of natural and synthetic rubber, carbon black, sulphur, zinc oxide, and coloring agents. It is well known that the crumb rubber absorbs the asphalt binder and swells with the amount, and is dependent on the nature, temperature, and viscosity of the asphalt. The swelling of crumb rubber is a diffusion process, and increases the dimension of the rubber network until the concentration of asphalt uniform and equilibrium swelling is achieved. This complex process affects the performance grade (PG) of rubberized asphalt binder, especially because rubber size, type, and blending processes are different.

Terminally blended (TB) GTR-modified binder materials use finely ground crumb rubber (minus #30 or minus #40 mesh), and are typically blended at the asphalt refinery or the 'terminal'. The use of terminal-blend technology to produce TB-modified asphalt binders has been increasing since its introduction in the mid-1980s.

Historically, the primary differences between TB and asphalt rubber (AR) binders were the amount of GTR used in the binder (TB: <10%; AR: 15-20%), the size of the crumb rubber used, and the use of specialized mixing equipment for AR due to larger crumb rubber sizes and amounts. However, in recent years, the rubber content in some TBs has increased to 15% to 20% or more. This technology eliminates the need for the blending unit at the job site, and reduces the associated costs. Additionally, TB-modified asphalt binders are handled similar to polymer modified asphalt binders without any need for excessive heating.

The main concern for NDOT is that there are very few performance records for TB-asphalt mixtures in the laboratory and the field compared to the documented and outstanding performance of SBS-modified asphalt mixtures typically used in Nevada. These limited records cannot provide enough reliable data to develop the required NDOT specifications. In addition, Nevada has a wide variation in environment, traffic, and aggregate quality; these must be considered when designing flexible pavements. Consequently, more research should be conducted to achieve this purpose.

1.3 Objectives

The objective of the proposed research project is to determine the feasibility of utilization of laboratory blended GTR, terminally-blended GTR following NDOT's specifications, or other CRM products to meet the rheological and engineering properties of asphalt modified binders and mixtures. The test results will be compared to SBS modified binders used in Nevada. The specific objectives of the research project will include the following:

- Determining initial recommendations for terminally-blended GTR mix design guidelines based on the literature review and basic laboratory test results;
- Investigating the rheological characteristics of various crumb rubber types (e. g. -30, -40, and terminal blend) at high, intermediate, and low performance temperatures through the performance of AASHTO standards and any other NDOT's specification requirements.
- Investigating the effects of various rubber modifiers on NDOT's mix design including the mix volumetric properties such as air voids, VMA, and optimum asphalt binder ratio specifications from AASHTO and NDOT.
- Determining the Hveem stability, moisture susceptibility, permanent deformation, dynamic modulus, flow number characteristics of various alternate modifiers with hydrated lime in terms of specifications from AASHTO and NDOT.
- Developing recommended specifications for Nevada DOT regarding the utilization of these materials.

1.4 Scope

A detailed research plan was prepared, in coordination with NDOT officials, for a coordinated series of laboratory experiments in assessing the rheological and engineering properties of new innovated mixtures made with rubberized binders. The plan provided specific information on and justification for the above mentioned areas of research including the following tasks:

Task 1: Conduct an extensive literature review on the topic of terminal blended rubber asphalt binder and the utilization of rubberized asphalt binders around the country. This will result in initial recommendations for terminally-blended GTR mix design guidelines for NDOT's specifications based on laboratory test results;

Task 2: This task will be divided into three sections (A-C). Section A will include the investigation of the high temperature rheological properties of original rubberized asphalt binders. Virgin (unmodified) asphalt cement from several different sources will be mixed with different types of CRM in different percentages and then rheological property tests will be conducted on the modified asphalt binders. The testing procedures will include all SHRP tests for quality control of original asphalt binders (AASHTO T48, AASHTO T316 and AASHTO T315) plus added tests required by Nevada DOT (Nev. T730, Nev. T745, and Nev. 746, etc.).

Section B will include the investigation of the high temperature rheological properties of rubberized asphalt binders from Section A after aging in rolling thin film oven (RTFO) (Nev. 728). This will assess the major effects of a short term aging procedure on rheological properties of these binders. The testing procedures will include essential tests for SHRP and Nevada DOT specifications plus Multiple Stresses Creep Recovery (MSCR) – AASHTO TP70 tests.

Section C will investigate the low temperature rheological properties of rubberized asphalt binders after aged by RTFO and pressure aging vessel (PAV). This will assess the major effects of a long term aging procedure on rheological properties of these binders (AASHTO T313 and AASHTO T315). Tasks 1 and 2 will be completed during the first year of the research project. A final report will be provided for Tasks 1 and 2 for NDOT to review.

Task 3: Investigate the properties of asphaltic mixture produced with the rubberized asphalt binders. Hveem mix designs will be performed for rubberized mixtures using selected two aggregate sources, up to seven binder sources, and one solid Anti Stripping Agent (ASA) in accordance with the conventional hot mix asphalt mix procedures following Nevada DOT's specifications. In addition, the effects of selected crumb modified binders on Hveem mix design with respect to air void, VMA, VFA, optimum binder content, etc. will be investigated. Any recommended changes to mix design procedures for crumb rubber modified mixes will be provided to DOT in the interim and final reports. The following testing procedures will be followed: a) Moisture susceptibility– Nev. T341D; b) Rut Resistance – AASHTO TP 63 (APA); c) Dynamic modulus and flow number - AASHTO TP 79; and d) Dynamic modulus master curves - AASHTO PP61.

In order to investigate the low temperature performance of the mixtures several testing procedures will be evaluated and considered. For example, the Disc-Shaped Compact Tension test (DCT) will be used to determine the low-temperature fracture properties of cylindrically-shaped asphalt concrete test specimens. This testing procedure offers many advantages including easy specimen fabrication and it is a standard fracture test configuration (ASTM E399 Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials). Another test that will be considered is Semi-Circular Bending (SCB) test. This test uses simple specimen preparation from Superpave Gyratory compacted cylinders and a simple loading setup. In this proposed research project, a MTS servo-hydraulic testing system equipped with an environmental chamber will be used to perform the test. The samples will be symmetrically supported by two fixed rollers and will have a span of 120mm. The Indirect Tension test loading plate will be used to load the SCB specimens.

CHAPTER 2

Literature Review

2.1 Background

In 2013, in the United States, approximately 254 million tons of trash was generated and recycled and composted almost 87 million tons equivalent to a 34.3 percent recycling rate. On average, in US, over 1.51 pounds is recycled and composted out of approximately 4.4 pounds of our individual waste generation rate per person per day (1) (Figures 1 and 2). The recycling rate in the United States is shown in Figure 3 (1). One of the materials around the country that has been a major interest from the collection and recycling stand point has been scrap tires.

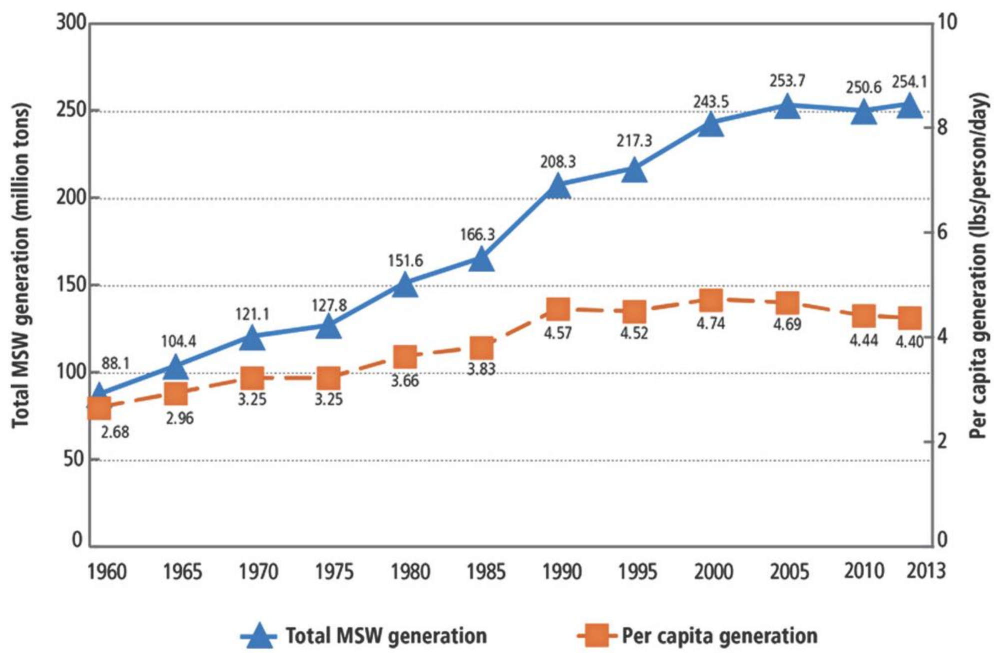


Figure 2.1. Municipal Solid Waste (MSW) generation rate from 1960-2013 (1)

In 1999, lightning struck a tire dump in Westley, California; the resulting smoke plume impacted nearby farming communities and caused widespread concern of potential health effects from exposure to the smoke emissions (2-4). The tire fire produced large quantities of pyrolytic oil which flowed off the slope and into the drainage of a nearby stream.

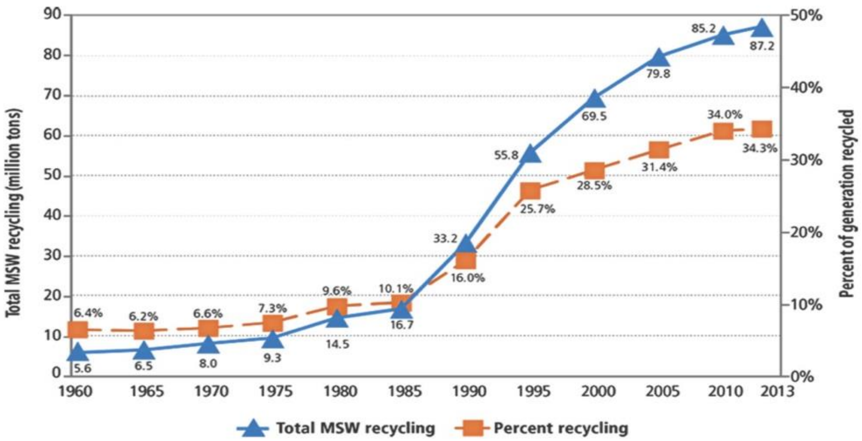


Figure 2.2. MSW recycling rate from 1960-2012 (1)

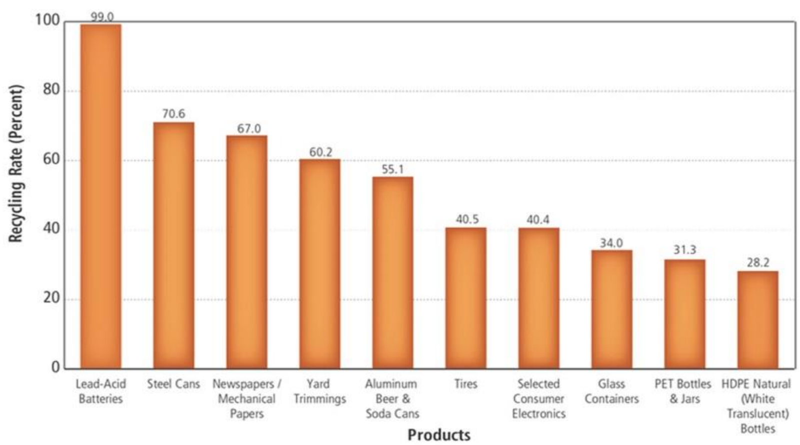


Figure 2.3. Recycling rates of selected products, 2013 (1)

The pyrolytic oil was also ignited and caused significant smoke emissions on the ground due to the raging oil fire. Local and state agencies were unable to respond to the oil and tire fires, thus requiring the Environmental Protection Agency (EPA) regional coordinator to intervene using the

Oil Pollution Act of 1990. In the end, the tire fire lasted for 30 days and the EPA response costs were estimated to be $3.5 million (2-4).

While tire fires are infrequent, they cause a serious concern to public safety as well as being expensive to remedy. As seen in Figure 4, the number of open landfills in the United States has been in a steady decline; more than 75% of all landfills have been closed within the past 18 years (5). As of 2011, the number of landfills has stayed constant compared to 2005. As such landfilling can no longer be considered a suitable, or sustainable, disposal practice.

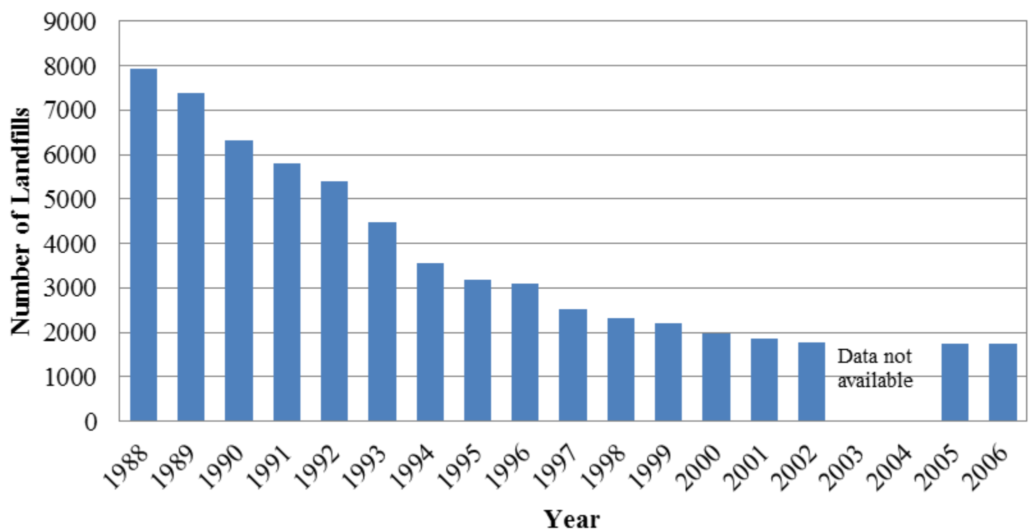


Figure 2.4. Number of Landfills in the United States, 1988-2006 (5)

2.2 Scrap Tires.

The increasing number of vehicles on the roads generates millions of scrap tires every year around the world. It is estimated that approximately 1.4 billion tires are sold worldwide each year and subsequently as many are scraped every year (Figure 5) (6). In addition, it is estimated that there will be an increase in number of scrap tires in many parts of the world including United States due to many reasons (e.g., increase in population and traffic volume). The EPA estimates that over 300 million scrap tires are being generated each year in the United States. There are many applications that these scrap tires are used including in paving operations. Figure 6 shows the scrap tire disposition in the United States for 2009 (2). Over 40% of the scrap tires are used for tire-derived fuel; and approximately 20.6% is ground rubber while only 5.5% is used in civil engineering applications (2).

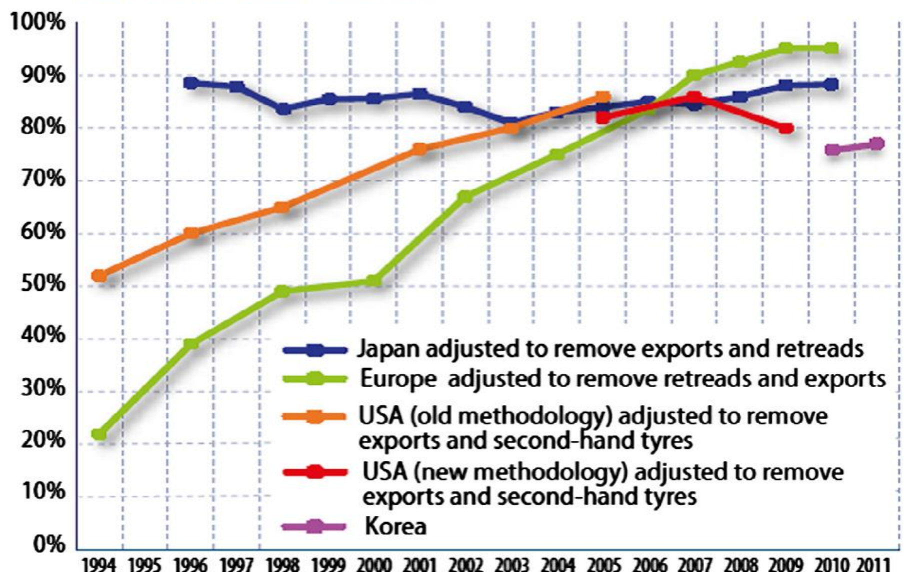


Figure 2.5. Recovery rate in major markets around the world (6)

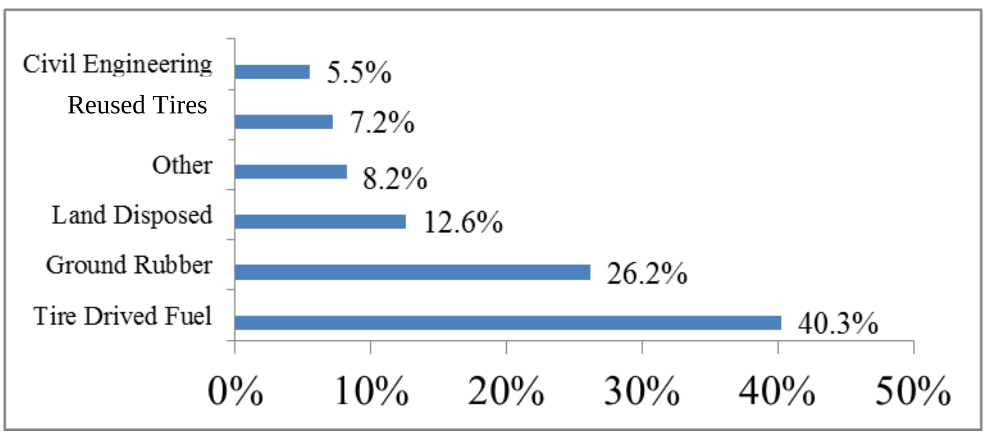


Figure 2.6. Utilization of Scrap Tires in the USA (7)

In addition, there are over 185 million tires stock pilled around the country. The inadequate disposal of scrap tires, in many cases, pose a potential threat to human health (e.g., fire hazard, haven for mosquitoes) and potentially increase environmental risks. The evolution of this problem has prompted the establishment of legislation limiting the disposal options for scrap tires

(8). Addition of crumb rubber (crumb rubber modifier: CRM) to binder has been identified as one solution to the scrap tire issue; some studies even suggest that if only 10% of all asphalt pavements laid each year in the U.S. contained 3% rubber by weight of binder, all scrap tires produced for that year would be utilized (9).

Rubberized asphalt binder is a type of modified asphalt binder with improved temperature susceptibility and flexibility. It is formed by the interaction of ground reclaimed tire rubber with asphalt binder at elevated temperatures for a certain period of time. This type of modified binder has several advantages. The ground tire rubber not only increases the binder's elasticity, but also increases its resistance to aging due to anti-oxidants contained in tires. It is broadly used as a sustainable material in improving the long term performance of asphalt pavement.

Crumb rubber modifier (CRM) is a general type of asphalt modifier that contains scrap tire rubber. Crumb rubber modified asphalt binder pavement products are produced from crumb rubber modifier by several techniques including a) wet process and b) dry process. These crumb rubber modified asphalt binders may contain additional additives or modifiers (i.e., rubber polymers, diluents, and aromatic oils) besides scrap tire rubber.

The primary use of crumb rubber modified asphalt binders in pavement applications include crack and joint sealants; binders for chip seals, interlayers, and hot-mix asphalts; and membranes.

2.3 Background of CRM Binder

The introduction of CRM binder as an engineering material has occurred due to the occurrence of a number of events. The work done by Charles McDonald on asphalt rubber as a crack sealant in Arizona has proved to be a precursor for the growing environmental sustainability movement. Coupled with dwindling resources, increased environmental problems, and the quest for improved paving materials, CRM binder has emerged as an efficient and "green" alternative to conventional polymer modified binders.

Crumb rubber modifiers have been used in asphalt binders for hot-mixes since the 1960s (10). They have contained binders prepared from both the wet process (asphalt rubber) and the dry process (rubber modified). The dry process was a patented process called PlusRide. This process is not being utilized in the United States anymore. Dense-, open-, and gap-graded aggregates have been used and field tested in various states with crumb rubber modifiers.

Currently, the majority of crumb rubber binder used in hot-mix asphalt is placed in the states of Arizona, California, Florida, and Texas. Arizona DOT and local governments in Arizona primarily use asphalt rubber binder in open-graded and gap-graded hot-mixes. The use of asphalt rubber binder in open-graded friction courses is now the most popular use of this type of binder by the Arizona DOT. Arizona first placed hot-mix asphalt containing asphalt rubber in 1975. California DOT uses asphalt rubber in dense-, gap-, and open-graded hot mix asphalt. California DOT and local governments in southern California utilize rubberized asphalt rubber binders in gap- and open-graded mixtures. Texas DOT uses asphalt rubber primarily in gap-graded mixture identified as coarse matrix, high binder (CMHB) (11).

Florida DOT uses a fine ground rubber at typically 6-12% by weight of asphalt binder in dense- and open-graded hot mixtures. These binders are not asphalt rubber as defined by ASTM (11). ASTM defines ‘asphalt rubber” as materials consisting of a virgin binder and a minimum of 15% CRM.

Crumb rubber produced from scrap tires consist mainly of natural and synthetic rubber, carbon black, sulphur, zinc oxide and coloring agents. It is well known to absorb asphalt binder and swell with the amount being dependent on the nature, temperature and viscosity of the asphalt binder. The swelling of crumb rubber is a diffusion process and increases the dimension of the rubber network until the concentration of asphalt uniform and equilibrium swelling is achieved. This complex process severely affects the performance grade (PG) of rubberized asphalt binder, especially, as rubber size, type, and blending process are different.

There are several benefits of using rubberized asphalt mixtures including the following (12):

- Improved resistance to surface initiated cracking due to higher binder contents
- Improved aging and oxidation resistance due to higher binder contents
- Improved resistance to fatigue and reflection cracking due to higher binder contents

- Improved resistance to rutting due to higher viscosity and softening points
- Increased night-time visibility due to contrast in the pavement and striping
- Reduced tire noise due to increased binder film thickness and open texture
- Reduced splash and spray during rain storms due to open texture
- Reduced construction times because less material is placed
- Lower pavement maintenance costs due to improved pavement performance
- Better chip retention due to thick films of asphalt
- Lower life cycle costs due to improved performance
- Savings in energy and natural resources by using waste products

The limitations of CRM binders include the following (12):

- Higher initial unit costs (compared to conventional mixes), which are offset by using reduced thickness, resulting in lower life cycle costs. As such, they are primarily used for surface courses only.
- In the past, variable performance due mainly to poor construction practices or construction during inclement weather. These deficiencies have been corrected through improved specifications
- More challenging construction, due to more restrictive temperature requirements
- Potential odor and air quality problems
- Difficult to handwork

2.4 CRM Binder

ASTM D 6114 defines asphalt rubber as “a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in hot asphalt cement sufficiently to cause swelling of the rubber particles” (13). Research has shown that the addition of crumb rubber to virgin asphalt produces binders with improved resistance to rutting, fatigue cracking, and thermal cracking (14 and 15) as well as reduces the thickness of asphalt overlays and reflective cracking potential (16).

Research has shown that crumb rubber modification of asphalt binder has many similar effects to polymer modification. The major changes noted by these researchers are seen with the increase in the high temperature stiffness, these are often seen to exceed levels normally achieved by polymer modification. Similarly it has been shown that crumb rubber modifier also results in a reduction of dependency on temperature and loading frequency. However, it has also been suggested that the main function of crumb rubber is that of interactive filler as crumb rubber remains as a particulates even after mixing (17). As the crumb rubber particles do not dissolve in the asphalt, they have been shown to swell in the asphalt resulting in effective volumes that are larger than their initial volume (18-20).

2.5 Tire Composition

Tires are composed of three main components: rubber, steel, and fiber. Rubber contributes the greatest amount of material to the tire, contributing approximately 60% by weight of the tire mass. Typically natural/isoprene rubber is used for both truck and passenger car tires in the tread, sidewall, belt, carcass ply, and inner liner. Differences arise in the amount of styrene butadiene rubber used; truck tires tend to contain higher amounts of styrene butadiene rubber in the carcass ply and base tread. Higher amounts of butadiene rubber may be found in the base tread of truck tires as well (21 and 22). The tire composition and its components are shown in Figure 7 and Table 1 (23 & 24).

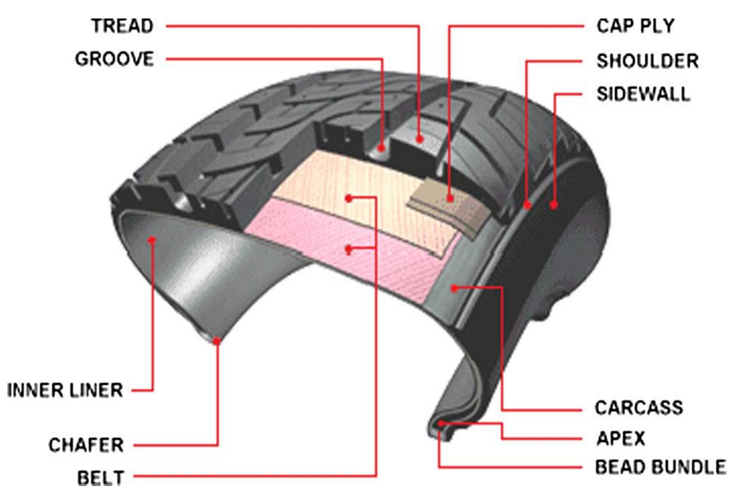


Figure 2.7. Tire Structure (23)

Table 2.1 Composition of Passenger and Truck Tires (24)

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

2.6 Crumb Rubber Grinding Procedures

In order for crumb rubber to be added to asphalt it must first be reduced in size; this is generally undertaken by ambient or cryogenic grinding of the scrap tires. The ambient method involves the use of medium to high speed granulators (100-1200 rpm) which utilize a rotor in which fly knives are attached. Prior to being introduced to the fly knives the tires are already ground to approximately 2.5-7.6 cm size. The fly knives move within a close distance of stationary knives which cause a cutting and shearing motion. The size of the ambient ground crumb rubber is controlled by a screen within the machine. Once the material has been processed through primary granulator, it is then passed through a magnetic separation system where a majority of the belt wire steel is removed. The majority of the fiber is removed using an air gravity separation table (25).

The cryogenic process also starts with chunks of tire approximately 2.5-7.6 cm size in size. These chunks are then chilled with liquid nitrogen and ground in a mill; this is followed by the separation of the fiber, metal, and rubber. The ground crumb rubber is then finally sorted according to size; typically 70 to 80% of the crumb rubber is finer than 10 mesh (2 mm) (25).

The principal difference between rubber particles produced using the cryogenic and ambient procedures lies in the shape of the resulting particle. Crumb rubber produced using cryogenic means tends to exhibit a smooth surface, comparable to shattered glass. Ambient grinding tends to yield particles with a rougher surface, thus producing greater surface area than cryogenic particles (25 and 26).   From Figure 8, it can be seen that the cryogenically ground crumb rubber particles exhibit more of a crystalline morphology when compared to the ambient ground crumb rubber particles. Research has also shown that the differences in morphology account for a significant difference in surface areas, where ambient ground crumb rubber typically exhibits surface areas approximately 2.5 times greater than cryogenic ground crumb rubber (26).

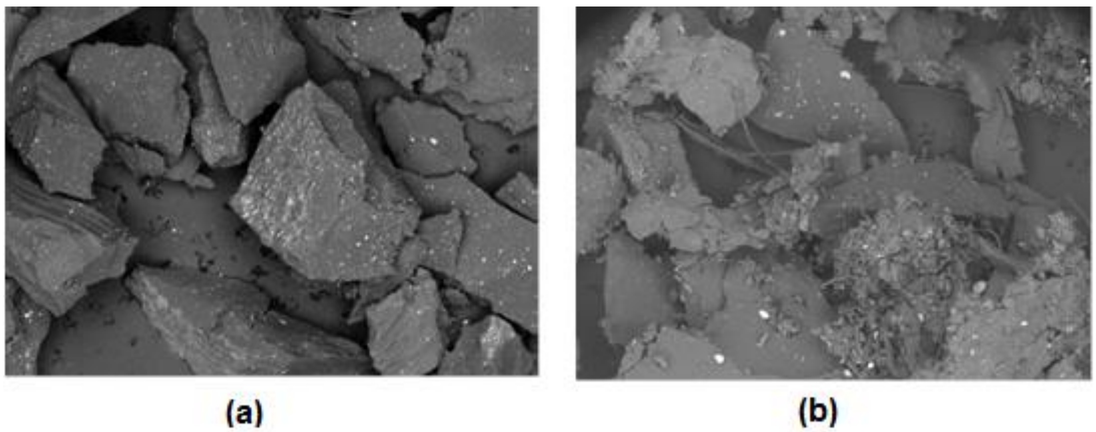


Figure 2.8. SEM micrographs of a) Cryogenically and b) Ambient Ground CRM (at 30x magnification)

2.7 Mixing Procedures

The incorporation of crumb rubber into the asphalt mixtures is generally performed using the dry process or the wet process. The dry process is characterized by the use of coarse graded rubber as an aggregate with no opportunity for the asphalt and rubber to react before mixing with hot aggregate. The wet process involves blending the asphalt cement with the crumb rubber prior to the mixing operation. During this process, the rubber reacts with the asphalt binder and changes the binder properties (27).   A schematic of a typical system is shown in Figure 9 (28).

Today, the wet process is the most widely used method of crumb rubber modification; reported advantages of using this procedure include (16):

- Increased pavement life
- Reduced reflective cracking
- Reduced permanent deformation (rutting)

- Reduced maintenance costs
- Reduced pavement noise generation
- Recycling of waste tires

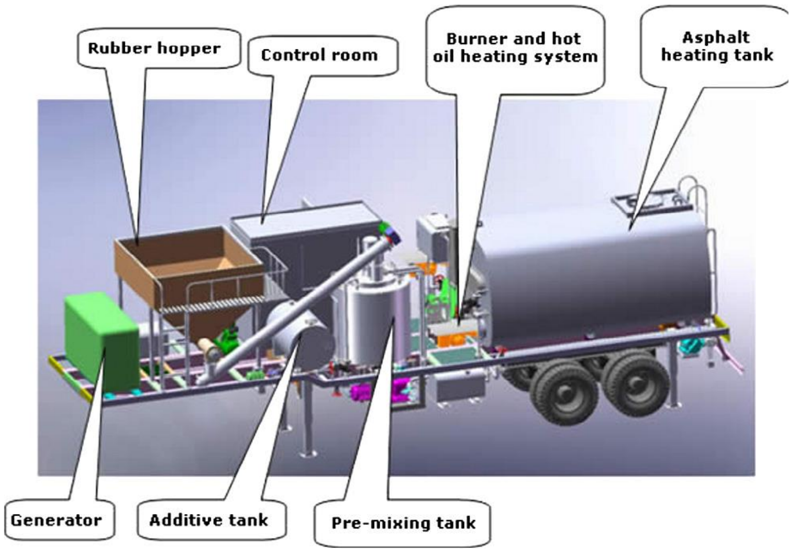


Figure 2.9. A Typical On-Site Blending System for Rubberized Binder (28)

However, a number of state highway agencies and studies have also suggested that common problems associated with the use of the "wet" process include (16):

- Higher initial cost: Some highway agencies claim an increase of approximately 25% to over 200% in the cost of the pavement;
- Higher viscosity than conventional asphalt;
- Increased mixing temperature: Asphalt cement and ground tire rubber should be mixed at approximately 204˚C to obtain uniform mixture and standard viscosity; and
- There are modifications, in some cases, that may be incurred to the asphalt plant, paving, and compacting equipment.

There is another method of mixing the CRM with the binder that is referred to as terminal blending. This binder is produced by mixing of virgin binder with Crumb Rubber Modifier (CRM) where the binder is digested into the bitumen at the refinery (Figure 10) or at an asphalt terminal and then delivered to the plant. Some of these binders are blended with various patented processes and in some cases they could present problems of phase separation.

2.8 Properties of CRM Binder

Ground tire rubber doesn't combine with asphalt binders in quite the same way as a polymer; it offers many of the same benefits when used as a modifying agent. The increased viscosity in polymer-modified binders results from the swelling of polymer molecules. Similarly, crumb rubber particles also swell and cause an increase in viscosity when combined, or "reacted", with asphalt. In addition, ground tire rubber facilitates an increase in elasticity similar to that seen in polymer-modified binders. Thus, rubber modified binders also prevent rutting and cracking. In addition to offering advantages similar to those gained with polymers, crumb rubber can extend pavement life in a different way. During the process of manufacturing tires, items such as carbon black and anti-oxidants are added to the rubber to prevent the aging.

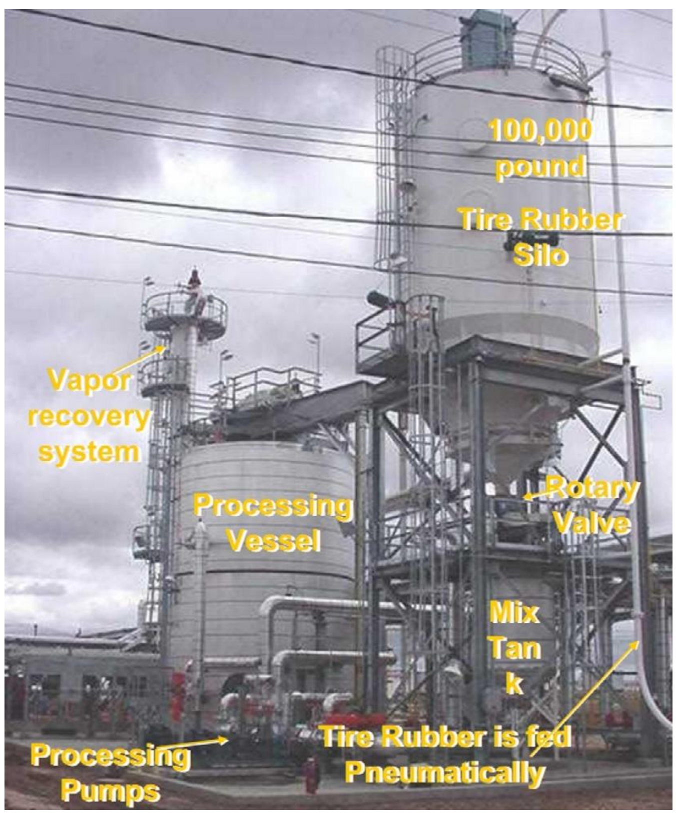


Figure 2.10. Terminal Blending Process of Rubberized Binder (29)

Specifying CRM is normally done in terms of physical and/or chemical properties. Commonly specified properties include: size/gradation, specific gravity, acetone extract, ash, carbon black, rubber hydrocarbon, and natural rubber content. The size/gradation of the CRM can influence the interaction of the asphalt rubber blend – a coarser CRM gradation generally requires a longer time to react than a fine grind.

Chemical properties of the rubber are important and have been established to define the CRM material. These requirements insure the proper use of auto/truck tires in CRM materials. The inclusion of specification requirements for ash, carbon black, and rubber hydrocarbon insures that unacceptable materials (e.g., conveyor belts) are not used.

Asphalt binder can affect the final asphalt rubber binder product in several ways. It must be compatible with the CRM. Compatibility is controlled by the chemical composition of both the asphalt cement and the CRM as demonstrated by an increase in the viscosity of the rubberized asphalt rubber blend with time. Most of the CRM produced today is a homogenous blend of different rubber polymers; hence, compatibility is primarily dependent on the properties of the asphalt cement rather than the composition of the CRM material.

2.9 SHRP Tests

Transportation Research Board (TRB) special report 202: America's Highways: Accelerating the Search for Innovation first detailed the objectives of the Strategic Highway Research Program. They were identified as follows: "To improve pavement performance through a research program that will provide increased understanding of the chemical and physical properties of asphalt cements and asphalt concretes. The research results would be used to develop specifications and tests needed to achieve and control the pavement performance desired" (30).

Emphasis was placed on developing a specification that would be valid for both modified and unmodified asphalt binders. The end product of the binder research program was called Superpave. The binder specifications were outlined in order to classify binders by performance criteria. Doing so allowed the binder to be evaluated based on performance criteria specific to the application, thus permitting the designer to anticipate the field conditions and ultimately design the pavement accordingly. However, not much research work was conducted regarding the use of modified binders containing CRM.

2.9.1 Binder Viscosity

AASHTO T 316 is the commonly used SHRP procedure for evaluating asphalt binder viscosity. Achieving asphalt viscosity requirements is of utmost importance for ease of pumping as asphalt is generally stored in asphalt plants at temperatures between 149˚C and 177˚C depending on the grade or viscosity (31). However, fulfilling these requirements becomes more difficult with the increasing viscosity due to modification of the binder by crumb rubber (32) as well as the specifications established by SHRP indicating that asphalt viscosity should not exceed 3.0 Pa-s at 135˚C (33).

Research has shown that rubberized asphalt viscosity increases as rubber concentration is increased, regardless of rubber type. Non-Newtonian behavior of the rubber modified binders was also shown to be more pronounced with increasing amounts of rubber. The same study also concluded that lower viscosity asphalt increases the rate of the modified binder reaction when compared to higher viscosity binders from the same source (34).

All combinations of rubber and binder produce a uniquely modified binder, and the resulting viscosity increases occurring with the addition of crumb rubber are due to the amount of aromatic oil absorption and rubber particle swelling. It has been shown that the increase in rubber concentration yielded significant increase in viscosity (34). Viscosity of CRM binder is known to be dependent on crumb rubber content (33), particle size and processing method (26), mixing temperature and duration (35), and rubber type (passenger tire or truck tire) (36).

2.9.2 G*/sinδ and Failure Temperature

Since the implementation of SHRP, the Dynamic Shear Rheometer has been used for the determination of G*/sinδ values as well as the high failure temperature of the binder. Results obtained from the DSR are vital to pavement performance when determining its resistance to rutting (33).

The complex shear modulus (G*) and phase angle (δ) are indicators of rutting tendency in the pavement (G*/sinδ) at high temperatures and of fatigue cracking (G*sinδ) at medium range temperatures. AASHTO TP 315 provides specifications and procedures for obtaining experimental values of the complex shear modulus and phase angle using the DSR (37).

As specified by previous studies, a gap height of 2 mm should be used for testing CRM binder samples, while virgin binders could be tested using a 1 mm gap. The differences in gap height were applied to account for the effect of the differing rubber particle sizes present in the CRM binder. Previous studies have shown that if the binders are tested in the linear viscoelastic region, the variation in the gap size will not have a significant impact on the results. Another advantage to using this procedure was the decreased variability noticed when the 2 mm gap data was compared to the 1 mm gap. It has been suggested that the decreased variability of the 2 mm gap data was due to the fact that there was a lower possibility of rubber particles coming in contact with the plates, thus adversely affecting the rheological measurements of the sample (39-40).

The high-temperature portion of the PG grade is determined by measuring the temperature at which the un-aged asphalt binder's complex shear modulus divided by the sine of the phase angle (G*/sinδ) is at least 1.0 kPa when measured at a frequency of 10 radian per second in accordance with AASHTO M 320 (41).

Studies have shown that the addition of crumb rubber to asphalt binder tends to increase the G*/sinδ values of the CRM binder. Typically, the addition of crumb rubber to binder is characterized by an increase in G* values and a decrease in phase angle, thus resulting in an overall increased rutting parameter of G*/sinδ (26).

2.10 California's Experiences with Rubberized Asphalt

There are many state agencies that utilize rubberized asphalt in their mixtures. Several states are the leaders in the use of rubberized asphalt including Arizona, California, Florida and Texas. In recent years, the use of rubberized binders has been increased for many reasons (e.g., increase in the cost of virgin binder, shortage of SBS, etc.). In the following section a brief description of one state's experience (California) with rubberized asphalt mixtures.

In late 1930s, the development of asphalt rubber materials for use as joint sealers, patches, and membranes initiated. In the early 1950s, the Bureau of Public Roads (BPR) conducted a study entitled “The Effect of Various Rubbers on the Properties of Petroleum Asphalts.” In this laboratory study, 14 types of rubber crumb and three asphalts were used. The results were published in the October 1954 issue of Public Roads. In addition, there was another research result entitled “Laboratory Study of Rubber-Asphalt Paving Mixtures,” conducted by Rex and Peck at BPR. The study included several materials such as vulcanized and unvulcanized rubber materials including tread from scrap tires, styrene-butadiene rubber (SBR), natural rubber, polybutadiene, and reclaimed (devulcanized) rubber and at both wet and dry methods of adding them to asphalt mixtures. The work in this area continued to grow in addition to an increase in number of patent applications.

In March 1960, the Asphalt Institute held the first Symposium on Rubber in Asphalt in Chicago, IL. In this conference 5 papers/presentations were made and many issues were discussed. Charles H. McDonald of the City of Phoenix Arizona worked extensively with asphalt and rubber materials in the 1960s and 1970s. He was very instrumental in development of the “wet process” (also called the McDonald process) of producing asphalt rubber. He used the newly developed materials in hot mix patching and surface treatments for repair and maintenance. Because of his work, for approximately 20 years, asphalt rubber chip seals served as the City’s primary pavement maintenance and preservation strategy for roadways. After several years of laboratory and field work, gap-graded asphalt rubber concrete mixtures were developed as a substitute.

In 1975, Caltrans began experimenting with asphalt rubber chip seals in the laboratory and small test patches with generally favorable results. In 1978, the first Caltrans dry process rubber-modified mix was constructed that included 1% ground rubber by mass added to the dry aggregate prior to mixing with the asphalt binder. The results of this project including the performance were rated good. In 1980, Caltrans, a couple of projects were constructed using the early versions of “wet-process” asphalt rubber binder and dense-graded aggregate. The next three projects were located in “snow country” at high elevations. The rubberized pavements performed well in resisting chain abrasion and reflective cracking. In 1983, the results of one project changed the views of Caltrans regarding the utilization of rubberized asphalt. This project was the Ravendale project (02-Las-395). For this project, the cost of rehabilitation by overlaying with dense graded mixture was too high so less costly alternatives were considered, including thinner sections of rubberized mixtures. The project was designed as a series of 13 test sections that included two different thicknesses (dense graded) each of wet process and gap-graded dry process rubberized mixtures, Stress Absorbing Membrane Interlay (SAMI) (4 sections), and some other combinations.

The test sections were monitored over time. The dry process section at this site lasted over 19 years before it was overlaid in 2002. By 1987, the Caltrans concluded that the thin rubberized pavements were performing better than thicker conventional dense graded mixes. Caltrans initiated more rubberized projects and continued to study the performance of rubberized pavements constructed at reduced thickness relative to conventional dense graded mixes. Through 1987, Caltrans constructed one or two rubberized projects a year having thicknesses ranging from 24 mm for open-graded to 76 mm for other rubberized mixtures. Some projects included other forms or materials such as reinforcing fabric (PRF) and SAMI under the asphalt rubber mixes.

Based on these field projects and observations over many years, in March 1992, Caltrans published a "Design Guide for Asphalt Rubber Hot Mix-Gap Graded (ARHM-GG)". The Guide presents structural and reflection crack retardation equivalencies for gap-graded asphalt rubber mixtures (now designated RAC-G) with respect to conventional dense graded mixtures with and without SAMI. These equivalencies have since been validated (Tables 3 and 4 of the Caltrans Flexible Pavement Rehabilitation Manual (June 2001). Some of these rubberized mixtures can generally be substitute for dense graded mixtures at about one-half the thickness.

By 1995, over 100 Caltrans rubberized projects had been constructed. In addition, several cities and counties in California constructed over 400 asphalt rubber projects (e.g., asphalt rubber chip seals). In some cases; however, there were cases of premature distress. At this point, Caltrans engineers reviewed the performance of several rubberized asphalt projects around California and 41 Arizona DOT projects. Some of the problems were construction related due to lack of experience dealing with these mixtures. A Caltrans-Industry review concluded that asphalt rubber materials can perform very well when properly designed and constructed. In addition, they recommended that Caltrans should continue using and studying asphalt rubber. The results of these studies indicated that the distresses in these pavements appeared to progress at a much slower rate than would be expected in a structurally equivalent conventional dense graded pavement. For the rubberized mixtures, in many of the cases with premature distress (such as cracking), relatively little maintenance was required to achieve adequate pavement service life because the subsequent distress developed slowly. Many of these pavements performed very well after 15 and in some cases 20 years of service life.

By mid-2001, over 210 Caltrans rubberized projects had been constructed around California. In addition, many municipalities and counties also continued to use asphalt rubber for hot mixes and surface treatments with good performance in many cases. However, in some cases, there were problems with the performance for many reasons (e.g., lack of experience, etc.). A Modified Binder (MB) specification was developed in the early 1990s as part of a continuing movement towards performance-based specifications. The references for this section of the progress report are included below (42-53).

CHAPTER 3

Experimental Design and Rankings of the Binders

3.1 General background

This design will be divided into three sections, A-C, as explained in Chapter 1. Section A included the investigation of the high-temperature rheological properties of original rubberized asphalt binders. Figure 1 shows the experimental design for this portion of the research project.

Section B included the investigation of the high-temperature rheological properties of rubberized asphalt binders from Section A, after aging in a rolling thin-film oven (RTFO) (Nev. 728). The experimental section for this portion of the research project is show in Figure 1. Section C (Figure 1) included the investigation of the low-temperature rheological properties of rubberized asphalt binders after being aged by RTFO and a pressure aging vessel (PAV).

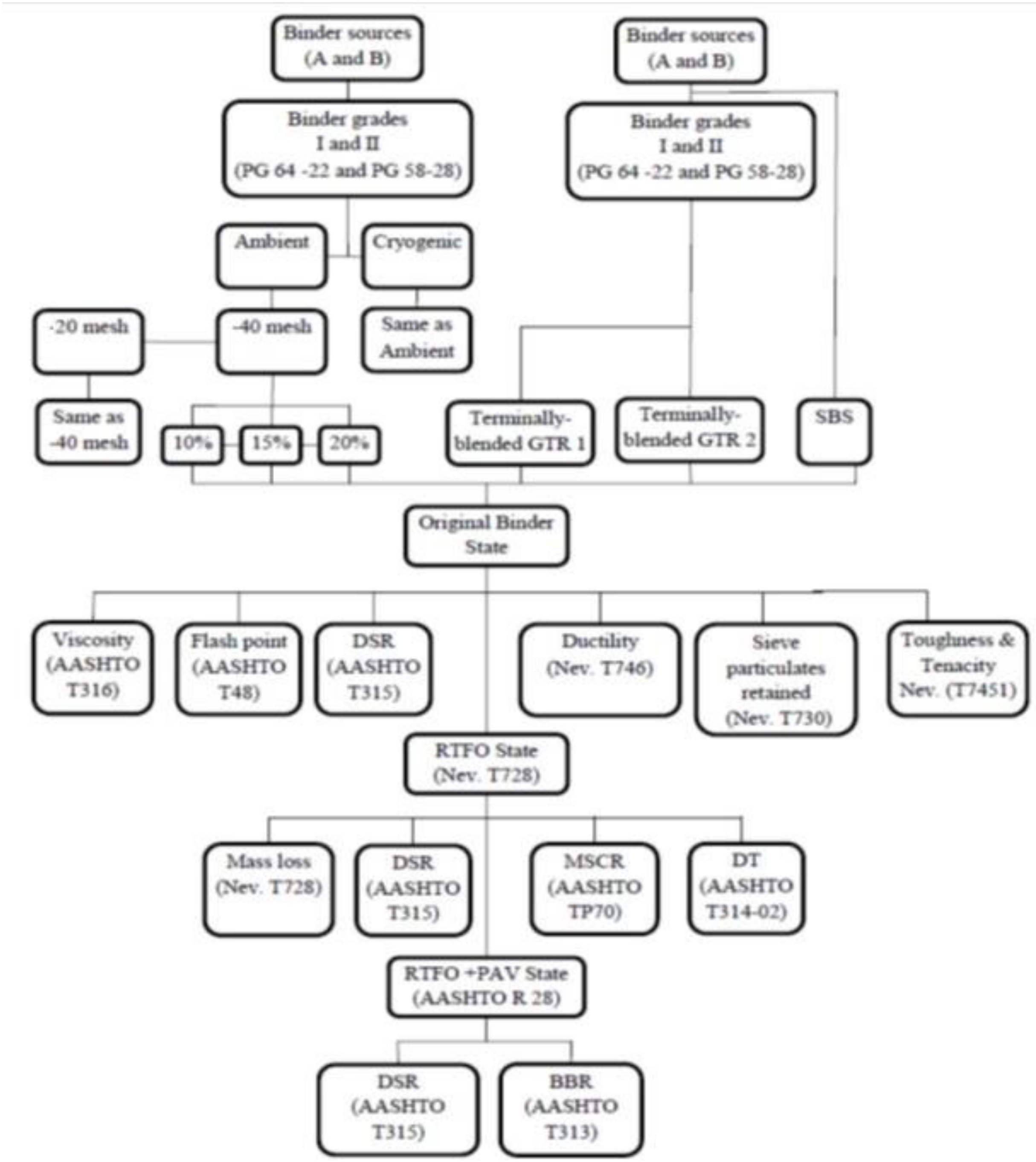


Figure 3.1. Rheological properties of rubberized binders at three aging states

3.2 Sources of Asphalt Binder

Three suppliers were suggested by NDOT as the source of virgin, polymer modified and terminal blend tire rubber asphalt binders. One of the sources refused to send the requested sample and was eliminated from the list of sources. In order to keep the sources of the binders anonymous at this time, alphabetic letters of A and B were used to identify these sources. From source A, the virgin binders of PG58-28 and AC-20 as well as polymer modified PG64-28NV and PG76-22NV and terminally blend tire rubber modified PG64-22TR and PG76-22TR were obtained by the research team. From source B, the virgin binder of PG64-16 and polymer modified of PG76-22NV were obtained. The research team also obtained the asphalt rubber binder of PG76-22 that was made in an asphalt plant in southern Nevada from the virgin binder of source B. Figure 2 shows the chart of the entire asphalt binder samples obtained from sources A and B and made in the lab.

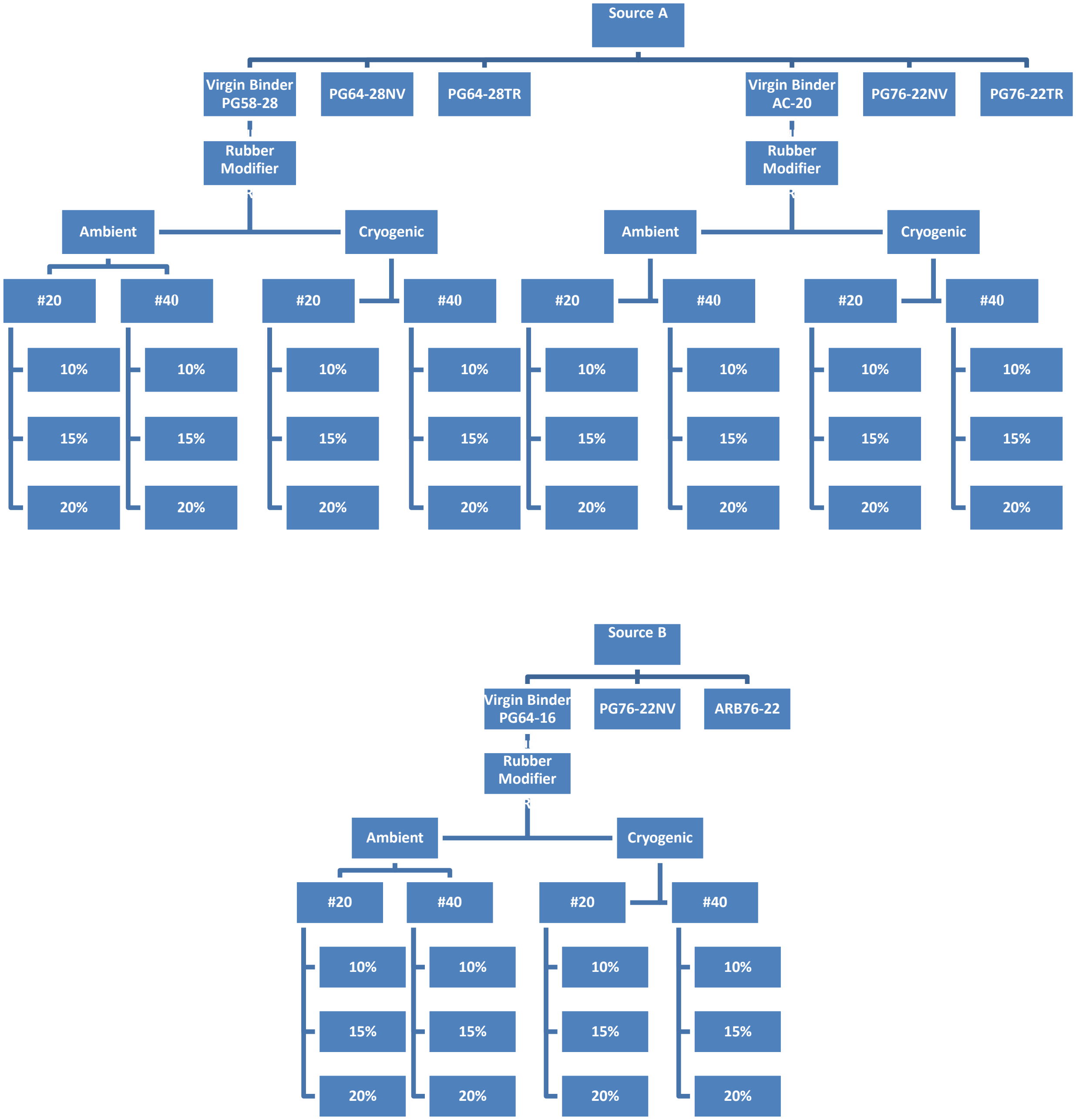


Figure 3.2. Asphalt binder samples obtained from sources A and B and made in the lab

3.3 Mixing the crumb rubber with virgin binder

Several types of Crumb Rubber Modifiers (CRM) will be utilized for this research: various sizes and different method of production (i.e., ambient or cryogenic). First, sieve analysis was performed for each CRM source. Then, required amount of virgin binder (e.g., PG 64-22) was heated to 177 ˚C. Usually, a container of approximately 600 grams of binder was used. The required amount of CRM (e.g., 10% by total weight of the binder) was added to the hot binder as the matrix was blended (700 rpm). This blending continued for 30 minutes or longer ensuring that a homogenous matrix was obtained. Immediately, after the mixing was completed, the binder was tested (e.g., DSR). If the binder had to be stored and tested at a later date, the binder was heated and stirred vigorously before testing was initiated.

3.4 Sample Labeling

Each asphalt binder sample is identified by combination of alphabetic letters and numbers. Alphabetic letters are used to identify the sources of virgin and modified asphalt binders and it is the first character in the ID name. Grade of the asphalt binder as given by the source-with no dash line- is following the letter, representing the source. For example A6428 is the PG64-28 asphalt binder sample from the source A. If the sample is mixed with crumb rubber following characters are added to the ID.

- Am or Cr for ambient or cryogenic crumb rubber; respectively.
- 20 or 40 for mesh # 20 and #40; respectively.
- 10, 15, or 20 for 10%, 15%, or 20% added crumb rubber to virgin asphalt; respectively.

For example, A5828-Am-40-10 is the sample of PG58-28 from source A mixed with 10 percent of ambient crumb rubber with particles smaller than 40 mesh.

3.5 Testing the original asphalt binders

First section of Task 2 concludes testing on the original (un-aged) asphalt binders. This includes performing the test presented in Figure 1 on virgin, polymer modified, and terminal blend rubber modified as well as samples of base binders mixed with CRM selected by the research team. For all tests, three test specimens were made and tested (except for DSR test which two specimens were tested). Results of each specimen as well as the average were reported. Following is the description of the performed tests.

3.5.1 G*/sinδ and Failure Temperature

Since the implementation of SHRP, the Dynamic Shear Rheometer has been used for the determination of G*/sinδ values as well as the high failure temperature of the binder. Results obtained from the DSR are vital to pavement performance when determining its resistance to rutting (54). The complex shear modulus (G*) and phase angle (δ) are indicators of rutting tendency in the pavement (G*/sinδ) at high temperatures and of fatigue cracking (G*sinδ) at medium range temperatures. AASHTO TP 315 provides specifications and procedures for obtaining experimental values of the complex shear modulus and phase angle using the DSR (55).

As specified by previous studies, a gap height of 2 mm should be used for testing CRM binder samples, while virgin binders could be tested using a 1 mm gap. The differences in gap height were applied to account for the effect of the differing rubber particle sizes present in the CRM binder. Previous studies have shown that if the binders are tested in the linear viscoelastic region, the variation in the gap size will not have a significant impact on the results. Another advantage to using this procedure was the decreased variability noticed when the 2 mm gap data was compared to the 1 mm gap. It has been suggested that the decreased variability of the 2 mm gap data was due to the fact that there was a lower possibility of rubber particles coming in contact with the plates, thus adversely affecting the rheological measurements of the sample (56-57).

The high-temperature portion of the PG grade is determined by measuring the temperature at which the un-aged asphalt binder's complex shear modulus divided by the sine of the phase angle (G*/sinδ) is at least 1.0 kPa when measured at a frequency of 10 radian per second in accordance with AASHTO M 320 (58).

3.5.2 Viscosity of Asphalt Binder

AASHTO T 316 is the commonly used SHRP procedure for evaluating asphalt binder viscosity. Achieving asphalt viscosity requirements is of utmost importance for ease of pumping as asphalt is generally stored in asphalt plants at temperatures between 149˚C and 177˚C depending on the grade or viscosity (59-60). However, fulfilling these requirements becomes more difficult with the increasing viscosity due to modification of the binder by crumb rubber (61) as well as the specifications established by SHRP indicating that asphalt viscosity should not exceed 3.0 Pa-s at 135˚C (54).

Research has shown that rubberized asphalt viscosity increases as rubber concentration is increased, regardless of rubber type. Non-Newtonian behavior of the rubber modified binders was also shown to be more pronounced with increasing amounts of rubber. The same study also concluded that lower viscosity asphalt increases the rate of the modified binder reaction when compared to higher viscosity binders from the same source (62).

3.5.3 Ductility

The ductility test was conducted in accordance with Nev. T746E. It provides a measure of tensile properties of bituminous materials. The ductility is measured by the distance in centimeters to which standard specimen will elongate before breaking.

3.5.4 Flash Point

The flash point test was conducted in accordance with AASHTO T48. The flash point is the lowest liquid temperature at which application of the test flame causes the vapors of the sample to ignite.

3.5.5 Toughness and Tenacity

The toughness and tenacity test was conducted in accordance with Nev 745I. Toughness of the asphalt binder is the area underneath the curve of variation of force versus elongation and represents the strength of the asphalt binder as well as the capability to be stretched. Tenacity is the area underneath the curve of variation of force versus elongation after the initial strength has been overcome and represents the capability of the asphalt binder to be stretched after the initial strength has been overcome. This test is performed at 25˚C.

3.5.6 Sieve Particulates Retained

The sieve test was performed on the samples made with CRM according to Nev. 730C. The general trend observed in the sieve tests was no particulates retained when 10% of mesh 40 was mixed with virgin binder, some particulates retained for 15% and lots of particulates retained for binders containing 20% crumb rubber. For mesh 20, the amount of retained particles was more that mesh 40 for all percentages.

3.6 Testing the RTFO-aged asphalt binders

Second section of Task 2 concludes testing on the RFTO-aged (rolling Thin Film Oven) asphalt binders. This includes performing the test presented in Figure 1 on samples that have been conditioned in a Rolling Thin Film Oven according to Nev T728. Tests were performed on virgin, polymer modified, and terminal blend rubber modified as well as samples of base binders mixed with CRM selected by the research team. Two test specimens were made and tested.

3.6.1 G*/sinδ and Failure Temperature

For this portion of the research, the samples were tested as described before after the RTFO aging process. The testing procedures followed AASHTO guidelines.

3.6.3 Ductility

The ductility test was conducted in accordance with Nev. T746E. As described before, this test was conducted on samples after RTFO aging process.

3.7 Testing the PAV-aged asphalt binders

Third section of Task 2 concludes testing on the PAV-aged (rolling Thin Film Oven + pressure aging vessel) asphalt binders. This includes performing the test presented in Figure 1 on samples that have been conditioned in a Rolling Thin Film Oven according to Nev T728 and then PAV aged according to AASHTO R28. Tests were performed on virgin, polymer modified, and terminal blend rubber modified as well as samples of base binders mixed with CRM selected by the research team.

3.7.1 G*sinδ

The Dynamic Shear Rheometer has been used for the determination of G*sinδ values as well as the medium temperature of the binder. Results obtained from the DSR are vital to pavement performance when determining its resistance to fatigue cracking. The complex shear modulus (G*) and phase angle (δ) are indicators of fatigue cracking (G*sinδ) at medium range temperatures.

3.7.2 Stiffness (S_{60}) and m-value

The Bending Beam Rheometer (BBR) test provides a measure of low temperature stiffness and relaxation properties of asphalt binders. These parameters give an indication of an asphalt binder's ability to resist low temperature cracking.

3.8 Analysis and Discussion Regarding the Ranking of the Binders

The main goal of Tasks 1 and 2 in this project is to determine the best combination of crumb rubber modifier (CRM) with virgin binder based on the tests that are performed on binder samples made in the lab and obtained from the various binder sources. To achieve this goal, the properties of the polymer modified and terminally blend tire rubber asphalt binder were considered as reference and whichever combination of CRM with virgin binder that its test results are closer to the average of those two is defined as the best alternative. Since there are multiple tests were performed the process method is needed to be used for this matter. The research team decided to use the Analytic Hierarchy Process (AHP) as the method for determining the best alternative.

3.8.1 Analytic Hierarchy Process (AHP) Method

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 3.1 through 3.3 show the rank of each alternative in each criterion for virgin binders of PG58-28, PG64-16, and AC-20, respectively.

Table 3.1 - 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 3.2 - 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 3.3 - 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 3.4 shows the weight of each property (criterion) for different grades.

Table 3.4 - 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

3.8.2 Virgin binder A58-28 + CRM

Some properties of rubberized asphalt in this study like ductility and "toughness and tenacity" did not meet the specifications and were excluded from the process of selecting the optimum combination. Three approaches were examined. In approach 1, failure temperatures (original and RTFO) are not considered. Remaining options are ranked based on their ductility and "toughness and tenacity". Ambient-Mesh20-15% shows the highest ductility (original and RTFO) as well as highest toughness and tenacity and is selected according to this approach. In approach 2, m-value is excluded and the only remaining option is Cryogenic-Mesh20-10%. In approach 3, m-value and RTFO failure temperature are not considered and among the remaining options Ambient-Mesh20-10% shows the highest ductility and is selected. Each approach resulted in different combinations and selection among them is left to further investigation and discussion with Nevada DOT representatives.

3.8.3 Virgin binder AC-20+ CRM

Excluding the original ductility the remaining options that meet all the specifications are Ambient-Mesh40-15% and Cryogenic-Mesh40-20%. Between these two, Ambient-Mesh40-15% shows higher creep recovery as well as ductility and is selected as the best combination.

3.8.4 Virgin binder B64-16+ CRM

Original ductility is excluded for this virgin binder, as well. Four alternatives (Ambient-Mesh40-15%, Ambient-Mesh20-15%, Cryogenic-Mesh40-20%, and Cryogenic-Mesh20-20%) meet all the specifications. The research team decided to use the Analytic Hierarchy Process (AHP) as the method for determining the best alternative.

3.8.5 Analytic Hierarchy Process (AHP) Method

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. Software "MakeItRational" (http://makeitrational.com/) was used to analyze the data for AHP method.

Four alternatives are ranked (weighted), as shown in table 3.5, in each criteria based on the test results and their deviation from the results of polymer modified.

Table 3.5 Weight of different alternatives based on test results

	FP		Vis.		G*/sinδ		Cr. Rec.		Jnr		G*× sinδ		S60		m-value	
	value	weight	value	weight	value	weight	value	weight	value	weight	value	weight	value	weight	value	weight
Am#40-15%	298	5.26	2.52	30.30	2.25	11.11	50.4	31.25	0.0347	30.86	607	27.32	48.43	14.75	0.364	16.67
Am#20-15%	308	11.11	2.55	33.33	1.55	50.00	54.5	35.84	0.0277	25.38	849	16.45	53.22	2.43	0.349	11.11
Cr#40-20%	302	6.67	2.38	21.28	2.38	9.71	48.8	29.76	0.0228	22.57	601	27.78	43.68	1.84	0.353	20.00
Cr#20-20%	293	4.17	2.07	12.82	2.07	13.89	60.3	45.25	0.0159	19.53	682	22.68	53.53	2.26	0.339	5.26

The analysis was performed and it revealed that Ambient-Mesh20-15% was the best combination for this virgin binder. It turns out that this alternative had a highest ductility among the all four.

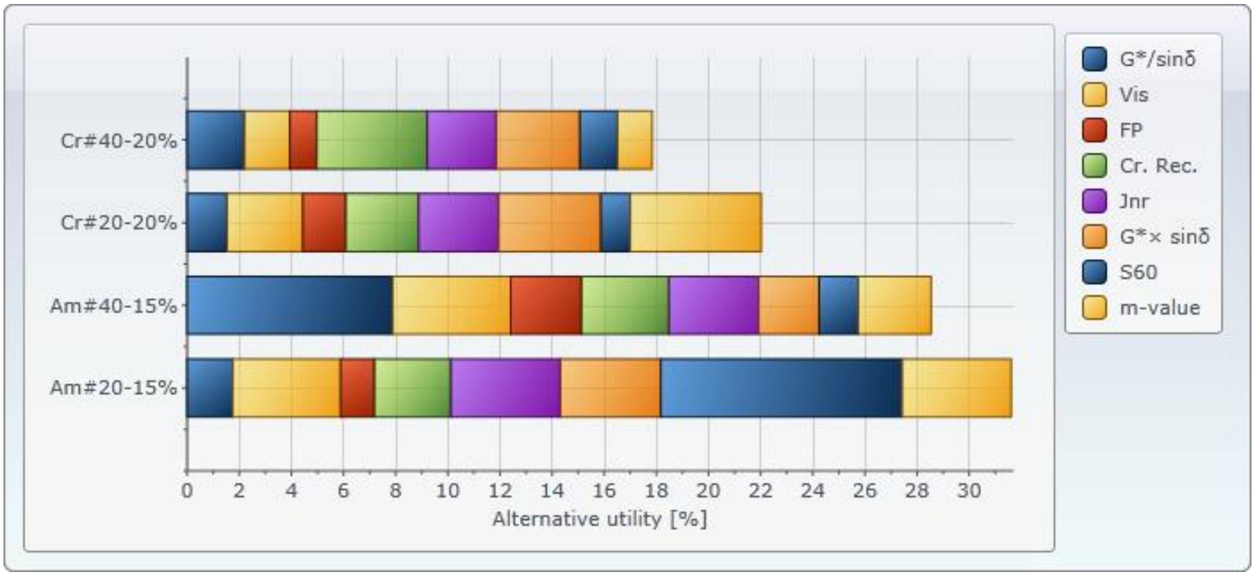


Figure 3.3. Analysis of each alternative

CHAPTER 4

Results and discussions of rubberized binders

4.1 Testing the original asphalt binders

4.1.1 G*/sinδ and Failure Temperature

The results of the DSR test are presented in Appendix A of this report. For PG58-28 from source A mixed with Ambient CRM, there was not much difference observed between #40 and #20 regarding G*/ sinδ. But for Cryogenic CRM, binders containing #40 showed higher numbers compared to binders made with #20 mesh CRM. The PG64-16 of source B containing #40 CRM showed higher numbers than #20 for both ambient and cryogenic. Failure temperature of these binders increases by increase in percentage of CRM. For PG58-28 source A and 10% CRM, the binder made with the ambient #40 has the highest failure temperature compared to other binders. The binder source B and made with ambient #20 produced the highest failure temperature.

In this study, it can be found that the G*/ sin δ values of various asphalt binders were obtained through a series of dynamic shear rheometer (DSR) tests. As shown in Appendix A, Tables A-1 to A-11 presented the G*/ sin δ values, phase angles and failure temperatures of all modified binders.

All G*/ sin δ values were summarized and are shown in Figures A-1 to A-12. As expected, an increased rubber concentration results in an increase of G*/ sin δ value regardless of binder source and grade, rubber type and size, and test temperature. However, an increase in temperature resulted in a decrease of G*/ sin δ value. Obviously, the binder modified with a stiffer binder (PG 64-16 / AC 20) has a higher G*/ sin δ value compared to those binders modified from a softer binder (PG 58-28).

In addition, in terms of the impact of rubber size, it can be noted that the modified binder containing -40 mesh rubber has a higher G*/sin δ value than the binder containing -20 mesh rubber under an identical condition. Meanwhile, rubber type has a slight influence on the G*/sinδ value because, in most cases, the binder containing ambient rubber displays a slightly higher G*/sinδ value compared to the binder containing cryogenic rubber, but the binder source and grade as well as rubber size affect this trend.

Failure temperature is defined based on the G*/sin δ value of asphalt binder equaling 1.00 kPa. Figures A-13 to A-15 present the failure temperatures of the modified binders blended with three base binders and various rubbers, as well as the base binder and SBS modified or TB binders.

As shown in Figure A-13, a greater rubber percentage results in a higher failure temperature irrespectively of rubber type and size. In addition, it can be found that PG 58-28 binder blended with 20% rubber has a failure temperature higher than 76C, but the failure temperature is higher than 64C when used 10% rubber. Moreover, the binders PG 64-28NV and PG 64-28TR have failure temperatures less than 76C. Therefore, it is definitely necessary to use over 20% rubber to produce a modified PG 76 binder when used PG 58-28 binder as a base binder.

Figure A-14 indicates that, regardless of rubber type and size, the PG 64-16 binders mixed with 20%, 15% and 10% rubber have failure temperatures over 82C, 76C and 70C, respectively. Obviously, a 15% rubber can help PG 64-16 binder achieve a grade of PG 76. In addition, the plant produced binder PG 76-22NV has a failure temperature of 76C-82C, but ARB76-22 binder has a quite high failure temperature close to 94C. Consequently, based on these results, it is easy to produce a proper rubberized binder satisfying the performance grade in the field.

The failure temperatures of rubberized binders modified from AC20 base binder are summarized in Figure A-15. Similarly to PG 64-16 binder, the AC20 binders mixed with 20%, 15% and 10% rubber have failure temperatures over 82C, 76C and 70°C, respectively, irrespectively of rubber type and size. In addition, plant produced binders of PG 76-22NV and PG 76-22TR have failure temperatures over 76°C. Thus, AC20 can be used to produce the binders with a high performance grade to meet the requirements of high temperature in Nevada.

Phase angles of various rubberized binders are presented in Figures A-16 to A-27. In general, it can be noted that, as expected, an increased temperature results in an increase of phase angle and a higher rubber content results in a low phase angle regardless of the binder source and grade, rubber type, size and percentage. In other words, the binder exhibits the viscous characteristics at a relatively high temperature and displays the elastic behavior at a low temperature. In addition, a higher rubber percentage reduced phase angles of the rubberized binder, exhibiting the elastic properties.

In addition, the rubber type (ambient and cryogenic) generally has a slight effect on the phase angle. The binder mixed with ambient rubber has a relatively lower phase angle when 20% rubber was added, but this difference is not remarkable when 10% and 15% rubber were used. Moreover, the binder source and grade affect the phase angle under identical condition. The rubber size has a slight influence on the phase angle when used same binder grade and source and the same percentage.

4.1.2 Viscosity of Asphalt Binder

The results of the viscosity test on the samples are presented in Appendix A. The overall results indicated that the viscosity of the asphalt binder increases by the CRM content. For example, the PG64-16 from source B mixed with -40 mesh CRM showed higher viscosities compared to that of -20 mesh size. In addition, binders containing ambient CRM produced higher viscosity compared to binders made with cryogenic CRM.

The viscosity values of various binders at 135°C are summarized in Figures A-28 to A-30. It can be seen that an increased rubber percentage results in an increase of viscosity value regardless of rubber type and size, as well as binder grade and source. In most cases, the binder containing ambient rubber has a higher viscosity than the binder containing cryogenic rubber irrespectively of rubber size and binder type. In terms of rubber size, it can be noted that no trends can be found because it seems that it is binder source and grade dependent. In addition, it can be noted that the plant produced binders such as A7622NV and A7622TR have viscosity values greater than the rubberized binder containing 10% but less than those binders containing 15% and 20% rubber. However, B7622NV and ARB7622 binder have relatively higher viscosity than the binder containing 15% CRM and even greater than those binders containing 20% in some cases.

4.1.3 Ductility

The ductility result was conducted at 4°C for different crumb rubber contents as illustrated in Figures A-31 to A-33.

The results revealed that the highest ductility is achieved in 10% ambient -20 mesh CRM mixed with PG58-28 from source A, and 20% ambient -40 mesh mixed with PG64-16 from source B. Ductility of asphalt rubber samples are very low compared to polymer modified and terminal blended samples.

Being non-homogeneous and having a matrix structure could be stated as the main reason for low ductility values for asphalt rubber samples.

4.1.4 Flash Point

The results of the flash point test are presented in Figures A-34 to A-36. The results indicated that samples with CRM have lower flash point yet higher that minimum requirement.

4.1.5 Toughness and Tenacity

The results of the toughness and tenacity test are presented in Figures A-37 to A-56 and summarized in Figures A-57 to A-65. Overall results indicated that the addition of CRM to the virgin binder increases the toughness and maximum initial strength but it reduces the tenacity. The results revealed that the highest toughness in achieved in 20% ambient #20 for both PG58-28 from source A, and PG64-16 from source B. Maximum tenacity was observed in 10% ambient #20 mixed with PG58-28 from source A, and 10% ambient #40 mixed with PG64-16 from source B.

4.1.6 Sieve Particulates Retained

The sieve test was performed on the samples made with CRM according to Nev. 730C. The general trend observed in the sieve tests was no particulates retained when 10% of mesh 40 was mixed with virgin binder, some particulates retained for 15% and lots of particulates retained for

20%. For mesh 20 the amount of retained particles was more that mesh 40 for all percentages. It was also observed that with the same percentage amount of retained for ambient CRM is significantly higher that Cryogenic CRM. Some images of retained particles on sieves are presented in Figures A-66 to A-A77.

4.2 Testing the RTFO-aged asphalt binders

Second section of Task 2 included the testing of the RFTO-aged (rolling Thin Film Oven) asphalt binders. Results of the testing for each specimen as well as the averages were obtained and reported. Following is the description of the performed tests and their results.

4.2.1 G*/sinδ and Failure Temperature

Results of the DSR test on RTFO samples of PG64-16 from source B mixed with CRM are presented in Figures A-78 to A-89. For Ambient #40 CRM 167% increase was observe in regards to G*/Sinδ value in average compared to the results obtained from the original state. These increases for Cryogenic #40, Ambient #20, and Cryogenic #20 were 225%, 218%, and 306%, respectively.

Similar to the G*/ sin δ values of the binders at virgin states, G*/ sin δ values of the binders at RTFO states are summarized in Figures A-78 to A-89. It can be seen that an increased rubber content results in an increase of G*/ sinδ value and a high test temperature reduces the G*/ sinδ value regardless of binder source and grade, as well as rubber size and type.

The failure temperatures of various rubberized binders at RTFO state are presented in Figures A-90 to A-92. It can be noted that, as expected, an increased rubber content results in an increase of failure temperature of rubberized asphalt binder regardless of the rubber type and size, as well as binder grade. In addition, it ca be seen that, the failure temperature of the binder with ambient rubber is higher than those temperatures of the binders with cryogenic rubber under an identical condition. The effect of rubber size on the failure temperature is not noticeable for the binders tested for this research project.

Figures A-93 to A-96 show the phase angles of various rubberized asphalt binders. Similar to the virgin binders, it can be noted that an increase in temperature resulted in an increase of phase angle irrespective of binder grade, rubber type, size and content. In addition, the binder containing higher rubber content has a lower phase angle due to a higher stiffness. In general, the influence of rubber size and type on phase angle are not remarkable in this study.

4.2.2 Ductility

The ductility result was conducted at 4°C for different crumb rubber contents as illustrated in Figures A-97 to A-99. The overall results showed decrease in ductility due to RTFO conditioning the samples.

4.3 Testing the PAV-aged asphalt binders

Third section of Task 2 included the testing on the PAV-aged (rolling Thin Film Oven + pressure aging vessel) asphalt binders. Tests were performed on virgin, polymer modified, and terminal blend rubber modified as well as samples of base binders mixed with CRM selected by the research team.

4.3.1 G*×sinδ

The Dynamic Shear Rheometer has been used for the determination of G*×sinδ values as well as the medium temperature of the binder. Results obtained from the DSR are vital to pavement performance when determining its resistance to fatigue cracking. The complex shear modulus (G*) and phase angle (δ) are indicators of fatigue cracking (G*sinδ) at medium range temperatures.

As shown in Table A-1, it can be noted that the G*sin δ value is close to 500 kPa when A64-28TR binder was used, but this value is lower, only 166 kPa, if binder A64-28NV was utilized. In addition, their phase angles are obviously different.

Tables A-1 to A-6 indicate that the G*sin δ values of various rubberized binder generally have the same trends. That is an increase in rubber content results in a lower G*sin δ value regardless of rubber type and size, and binder grade. In addition, the phase angles decreases. The impacts of rubber type on the G*sin δ values are not as obvious though.

4.3.2 Stiffness (S_{60}) and m-value

The Bending Beam Rheometer (BBR) test provides a measure of low temperature stiffness and relaxation properties of asphalt binders. These parameters give an indication of an asphalt binder's ability to resist low temperature cracking.

Two binders (B76-22NV and A64-22TR) have the stiffness values less than 300 MPa and m-values greater than 0.300 at a test temperature of -12°C, the requirement set forth by specification. In addition, the stiffness and m-value of A5828 modified with various rubber types, contents, and sizes are presented in Table A-7 to A-10. As expected, it can be noted that the rubber content results a difference in the stiffness values. In addition, the rubber type does not generally have the influence on the stiffness values. Moreover, a larger size of rubber results in a slight reduction in this limited study.

In terms of m-value, it can be noted that rubber content and size have slight influence on the m-value, but the rubber type (ambient and cryogenic) does have the impact on the m-value. The cryogenic rubberized binders generally have m-values less than 0.300 regardless of rubber content and size.

The stiffness and m-values of the rubberized binders from AAC20 and B6416 are shown in Tables A-7 and A-10, respectively. In general, similar trends can be found in terms of rubber content and size. However, it can be noted that rubber type generally has the influence on the m-values in Table A-7. Apart from Tables A-8 and A-9, the m-values of the binders with cryogenic rubber are greater than 3.00 regardless of rubber content and size.

CHAPTER 5

Experimental designs of asphaltic mixtures

5.1 Background

Properties of asphaltic mixture produced with the selected rubberized asphalt binders from Task 2 were investigated in this Task. Hveem mix designs were performed for rubberized mixtures using selected two aggregate sources (one from southern Nevada(A), and one from northern Nevada(B)); seven binders (Two polymer modified, two terminal blend tire rubber, and three rubberized selected from previous Task), and one solid Anti Stripping Agent (ASA) in accordance with the conventional hot-mix asphalt mix procedures, following Nevada DOT's specifications. In addition, the effects of selected crumb-modified binders on Hveem mix design are investigated with respect to air void, VMA, voids filled with asphalt (VFA), optimum binder content, etc.

The following testing procedures were conducted for all of the mixtures: a) Moisture susceptibility– Nev. T341D; b) Rut Resistance – AASHTO TP 63 (APA); c) Dynamic modulus and flow number - AASHTO TP 79; and d) Dynamic modulus master curves - AASHTO PP61. Figure 5-1 shows the experimental design for this portion of the research project.

In order to investigate the low-temperature performance of the mixtures, several testing procedures were evaluated and considered. For example, the Disc-Shaped Compact Tension test (DCT) was used to determine the low-temperature fracture properties for test specimens of cylindrically shaped asphalt concrete. This testing procedure offers many advantages, including easy specimen fabrication; also, it is a standard fracture test configuration (ASTM E399 Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials).

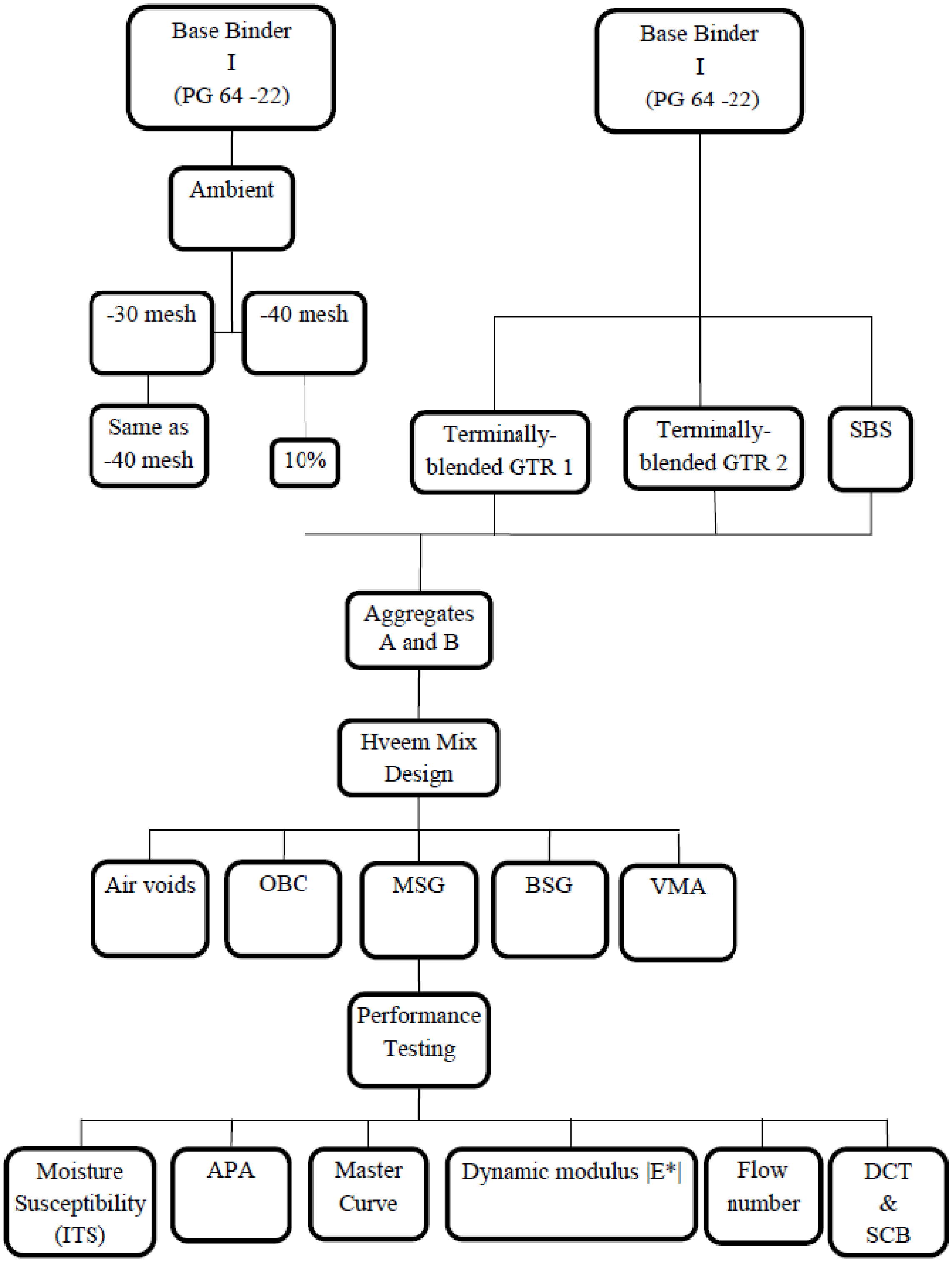


Figure 5.1 Engineering properties of general modified mixtures.

5.2 Combinations of Aggregate and Asphalt Binder/Asphalt Rubber Binder

Four different combinations of aggregate and asphalt binder (polymer modified and terminal blend tire rubber) and three combinations of aggregate and rubberized asphalt (selected from previous Tasks) were examined in this Task. Asphalt binders that are mixed with aggregates from southern Nevada are B76-22NV and A76-22TR. Rubberized asphalt binders that are mixed with aggregates from southern Nevada are AAC-20+Ambient-Mesh40-15% and B64-16+Ambient-Mehs20-15%.

5.3 Mix Design

Hveem method of mix design according to Nevada DOT and standard practice of Nev T760C was used to obtain the optimum proportion of aggregates and asphalt binder/rubberized asphalt. Type 2C gradation of aggregates was selected and other properties of aggregate were provided to the research team by Nevada DOT representatives. Table 5.1 shows the gradation and other properties of aggregate from the source in southern Nevada. Marinated aggregates were received in the lab in three sizes and were sieved through 8 sieve sizes of the Type 2C gradation. Batches were made based on the mid-points of range.

Table 5.1. Properties of aggregate from southern Nevada source

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

5.3.1 Mixing, Compaction, and Stability Test

Test Method Nev T303 was followed to conduct these tests. Appendix B includes the results of Stability Test on asphalt mix briquettes. Results of the Stability Test on two of mix sets are presented in Appendix B.

5.3.2 Volumertic Properies of compacted Mix

Bulk specific gravity and bulk density of compacted samples were obtained according to Test Method Nev T333. Theoretical maximum specific gravity of loose mixes was obtained according to AASHTO T 209. Estimated percent air void and actual air void were calculated based on test methods Nev. T321 and AASHTO T269. Appendix B includes the results of volumetric properties.

5.3.3 Optimum Binder Content (OBC)

According to test method Nev. T760C, the variation of Hveem Stability, Air Voids and Bulk Density with binder content are plotted. First the samples that meet both air void and stability values are determined. By considering the environmental area where this material is to be used and the type and amount of traffic to be carried and from reviewing the test results of the qualifying samples, plotted data points, and giving consideration for environment and traffic levels, an estimate of optimum is selected. At the estimated optimum bitumen ratio, samples for maximum theoretical specific gravity (Rice) are prepared.

From the result of the maximum theoretical specific gravity (Rice) determination, the air void percentage of each point on the curve is adjusted. This gives a more accurate representation of air voids than only a calculated theoretical value. From the data determined from testing, the following values are calculated with which to apply the required criteria.

VMA, Voids in Mineral Aggregate.
VFA, Voids Filled with Asphalt.
Film Thickness

After specification requirements are met, project criteria are applied to further identify the optimum bitumen ratio. Table 5.2 shows the OBC of various mixtures.

Table 5.2. Optimum bitumen content

Asphalt Type	Optimum Content (%)
PG76-22NV	5.8
PG76-22NVTR	6.0
PG64-28NV	5.0
PG64-28NVTR	5.0
PG64-16+15%Am#20	6.7
AC20+15%Am#40	6.6
PG58-28+15%Am#40	6.4

For mixes made with crumb rubber modified asphalt binders, the regular gradation of aggregates and compaction procedure did not result in satisfying results (air voids). To solve this issue, the research team decided to increase the compaction temperature (150 °C) to decrease the viscosity of asphalt rubber at the time of compaction to see if air voids requirements could be met. Specimens compacted at higher temperatures have higher Hveem Stability but amount of air void is still higher than required. On the second attempt, the gradation of aggregates was changed. The goal was to remain in the limitations of Type 2C but with the minimum surface area of aggregates. Figure 5.2 shows the proposed gradation. These mixes were also compacted at higher temperature than the required by specifications. The results were satisfying for Hveem Stability and air void. Results of the second attempt are presented in Appendix B. After consulting with Nevada DOT-Materials Division representatives, compaction temperature of 130 °C and new gradations was approved for mixes of crumb rubber modified asphalt rubber.

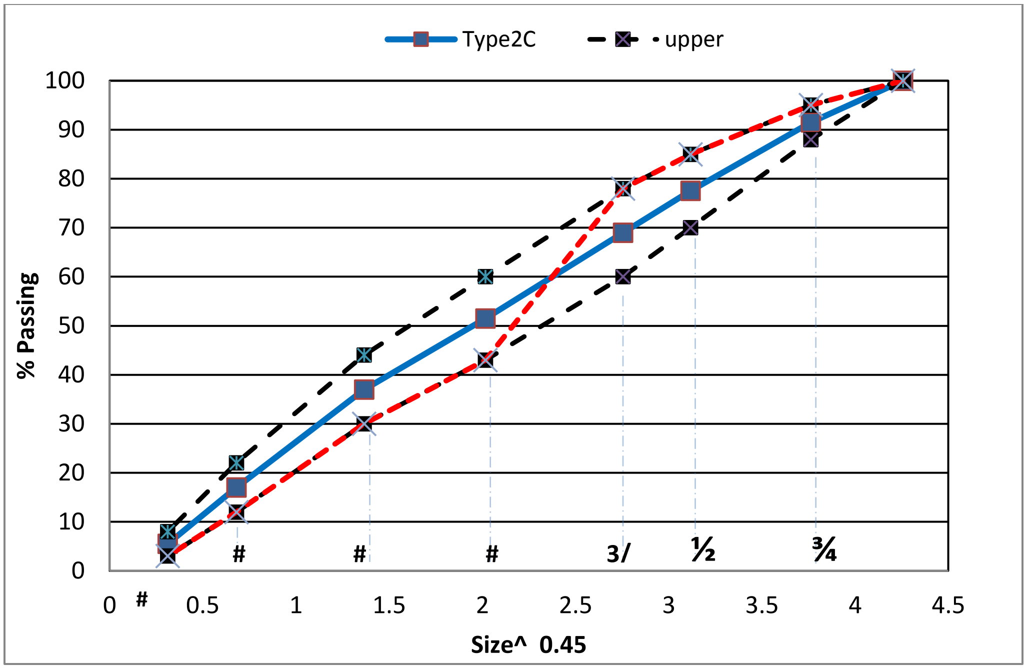


Figure 5.2 proposed gradation compared to Type 2C mid-point

5.4 Resistance to Moisture-Induced Damage (Lottman)

The effects of water damage with one cycle freeze and thaw on compacted asphalt mixes with the means of indirect tensile strength were tested in this section. The test procedure was according to Nev T341D which almost follows AASHTO T283 except for some changes. Test briquettes for this test were compacted with California kneading compactor and according to Nevada Test Method T342. Tables B-1 through B-7 in Appendix B includes the results of Lottman test for compacted mixes made with all selected asphalt binders

5.5 Semi-Circular Bending (SCB) Test

The semi-circular bending (SCB) test method takes advantage of the simple specimen preparation from Superpave Gyratory compacted (SGC) cylinders and the simple loading setup. Three SGC specimens with 7 ± 1% air void were prepared according to AASHTO T 312. From the center of each 115 ± 5 mm tall specimen, obtain a cylindrical slice that is 25 mm ± 2 mm thick. Cut the slice in two identical "halves" and then cut a notch along the axis of symmetry of each half that is 15 ± 0.5 mm in length and no wider than 1.5 mm. A schematic of the test set-up is shown in Figure 5-3. The detailed process can be found from AASHTO Provisional standard: Determining the Fracture Energy of Asphalt Mixtures Using the Semi Circular Bend Geometry (SCB). The crack mouth opening displacement (CMOD) vs the load has been presented in Figures 5.3 for various mixtures.   All testing was conducted at -12ºC. Result of SCB tests on mixtures are presented in Figures B-8 through B-14 in Appendix B.

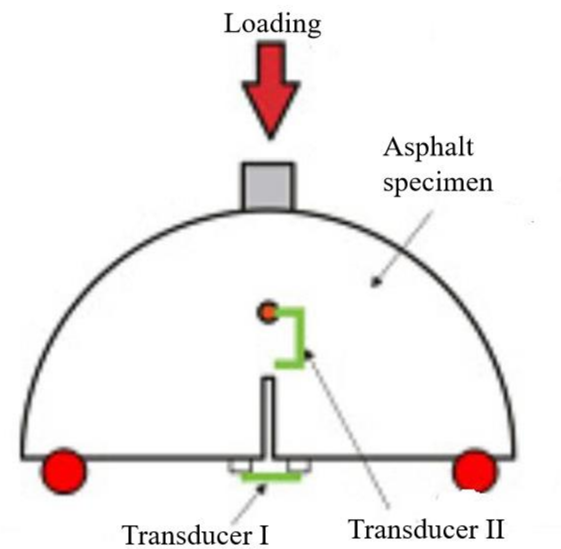
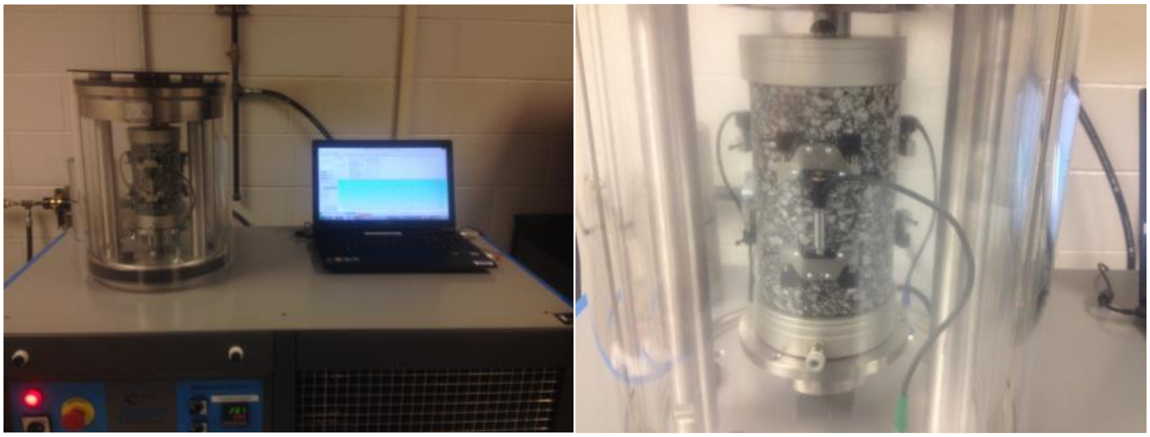


Figure 5.3. SCB test scheme

5.6 Dynamic Modulus and Phase Angles from Asphalt Mixture Performance Tester (AMPT)

The dynamic modulus test is a strain-controlled test on cylindrical specimens with 100 mm in diameter and 150 mm in height. The cored cylindrical specimen with 7 ± 1% air voids is subjected to a continuous haversine axial compressive load. Prior to testing, all samples were examined for air voids in accordance with AASHTO T269. Specimens were conditioned overnight in a calibrated environmental chamber to ensure an equilibrium temperature. The test process is presented in Figure 5.4.



(a) (b)

Figure 5.4. Dynamic modulus tests of various alternative polymerized mixtures

The flow number test is used to measure the rutting potential of asphalt concrete mixtures. The flow number is defined as the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated load test and is determined by differentiation of the permanent strain versus number of load cycle curve. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 59°C according to the LTPPBind 3.1 software. Results of dynamic modulus, phase angle and flow number are presented in Figures B-14 through B-24 in Appendix B.

5.7 Disk shaped compact tension test

The disk shaped compact tension test (DCT), developed at the University of Illinois, determines the fracture energy (Gf) of asphalt-aggregate mixtures. The test geometry is a circular specimen with a single edge notch loaded in tension as shown in Figure 5.5. The fracture energy can be utilized as a parameter to describe the fracture resistance of asphalt concrete, with a high Gf value being more desirable.

The 150 mm gyratory compacted samples or field cores can be prepared for DCT test specimens. The preparation of the test samples involves sawing and coring operations. The detailed information can be found in the ASTM D7313 (Standard Test Method for Determining

Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry).

The DCT test is run in crack mouth opening displacement (CMOD) control mode at a rate of 1 mm/min. This quick loading rate essentially removes any creep behavior of the mixture during the test. Typically, specimens are completely failed in the range of 1 to 6 mm of CMOD travel after approximately 5 minutes of testing time. The test produces data similar to the plot at the left. Fracture energy is essentially the area under the Load vs. CMOD curve, and a high Gf indicates a greater resistance to thermal cracking. Results of dynamic modulus, phase angle and flow number are presented in Figures B-25 through B-32 in Appendix B.

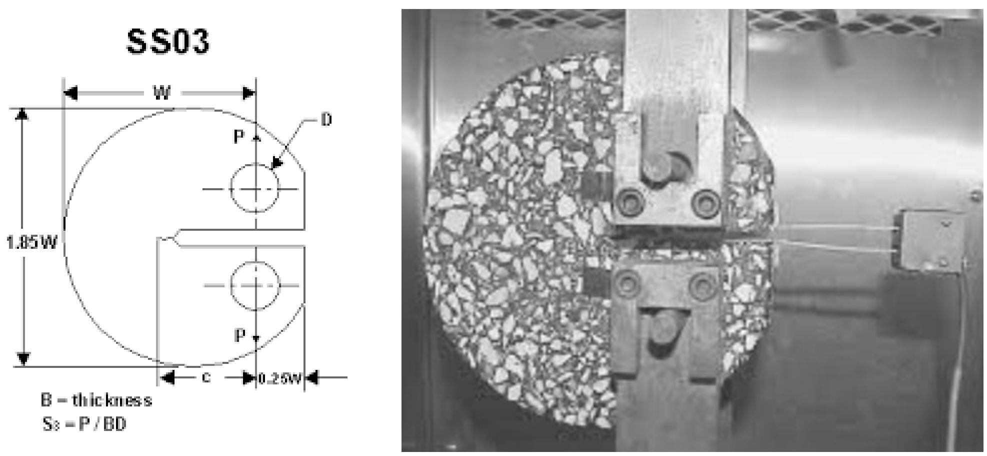


Figure 5.5. Disk shaped compact tension test

CHAPTER 6

Results and analysis of asphaltic mixtures

6.1 Mix Design

6.1.1 Optimum Binder Content

According to test method Nev. T760C, the variation of Hveem Stability, Air Voids and Bulk Density with binder content are ploted. First the samples that meet both air void and stability values are determined. By considering the environmental area where this material is to be used and the type and amount of traffic to be carried and from reviewing the test results of the qualifying samples, plotted data points, and giving consideration for environment and traffic levels, an estimate of optimum is selected. At the estimated optimum bitumen ratio, samples for maximum theoretical specific gravity (Rice) are prepared.

6.1.4 Resistance to Moisture-Induced Damage (Lottman)

Appendix B includes the results of Lottman test for compacted mixes. Asphalt mix made with CRM A58-28 + 15%Am#40 was the only mix that did not meet the requirements.

6.1.5 Low temperature performance of semi-circular test

Sample fabrication in this task followed the specimen fabrication process described earlier in Chapter 5. In each case, results from a total of three replicates were averaged. The test results are presented in Figures B-8 to B-14. In general, it can be found the values of the mixtures are showing differences in terms of variability of samples during the loading process. These differences from the same mixture might come from the distributions of air void and aggregate particles in the mix. For example, Figures B-8 and B-9 indicate that three loading curves are totally different when the mixtures were fabricated from A6428NV and A6428TR, respectively. Other mixtures, generally, showed similar loading curves.

In addition, as shown in Figure B-15, it can be found that the mixtures containing crumb rubber generally have lower load values during the loading process compared to other mixtures.

In other words, their loading curves are located the underneath of other loading curves from the mixture without crumb rubber. This means that these rubberized mixtures might have lower resistance to loading. However, from the test results, fracture energy was then calculated and statistical analysis was conducted to assess the sensitivity of test to detect the differences in the mixtures. The resulting values of fracture energy and the corresponding standard error bars are presented in Figure B-16. It can be observed that A6428NV has similar fracture energy with B6416-AM-20-15 with the lowest values, but A7622NV has the highest values. The mixtures of A7622TR, AAC20-AM-40-15, and A5828-AM-40-15 generally have close fracture energy values in this study. It can be concluded that the mixtures with crumb rubber could not resist the peak loads as much as virgin binders and SBS modified binders in some cases, but these rubberized mixtures have similar resistances to low temperature cracking with other or virgin modified mixtures due to close fracture energy. In addition, it can be found that the binder type played an import role in determining the fracture energy.

6.1.6 Dynamic Modulus and Phase Angles from Asphalt Mixture Performance Tester (AMPT)

The test results of dynamic modulus |E*| values and phase angles are shown in Figures B-18 through B-23 which include the test results of samples at three temperatures of 4°C, 20°C and 40°C per the recommendations from the specifications. It can be observed that the AAC20-AM-40-15 mixture has the highest dynamic modulus value, followed by the B6416-AM-20-15 mixture, regardless of test temperature. However, AAC20-AM-40-15 mixture has the lowest dynamic modulus value, followed by the B6416-AM-20-15, regardless of test temperature. Moreover, an increased frequency results in an increased dynamic modulus at three test temperatures and reduced phase angle at 4°C and 20°C regardless of mix type, but the phase angle slightly increase when the frequency increases in most cases.

In addition, Figure B-24 illustrates that the flow numbers of two mixtures including 15% 40AM are very high while the flow number of A5828-AM-40-15 is generally small. Meanwhile, A7622NV has flow number of 676. Per the specification, these mixtures with crumb rubber generally have better rut resistance than other mixtures in this study. In addition, it can be noted that, in general, the source of asphalt type played a key role in determining the flow number value of a mixture.

6.1.7 Low temperature performance of disk shaped compact tension (DCT) test

As shown in Figures B-25 to B-31, it can be found that the test results of peak load indicate differences from three replicated samples for A6428NV, A6428TR, and A7622NV mixtures. Similar to SCB test, the peak loads are affected by the notch type and distributions of air and aggregate particles in the mixture. Other mixtures have close peak load values. However, the A6416-AM-20-15 mixture was tested only one specimen because other specimens were destroyed very fast and could not be obtained any load curves. It may be due to the internal cracks, which occurred during the cutting and coring process. Additionally, similar to SCB test results, the peak loads from rubberized mixtures are generally lower than those values from other mixtures at a low temperature. As shown in Figure B-32, it can be noted that the fracture energy value of A7622NV mixture is the highest, but the B6416-AM-20-15 mixture has the lowest fracture energy. Other rubberized mixtures generally have the close fracture energy values compared with PG 64-28 and PG 76-22 binders tested in this study. Again, it can be concluded that the asphalt type played an essential role in determining the DCT test results.

CHAPTER 7

Summary, Findings, and Recommendations

7.1 Summary

The objective of the this research project was to determine the feasibility of utilization of laboratory blended GTR, terminally-blended GTR , or other CRM products to meet the rheological and engineering properties of asphalt modified binders and mixtures set forth by NDOT. The experimental work was performed in two stages. In the first stage rheological properties of rubberized asphalt at three aged conditioned were determined. The results then were compared with polymer modified (e.g., SBS) and terminal blend GTR asphalt binders satisfying NDOT's specifications in order to find the best combination. In the second stage, the performance properties of the asphaltic mixtures made with selected rubberized asphalt binders were determined. The mix design procedures set forth by NDOT were followed in finding the optimum asphalt content of the mixes.

7.2 Rubberized Asphalt Binders

Thirty six (36) different combinations of base (virgin) asphalt binder and CRM were made and tested according to NDOT's specifications. Results of Dynamic Shear (DSR) on rubberized asphalt binders showed that an increased rubber concentration results in an increase of $G^*/\sin \delta$ value regardless of binder source and grade, rubber type and size, and test temperature. However, an increase in temperature resulted in a decrease of $G^*/\sin \delta$ value. Also, a greater rubber percentage results in a higher failure temperature irrespectively of rubber type and size. Higher rubber content results in a low phase angle regardless of the binder source and grade, rubber type, size and percentage. In other words, the binder exhibits the viscous characteristics at a relatively high temperature and displays the elastic behavior at a low temperature. Results of the Rotational Viscosity test indicated that the viscosity of asphalt rubber binders at 135°C has a direct relationship with size and content of CRM. In some instants with high content of coarse CRM the viscosity is higher than specified. Test results indicated that the Ductility of asphalt rubber binder samples at low temperature (4°C) is lower than polymer modified and terminal blend tire rubber modified binders and does not meet the specification requirements. Being non-homogeneous and having a matrix structure could be stated as the main reason for low ductility values for asphalt rubber samples. Because of this reason, it is important to note that the ductility test is not being recommended to be one of the engineering properties being used in the selection process of rubberized asphalt binders. Although rubberized asphalt binder showed lower Flash Point compared to polymer modified and terminal blend tire rubber modified binders, it still meets the requirements. Toughness and Tenacity test results revealed that asphalt rubber samples show a high initial strength but reach the failure at the lower point compared to polymer modified and terminal blend tire rubber modified binder. Therefore, asphalt rubber binder does not meet the Tenacity requirements although Toughness requirements may be achieved.

Approximately 167% increase in results of the DSR test on RTFO samples of PG64-16 (Source B) mixed with ambient #40 CRM was observed in regards to G*/Sinδ value compared to the results obtained from the original state. These increases for Cryogenic #40 CRM, Ambient #20 CRM, and Cryogenic #20 CRM were 225%, 218%, and 306%, respectively. In general, an increased rubber content results in an increase of G*/ sinδ value and a high test temperature reduces the G*/ sinδ value regardless of binder source and grade, as well as rubber size and type. It can be noted that, as expected, an increased rubber content results in an increase in failure temperature of rubberized asphalt binder regardless of the rubber type and size, as well as binder grade. In addition, it can be seen that, the failure temperature of the binder with ambient rubber is higher than those temperatures of the binders with cryogenic rubber under an identical condition. The effect of rubber size on the failure temperature is not noticeable for the binders tested for this research project. For the phase angles of various rubberized asphalt binders for the RTFO samples, similar to the virgin binders, it can be noted that an increase in temperature resulted in an increase of phase angle irrespective of binder grade, rubber type, size and content. In addition, the modified binder containing higher rubber content produced a lower phase angle due to a higher stiffness values. In general, the influence of rubber size and type on phase angle are not remarkable for the binders used in this study.

The G*sin δ value of A64-28TR binder was found to be approximately 500 kPa but it was only 166 kPa for A64-28NV binder. In general, an increase in rubber content resulted in a lower

G*sin δ value regardless of rubber type and size, and binder grade. In addition, the phase angles decreases. The impacts of rubber type on the G*sin δ values are not as obvious though.

The Bending Beam Rheometer (BBR) test results indicated that two binders (B76-22NV and A64-22TR) have the stiffness values less than 300 MPa and m-values greater than 0.300 at a test temperature of -12°C, the requirement set forth by specification. As expected, it can be noted that the rubber content results in a difference in the stiffness values. In addition, the rubber type does not generally have the influence on the stiffness values. It can be noted that rubber content and size have slight influence on the m-value, but the rubber type (ambient and cryogenic) does have an impact on the m-value. The cryogenic rubberized binders generally have m-values less than 0.300 regardless of rubber content and size.

7.3 Rubberized Asphalt Mixtures

Hveem method of mix design was used according to NDOT specifications to obtain the optimum binder contents for rubberized asphalt as well as polymer modified and terminal blend tire rubber modified binders. Results of the mix design show that mixes made with rubberized asphalt binders have slightly higher optimum binder content. In order to meet the air void requirements, the mixes made with rubberized asphalt binders had to have a different aggregate gradation (more open-graded) and needed to be compacted at higher temperature (150C) compared to the conventional asphalt binders. Results of the Moisture Induced Damage (Lottman) tests indicated that all but one mix (base binder PG58-28) satisfied the requirements for Tensile Strength Ratio (TSR) and Tensile Strength of unconditioned samples.

The test results of dynamic modulus |E*| values and phase angles, at three temperatures of 4°C, 20°C and 40°C, indicated that the AAC20-AM-40-15 mixture has the highest dynamic modulus value, followed by the B6416-AM-20-15 mixture, regardless of test temperature. In addition, the results indicated that the AAC20-AM-40-15 mixture has the lowest dynamic modulus value, followed by the B6416-AM-20-15, regardless of test temperature. The results also showed that an increase in frequency resulted in an increase in dynamic modulus values at three test temperatures and reduced phase angle at 4°C and 20°C regardless of mix type, but the phase angle slightly increased when the frequency was increased in most cases. The flow numbers of two mixtures including 15% 40AM are very high while the flow number of A5828-AM-40-15 is generally small. Meanwhile, A7622NV has flow number of 676. Per the specification, these mixtures with crumb rubber generally have better rut resistance than other mixtures in this study. In addition, it can be noted that, in general, the source of asphalt binder played a key role in determining the flow number value of a mixture.

The fracture energy (Gf) of asphalt-aggregate mixtures was determined using the disk shaped compact tension test (DCT), where a high Gf value being more desirable . The test geometry is a circular specimen with a single edge notch loaded in tension. The results indicated that the fracture energy value of A7622NV mixture is the highest, but the B6416-AM-20-15 mixture has the lowest fracture energy. Other rubberized mixtures generally have similar fracture energy values compared with PG 64-28 and PG 76-22 binders tested in this study. Again, it can be concluded that the asphalt type influenced the DCT test results.

The fracture energy of asphalt mixtures using the semi-circular bend geometry (SCB) were determined. The crack mouth opening displacement (CMOD) vs. the load were recorded and reported for various mixtures. In each case, results from a total of three replicates were averaged. In general, it can be found the values of the mixtures are showing differences in terms of variability of samples during the loading process due the variation in distributions of air void and aggregate particles in the mix. In general, the results indicated that the mixtures containing crumb rubber have lower load values during the loading process compared to other mixtures. The results also indicated that A6428NV has similar fracture energy with B6416-AM-20-15 with the lowest values, but A7622NV has the highest values. The mixtures of A7622TR, AAC20-AM-40-15, and A5828-AM-40-15 generally have close fracture energy values. It can be concluded that the mixtures with crumb rubber could not resist the peak loads as much as virgin binders and SBS modified binders in some cases, but these rubberized mixtures have similar resistances to low temperature cracking with other or virgin modified mixtures.

7.4 Recommendations

Based on the laboratory test results especially the Performance Tests on mixes made with asphalt rubber it can be stated that asphalt rubber mixture, in many cases, compare favorably with polymer modified and terminal blend modified mixtures. Currently, Nevada DOT allows asphalt rubber in open graded friction courses but it follows Arizona DOT specifications. This research can be used as valuable resource in order to develop specifications for NDOT. It also may lead to develop specifications for dense graded asphalt layers and maintenance treatment such as chip seal or slurry mixes using asphalt rubber binders. It is recommended to conduct another research project to investigate the possibility of using GTR in other applications in the paving industry (e.g., pavement preservation). In addition, other modified binders (e.g., a combination of SBS and crumb rubber) should be also investigated.

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Appendix A

G*/sin(δ): Virgin binders

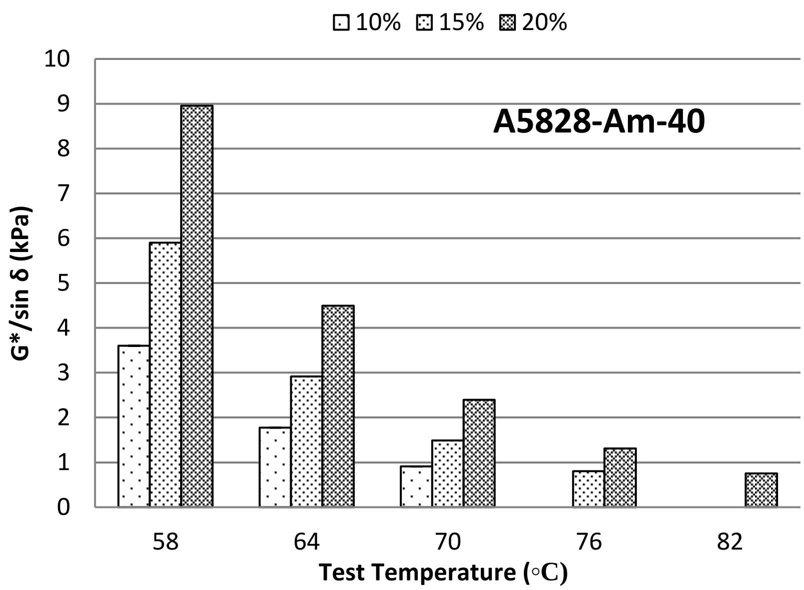

Figure A-1 G*/sin(δ) at different temperatures for A5828 mixed with CRM Ambient #40

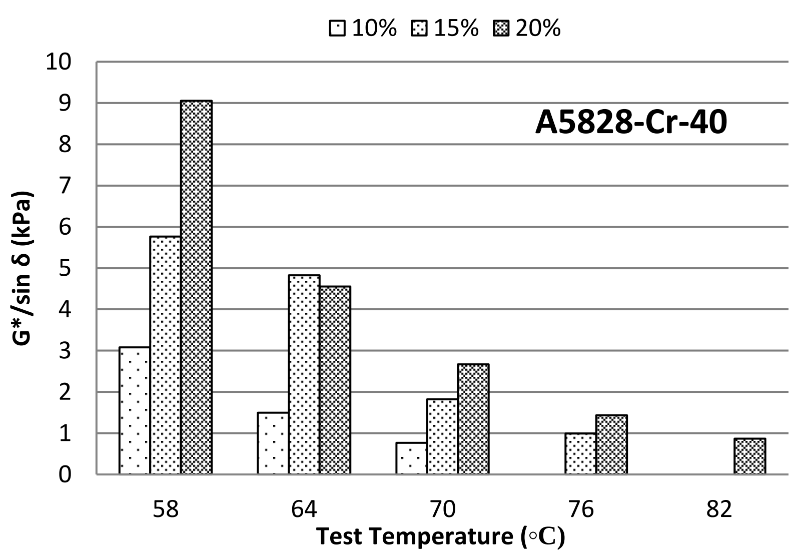

Figure A-2 G*/sin(δ) at different temperatures for A5828 mixed with CRM Cryogenic #40

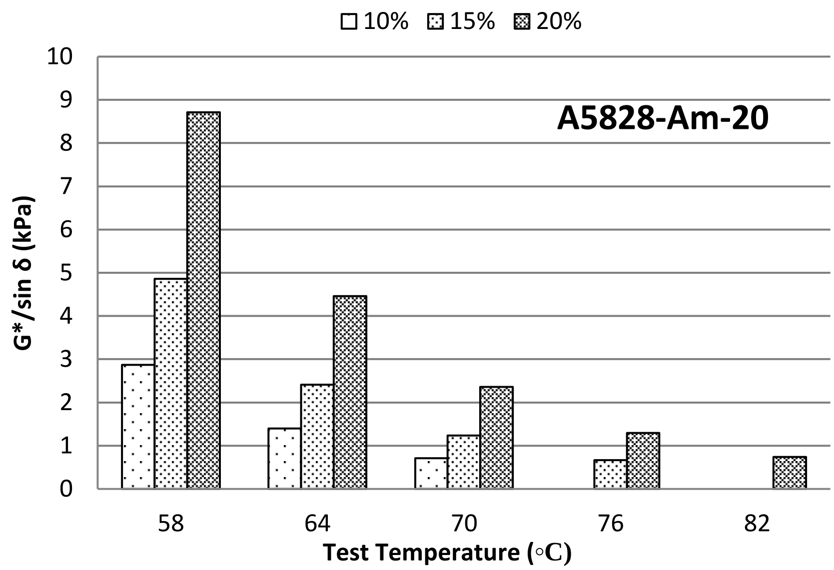

Figure A-3 G*/sin(δ) at different temperatures for A5828 mixed with CRM Ambient #20

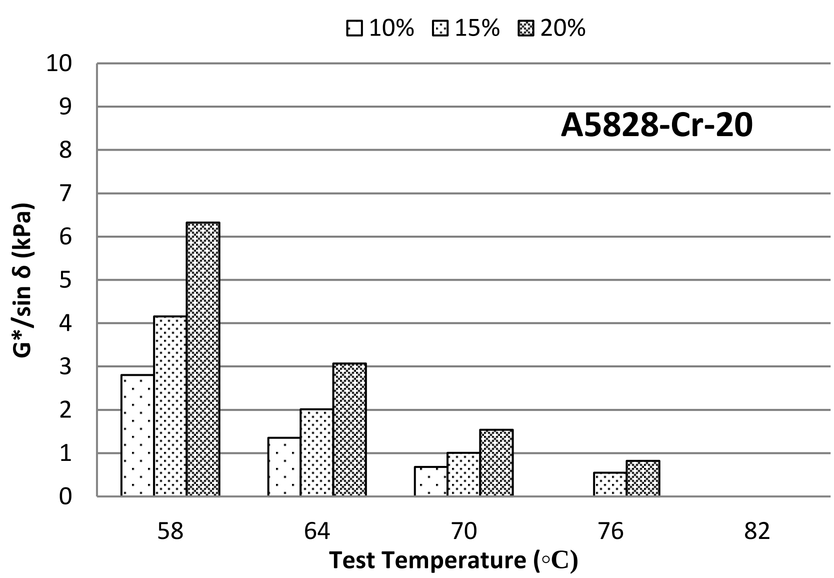

Figure A-4 G*/sin(δ) at different temperatures for A5828 mixed with CRM Cryogenic #20

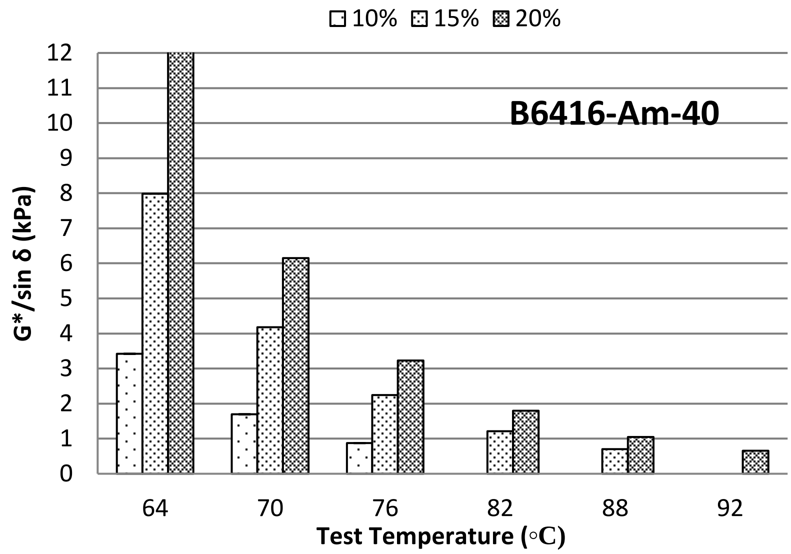

Figure A-5 G*/sin(δ) at different temperatures for B6416 mixed with CRM Ambient #40

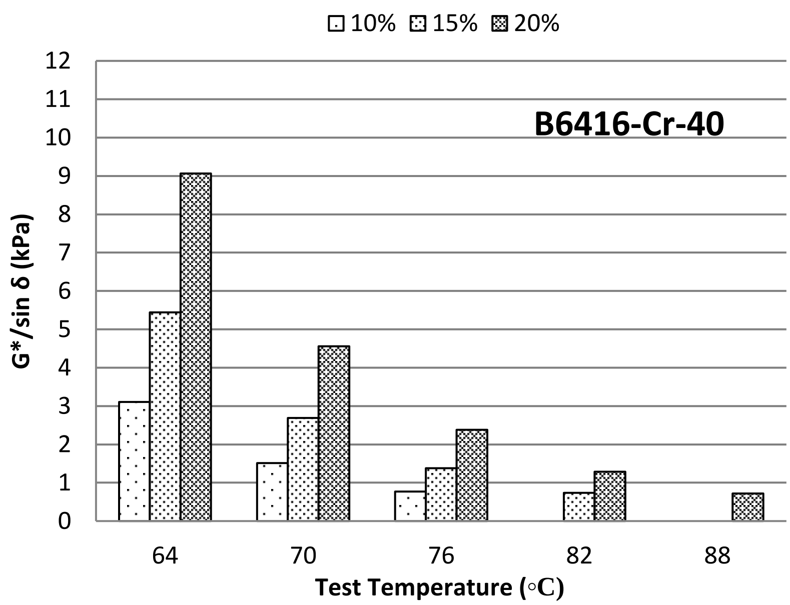

Figure A-6 G*/sin(δ) at different temperatures for B6416 mixed with CRM Cryogenic #40

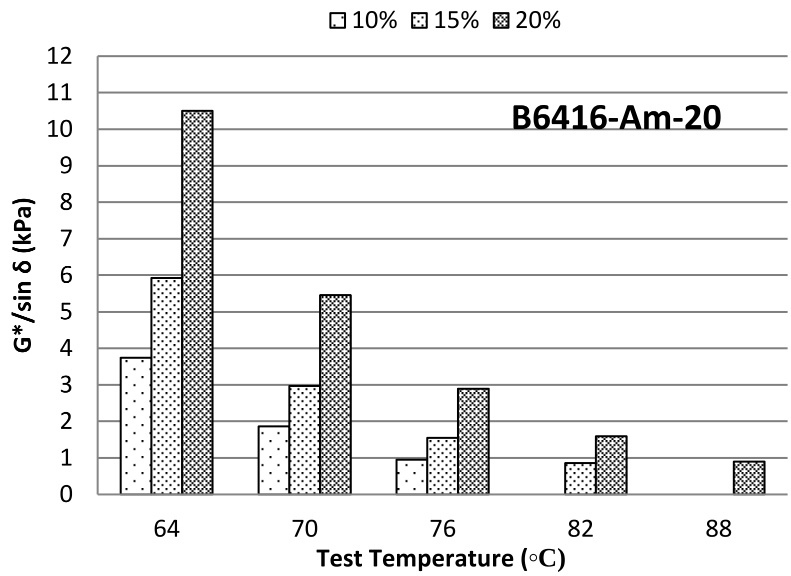

Figure A-7 G*/sin(δ) at different temperatures for B6416 mixed with CRM Ambient #20

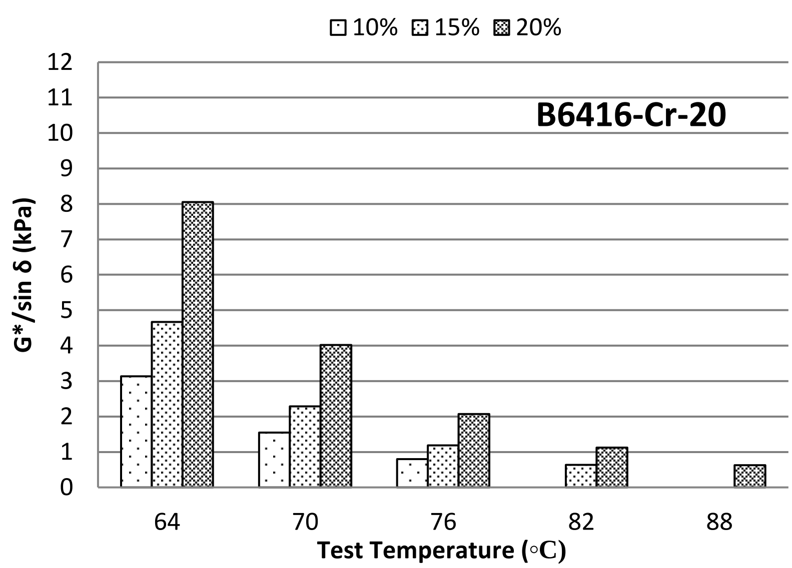

Figure A-8 G*/sin(δ) at different temperatures for B6416 mixed with CRM Cryogenic #20

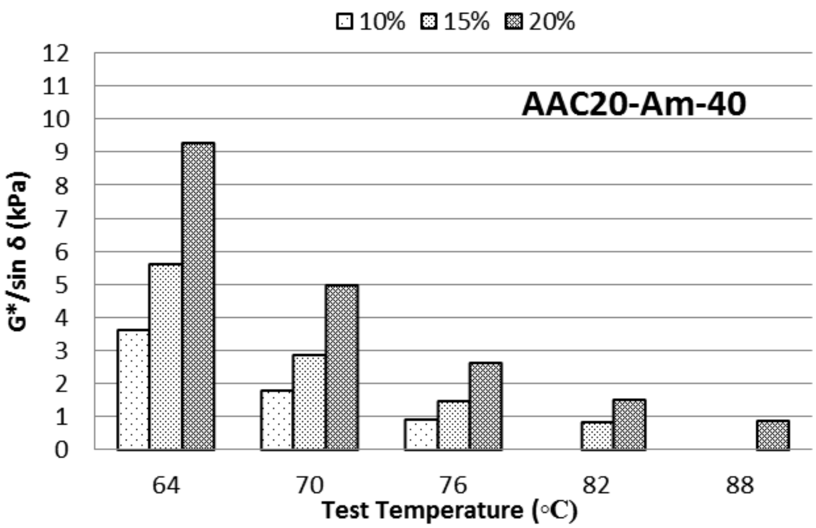

Figure A-9 G*/sin(δ) at different temperatures for AAC20 mixed with CRM Ambient #40

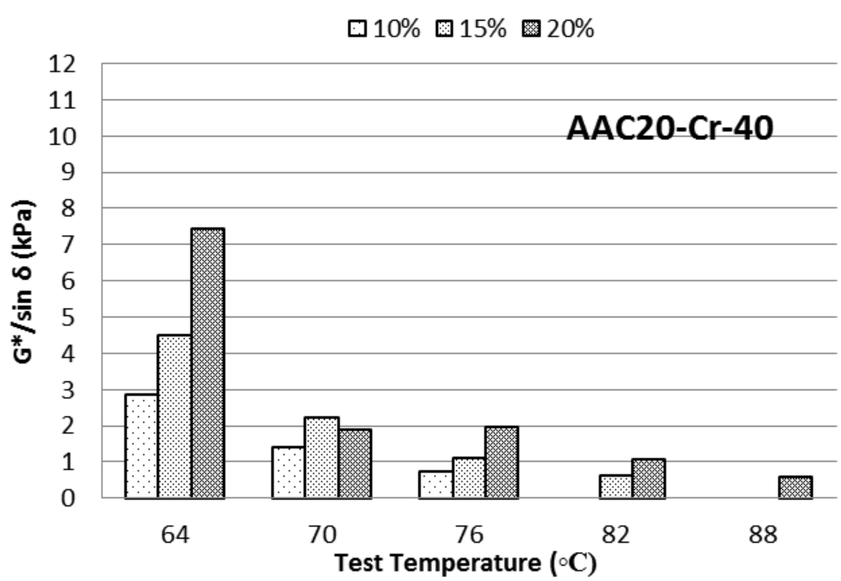

Figure A-10 G*/sin(δ) at different temperatures for AAC20 mixed with CRM Cryogenic #40

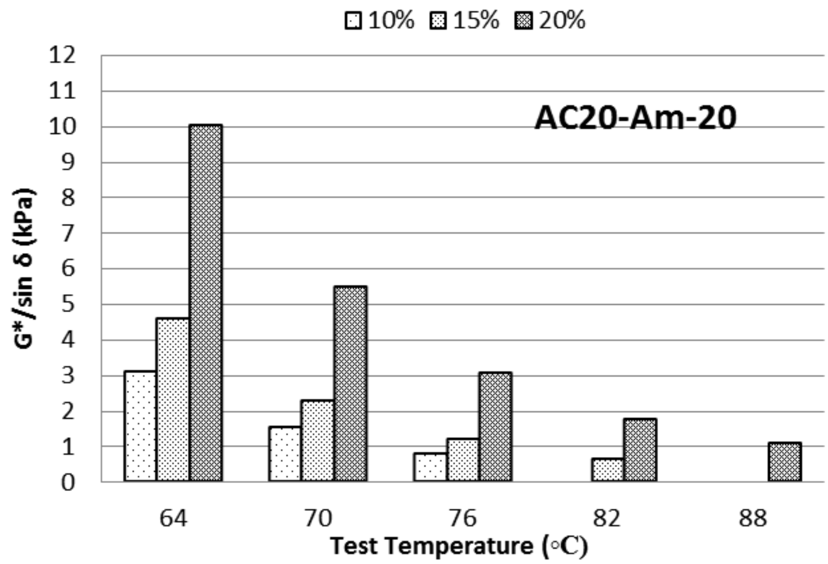

Figure A-11 G*/sin(δ) at different temperatures for AAC20 mixed with CRM Ambient #20

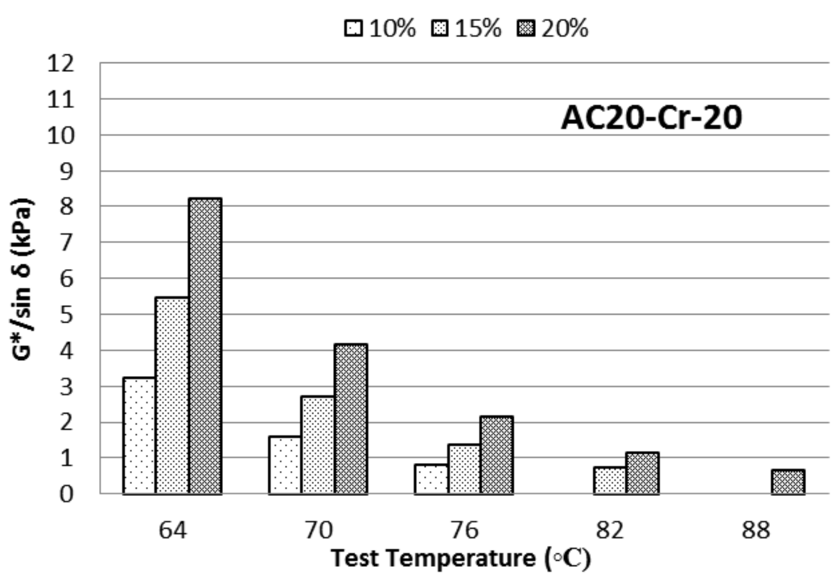

Figure A-12 G*/sin(δ) at different temperatures for AAC20 mixed with CRM Cryogenic #20

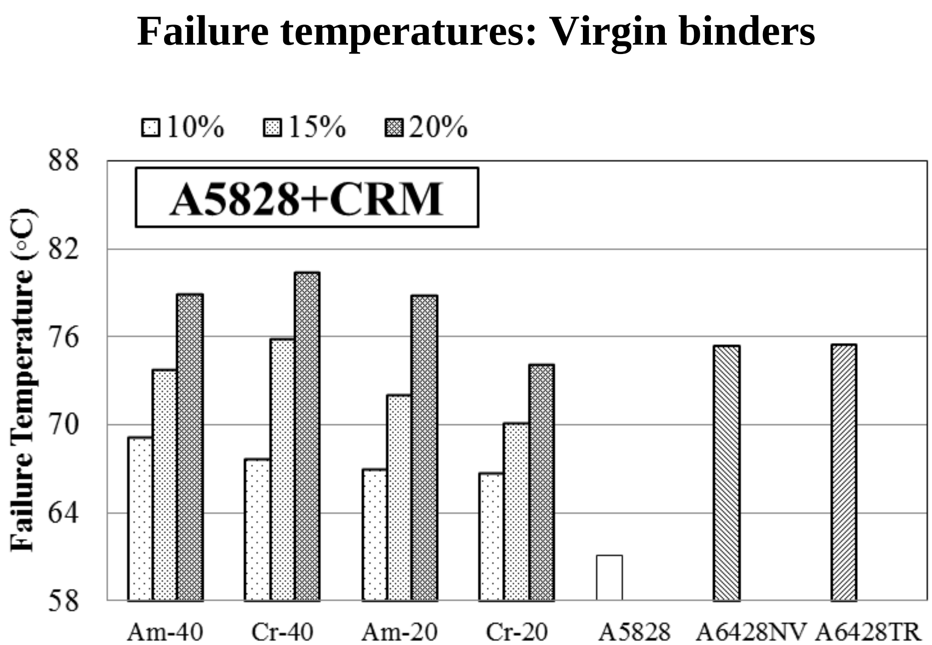

Figure A-13 Failure temperature for A5828 and mixed with CRM, polymer, and terminal blend tire rubber

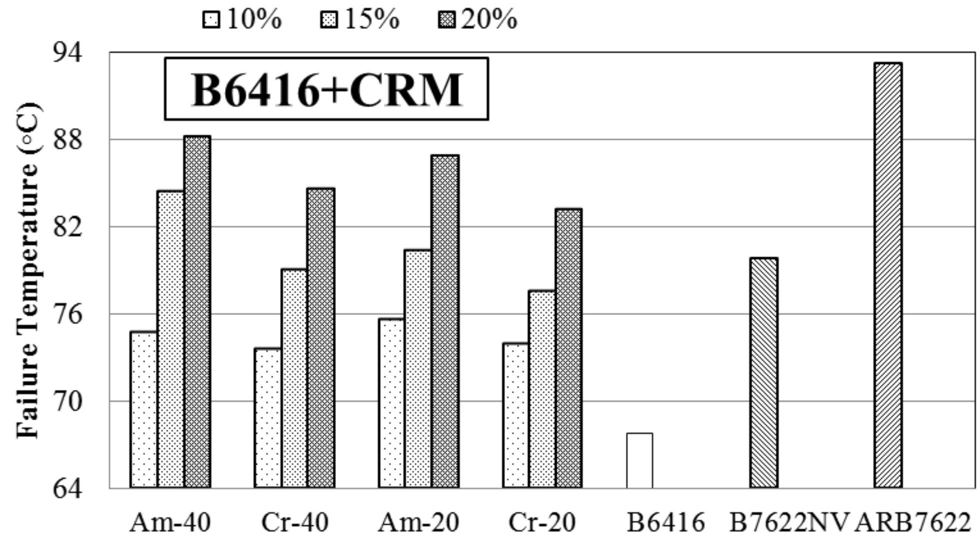

Figure A-14 Failure temperature for B6416 and mixed with CRM polymer, and asphalt rubber binder

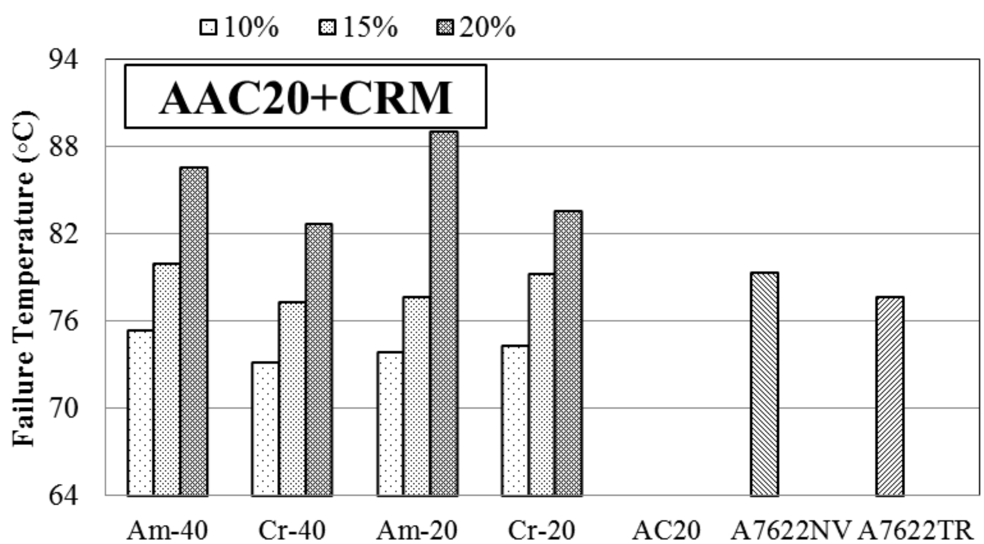

Figure A- 15 Failure temperature for AAC20 and mixed with CRM polymer, and terminal blend tire rubber

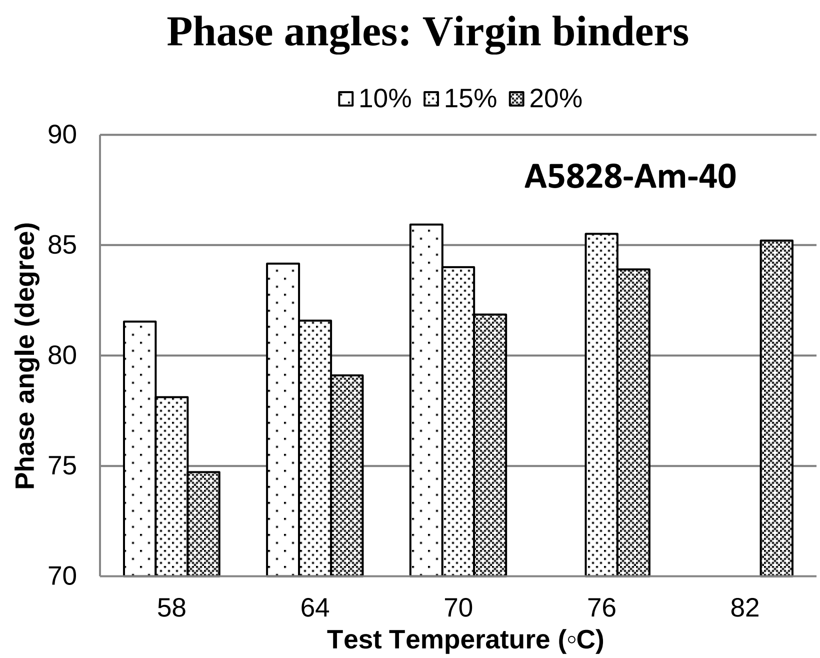

Figure A-16 Phase angle at different temperatures for A5828 mixed with CRM Ambient #40

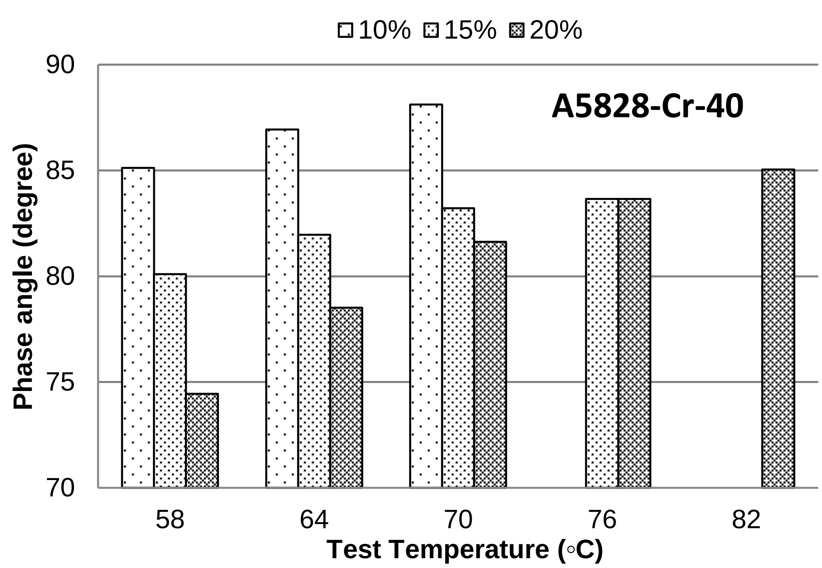

Figure A-17 Phase angle at different temperatures for A5828 mixed with CRM Cryogenic #40

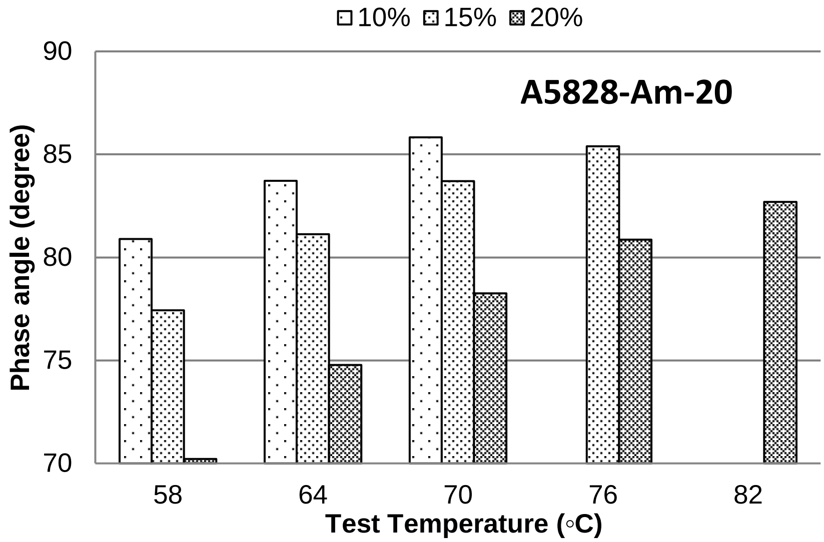

Figure A-18 Phase angle at different temperatures for A5828 mixed with CRM Ambient #20

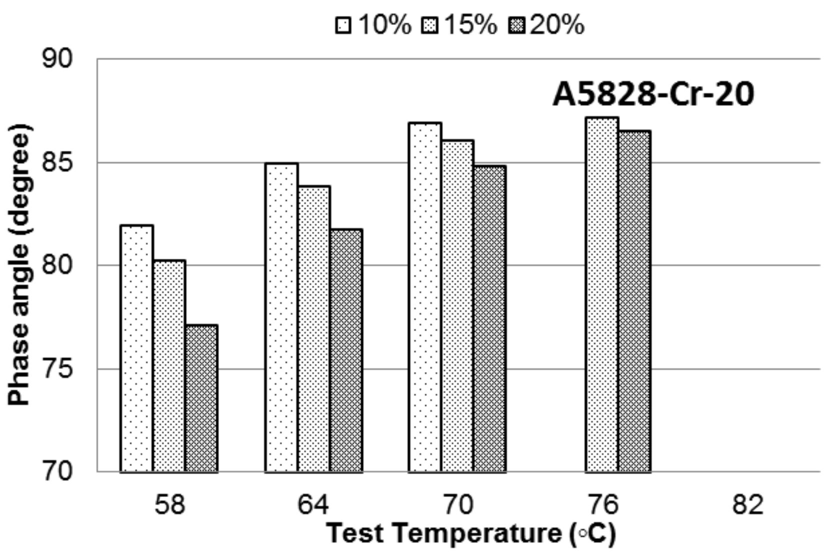

Figure A-19 Phase angle at different temperatures for A5828 mixed with CRM Cryogenic #20

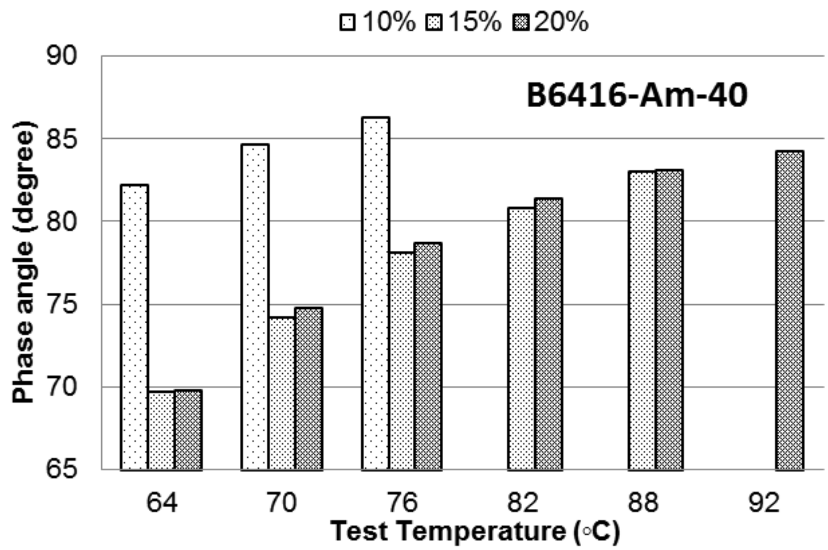

Figure A-20 Phase angle at different temperatures for B6416 mixed with CRM Ambient #40

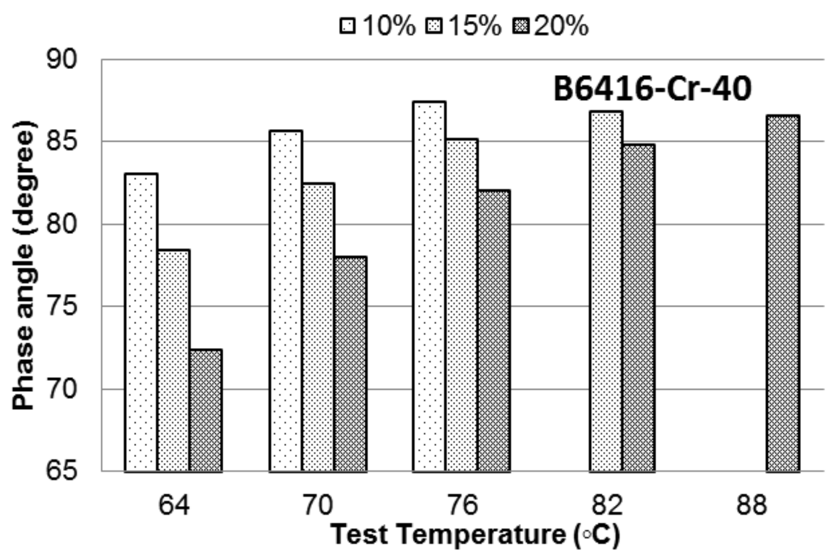

Figure A-21 Phase angle at different temperatures for B6416 mixed with CRM Cryogenic #40

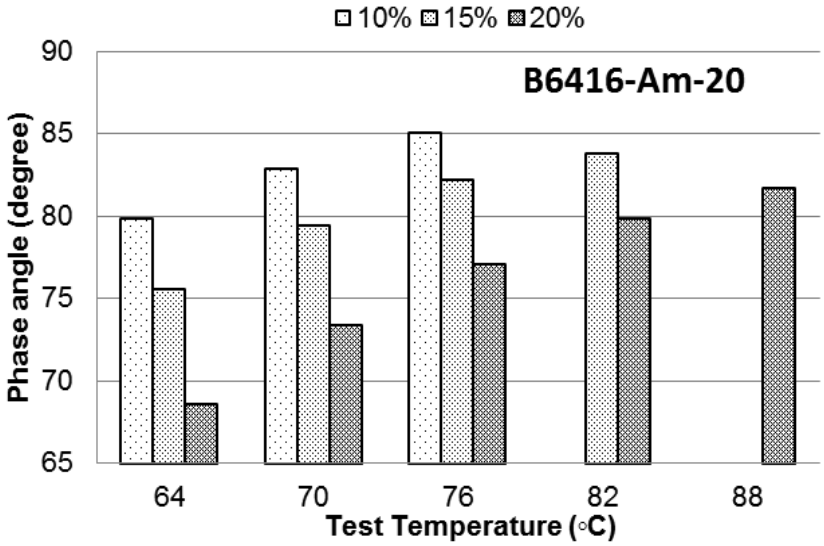

Figure A-22 Phase angle at different temperatures for B6416 mixed with CRM Ambient #20

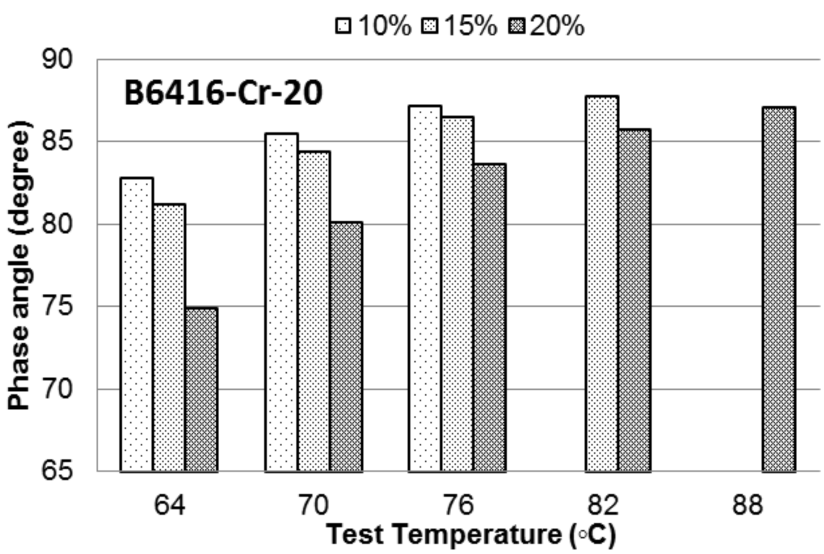

Figure A-23 Phase angle at different temperatures for B6416 mixed with CRM Cryogenic #20

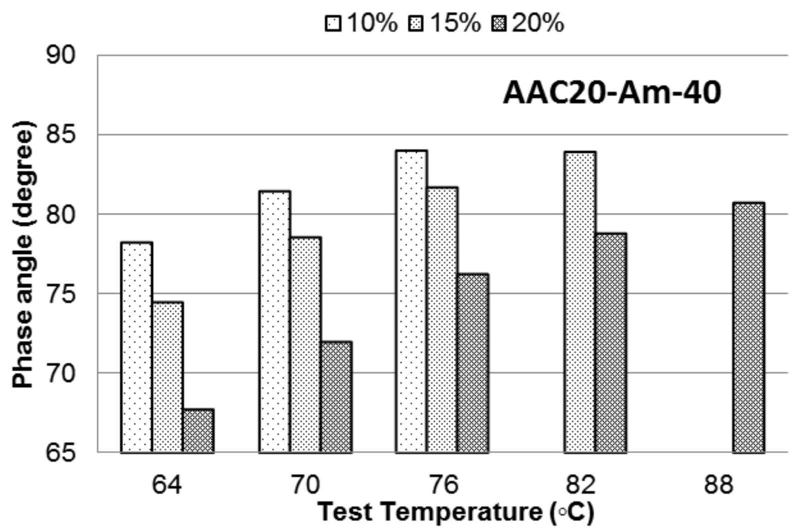

Figure A-24 Phase angle at different temperatures for AAC20 mixed with CRM Ambient #40

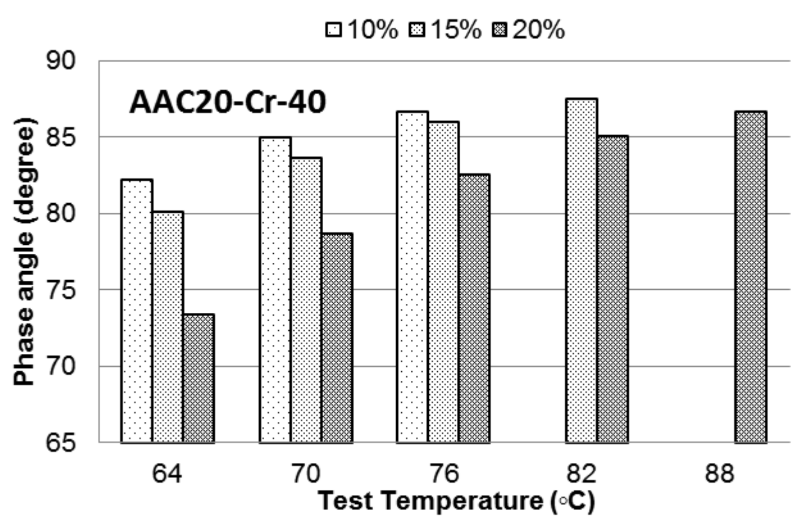

Figure A-25 Phase angle at different temperatures for B6416 mixed with CRM Cryogenic #40

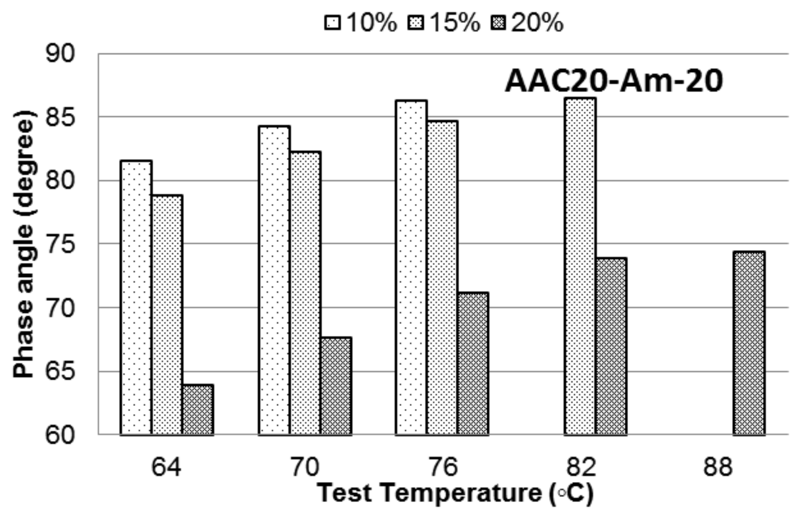

Figure A-26 Phase angle at different temperatures for AAC20 mixed with CRM Ambient #20

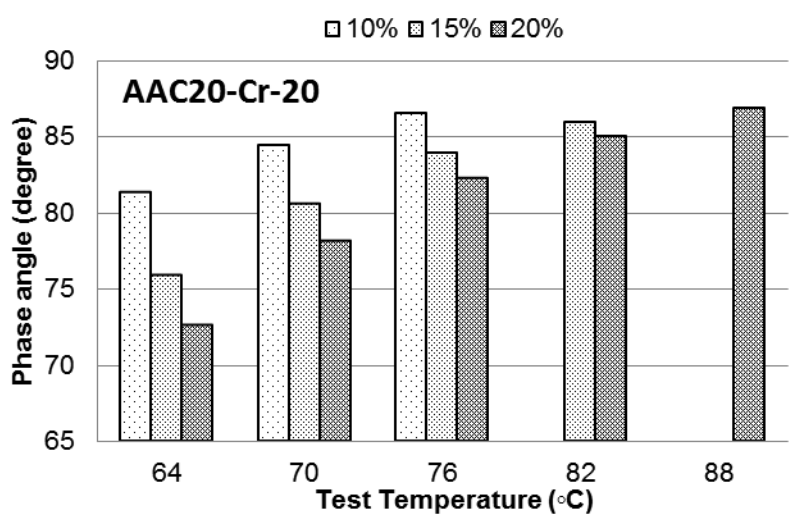

Figure A-27 Phase angle at different temperatures for B6416 mixed with CRM Cryogenic #20

Viscosity values: Virgin binders

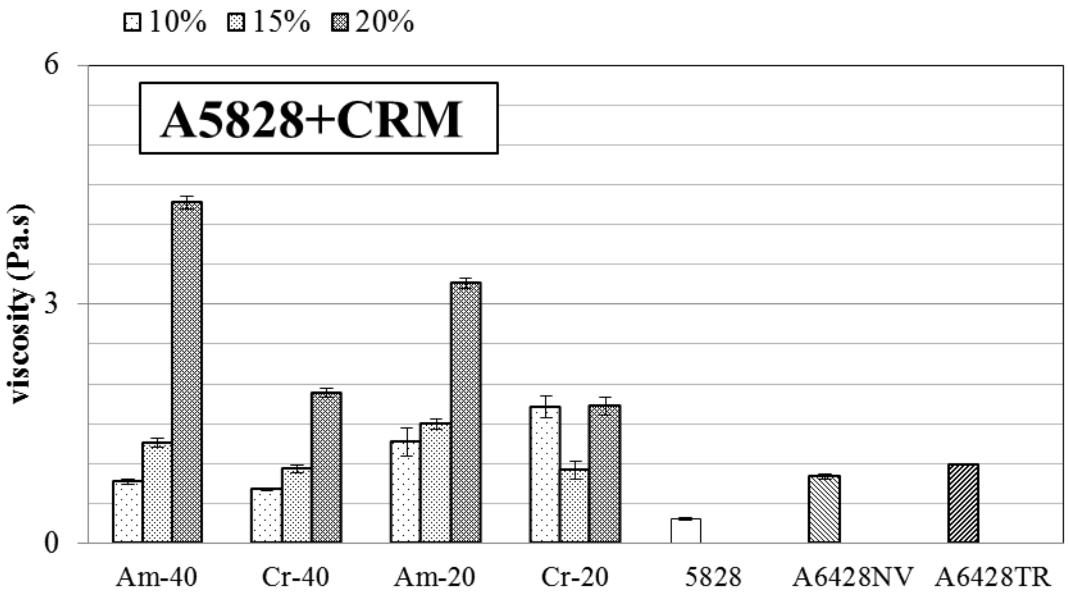

Figure A-28 Viscosity of A5828 mixed with CRM, polymer and terminally blend tire rubber

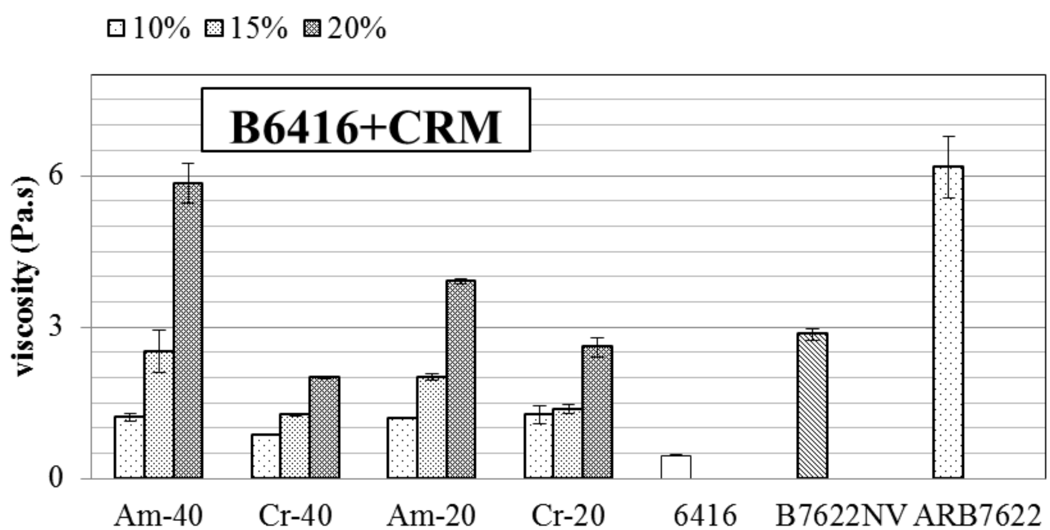

Figure A-29 Viscosity of B6416 mixed with CRM, polymer and terminally blend tire rubber

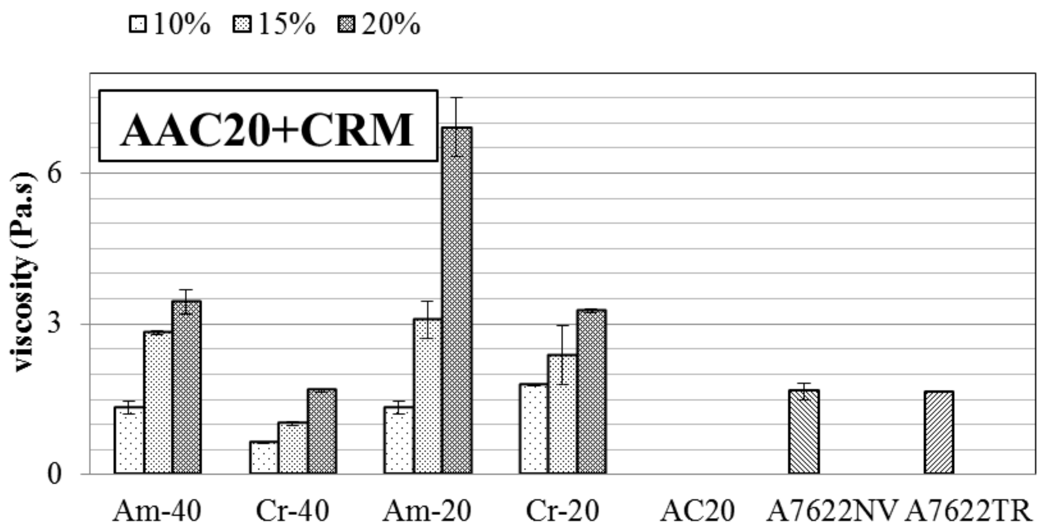

Figure A-30 Viscosity of B6416 mixed with CRM, polymer and terminally blend tire rubber

Ductility values: Virgin binders

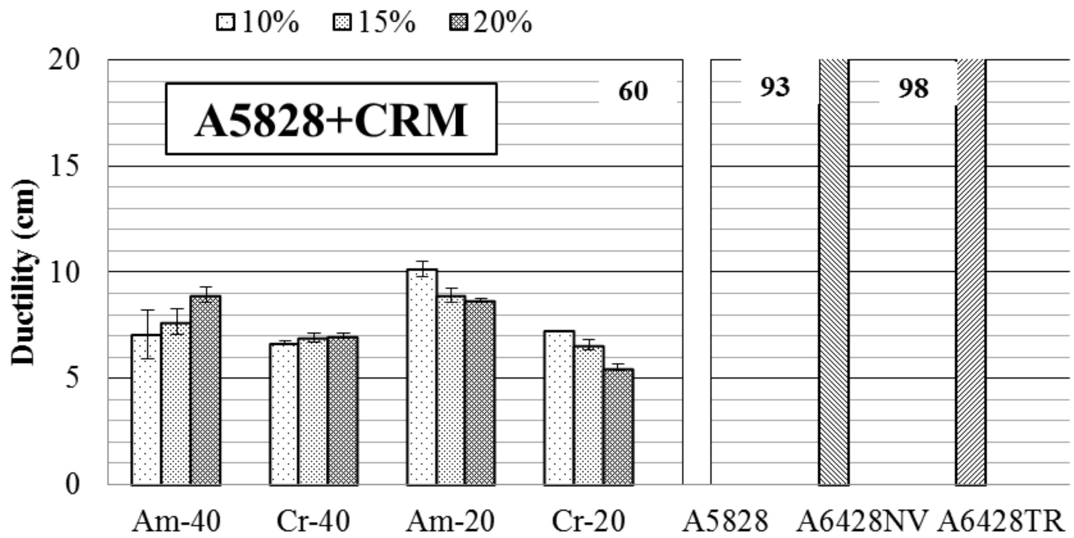

Figure A-31 Ductility of A5828 mixed with CRM, polymer modified and terminal blend

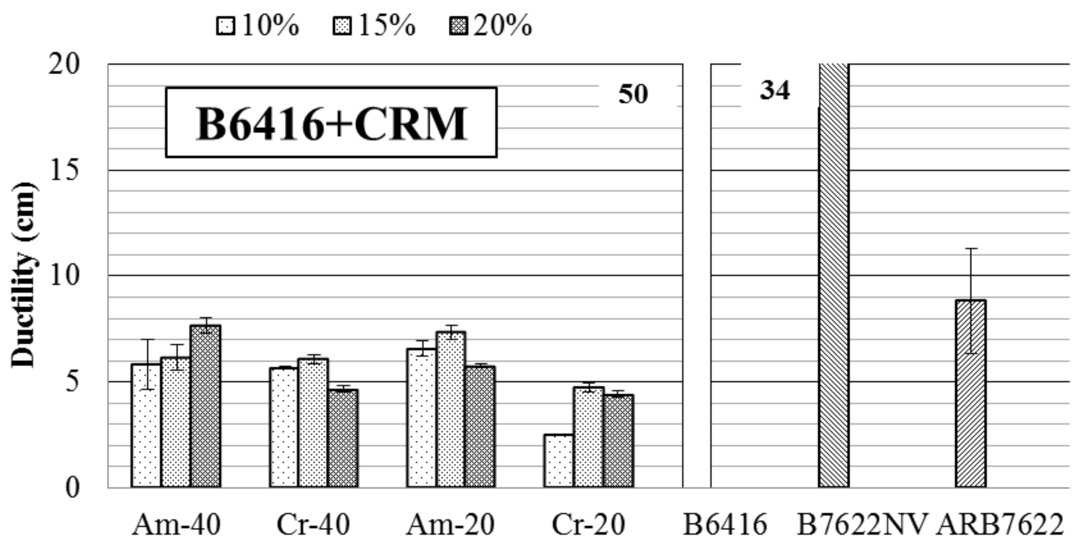

Figure A-32 Ductility of B6416 mixed with CRM, polymer modified asd asphalt rubber binder

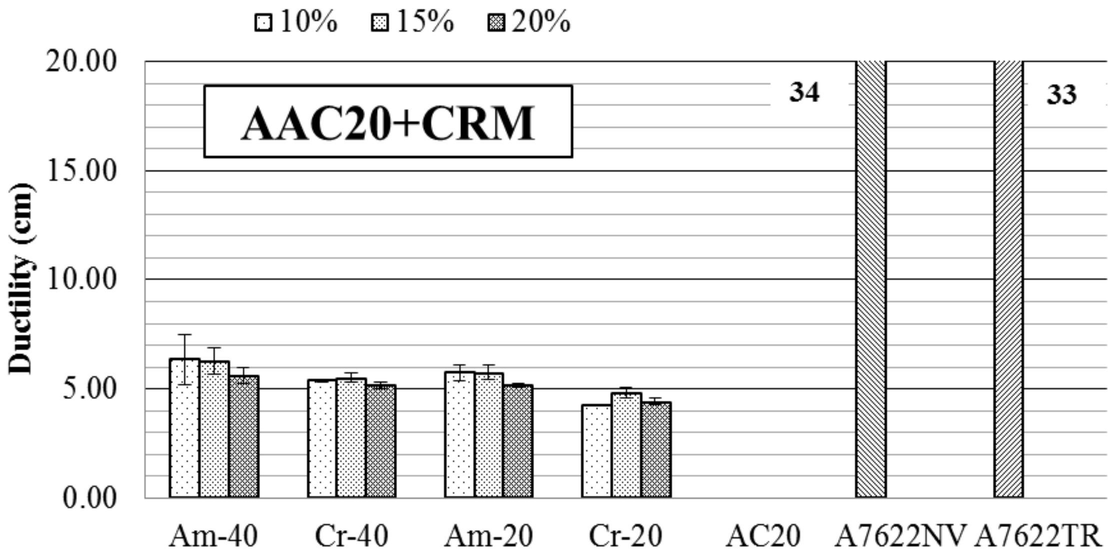

Figure A-33 Ductility of AAC20 mixed with CRM, polymer modified and terminal blend

Flash points: Virgin binders

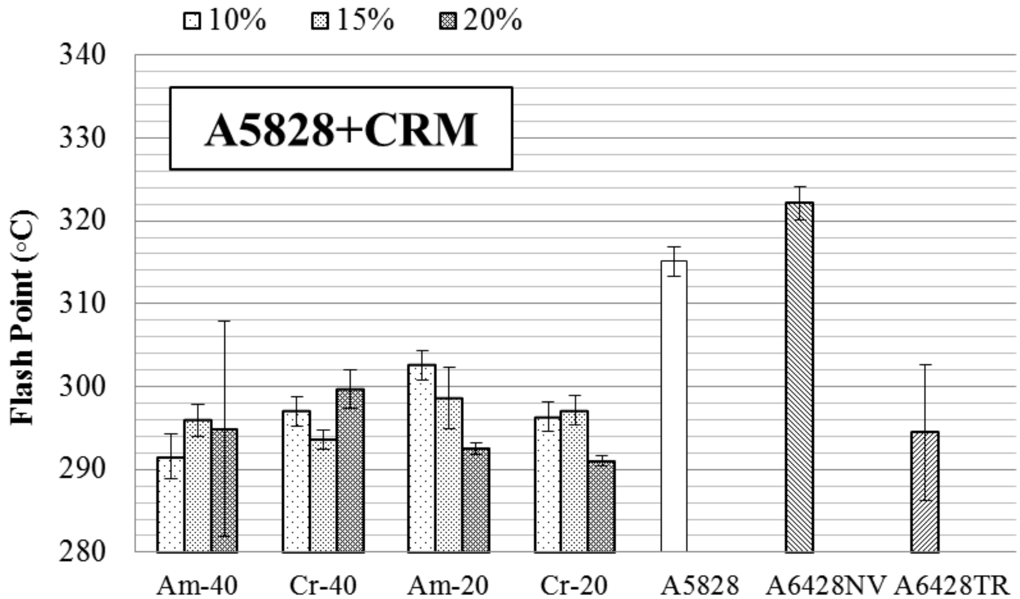

Figure A-34 Flash Point of A5828 samples mixed with CRM, polymer modified and terminal blend

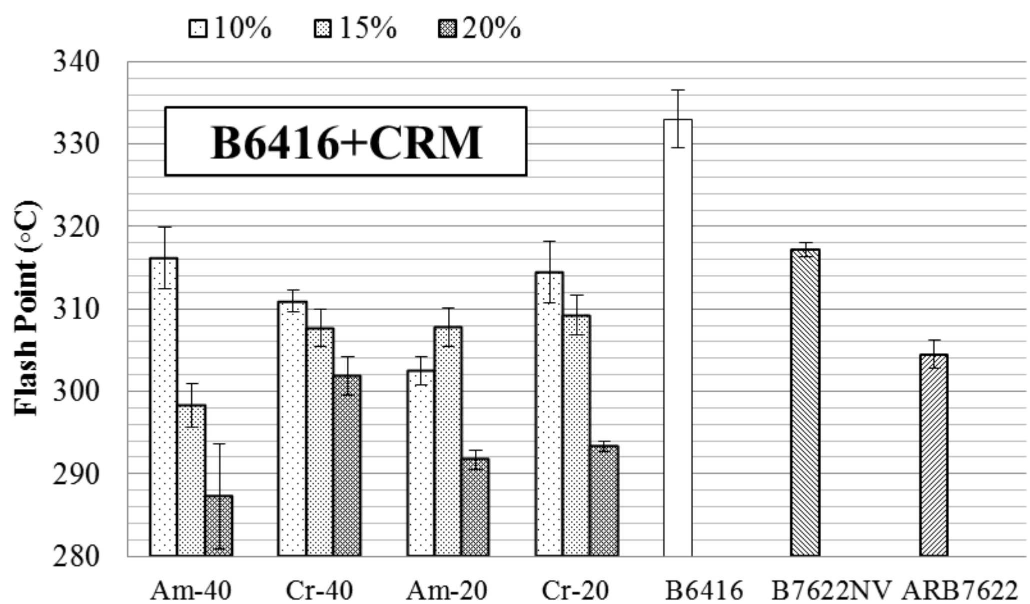

Figure A-35 Flash Point of B6416 samples mixed with CRM, polymer modified asd asphalt rubber binder

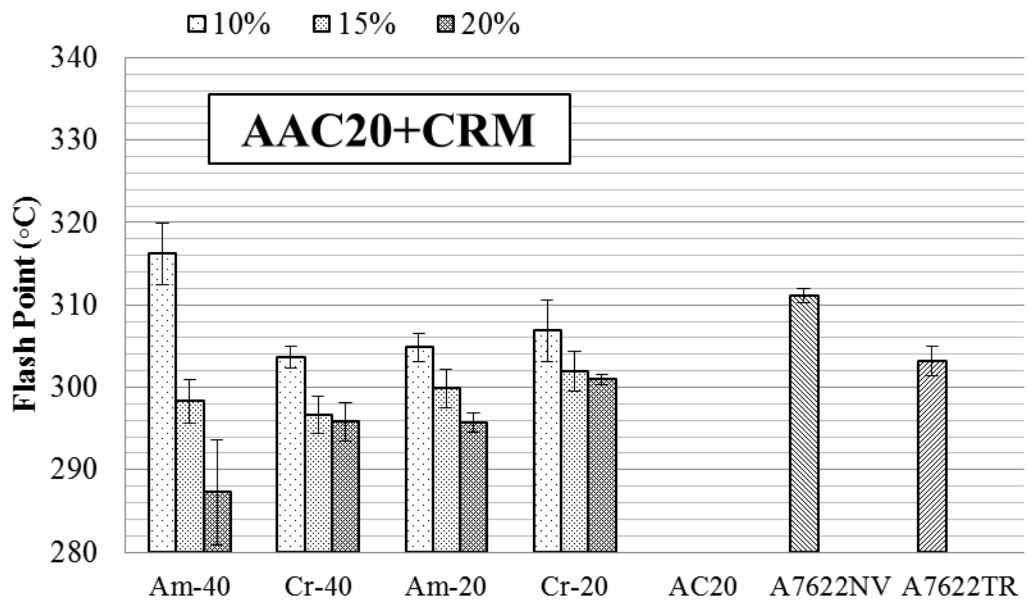

Figure A-36 Flash Point of AAC20 samples mixed with CRM, polymer modified and terminal blend

Toughness and Tenacity

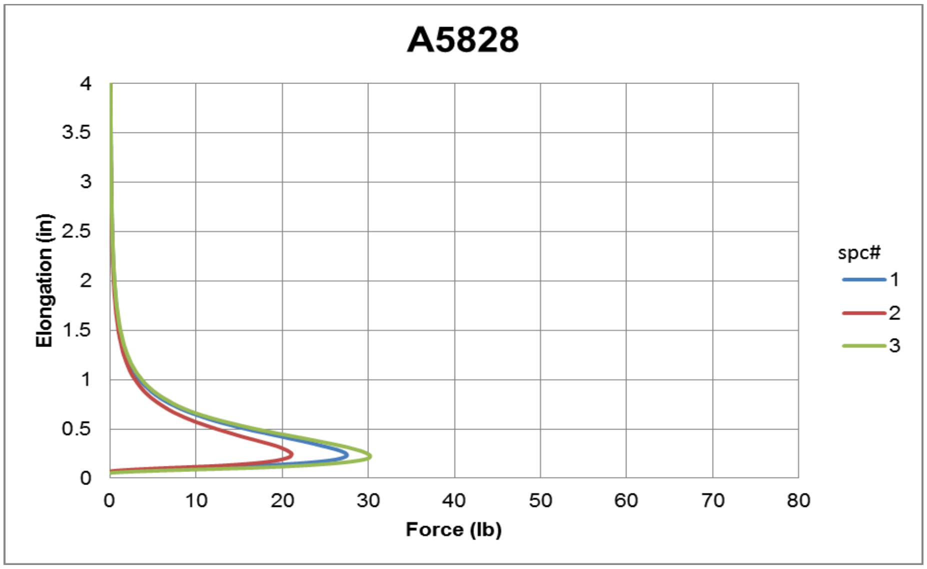

Figure A-37 Force vs Elongation for A5828

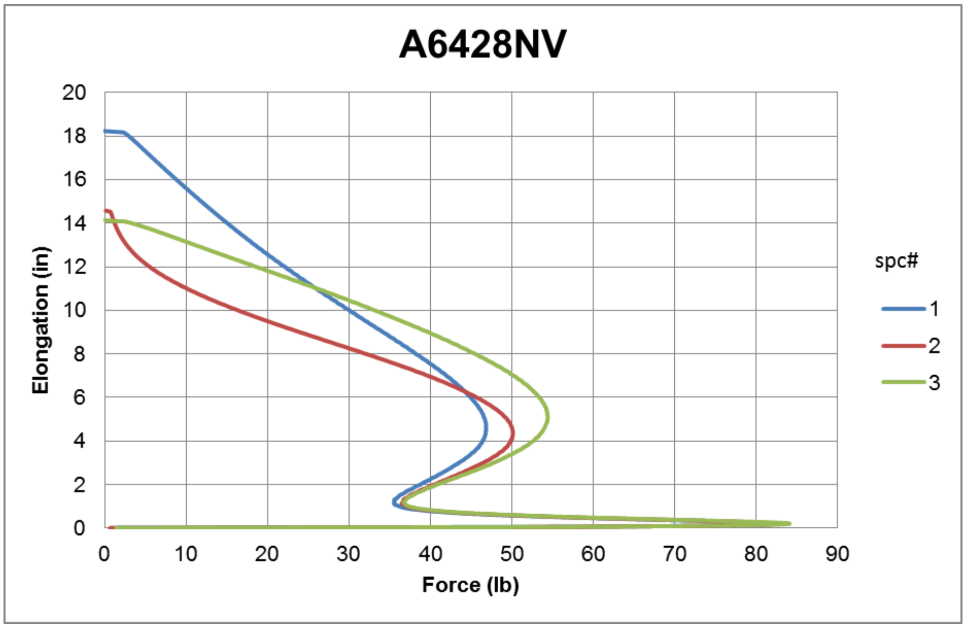

Figure A-38 Force vs Elongation for A6428NV

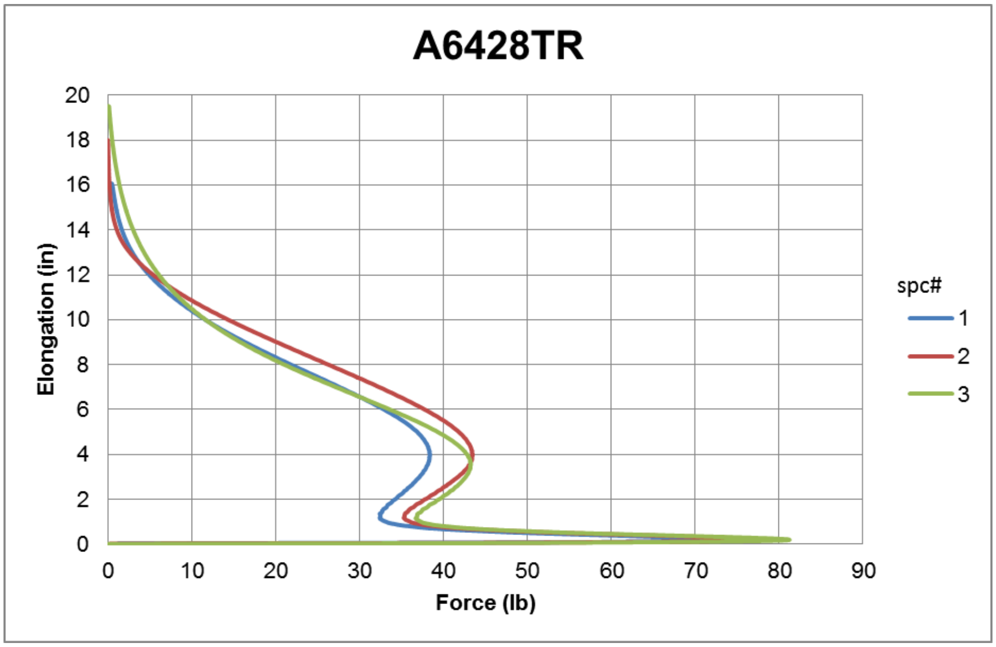

Figure A-39 Force vs Elongation for A6428TR

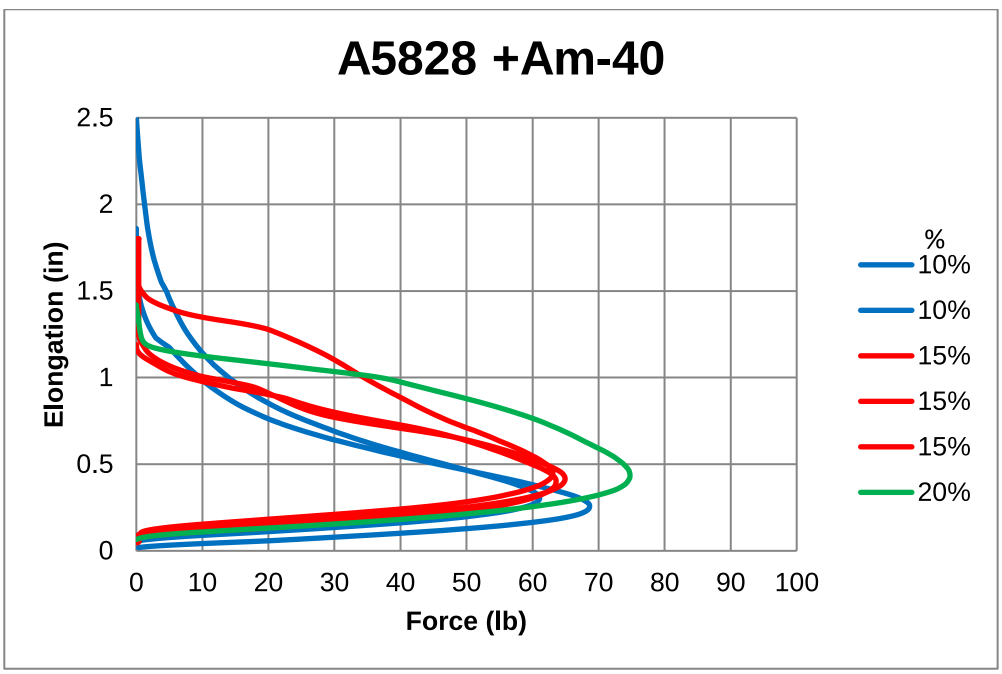

Figure A-40 Force vs Elongation for A5828 mixed with Ambient #40

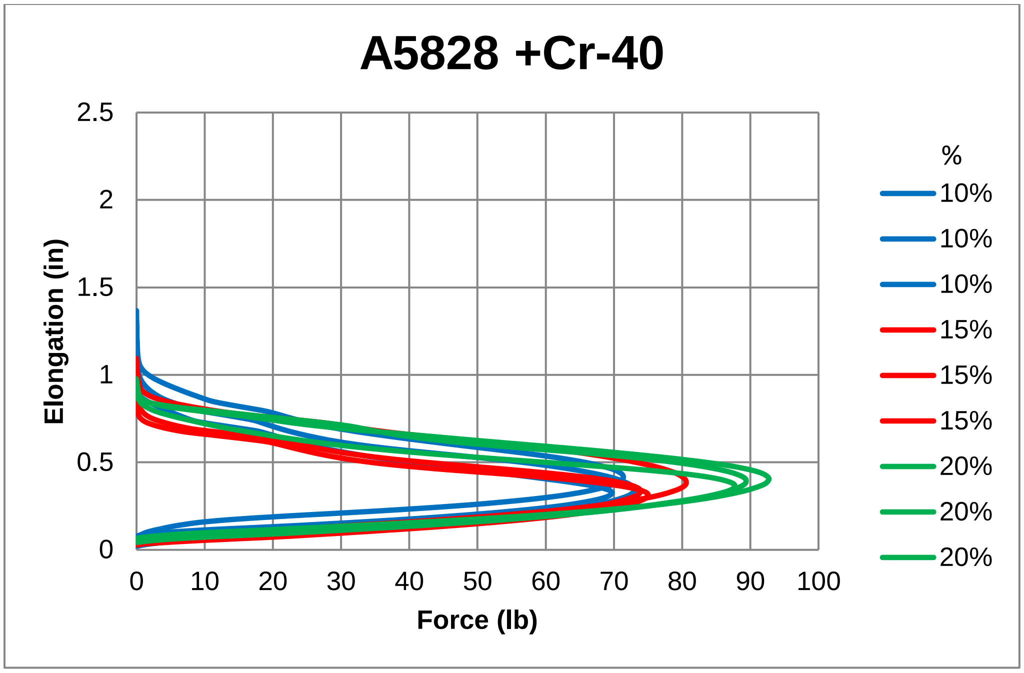

Figure A-41 Force vs Elongation for A5828 mixed with Cryogenic #40

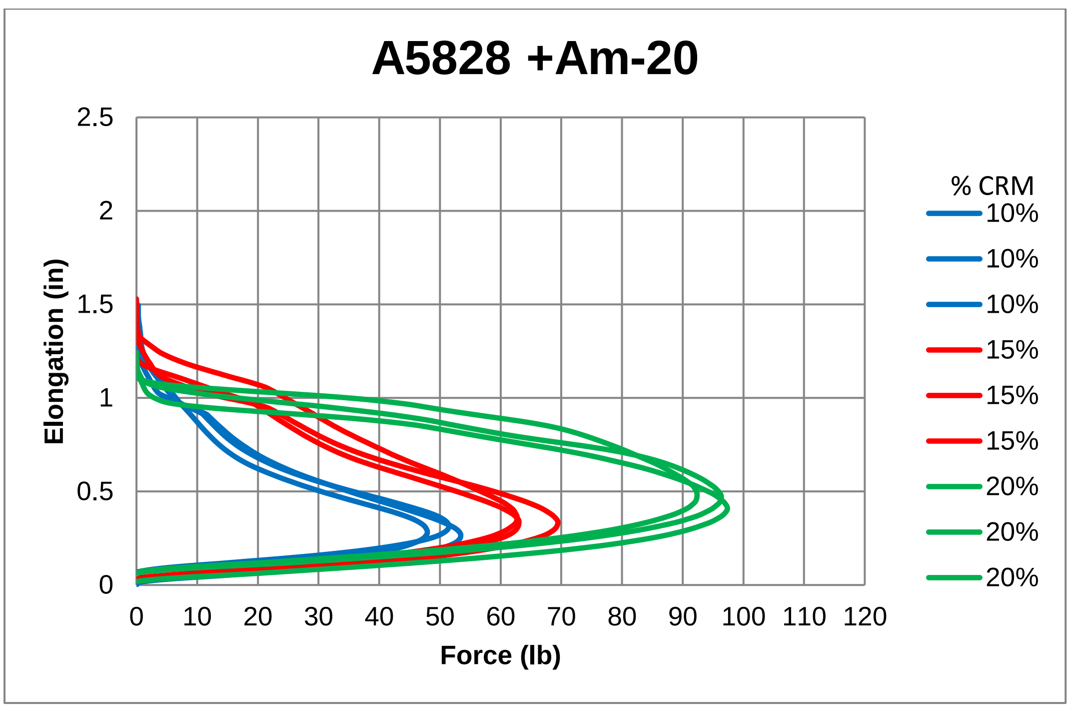

Figure A-42 Force vs Elongation for A5828 mixed with Ambient #20

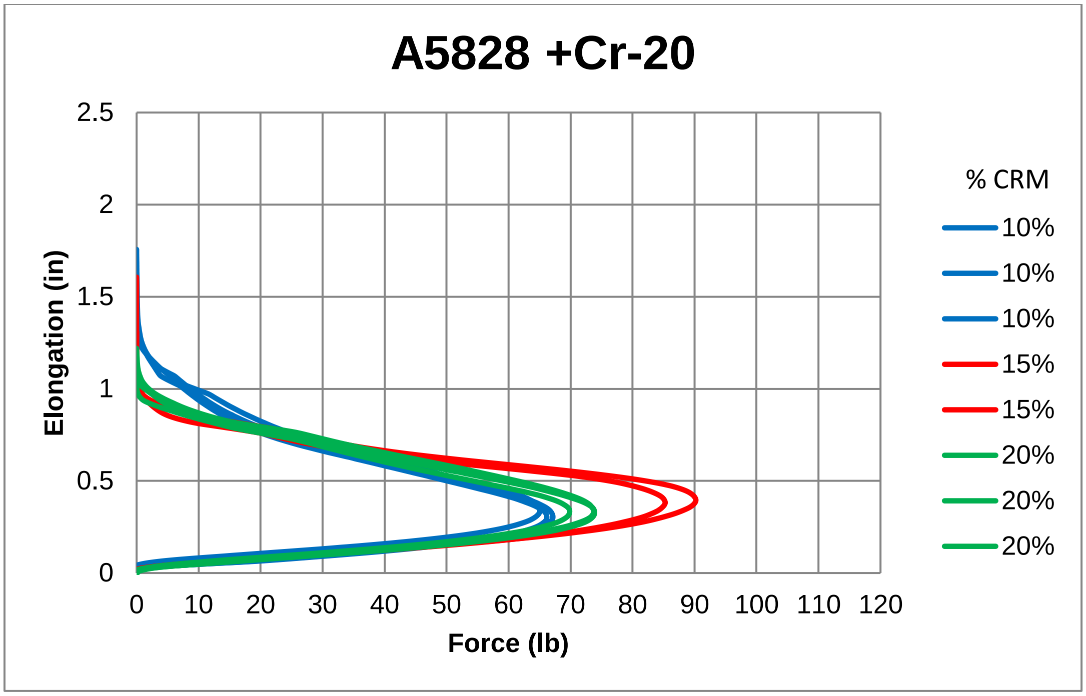

Figure A-43 Force vs Elongation for A5828 mixed with Cryogenic #40

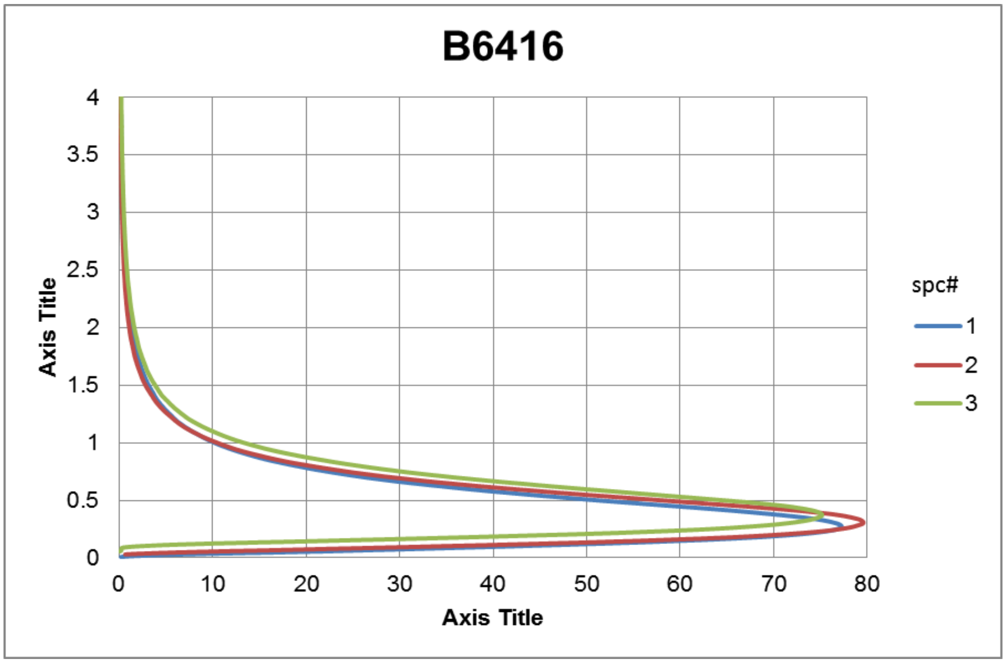

Figure A-44 Force vs Elongation for B6416

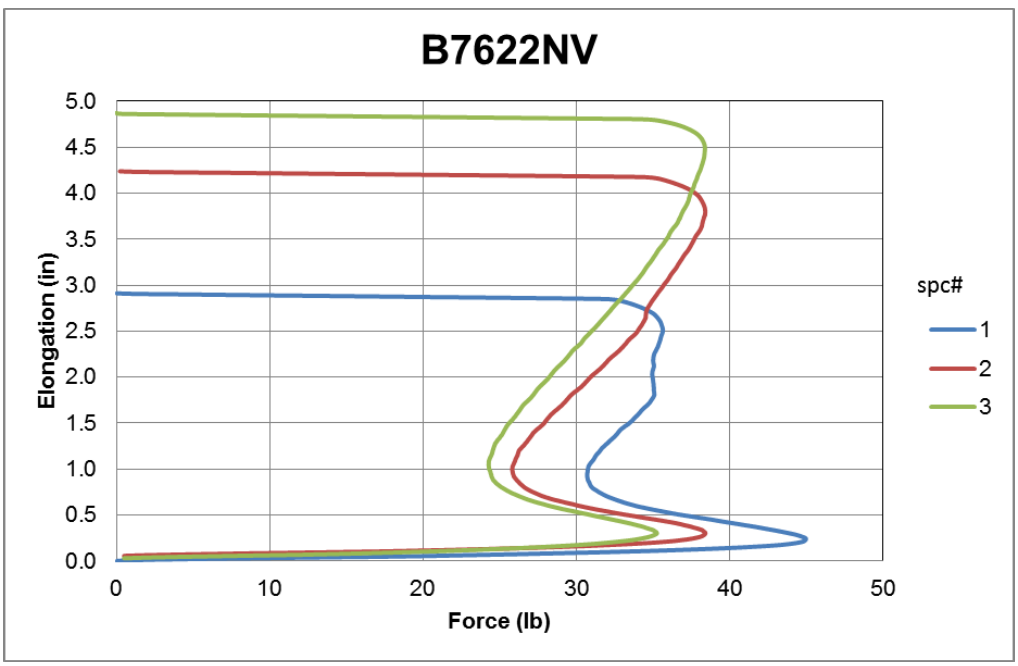

Figure A-45 Force vs Elongation for B7622NV from source B

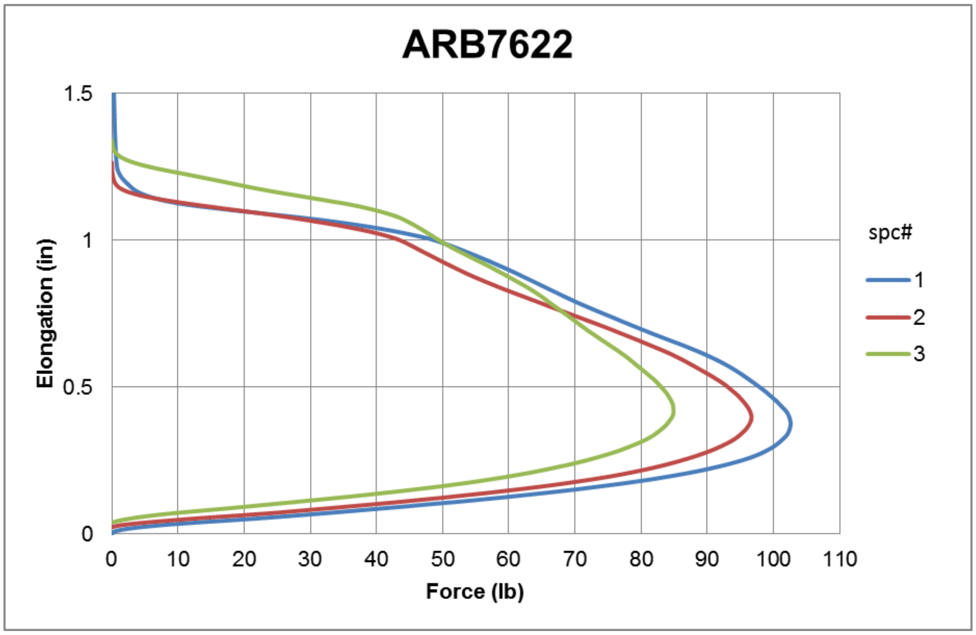

Figure A-46 Force vs Elongation for ARB7622 (asphalt rubber binder)

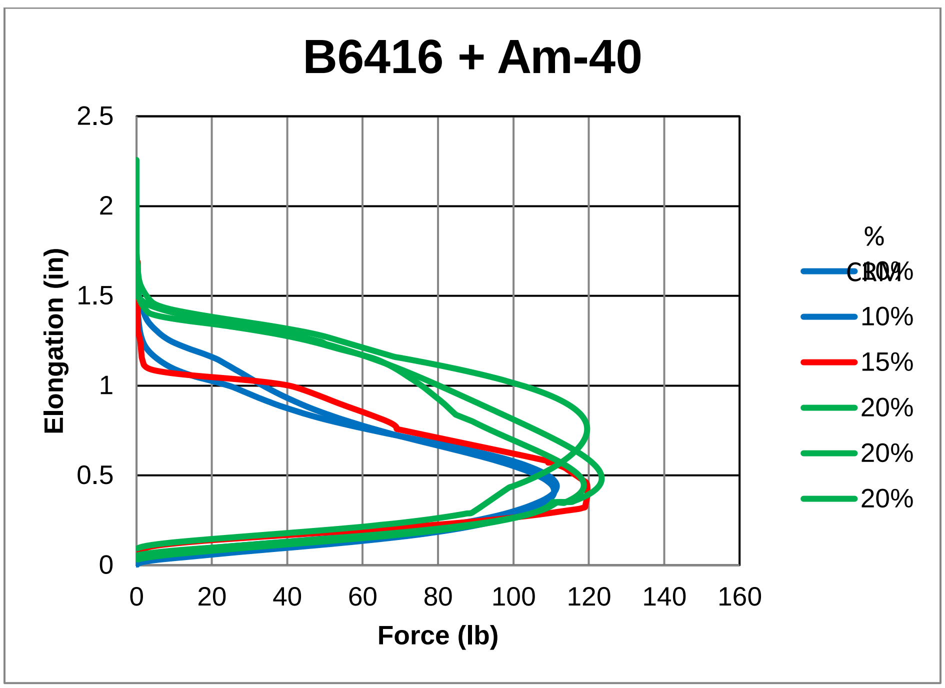

Figure A-47 Force vs Elongation for B6416 mixed with Ambient #40

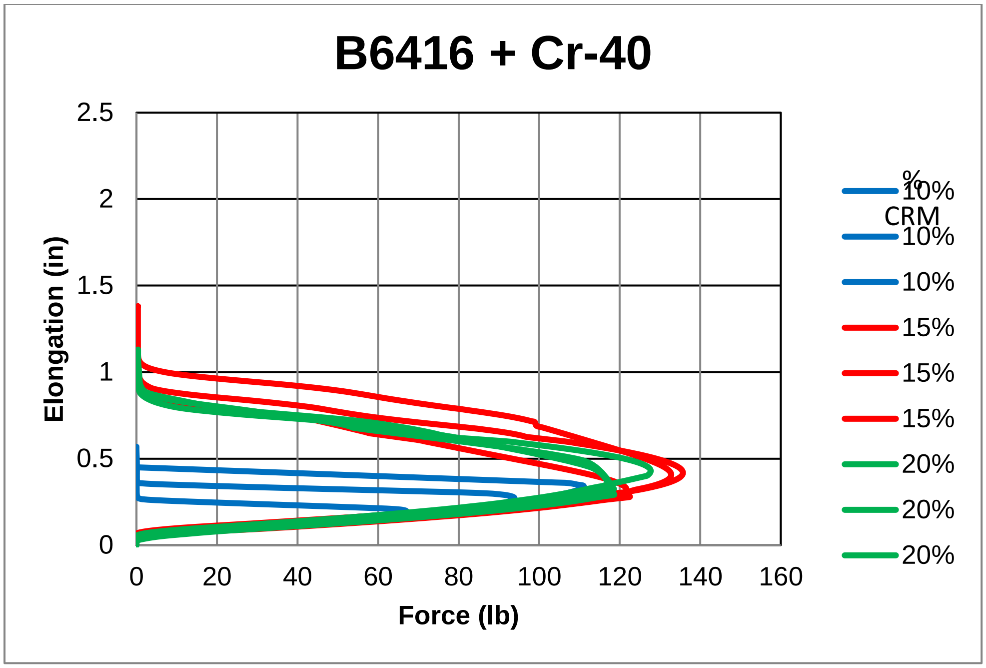

Figure A-48 Force vs Elongation for B6416 mixed with Cryogenic #40

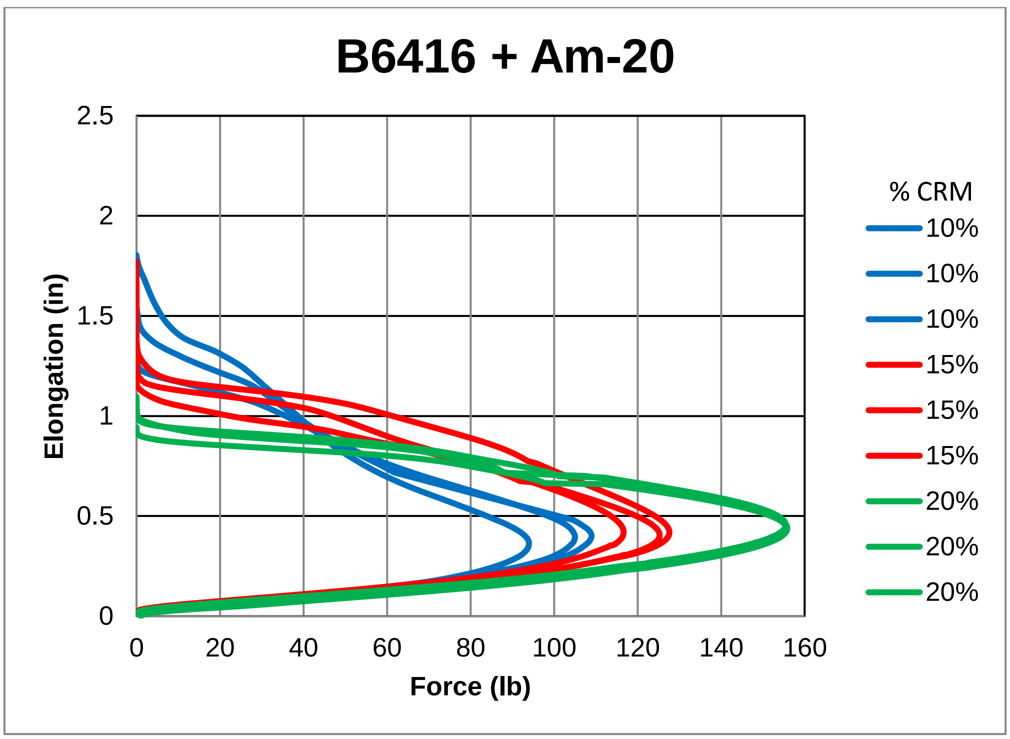

Figure A-49 Force vs Elongation for B6416 mixed with Ambient #20

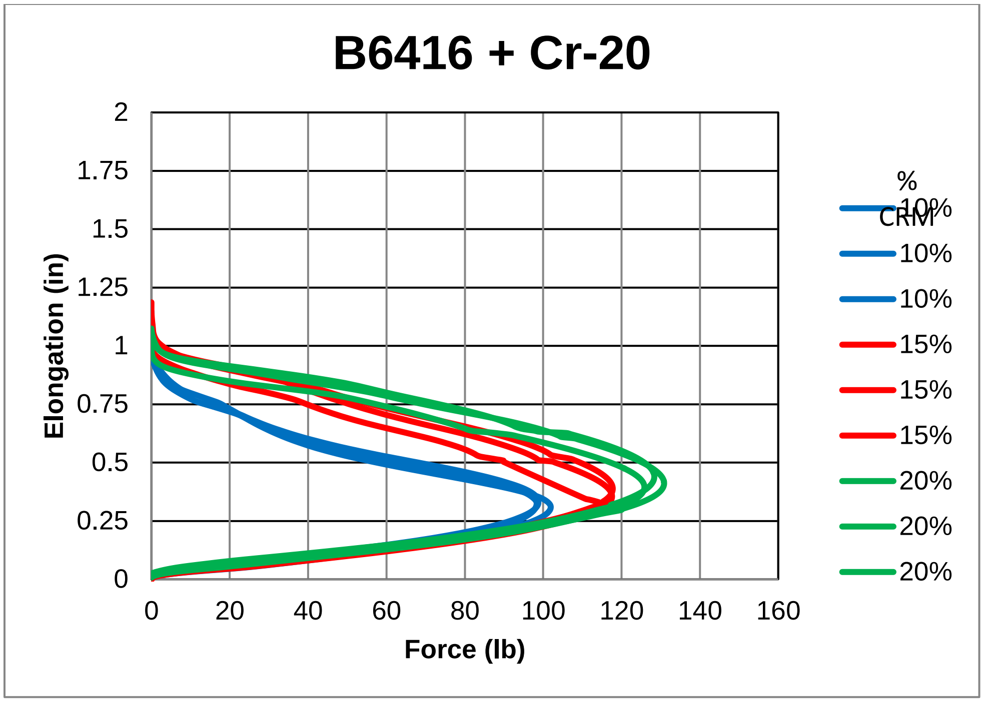

Figure A-50 Force vs Elongation for B6416 mixed with Cryogenic #40

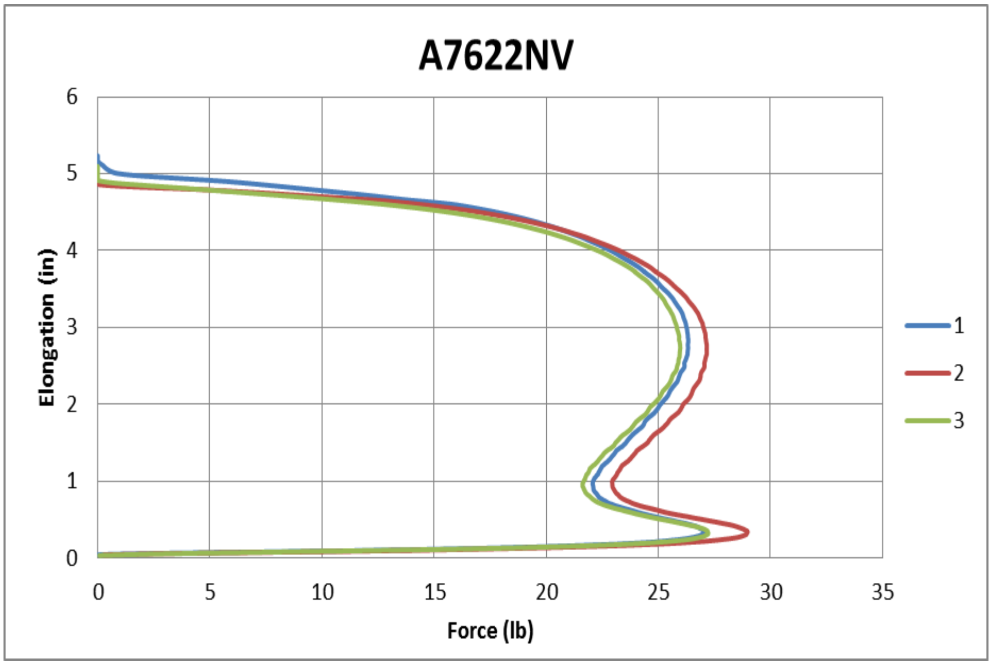

Figure A-51 Force vs Elongation for A7622NV

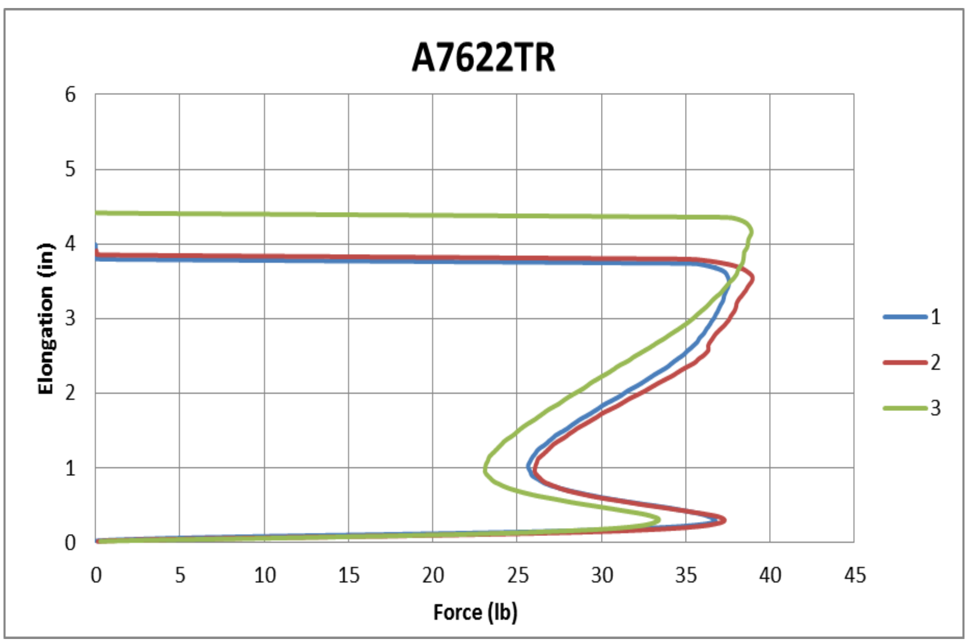

Figure A-52 Force vs Elongation for A7622TR

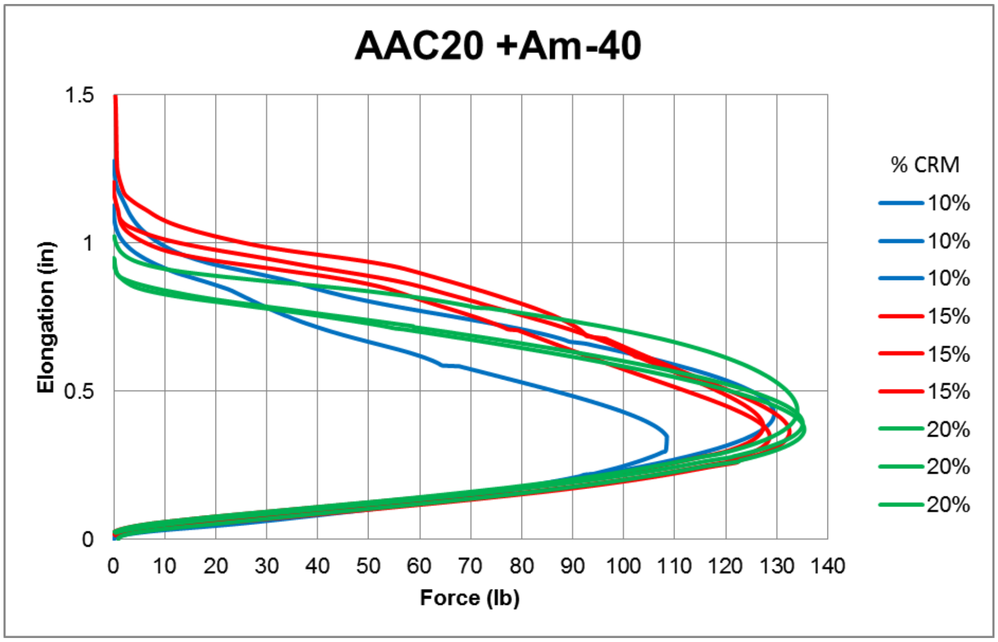

Figure A-53 Force vs Elongation for AAC20 mixed with Ambient #40

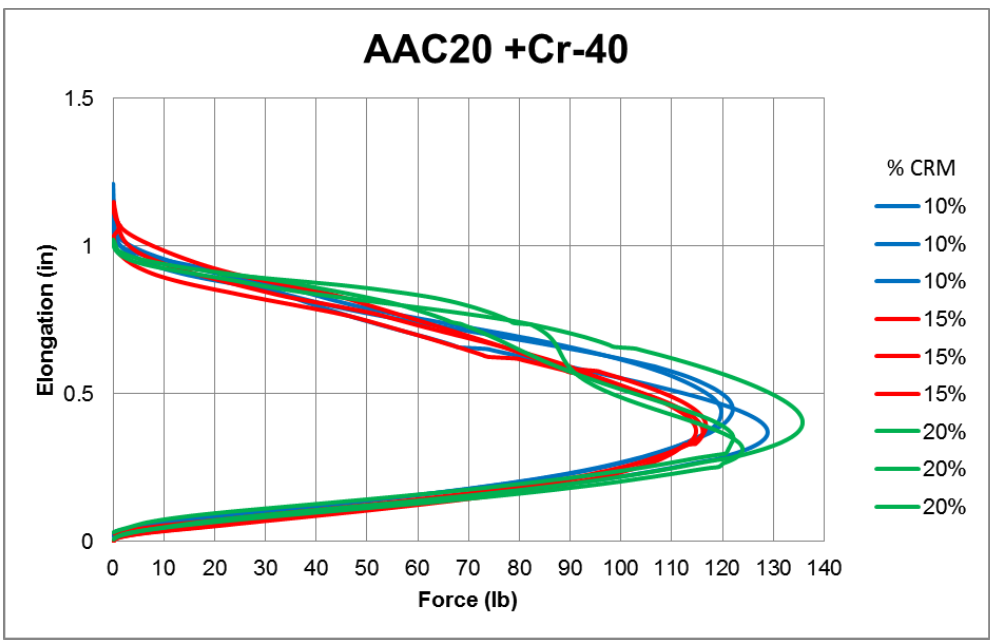

Figure A-54 Force vs Elongation for AAC20 mixed with Cryogenic #40

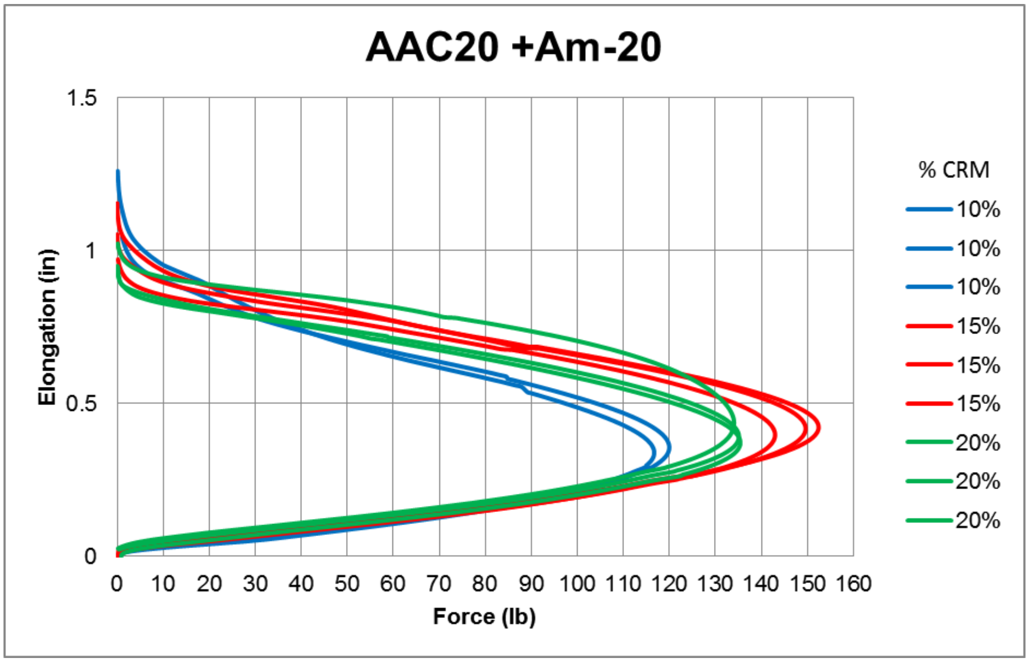

Figure A-55 Force vs Elongation for AAC20 mixed with Ambient #20

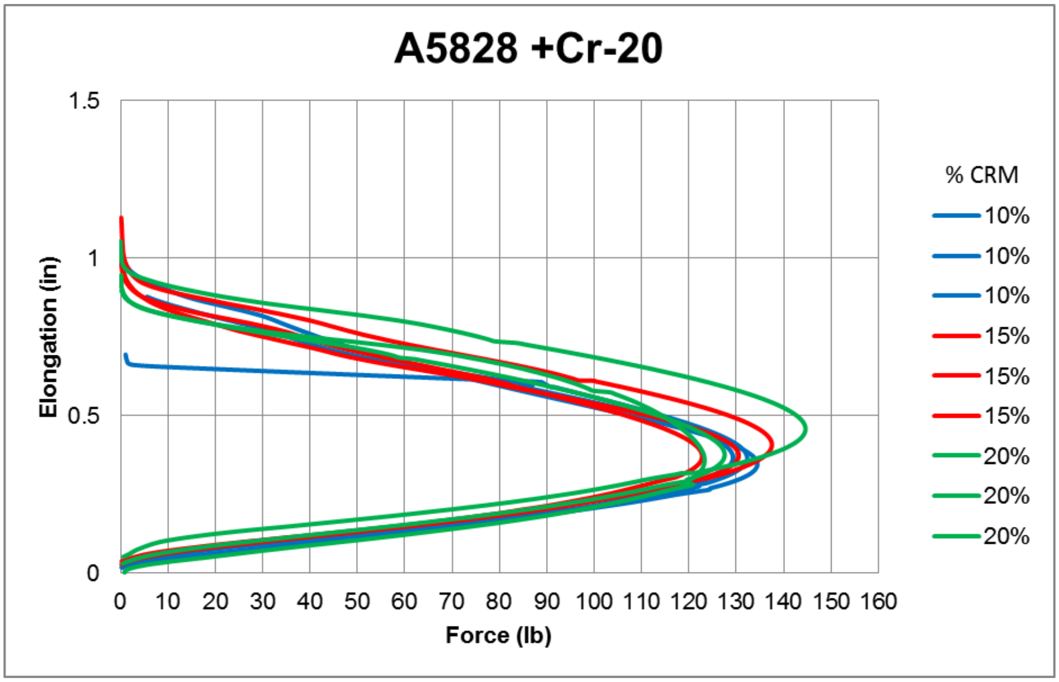

Figure A-56 Force vs Elongation for AAC20 mixed with Cryogenic #40

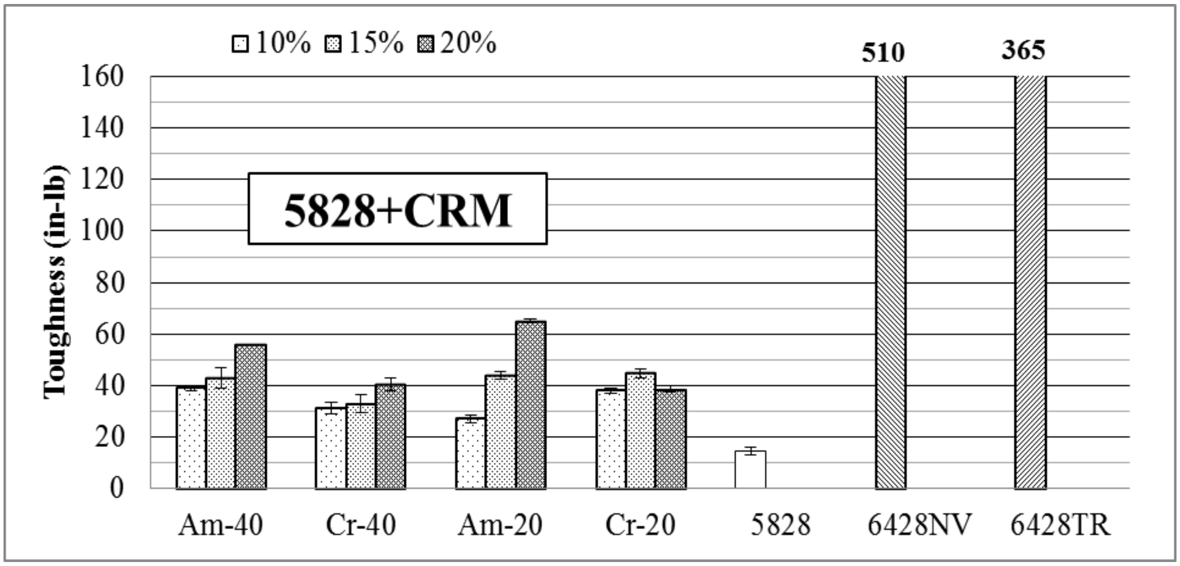

Figure A-57Toughness of A5828 samples mixed with CRM, polymer modified and terminal blend

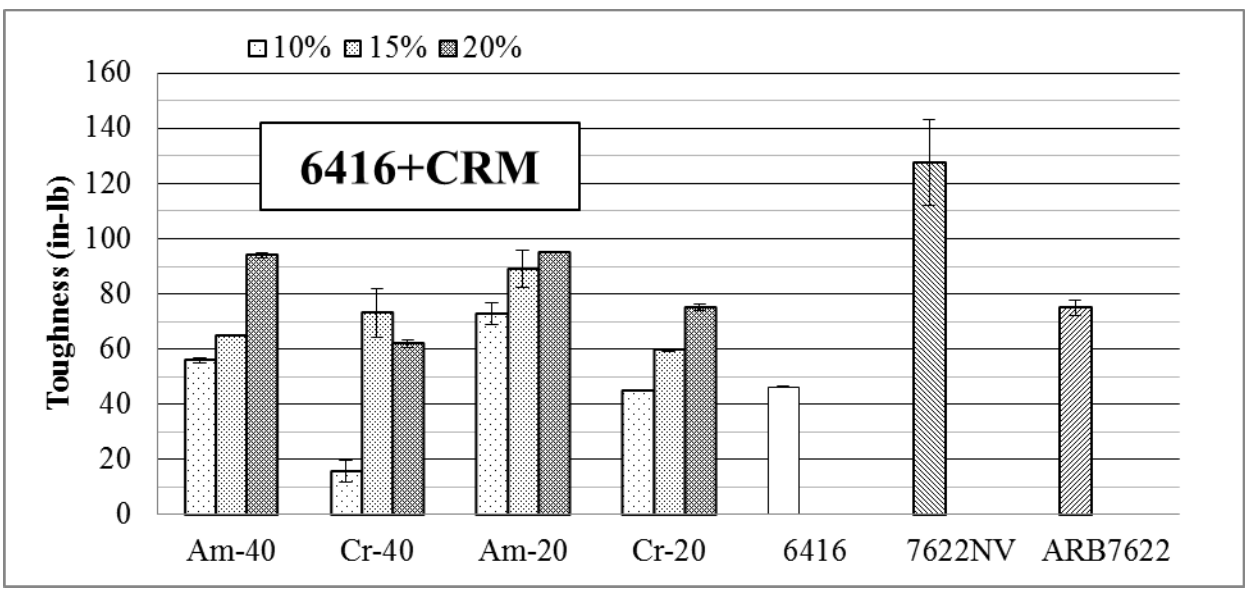

Figure A-58 Toughness of B6416 samples mixed with CRM, polymer modified asd asphalt rubber binder

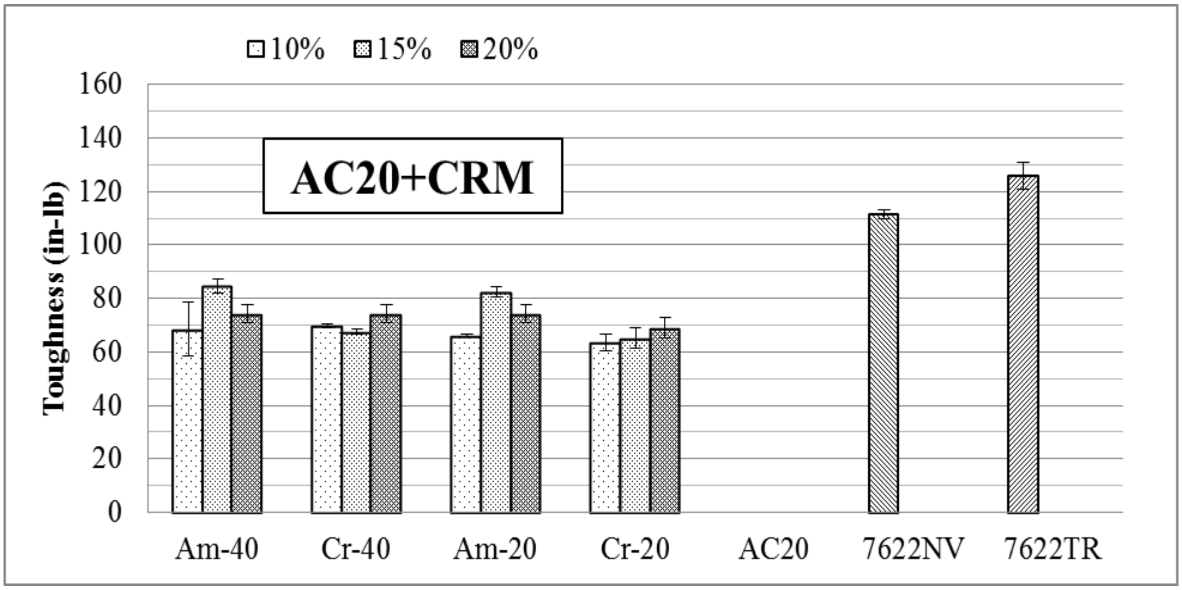

Figure A-59 Toughness of AAC20 samples mixed with CRM, polymer modified and terminal blend

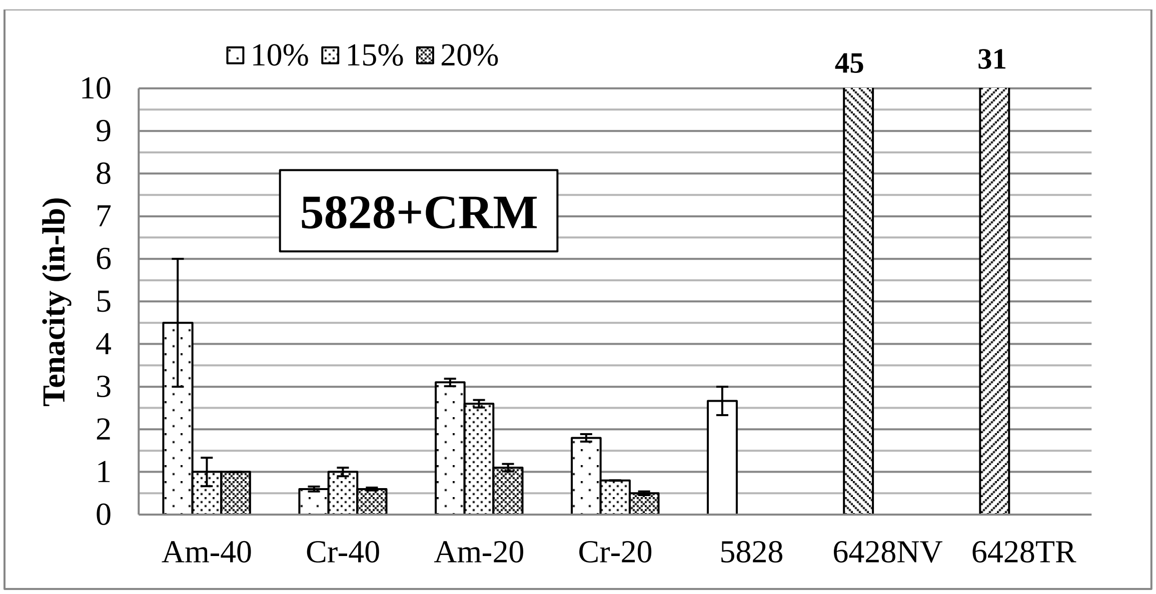

Figure A-60 Tenacity of A5828 samples mixed with CRM, polymer modified and terminal blend

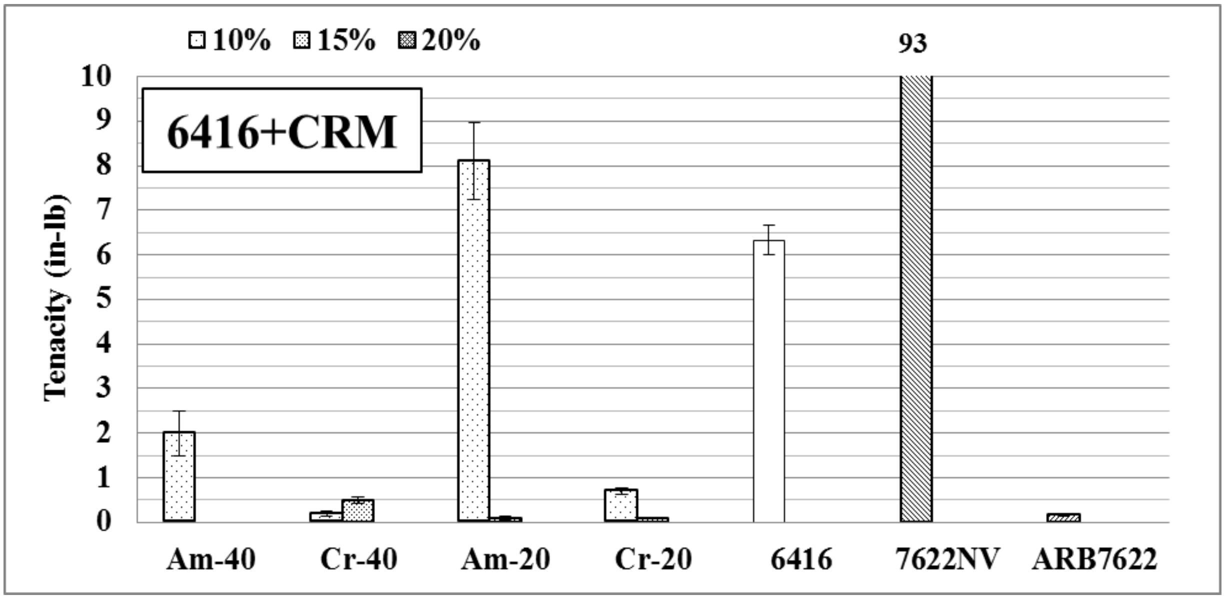

Figure A-61 Tenacity of B6416 samples mixed with CRM, polymer modified asd asphalt rubber binder

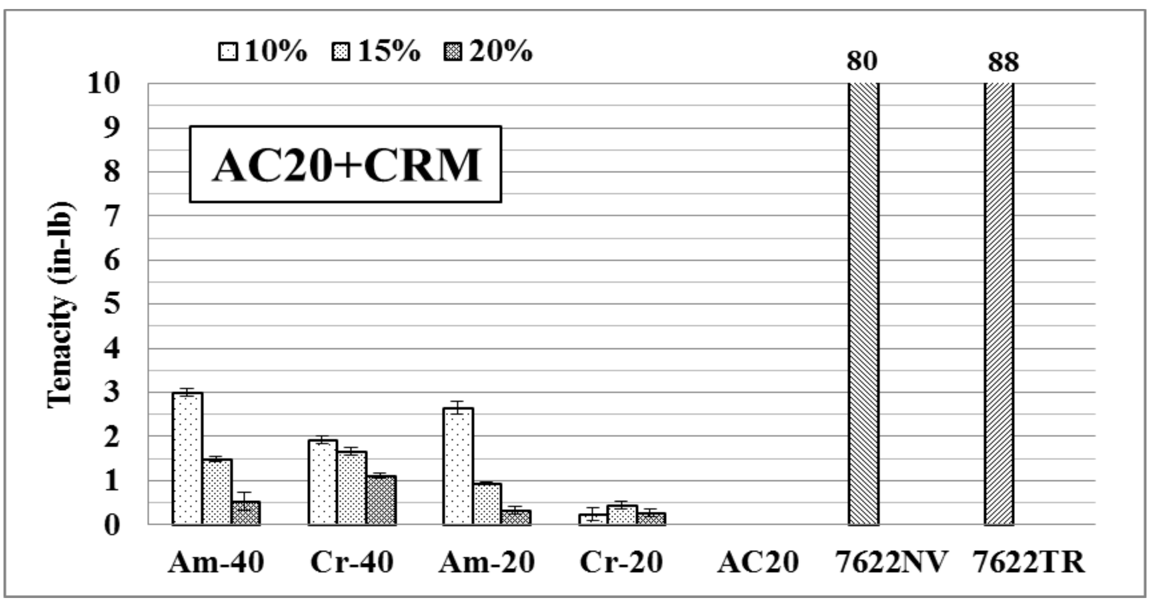

Figure A-62 Tenacity of AAC20 samples mixed with CRM, polymer modified and terminal blend

Initial Strengths: Virgin binders

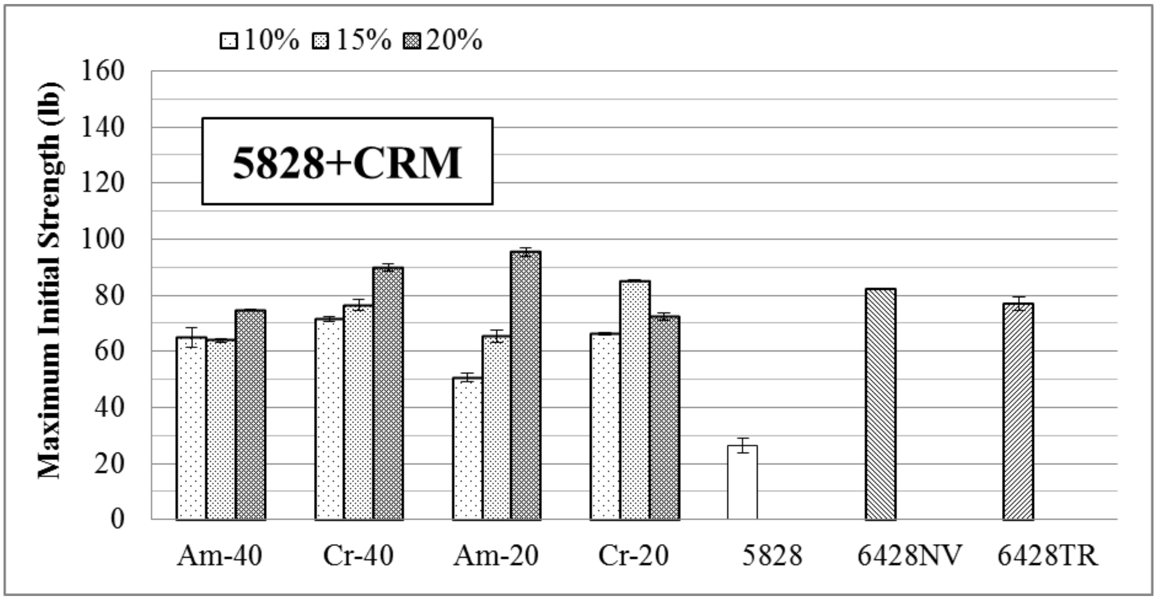

Figure A-63 Maximum Initial Strength of A5828 samples mixed with CRM, polymer modified and terminal blend

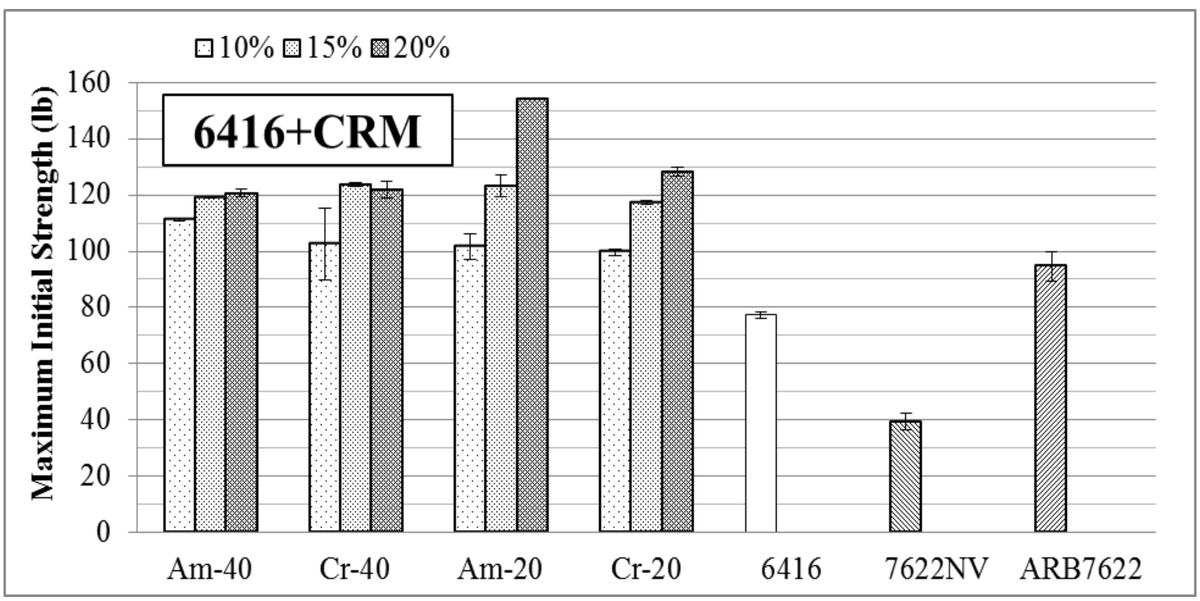

Figure A-64 Maximum Initial Strength of B6416 samples mixed with CRM, polymer modified asd asphalt rubber binder

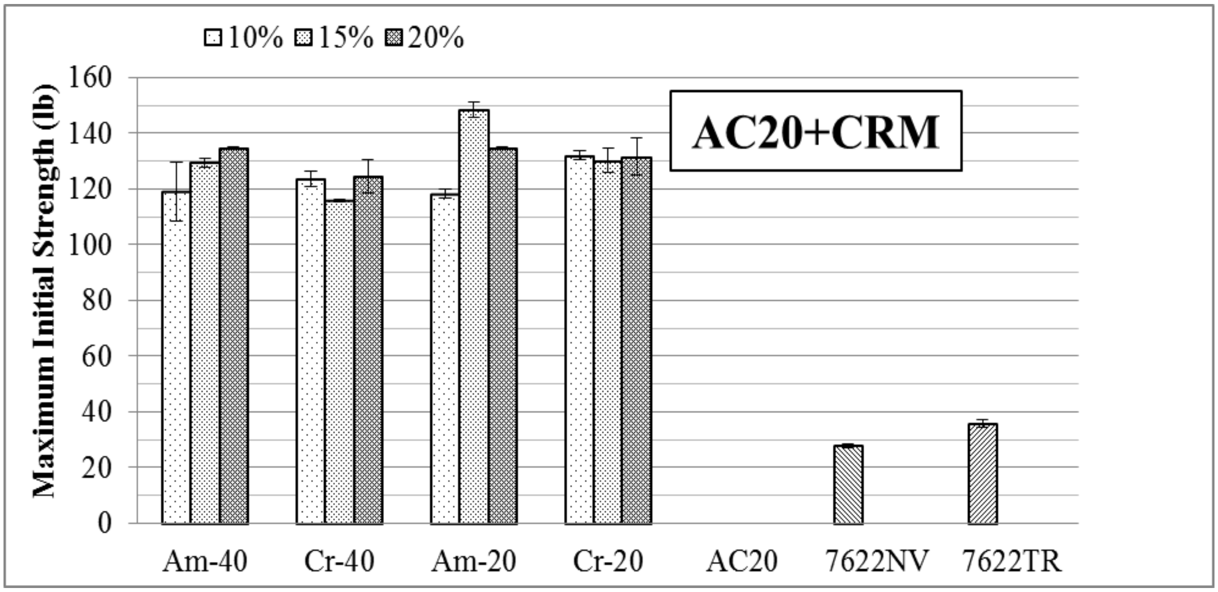

Figure A-65 Maximum Initial Strength of AAC20 samples mixed with CRM, polymer modified and terminal blend

Sieve Particulates Retained

Figure A-66 Few amount of particles retained on sieve for A5828-Cr-40-10

Figure A-67 particles retained on sieve for A5828-Cr-40-15

Figure A-68 particles retained on sieve for A5828-Cr-40-20

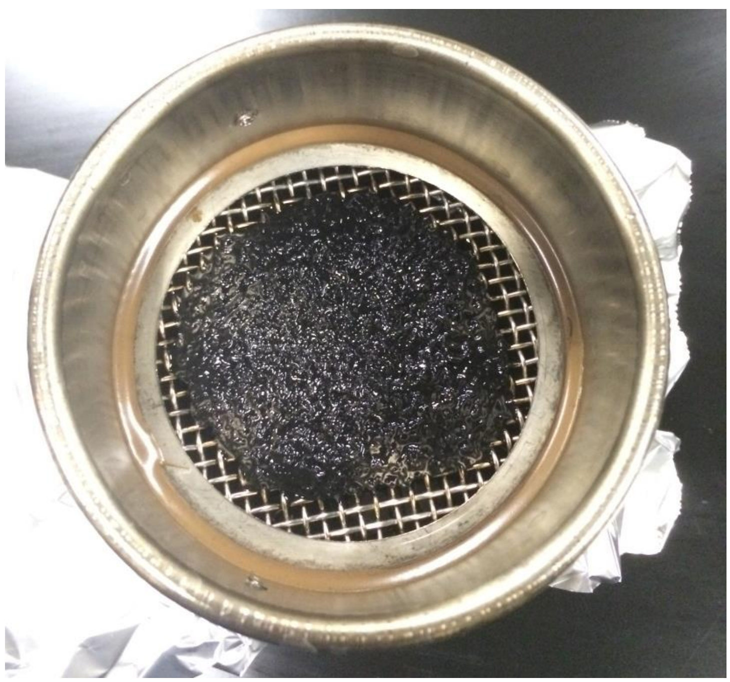

Figure A-69 particles retained on sieve for A5828-Am-20-10

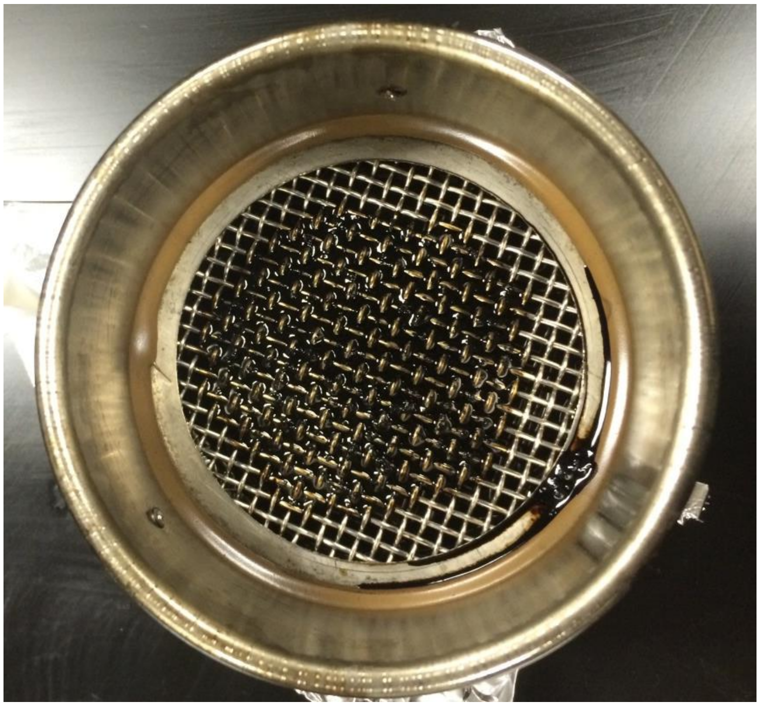

Figure A-70 few particles retained on sieve for B6416-Cr-40-10

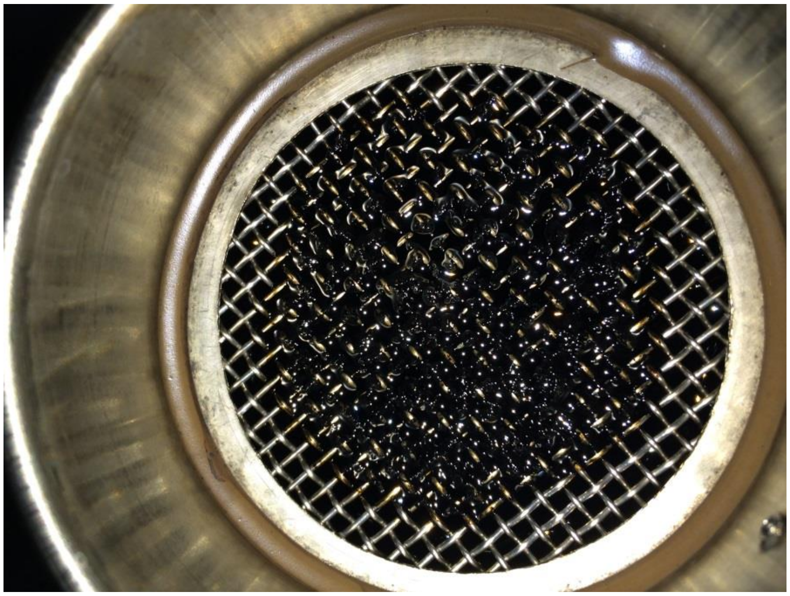

Figure A-71 particles retained on sieve for B6416-Cr-40-15

Figure A-72 particles retained on sieve for AAC20-Am-40-10

Figure A-73 particles retained on sieve for AAC20-Am-20-10

Figure A-74 particles retained on sieve for AAC20-Cr-20-10

Figure A-75 particles retained on sieve for AAC20-Cr-40-10

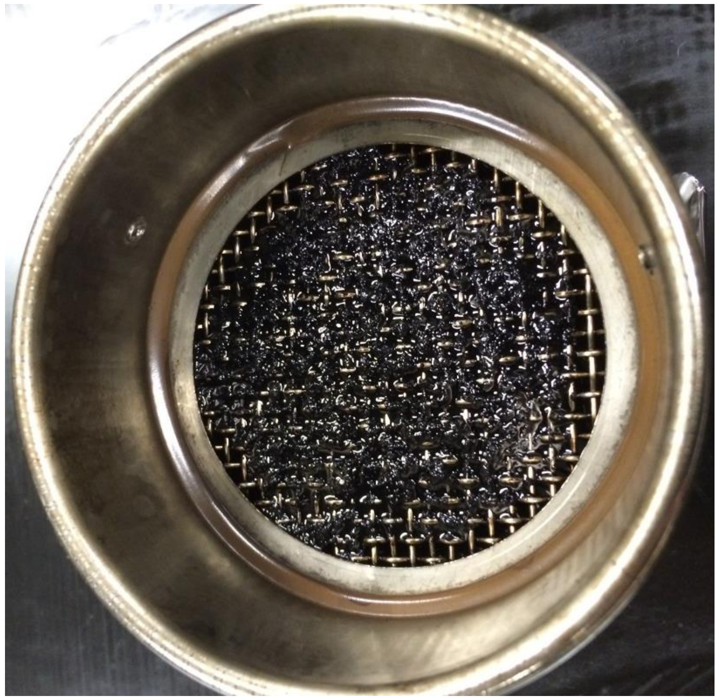

Figure A-76 particles retained on sieve for AAC20-Cr-40-15

Figure A-77 particles retained on sieve for AAC20-Cr-40-20

G*/sin(δ) values: RTFO binders

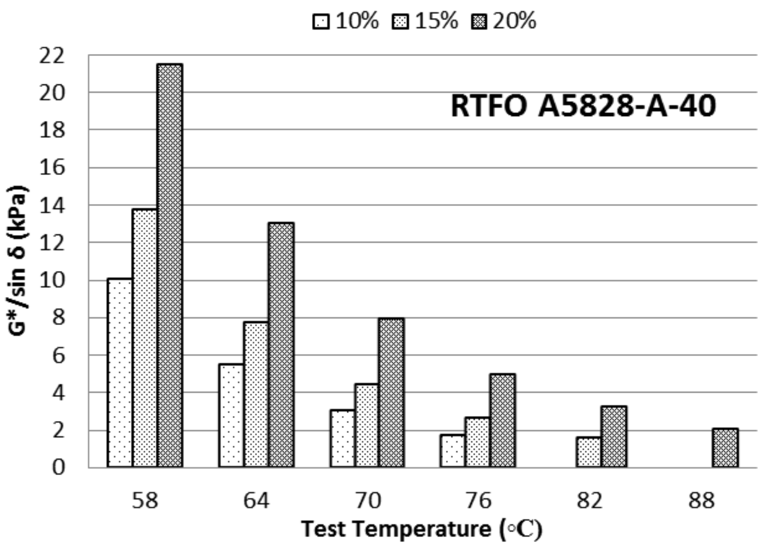

Figure A-78 G*/sin(δ) at different temperatures for RTFO A5828 mixed with CRM Ambient #40

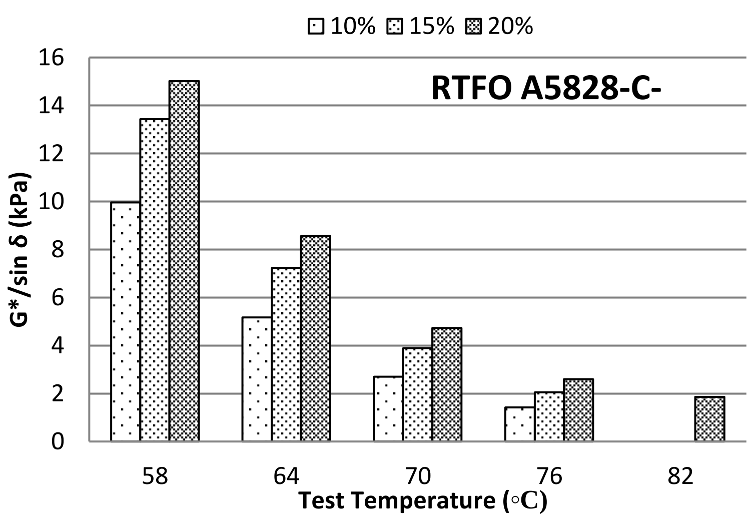

Figure A-79 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #40

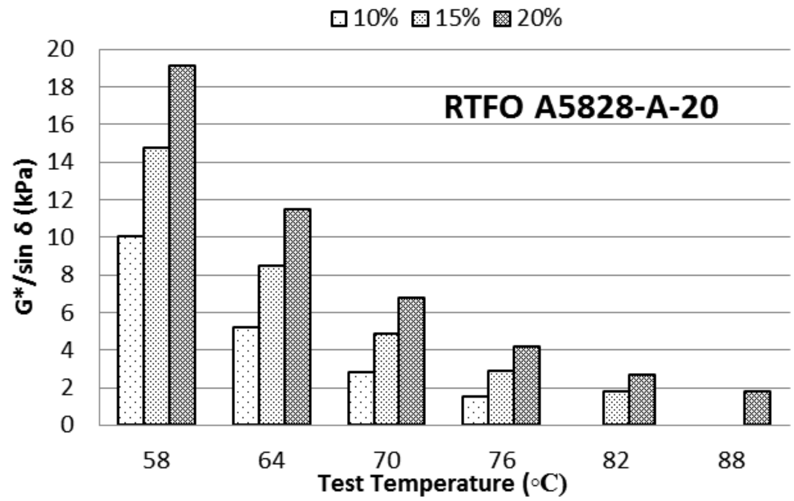

Figure A-80 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Ambient #20

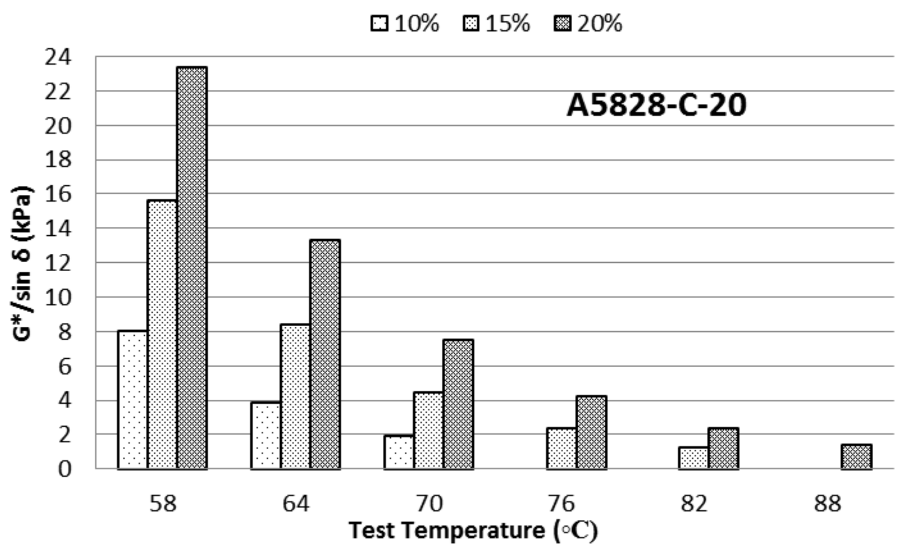

Figure A-81 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #20

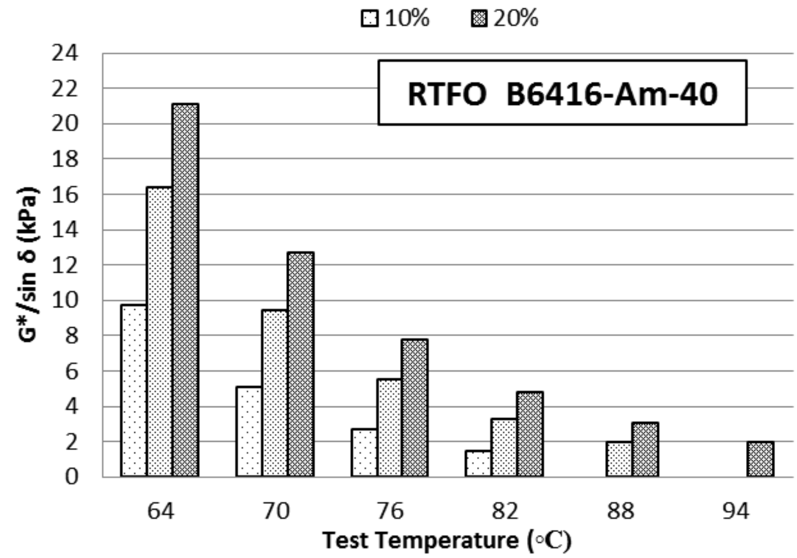

Figure A-82 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Ambient #40

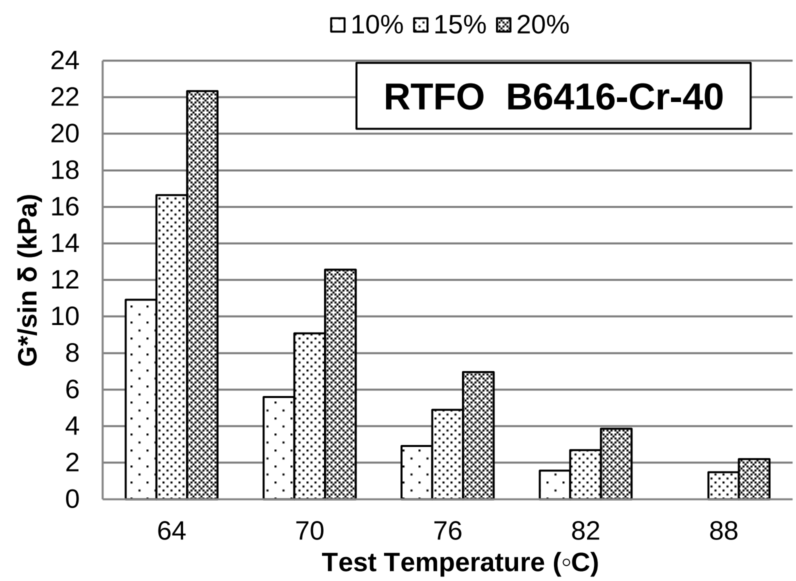

Figure A-83 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #40

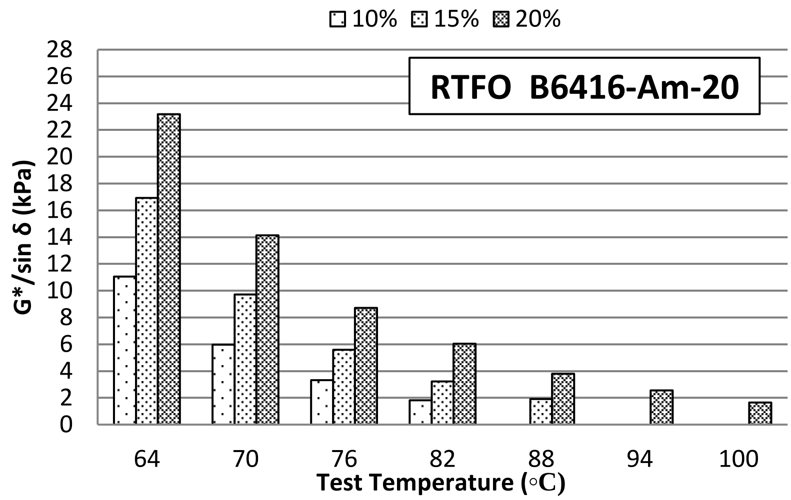

Figure A-84 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Ambient #20

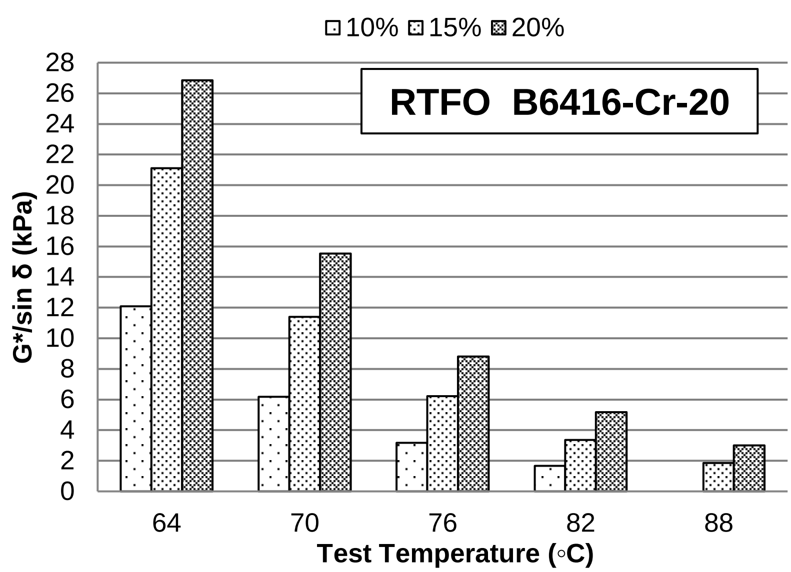

Figure A-85 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #20

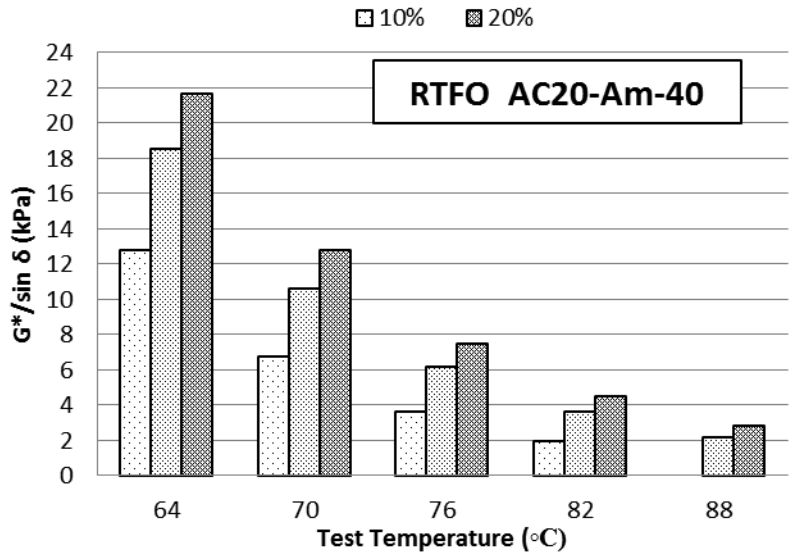

Figure A-86 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Ambient #40

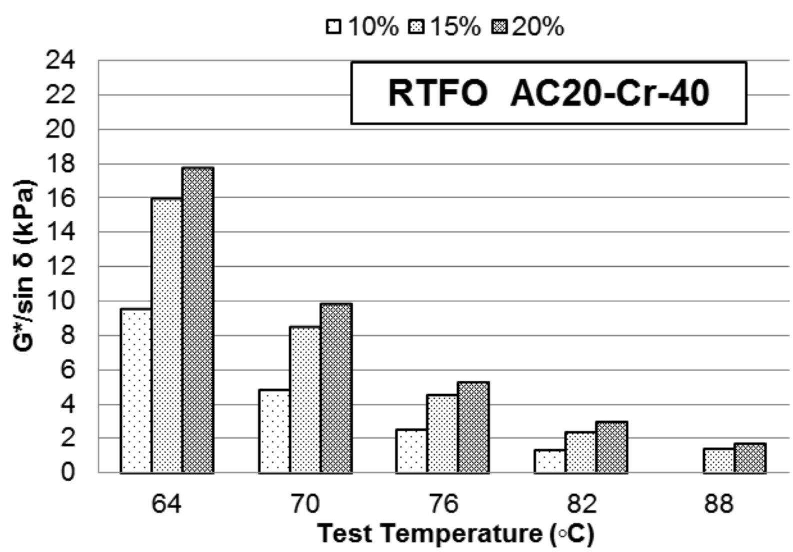

Figure A-87 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #40

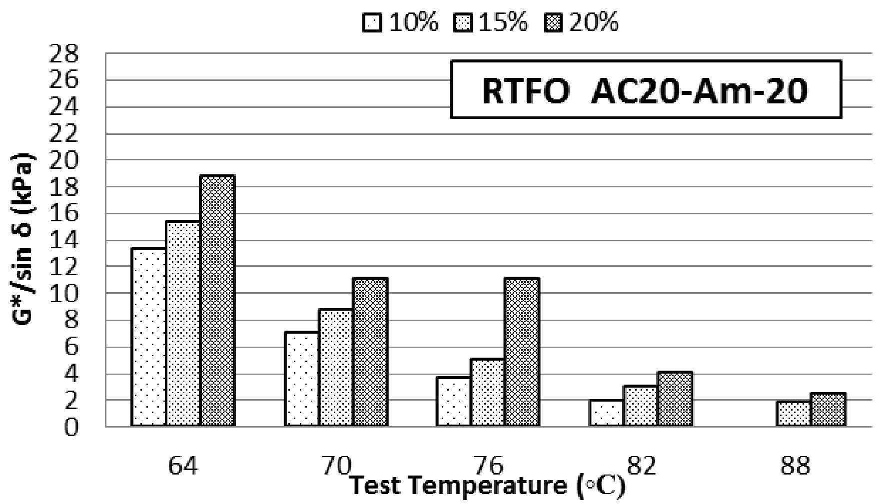

Figure A-88 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Ambient #20

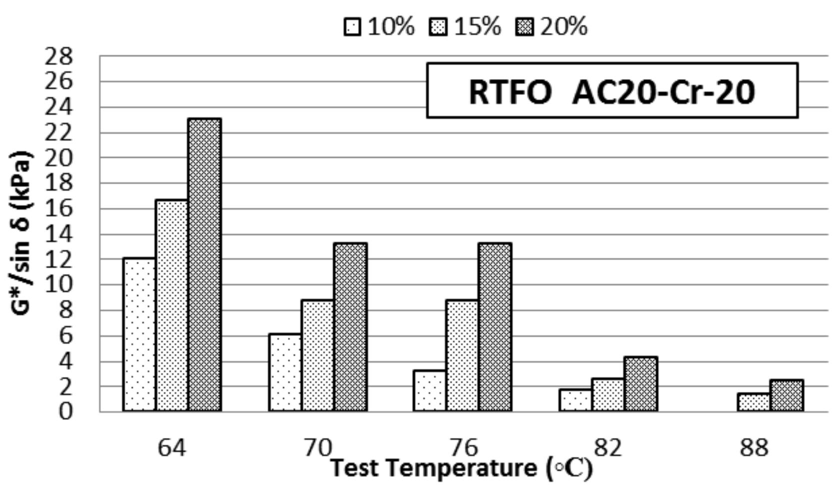

Figure A-89 G*/sin(δ) at different temperatures for RTFO B6416 mixed with CRM Cryogenic #20

Failure temperatures: RTFO binders

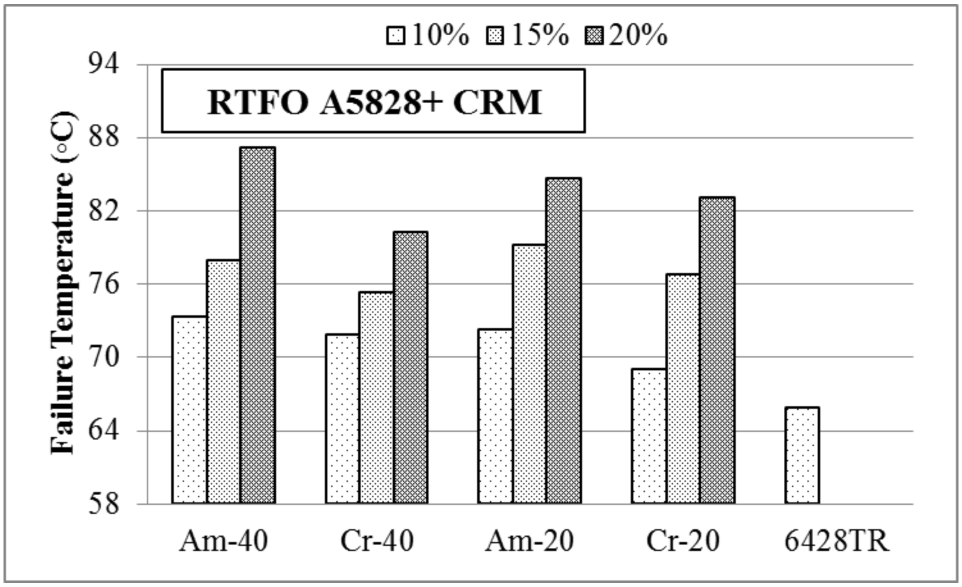

Figure A-90 Failure temperature for RTFO A5828 and mixed with CRM, and terminal blend tire rubber

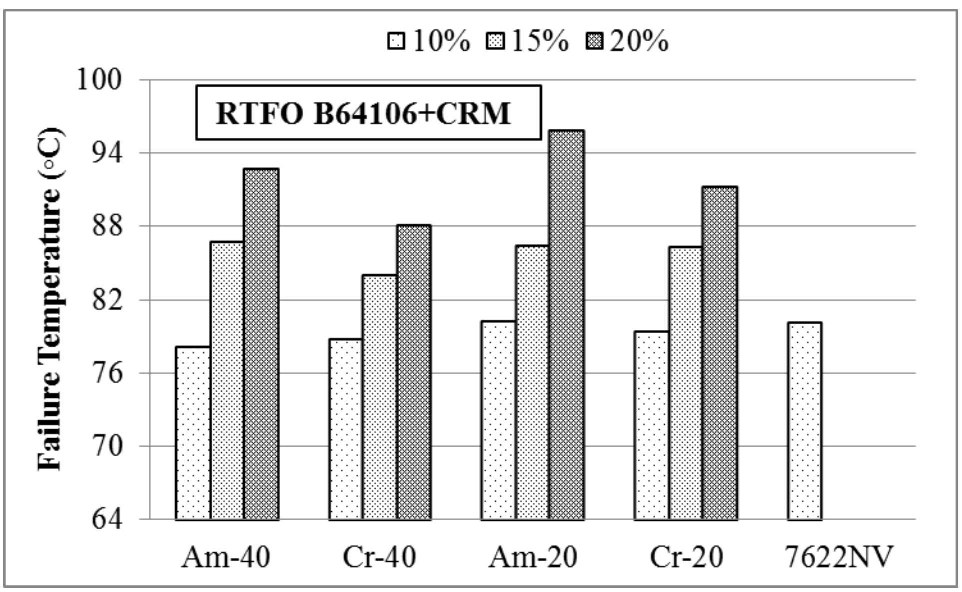

Figure A-91 Failure temperature for RTFO B6416 and mixed with CRM, and polymer modified 7622

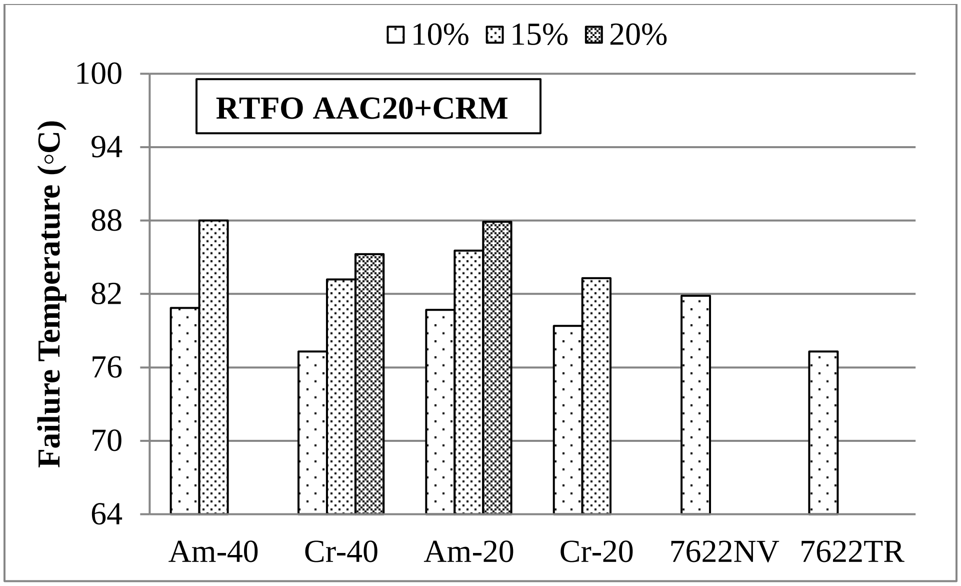

Figure A-92 Failure temperature for RTFO AAC20 and mixed with CRM, and polymer modified 7622 and terminal blend tire rubber

Phase angles: RTFO binders

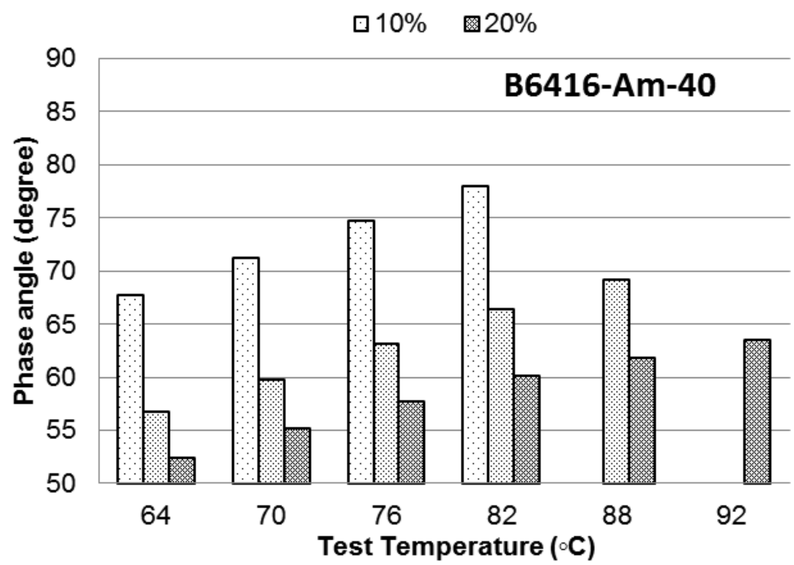

Figure A-93 Phase angle at different temperatures for RTFO B6416 mixed with CRM Ambient #40

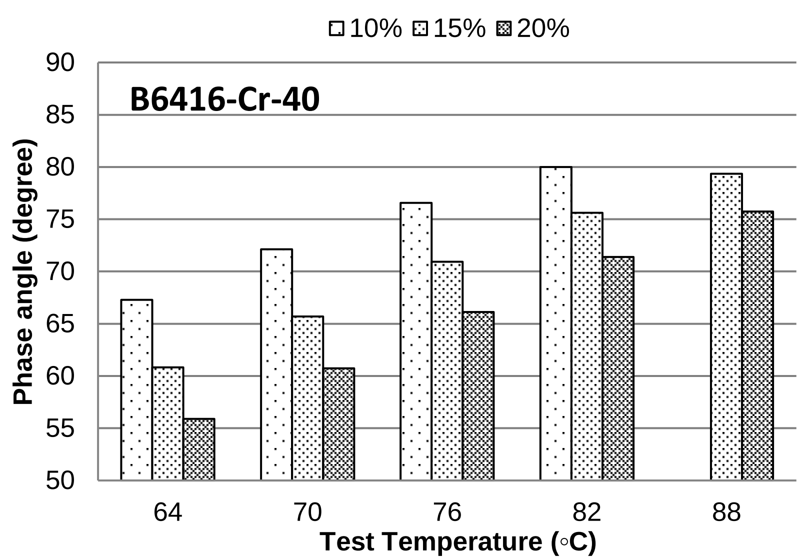

Figure A-94 Phase angle at different temperatures for RTFO B6416 mixed with CRM Cryogenic #40

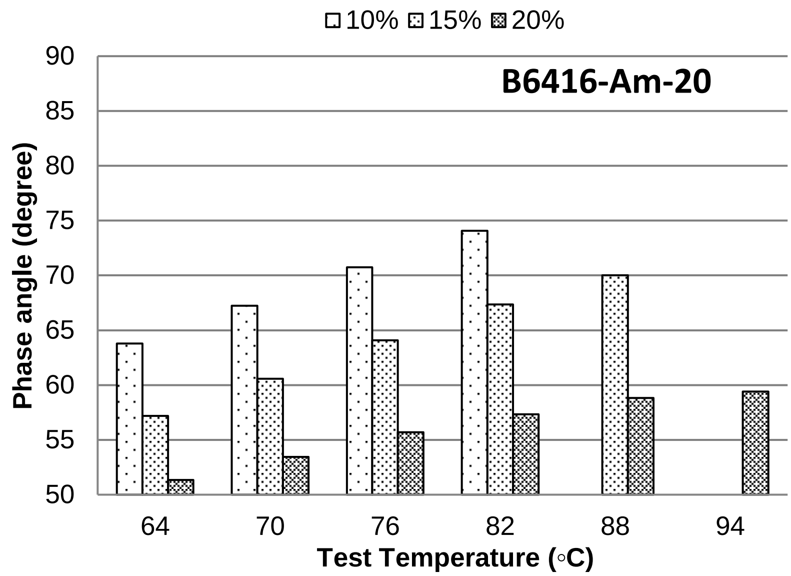

Figure A-95 Phase angle at different temperatures for RTFO B6416 mixed with CRM Ambient #20

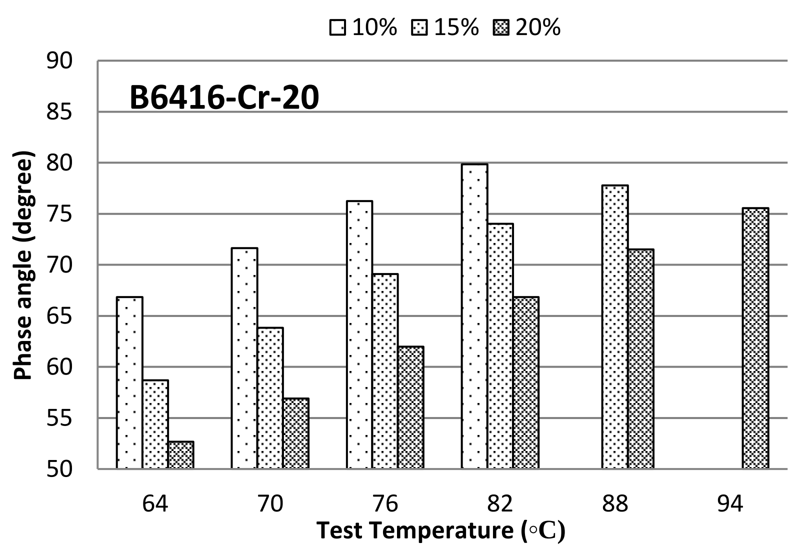

Figure A-96 Phase angle at different temperatures for RTFO B6416 mixed with CRM Cryogenic #20

Ductility: RTFO

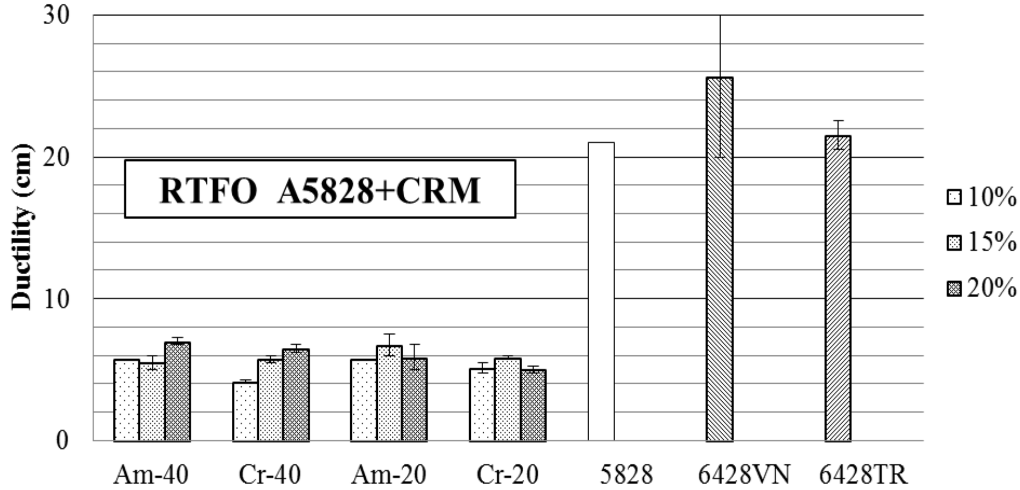

Figure A-97 Ductility of RTFO A5828 mixed with CRM, polymer modified and terminal blend tire rubber PG64-28

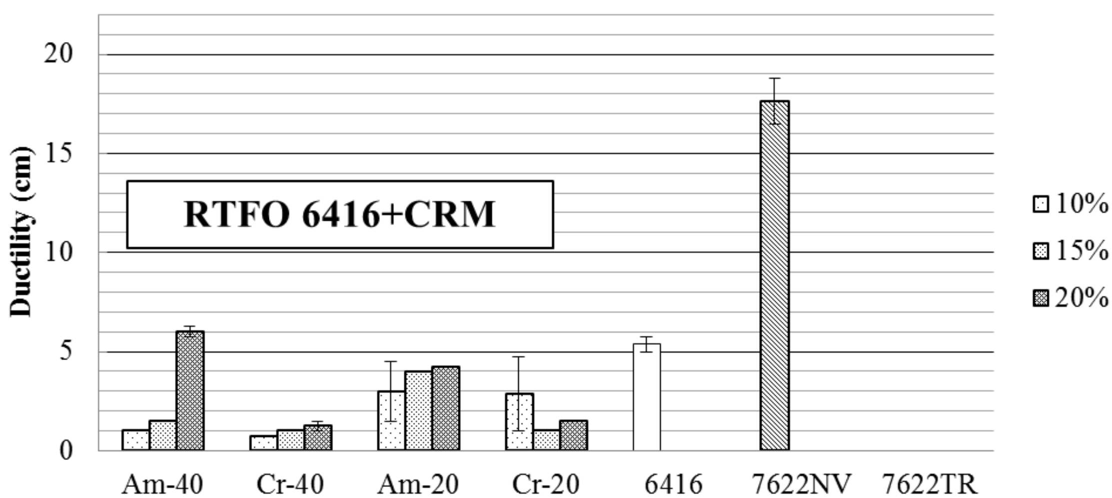

Figure A-98 Ductility of RTFO B6416 mixed with CRM, polymer modified and asphalt rubber binder PG76-22

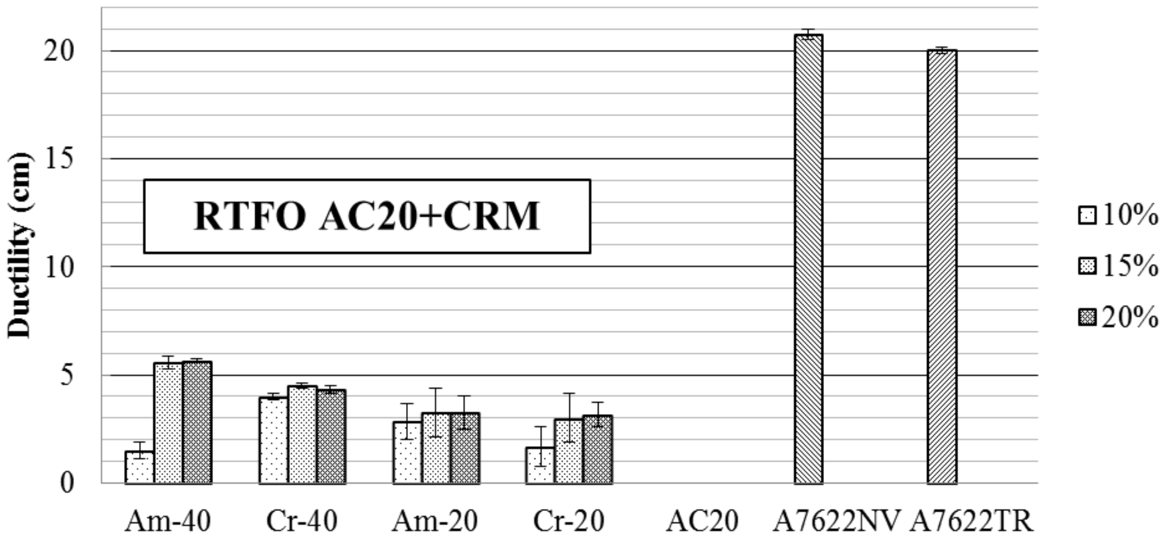

Figure A-99 Ductility of RTFO AAC20 mixed with CRM, polymer modified and terminal blend tire rubber PG76-22

DSR, PAV

Table A-1 data of the DSR-PAV test at 31 C on A6428NV (polymer modified) and A6428TR (terminal blend tire rubber)

		G*×sin(δ) (Pa)	Phase angle (δ) ∘
A64-28NV	1	1.44E+05	60.34
	2	1.87E+05	60.08
	Avg	**1.66E+05**	**60.21**
A64-28TR	1	4.80E+05	49.41
	2	4.82E+05	49.61
	Avg	**4.81E+05**	**49.51**

Table A-2 data of the DSR-PAV test at 31C on A5828 mixed with CRM

Size of GTR	Type of GTR	Percentage of GTR		G*×sin(δ) (Pa)	Phase angle (δ) ◦
40 mesh	Ambient	10%	1	6.38E+05	48.94
			2	6.46E+05	48.84
			Avg	**6.42E+05**	**48.89**
		15%		4.84E+05	47.61
				4.28E+05	48.13
			Avg	**4.56E+05**	**47.87**
		20%		3.41E+05	46.34
				3.52E+05	46.2
			Avg	**3.46E+05**	**46.27**
	Cryogenic	10%		5.78E+05	49.63
				5.20E+05	50.04
			Avg	**5.49E+05**	**49.84**
		15%		4.56E+05	47.53
				4.47E+05	47.6
			Avg	**4.51E+05**	**47.57**
		20%		3.51E+05	45.25
				3.59E+05	45.29
			Avg	**3.55E+05**	**45.27**
20 mesh	Ambient	10%		5.49E+05	49.62
				5.29E+05	49.67
			Avg	**5.39E+05**	**49.65**
		15%		4.29E+05	48.94
				4.07E+05	49.06
			Avg	**4.18E+05**	**49.00**
		20%		2.87E+05	47.47
				2.71E+05	47.62
			Avg	**2.79E+05**	**47.55**
	Cryogenic	10%		7.46E+05	48.81
				7.48E+05	48.72
			Avg	**7.47E+05**	**48.77**
		15%		5.40E+05	46.22
				4.99E+05	46.54
			Avg	**5.20E+05**	**46.38**
		20%		4.42E+05	44.99
				4.60E+05	45.07
			Avg	**4.51E+05**	**45.03**

Table A-3 data of the DSR-PAV test at 31 C on A7622NV (polymer modified)

		G*×sin(δ) (Pa)	Phase angle (δ) ◦
A76-22NV	1	2.58E+05	52.87
	2	2.65E+05	52.47
	Avg	**2.62E+05**	**52.67**

Table A-4 data of the DSR-PAV test at 31C on AAC20 mixed with CRM

Size of GTR	Type of GTR	Percentage of GTR		G*×sin(δ) (Pa)	Phase angle (δ) ∘
40 mesh	Ambient	10%	1	9.27E+05	47.76
			2	9.07E+04	48.13
			Avg	**5.09E+05**	**47.95**
		15%		6.84E+05	48.7
				6.62E+05	49.16
			Avg	**6.73E+05**	**48.93**
		20%		4.59E+05	49.07
				4.27E+05	49.6
			Avg	**4.43E+05**	**49.34**
	Cryogenic	10%		8.30E+05	50.66
				8.01E+05	50.9
			Avg	**8.15E+05**	**50.78**
		15%		6.80E+05	49.02
				6.47E+05	49.42
			Avg	**6.63E+05**	**49.22**
		20%		6.06E+05	47.49
				6.02E+05	47.98
			Avg	**6.04E+05**	**47.74**
20 mesh	Ambient	10%		9.62E+05	44.95
				9.53E+05	45.49
			Avg	**9.58E+05**	**45.22**
		15%		7.85E+05	47.74
				7.71E+05	48.04
			Avg	**7.78E+05**	**47.89**
		20%		5.30E+05	45.09
				5.34E+05	45.35
			Avg	**5.32E+05**	**45.22**
	Cryogenic	10%		8.39E+05	49.53
				8.31E+05	49.69
			Avg	**8.35E+05**	**49.61**
		15%		7.26E+05	47.83
				7.22E+05	48.15
			Avg	**7.24E+05**	**47.99**
		20%		6.01E+05	45.55
				5.96E+05	46.04
			Avg	**5.99E+05**	**45.80**

Table A-5 data of the DSR-PAV test at 31 C on B7622NV (polymer modified)

		G*×sin(δ) (Pa)	Phase angle (δ) ◦
B76-22NV	1	2.36E+05	56.18
	2	2.46E+05	55.93
	Avg	**2.41E+05**	**56.06**

Table A-6 data of the DSR-PAV test at 31C on B6416 mixed with CRM

Size of GTR	Type of GTR	Percentage of GTR		G*×sin(δ) (Pa)	Phase angle (δ) ∘
40 mesh	Ambient	10%	1	9.27E+05	48.98
			2	9.44E+05	48.84
			Avg	**9.36E+05**	**48.91**
		15%		5.94E+05	46.79
				6.20E+05	47.76
			Avg	**6.07E+05**	**47.28**
		20%		5.23E+05	46.45
				5.42E+05	46.37
			Avg	**5.33E+05**	**46.41**
	Cryogenic	10%		1.33E+06	46.65
				9.69E+05	48.62
			Avg	**1.15E+06**	**47.64**
		15%		8.20E+05	45.84
				7.92E+05	45.2
			Avg	**8.06E+05**	**45.52**
		20%		6.18E+05	44.62
				5.83E+05	44.49
			Avg	**6.01E+05**	**44.56**
20 mesh	Ambient	10%		7.00E+05	48.24
				7.17E+05	48.38
			Avg	**7.09E+05**	**48.31**
		15%		8.57E+05	46.66
				8.41E+05	46.87
			Avg	**8.49E+05**	**46.77**
		20%		5.09E+05	45.7
				5.30E+05	45.8
			Avg	**5.19E+05**	**45.75**
	Cryogenic	10%		1.02E+06	47.69
				9.12E+05	47.25
			Avg	**9.64E+05**	**47.47**
		15%		8.40E+05	45.03
				7.42E+05	44.46
			Avg	**7.91E+05**	**44.75**
		20%		7.63E+05	42.4
				6.02E+05	43.81
			Avg	**6.82E+05**	**43.11**

Table A-7 data of the BBR test at -12 C on B7622NV (polymer modified) and A64-22TR at -18 C

	Deflection (mm)	Stiffness (Mpa)	m-value
B76-22NV	1.372	57.889	0.323
	1.954	40.327	0.392
	Avg.	**49.108**	**0.358**
A64-22TR	1.379	57.363	0.392
	1.269	62.348	0.388
	Avg.	**59.856**	**0.390**

Table A-8 data of the BBR test at -18C on A5828 mixed with CRM

Type of GTR	Size of GTR	Percentage of GTR	Deflection (mm)	Stiffness (Mpa)	m-value
Ambient	20 mesh	10%	0.498	160.001	0.297
			0.431	184.666	0.296
			Avg.	**172.334**	**0.297**
		15%	0.677	117.422	0.299
			0.666	120.334	0.298
			Avg.	**118.878**	**0.299**
		20%	0.894	88.890	0.317
			0.809	98.103	0.311
			Avg.	**93.497**	**0.314**
	40 mesh	10%	0.514	154.516	0.287
			0.522	151.729	0.289
			Avg.	**153.123**	**0.288**
		15%	0.709	111.673	0.305
			0.689	115.132	0.309
			Avg.	**113.403**	**0.307**
		20%	0.865	91.571	0.308
			0.786	100.991	0.311
			Avg.	**96.281**	**0.310**
Cryogenic	20 mesh	10%	0.480	165.356	0.281
			0.436	182.737	0.283
			Avg.	**174.047**	**0.282**
		15%	0.558	142.122	0.279
			0.519	153.114	0.288
			Avg.	**147.618**	**0.284**
		20%	0.644	123.152	0.283
			0.620	127.954	0.280
			Avg.	**125.553**	**0.282**
	40 mesh	10%	0.532	149.915	0.291
			0.438	180.982	0.294
			Avg.	**165.449**	**0.293**
		15%	0.574	138.643	0.300
			0.577	137.806	0.303
			Avg.	**138.225**	**0.301**
		20%	0.679	117.229	0.288
			0.716	110.891	0.287
			Avg.	**114.060**	**0.288**

Table A-9 data of the BBR test at -12C on AAC20 mixed with CRM

Type of GTR	Size of GTR	Percentage of GTR	Deflection (mm)	Stiffness (Mpa)	m-value
Ambient	20 mesh	10%	0.557	141.782	0.282
			0.617	128.124	0.283
			Avg.	**134.953**	**0.283**
		15%	0.786	100.324	0.306
			0.920	85.676	0.308
			Avg.	**93.000**	**0.307**
		20%	0.887	89.236	0.301
			0.958	82.313	0.304
			Avg.	**85.775**	**0.303**
	40 mesh	10%	0,596	132.334	0.286
			0.623	126.713	0.283
			Avg.	**129.524**	**0.285**
		15%	0.861	92.008	0.299
			0.728	109.462	0..294
			Avg.	**100.735**	**0.299**
		20%	0.938	84.240	0.302
			0.803	98.240	0.309
			Avg.	**91.240**	**0.306**
Cryogenic	20 mesh	10%	0.566	139.597	0.293
			0.526	156.485	0.289
			Avg.	**148.041**	**0.291**
		15%	0.741	106.389	0.287
			0.738	106.991	0.287
			Avg.	**106.690**	**0.287**
		20%	0.824	95.711	0.284
			0.740	106.436	0.265
			Avg.	**101.074**	**0.275**
	40 mesh	10%	0.765	103.630	0.263
			0.647	121.904	0.306
			Avg.	**112.767**	**0.285**
		15%	0.763	103.818	0.306
			0.601	131.597	0.266
			Avg.	**117.708**	**0.286**
		20%	0.873	90.502	0.304
			0.965	81.911	0.307
			Avg.	**86.207**	**0.306**

Table A-10 data of the BBR test at -12C on B6416 mixed with CRM

Type of GTR	Size of GTR	Percentage of GTR	Deflection (mm)	Stiffness (Mpa)	m-value
Ambient	20 mesh	10%	1.440	54.770	0.366
			1.320	60.180	0.360
			Avg.	**57.475**	**0.363**
		15%	1.400	56.680	0.353
			1.590	49.760	0.345
			Avg.	**53.220**	**0.349**
		20%	1.880	42.160	0.366
			2.110	37.480	0.361
			Avg.	**39.820**	**0.364**
	40 mesh	10%	1.510	52.610	0.361
			1.480	53.890	0.361
			Avg.	**53.250**	**0.361**
		15%	1.490	46.910	0.367
			1.590	49.950	0.361
			Avg.	**48.430**	**0.364**
		20%	1.940	43.520	0.367
			1.990	40.110	0.369
			Avg.	**41.815**	**0.368**
Cryogenic	20 mesh	10%	1.325	59.871	0.353
			1.297	61.275	0.354
			Avg.	**60.573**	**0.354**
		15%	1.455	54.650	0.354
			1.371	57.942	0.346
			Avg.	**56.2960**	**0.350**
		20%	1.648	48.145	0.353
			1.349	58.920	0.325
			Avg.	**53.533**	**0.339**
	40 mesh	10%	1.188	67.340	0.344
			1.091	73.950	0.340
			Avg.	**70.645**	**0.342**
		15%	1.551	51.250	0.361
			1.567	50.690	0.365
			Avg.	**50.970**	**0.363**
		20%	1.806	43.912	0.358
			1.828	43.437	0.348
			Avg.	**43.675**	**0.353**

Appendix B

Asphaltic Mixtures

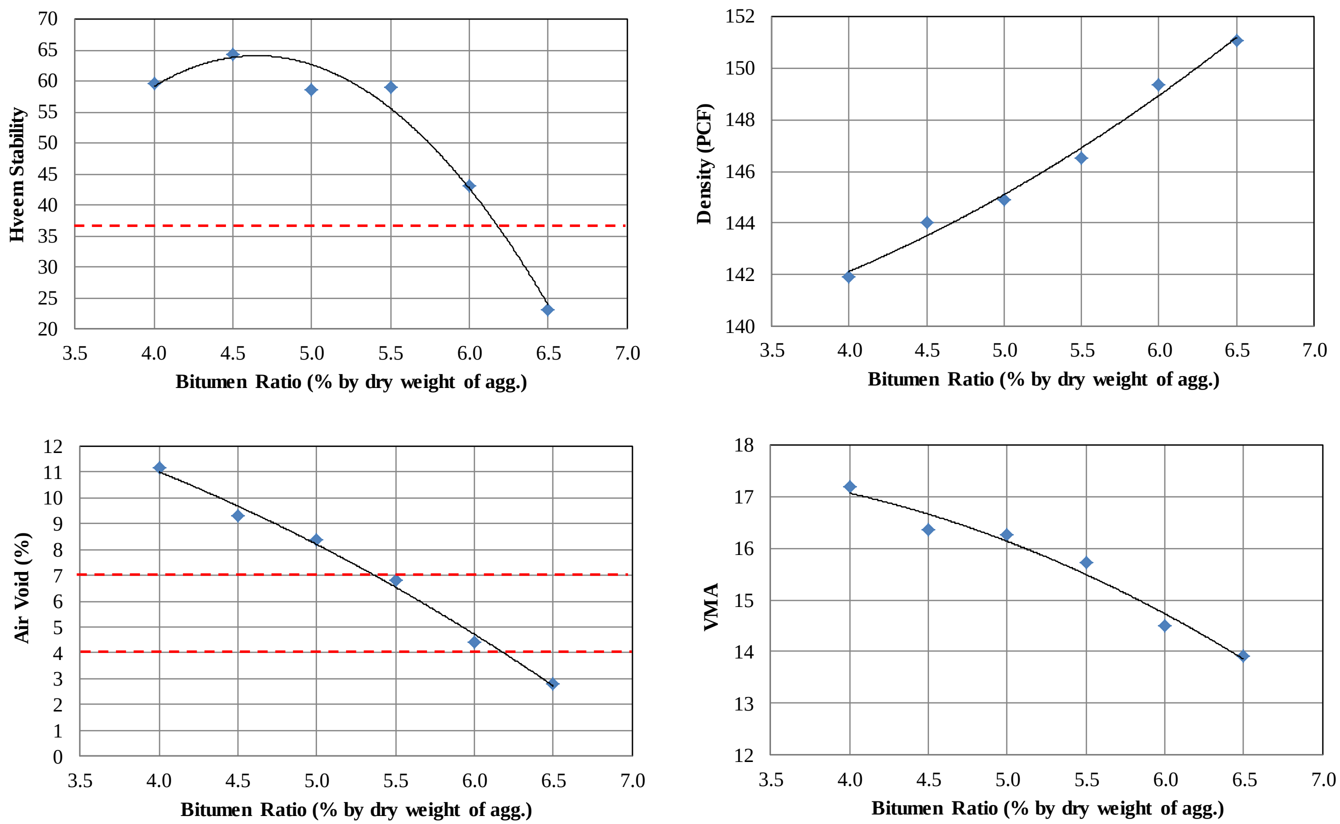

Figure B-1 Variation of mix design properties with binder content for B76-22NV

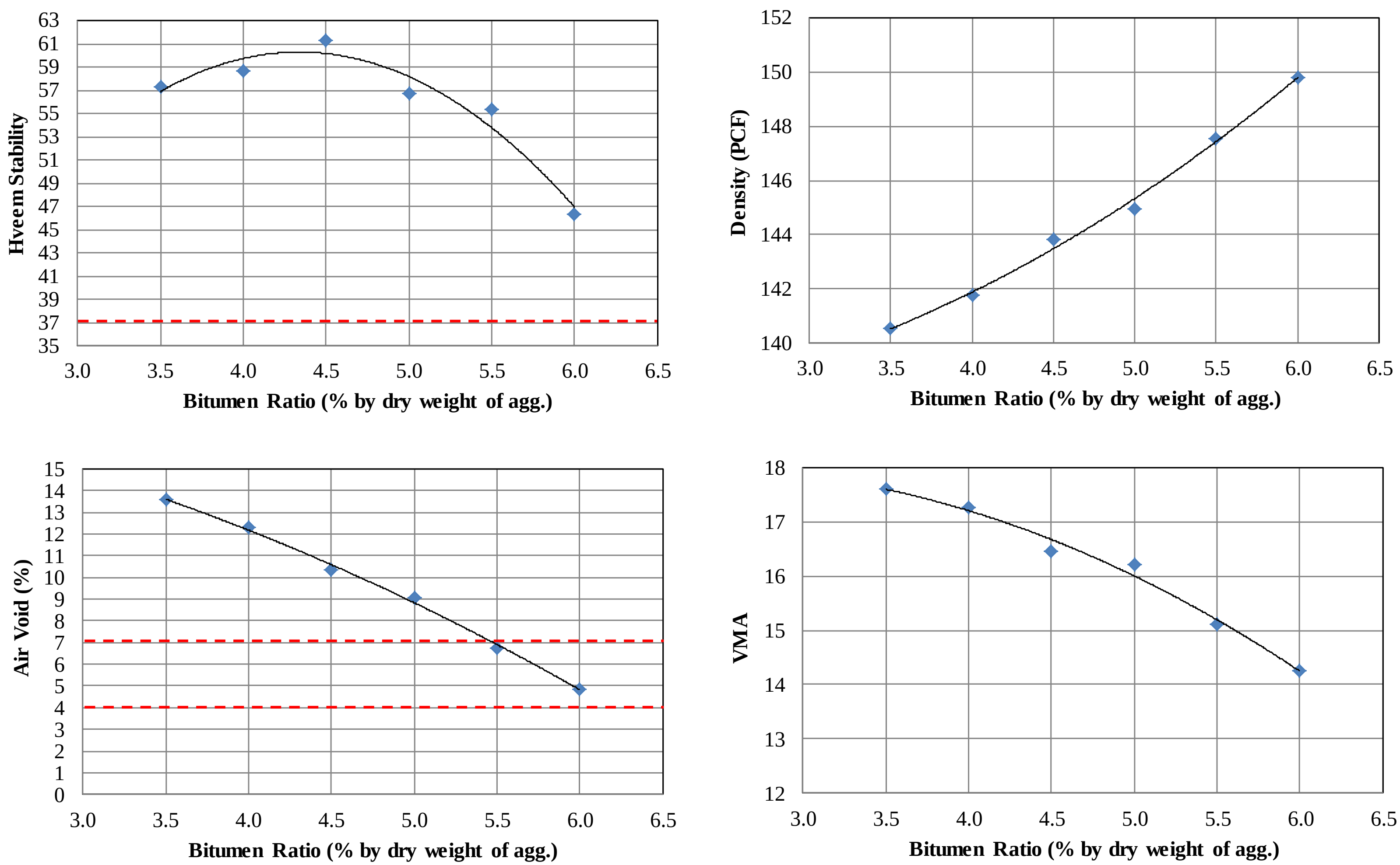

Figure B-2 Variation of mix design properties with binder content for B76-22NVTR

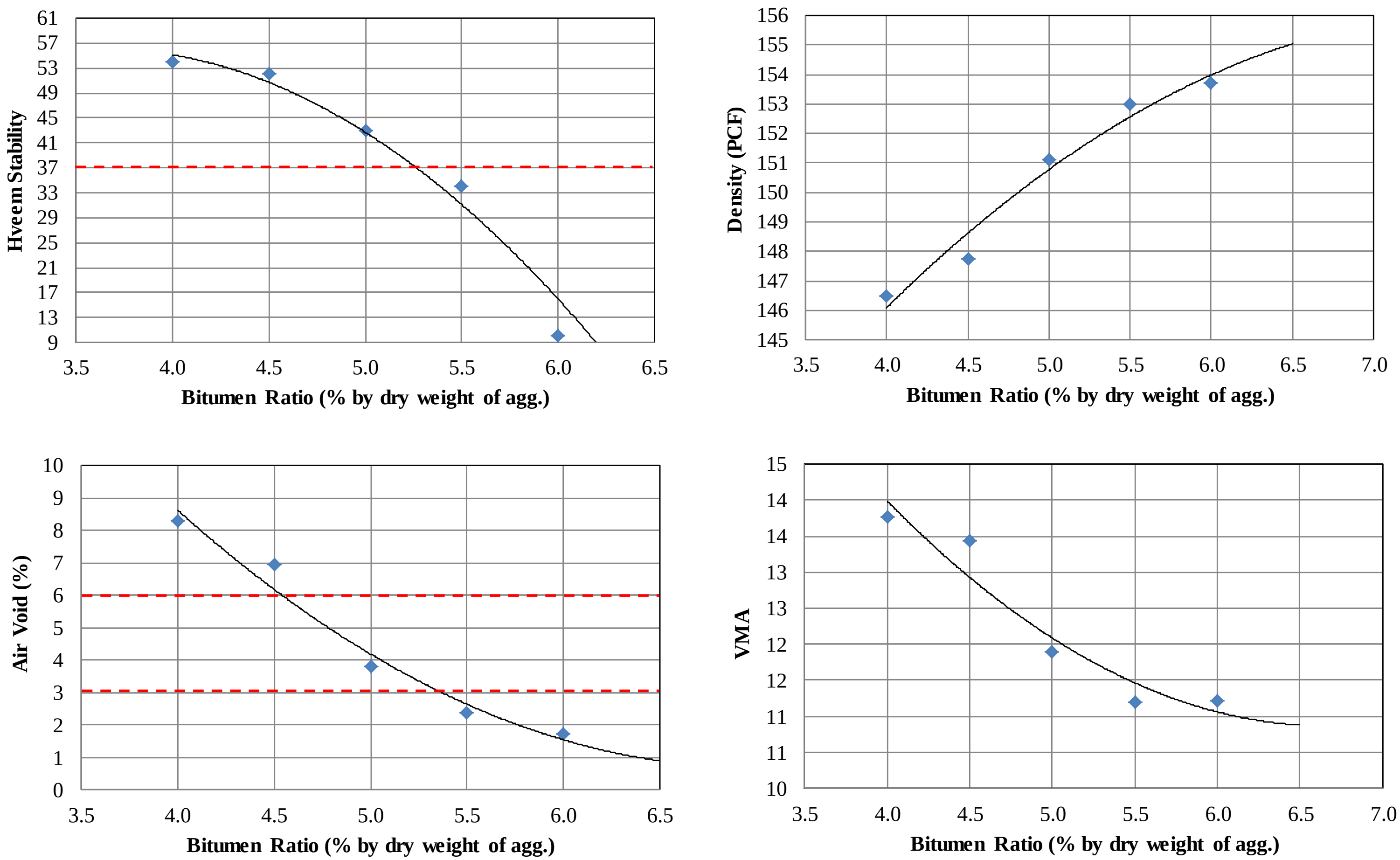

Figure B-3 Variation of mix design properties with binder content for B64-28NV

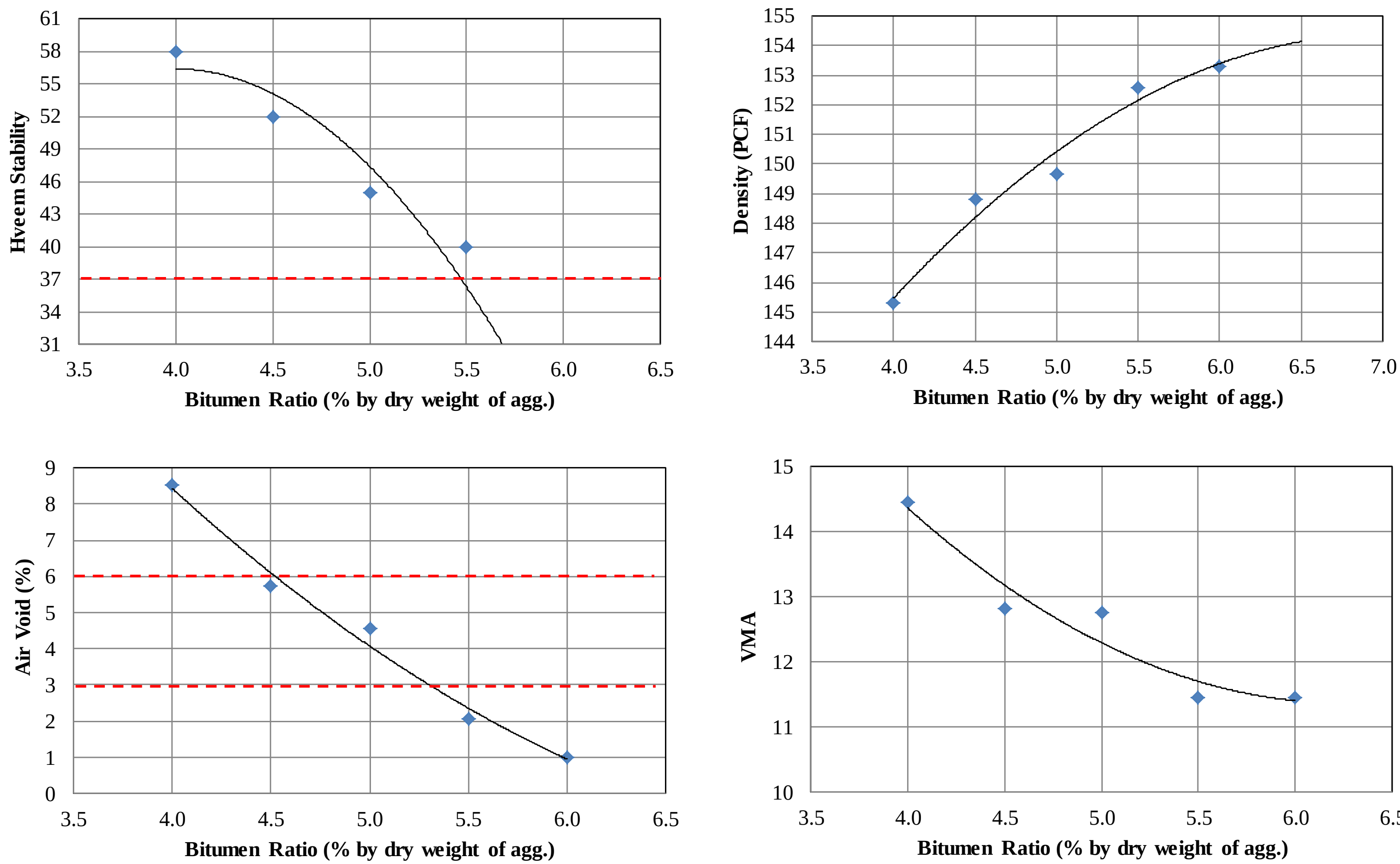

Figure B-4 Variation of mix design properties with binder content for B64-28NVTR

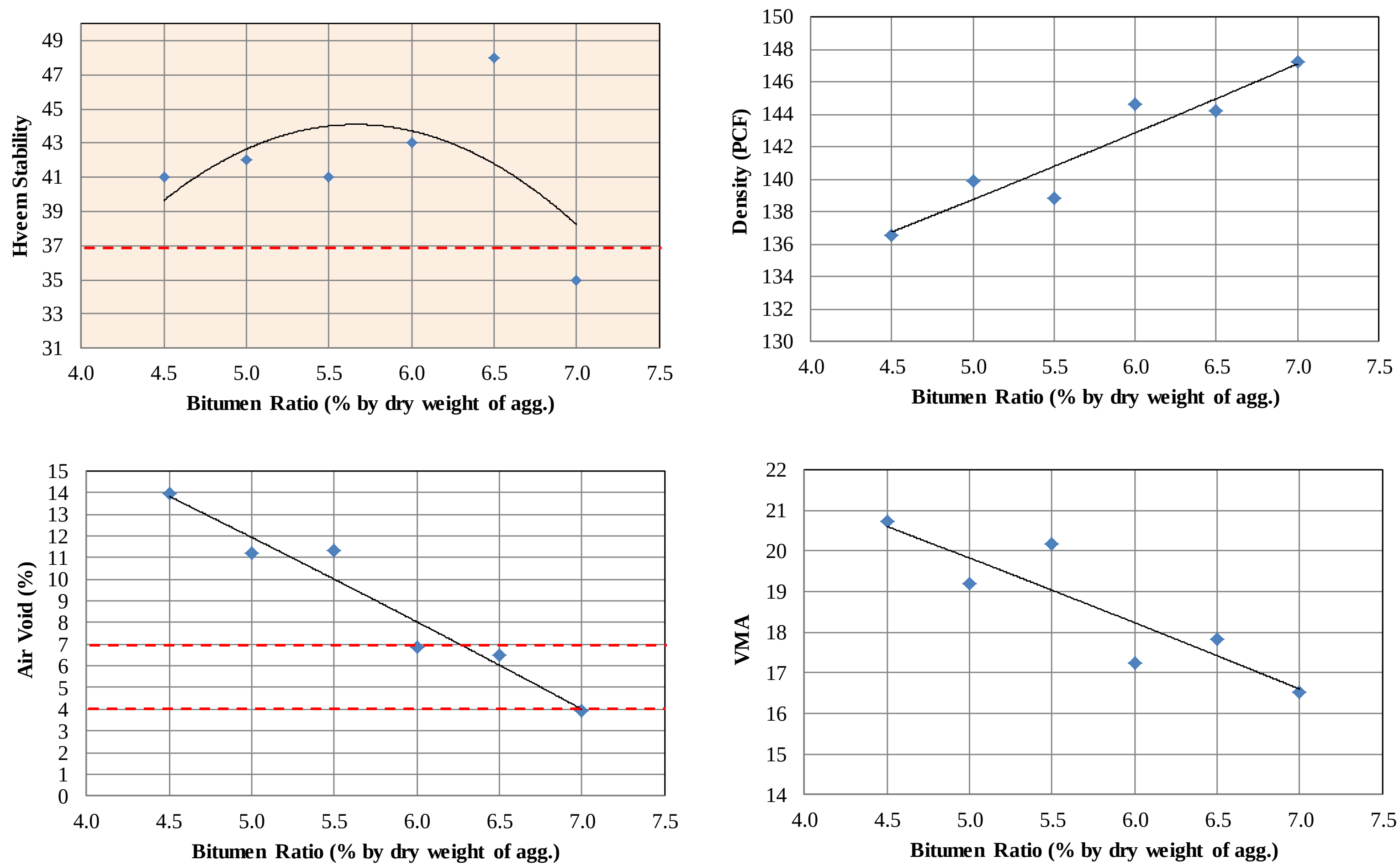

Figure B-5 Variation of mix design properties with binder content for A64-15 + 15%Am#20

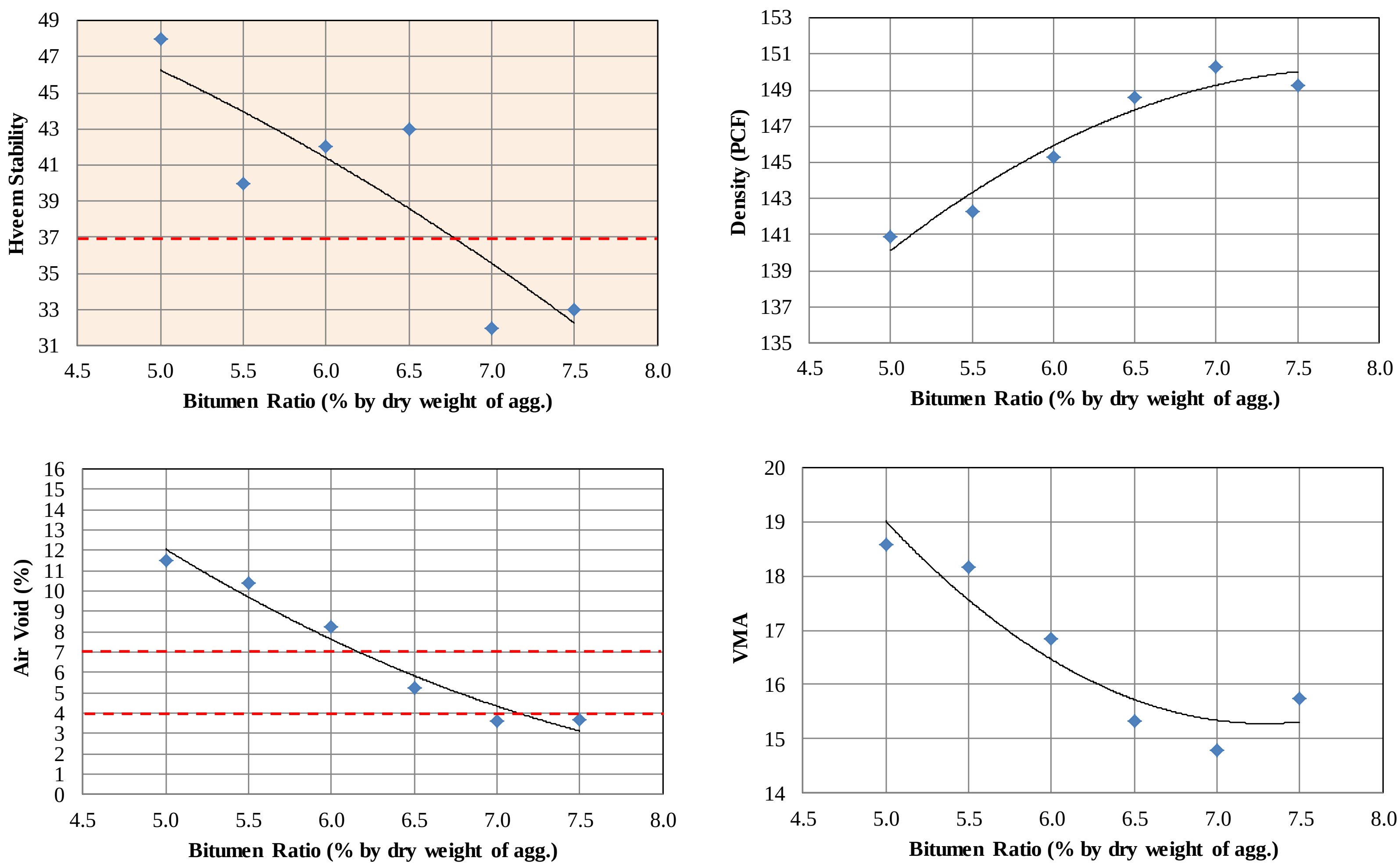

Figure B-6 Variation of mix design properties with binder content for AC20 + 15%Am#40

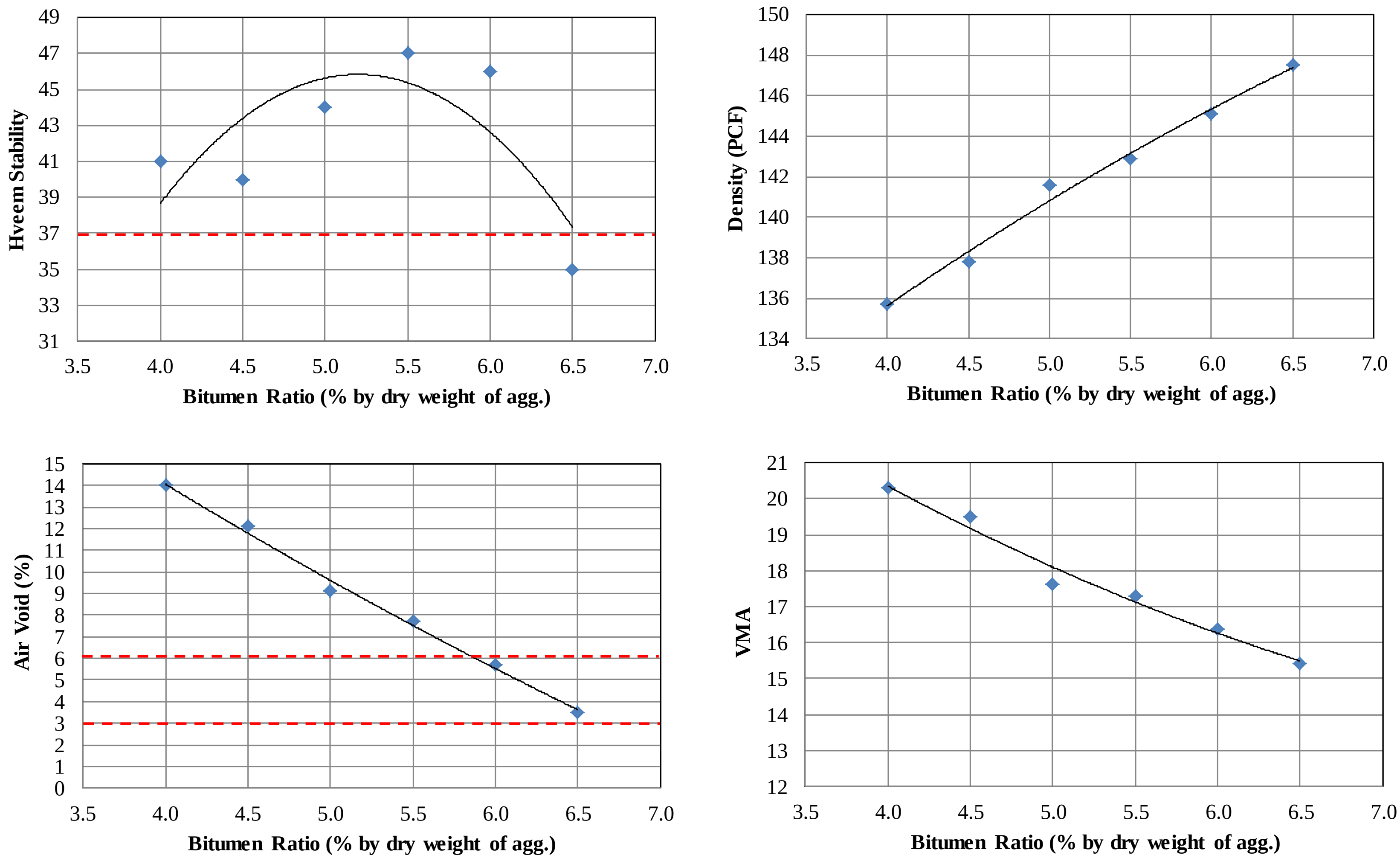

Figure B-7 Variation of mix design properties with binder content for B58-28 + 15%Am#40

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1*	1065.8	576.6	1071.3	2.154	12.0	7.4	7.5			1001.4	63.8	**109.6**	**105.3%**
	2	1146.3	647.2	1153.0	2.266	7.4					1622.6	103.3		
	3	1147.6	644.4	1151.3	2.264	7.5					1819.4	115.8		
CONDITIONED	4	1144.5	640.9	1148.8	2.253	8.0		7.4	1178.9	68.8	1600.0	101.9	**115.3**	
	5	1147.6	648.0	1153.3	2.271	7.2			1179.9	66.5	1768.0	112.6		
	6	1146.0	649.9	1152.7	2.279	6.9			1177.4	64.2	2066.7	131.6		

*excluded

Table B-1 –Result of Moisture-Induced Damage Test (Lottman) B76-22NV

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1	1125.7	622.5	1129.4	2.221	9.9	8.6	8.7			1266.9	80.7	**108.2**	**84.0%**
	2	1153.0	649.4	1156.6	2.273	7.8					1944.3	123.8		
	3	1147.0	642.8	1150.9	2.257	8.4					1886.8	120.1		
CONDITIONED	4	1152.5	645.4	1155.7	2.258	8.4		8.5	1189.5	79.2	1407.0	89.6	**90.8**	
	5	1149.0	643.1	1152.3	2.256	8.4			1186.5	79.5	1402.8	89.3		
	6	1152.4	644.7	1156.1	2.253	8.6			1190.9	79.4	1470.2	93.6		

Table B-2 –Result of Moisture-Induced Damage Test (Lottman) B76-22NVTR

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1	1146.1	654.0	1152.4	2.300	6.0					1436.2	91.4		
	2	1145.6	650.9	1150.2	2.294	6.2		5.9			1500.2	95.5	**91.1**	
	3	1144.3	655.4	1150.0	2.314	5.4	5.9				1354.7	86.2		**102.0%**
CONDITIONED	4	1145.6	655.3	1152.9	2.302	5.9			1174.5	73.4	1444.3	91.9		
	5	1144.5	652.1	1149.6	2.301	6.0		5.9	1171.2	72.6	1390.1	88.5	**92.9**	
	6	1144.3	654.5	1151.2	2.304	5.8			1170.8	67.5	1544.0	98.3		

Table B-3–Result of Moisture-Induced Damage Test (Lottman) B64-28NV

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1	1142.7	650.7	1150.5	2.286	6.4					1495.3	95.2		
	2	1141.9	650.4	1147.2	2.299	5.9		6.2			1535.4	97.7	**95.9**	
	3	1142.0	650.6	1149.2	2.290	6.2	6.1				1488.8	94.8		**84.8%**
CONDITIONED	4	1144.8	652.7	1150.5	2.300	5.8			1173.4	78.8	1192.7	75.9		
	5	1143.3	650.6	1150.8	2.286	6.4		6.1	1174.5	73.9	1359.0	86.5	**81.3**	
	6	1144.6	650.3	1149.4	2.293	6.1			1173.5	79.2	1281.1	81.6		

Table B-4–Result of Moisture-Induced Damage Test (Lottman) B64-28NVTR

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1	1129.9	629.0	1138.3	2.219	8.1	7.6	7.6			1804.0	114.8	**105.0**	**74.1%**
	2	1091.1	616.2	1100.7	2.252	6.7					1471.0	93.6		
	3	1131.1	627.7	1138.0	2.217	8.2					1674.0	106.6		
CONDITIONED	4	1130.8	630.1	1136.6	2.233	7.5		7.5	1164.7	74.1	1098.0	69.9	**77.8**	
	5	1130.9	626.9	1139.2	2.207	8.5			1169.5	69.3	1417.0	90.2		
	6	1131.3	641.4	1142.3	2.259	6.4			1167.5	78.4	1153.0	73.4		

Table B-5–Result of Moisture-Induced Damage Test (Lottman) A64-15 + 15%Am#20

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONE	1	1171.5	665.4	1175.0	2.299	8.0	7.5	7.6			2580.0	164.3	**159.8**	**71.5%**
	2	1171.5	669.0	1176.0	2.311	7.6					2417.0	153.9		
	3	1172.0	672.2	1176.9	2.322	7.1					2534.0	161.3		
CONDITIONED	4	1171.3	669.3	1175.8	2.313	7.5		7.7	1198.6	60.0	899.1	57.2	**114.2**	
	5	1171.3	665.0	1174.5	2.299	8.0			1197.4	55.9	1881.0	119.8		
	6	1171.1	671.5	1178.0	2.312	7.5			1199.0	55.2	1707.0	108.7		

Table B-6–Result of Moisture-Induced Damage Test (Lottman) AAC-20 + 15%Am#40

	Sample no.	dry	wet	SSD	Bulk S.G.	Air Void	Total Avg AV	Set Avg AV	Vac Sat	% Sat	Max Load	Tensile St.	Avg	TSR
UNCONDITIONED	1	1117.2	624.3	1126.5	2.225	6.7	7.1	7.2			1109.3	70.6	**66.9**	**52.3%**
	2	1116.8	624.7	1126.4	2.226	6.6					1144.6	72.9		
	3	1118.4	619.3	1130.3	2.189	8.2					955.5	60.8		
CONDITIONED	4	1115.8	623.9	1126.3	2.221	6.9		7.0	1151.7	73.7	511.1	32.5	**34.9**	
	5	1117.7	625.4	1128.8	2.220	6.9			1155.0	75.6	593.2	37.8		
	6	1116.4	622.4	1126.8	2.213	7.2			1151.5	68.3	542.1	34.5		

Table B-7–Result of Moisture-Induced Damage Test (Lottman) A58-28 + 15%Am#40

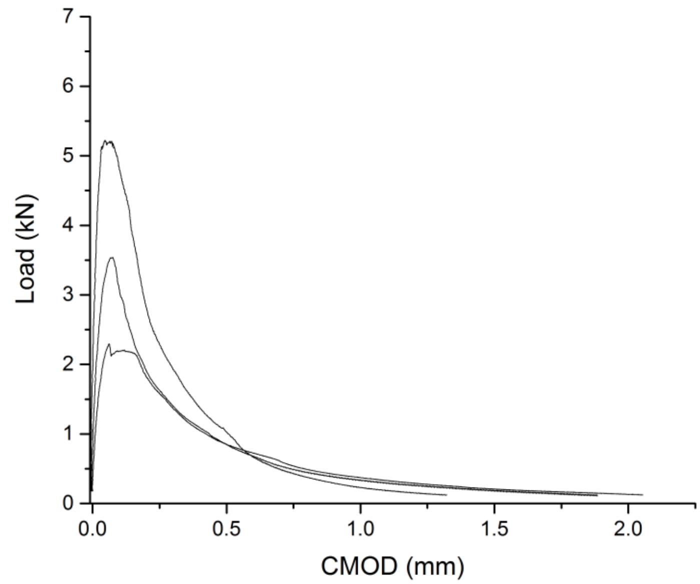

Figure B-8 The load curves of A6428NV mixtures under SCB test

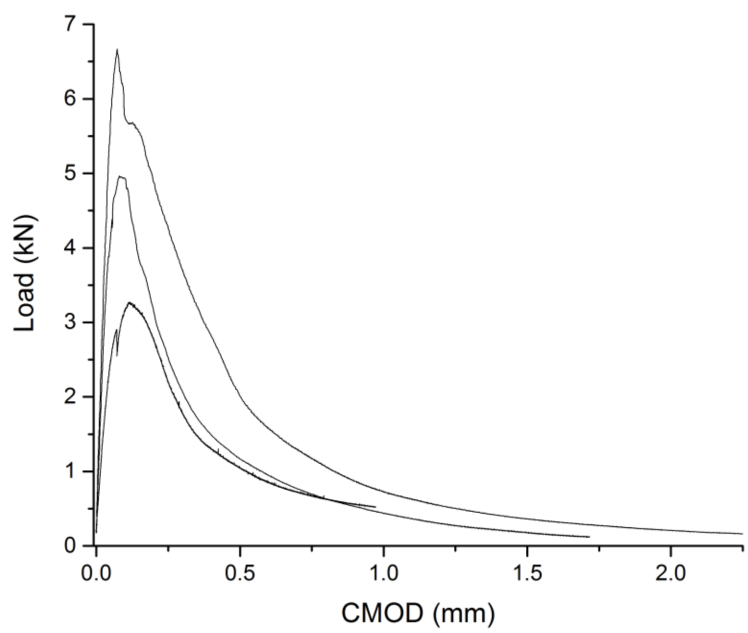

Figure B-9 The load curves of A6428NVTR mixtures under SCB test

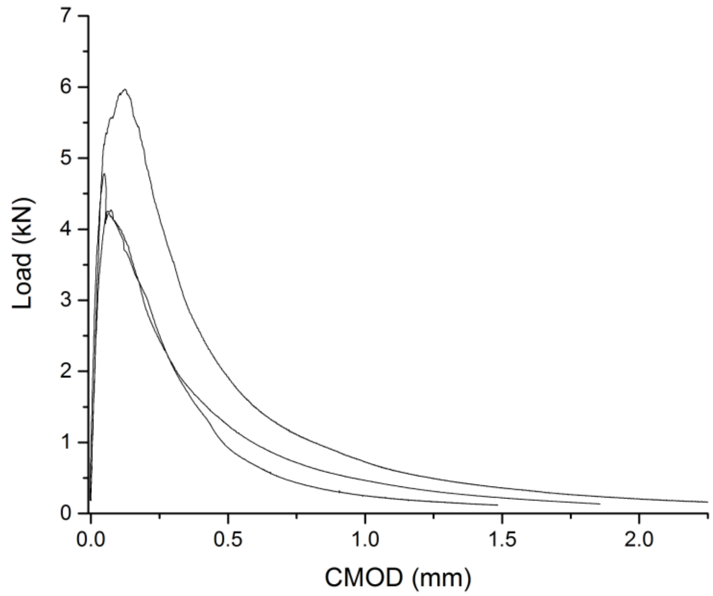

Figure B-10 The load curves of A7622NV mixtures under SCB test

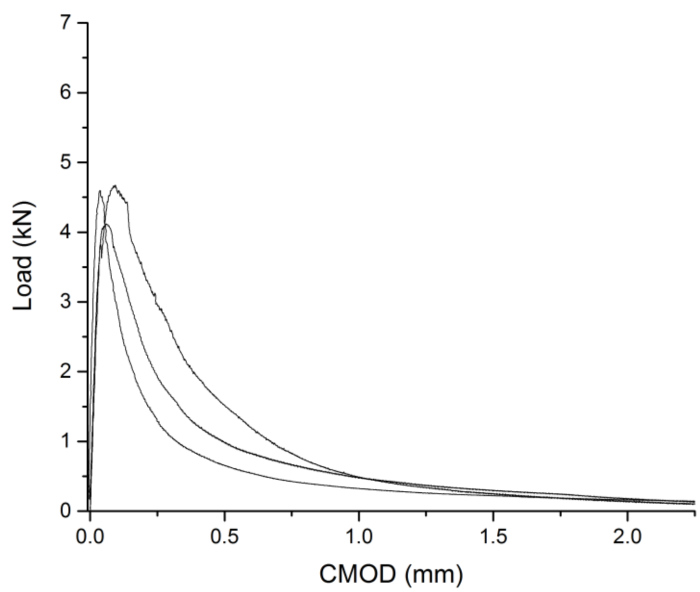

Figure B-11 The load curves of A7622TR mixtures under SCB test

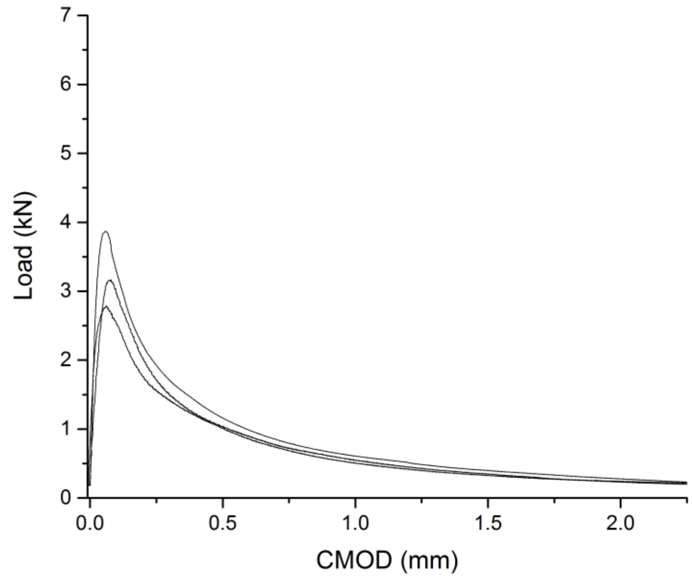

Figure B-12 The load curves of AAC20-AM-40-15 mixtures under SCB test

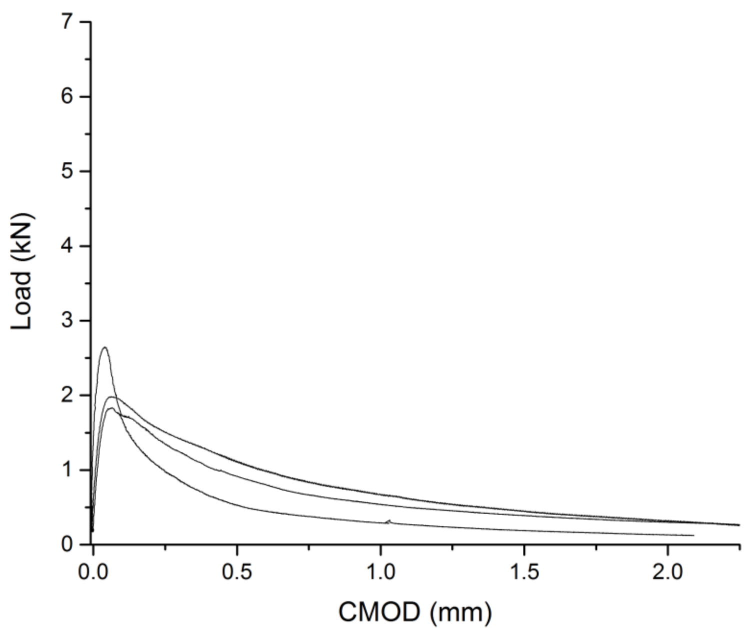

Figure B-13 The load curves of A6416-AM-20-15 mixtures under SCB test

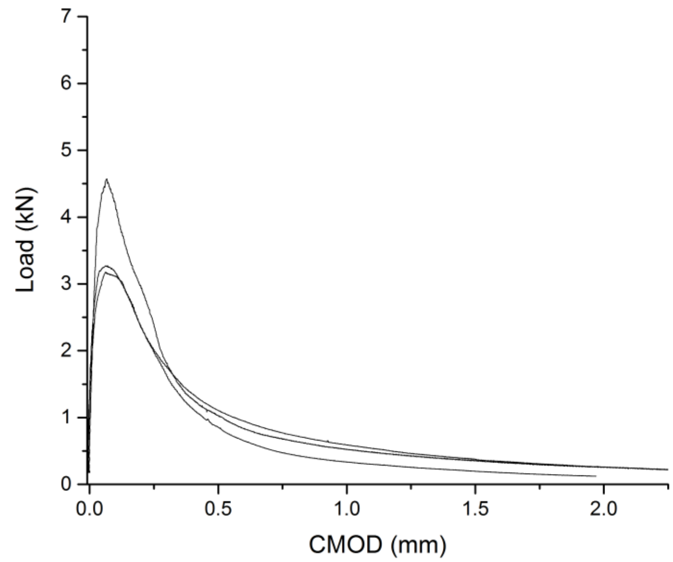

Figure B-14 The load curves of A5828-AM-40-15 mixtures under SCB test

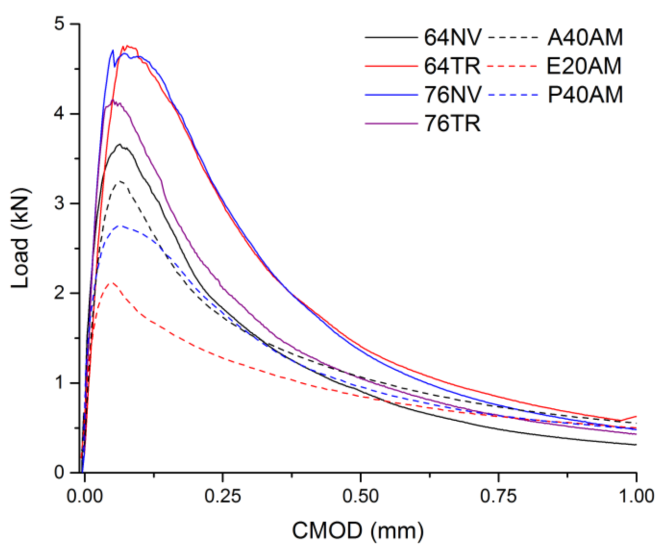

Figure B-15 The average values of various mixtures under SCB test

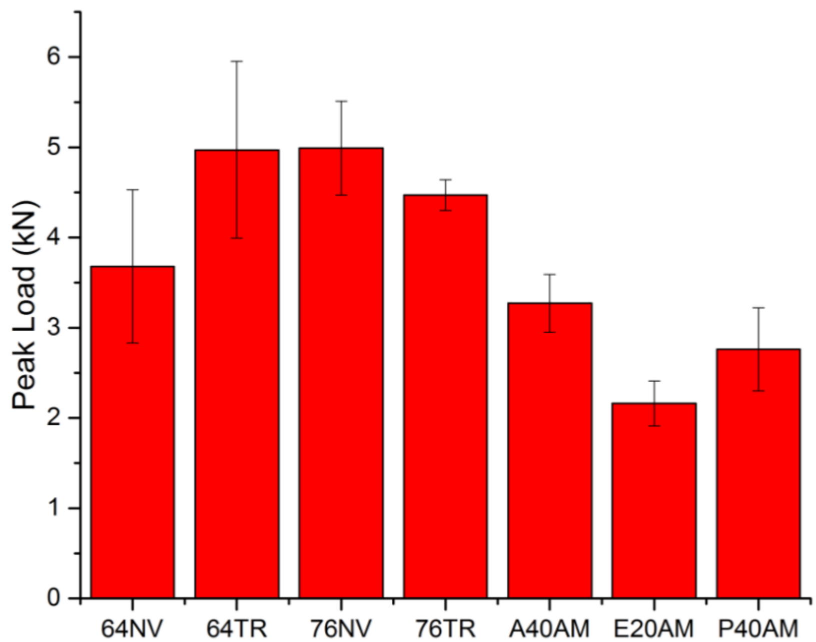

Figure B-16 The average peak load values of various mixtures under SCB test

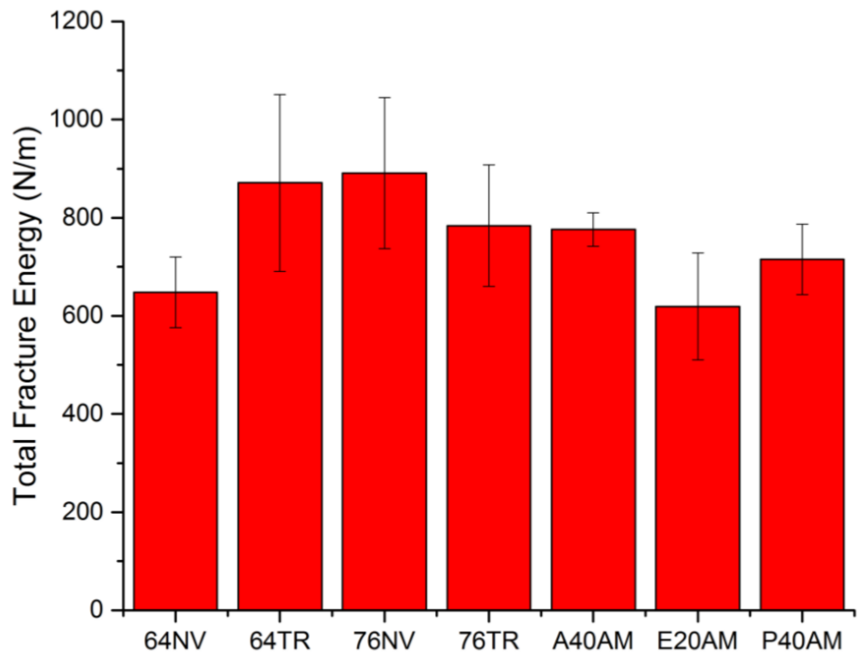

Figure B-17 The average total fracture energy values of various mixtures under SCB test

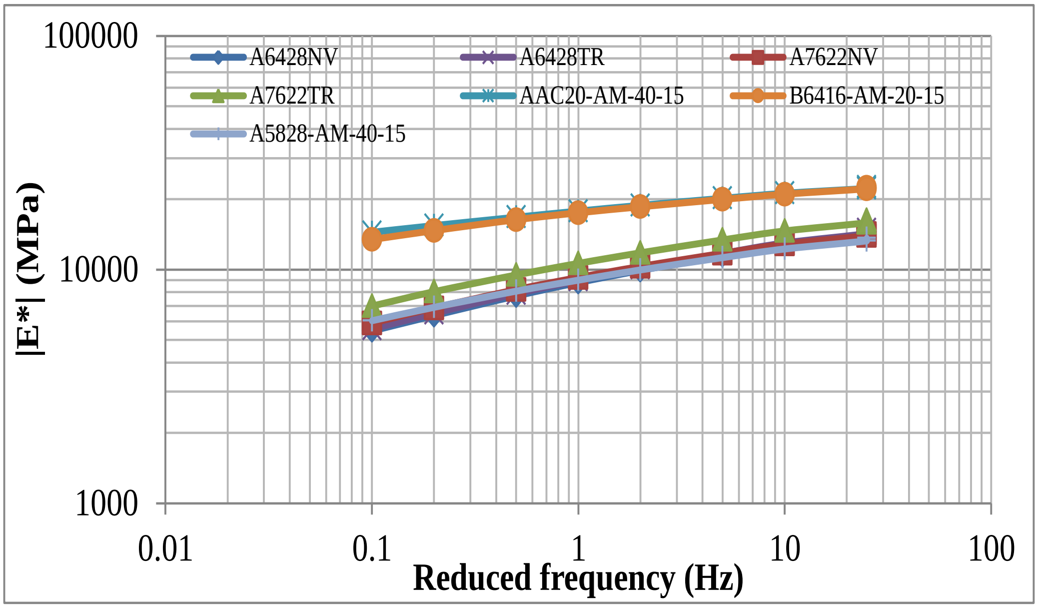

Figure B-18 Dynamic modulus values of various mixtures at 4° C

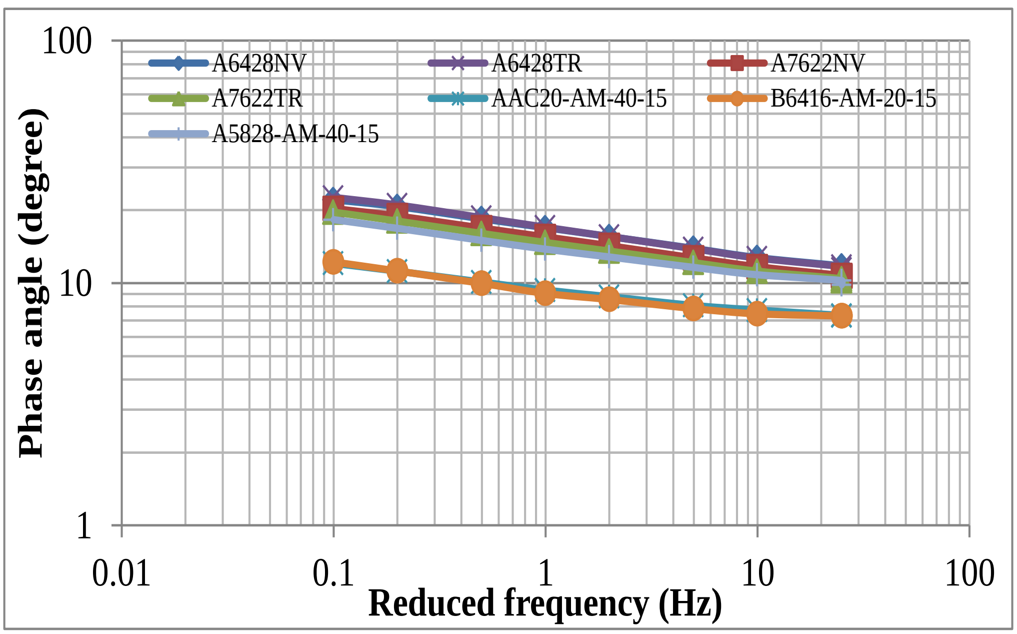

Figure B-19 Phase angle values of various mixtures at 4° C

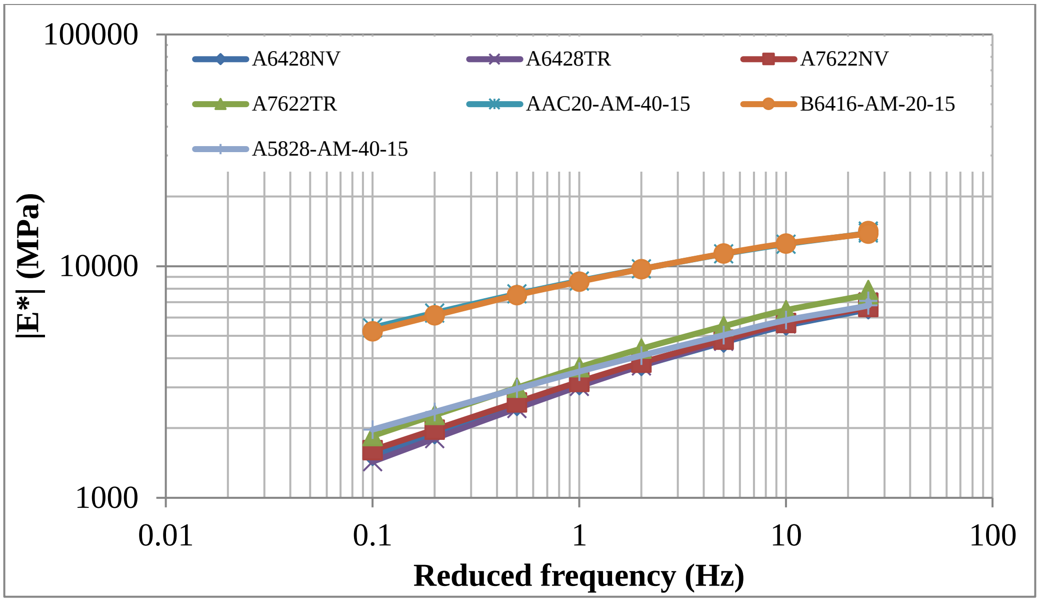

Figure B-20 Dynamic modulus values of various mixtures at 20° C

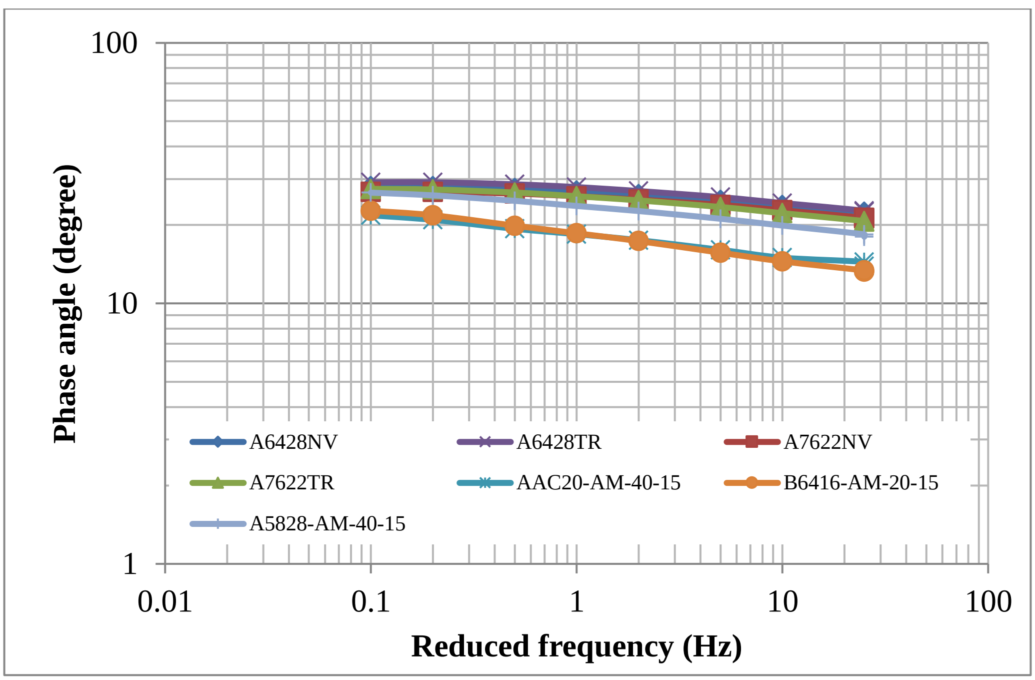

Figure B-21 Phase angle values of various mixtures at 20° C

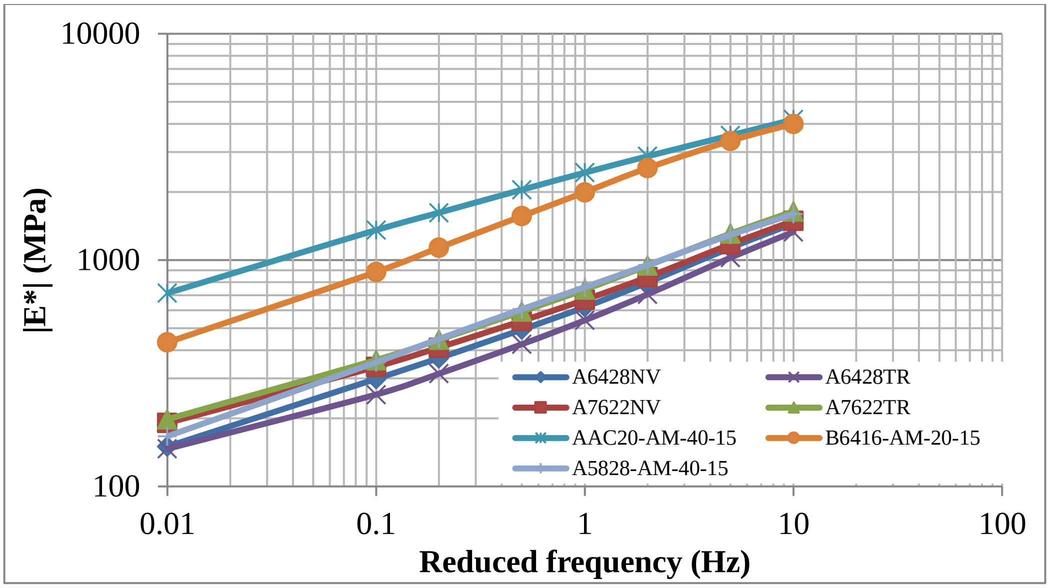

Figure B-22 Dynamic modulus values of various mixtures at 40° C

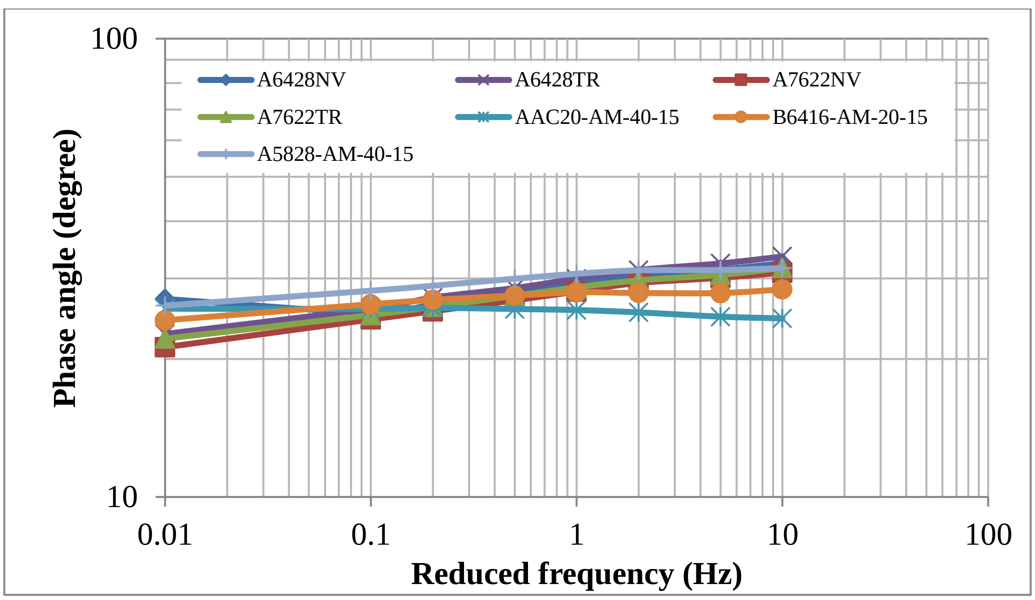

Figure B-23 Phase angle values of various mixtures at 40° C

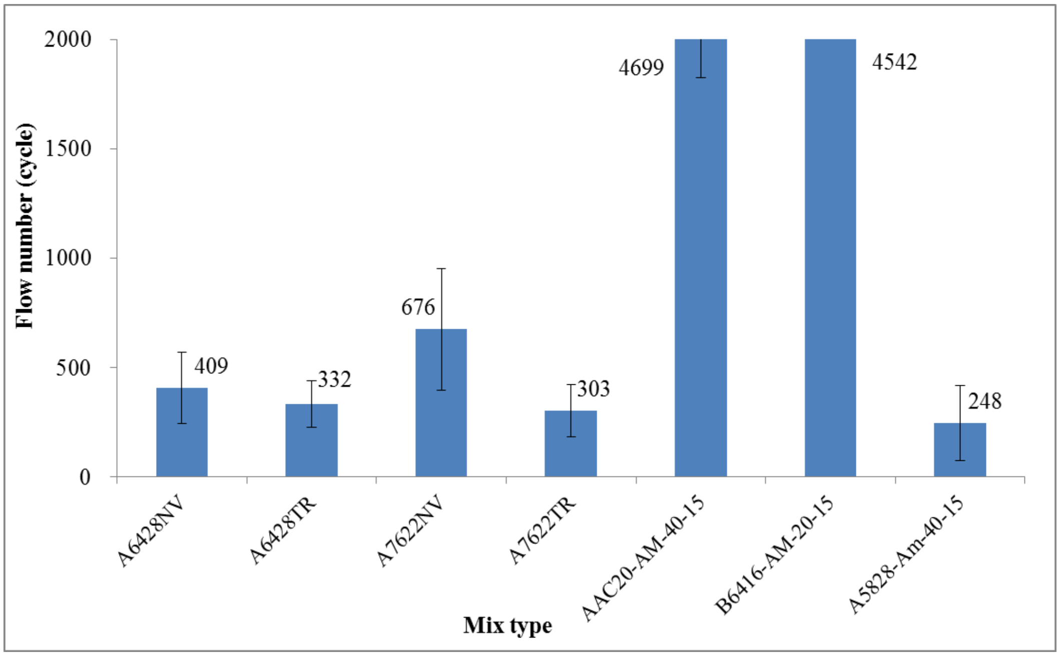

Figure B-24 Flow number values of various mixtures at 59^{o} C

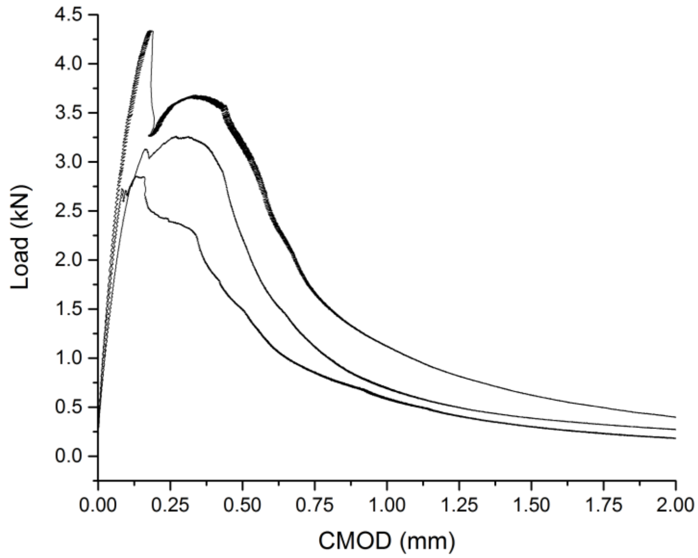

Figure B-25 The load curves of A6428NV mixtures under DCT test

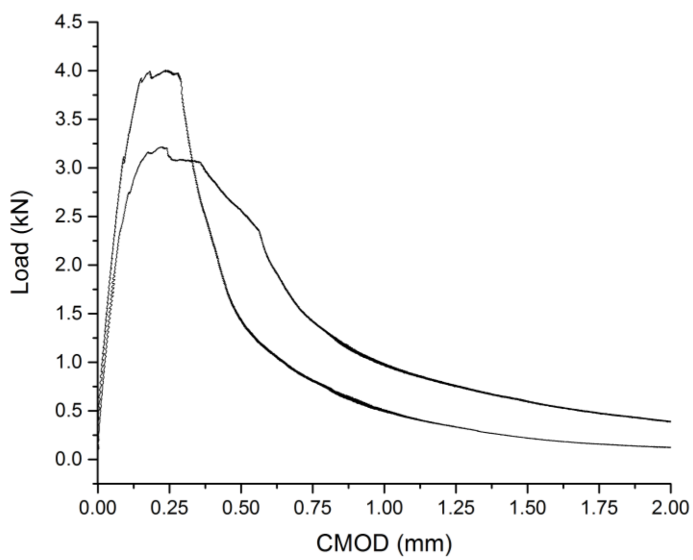

Figure B-26 The load curves of A6428NVTR mixtures under DCT test

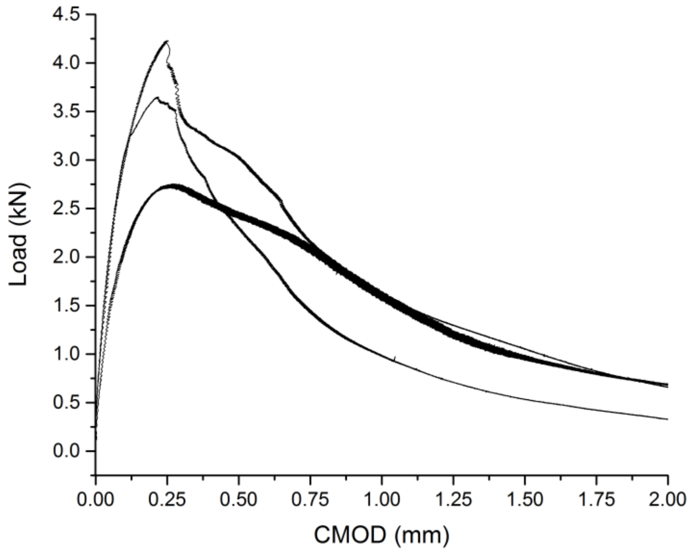

Figure B-27 The load curves of A7622NV mixtures under DCT test

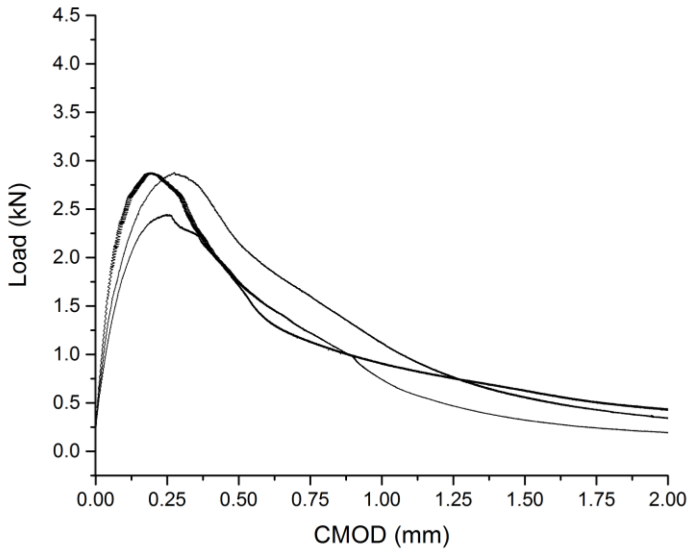

Figure B-28 The load curves of A7622VTR mixtures under DCT test

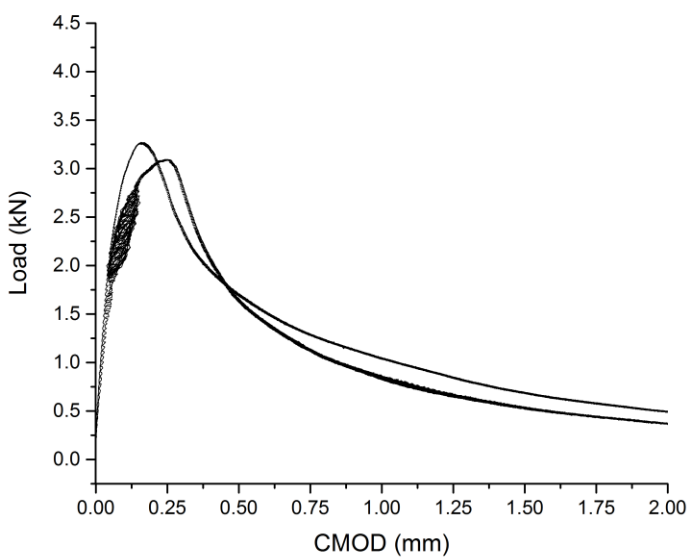

Figure B-29 The load curves of AAC20-AM-40-15 mixtures under DCT test

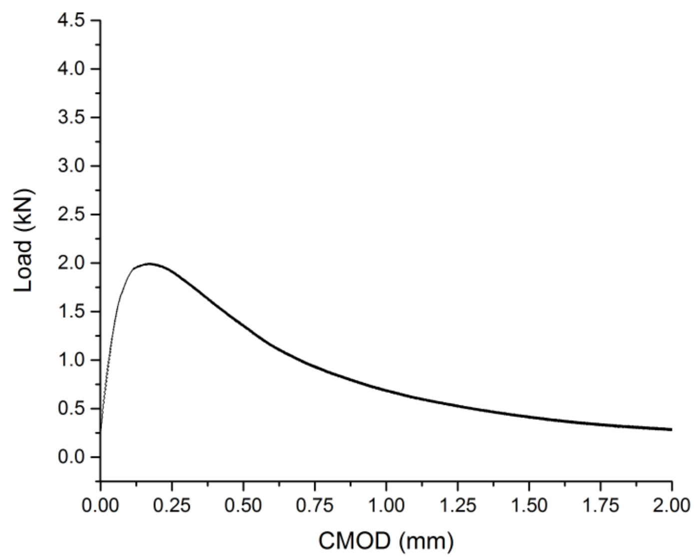

Figure B-30 The load curves of A6416-AM-20-15 mixtures under DCT test

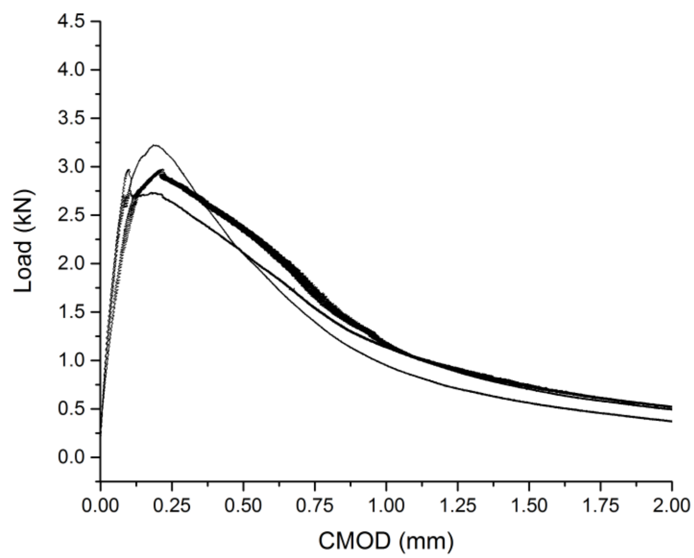

Figure B-31 The load curves of A5828-AM-40-15 mixtures under DCT test

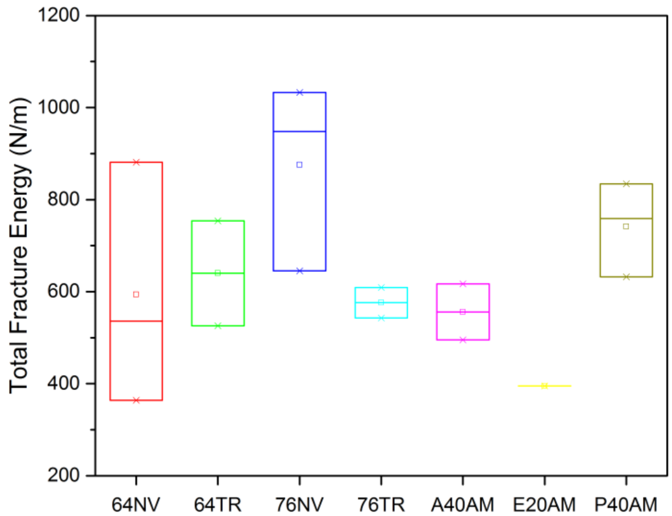

Figure B-32 The fracture energy of various mixtures under DCT test

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