PERFORMANCE OF ASPHALT MIXTURE BY ADDING CRUMB RUBBER AS MODIFIED BITUMEN

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ABSTRAK

Penggunaan serbuk getah diubahsuai bitumen dalam campuran asphalt akan memberi kebaikan dalam ekonomi terutamanya di Malaysia seperti yang kita tahu bahawa kenaikan serbuk getah yang terbuang akan menjadi isu yang serius di seluruh dunia. Banyak kajian telah dinilai oleh mereka berkenaan bentuk campuran asfalt untuk meningkatkan faedah kepada alam sekitar dan prestasi turapan menggunakan serbuk getah. Di Malaysia, sisa serbuk getah masih dalam kajian dan mungkin akan menjadi isu besar jika tiada siapa yang mengambil tindakan untuk mengitar semula tayar sekerap kerana bilangan tayar sekerap semakin meningkat dari tahun ke tahun. Tambahan pula, kenaikan kos bitumen dan penukar polimer dan kekurangan sumber telah mendorong jurutera lebuh raya untuk meneroka bahan baru untuk pembinaan jalan baru. Masalah turapan dan masalah alam sekitar yang majoriti datang dari sisa tayar getah mesti diselesaikan dengan bijak. Dari pemerhatian, prestasi campuran yang berbeza dengan pelbagai peratusan serbuk getah ditambah boleh dicapai. Jika prestasi campuran asfalt didapati terjejas dengan penambahan serbuk getah diubahsuai, peratusan serbuk getah yang optimum yang meningkatkan sifat-sifat campuran panas asfalt akan ditentukan. Di samping itu, Ujian Tegangan tidak langsung (Indirect Tensile Test) telah dijalankan untuk menentukan sumbangan serbuk getah dari segi prestasinya. Dari ujian, kajian itu berbanding 1%, 2%, 3% daripada serbuk getah kepada 0% serbuk getah yang dikenali sebagai sampel kawalan untuk menentukan peratus yang berhampiran dengan sampel kawalan. Daripada keseluruhan, penambahan 1% serbuk getah yang berhampiran dengan sampel kawalan telah disyorkan di dalam campuran panas asfalt. Dengan itu, penggunaan serbuk getah dalam pembinaan jalan raya perlu dipertimbangkan untuk menyediakan reka bentuk turapan dengan ketahanan yang lebih baik dan kekuatan untuk melanjutkan kajian pada masa depan. Akhir sekali, penggunaan serbuk getah sebagai bahan alternatif akan mengurangkan kos dengan mengitar semula bahan buangan.

ABSTRACT

The use of crumb rubber modified bitumen in asphalt mixture will beneficially in economy especially in Malaysia as we know that increment of waste crumb rubber will become serious issue over the world. Numerous studies have evaluated formulations design asphalt mixture to improve the environmental benefits and pavement performance using crumb rubber. In Malaysia, waste crumb rubber still being studied and may be will be major issue if nobody take action to recycle the scrap tire since the number of scrap tires steadily increased from year to year. Moreover, the inflation cost of bitumen and polymer modifiers and the lack of resources have motivated highway engineers to explore new material in the road pavement. Pavement problem and environmental problem which are majority came from waste rubber tire must be solved wisely. From the observation, the performance of asphalt mixes with different mixes with various percentage of crumb rubber added can be achieved. If the performances of asphalt mixture were found to be affected by the addition of modified crumb rubber, the optimum percentage of crumb rubber that enhances the properties of HMA mixes will be determined. In addition, Indirect Tensile Test was conducted to determine the contribution of crumb rubber in term of performance. From the test, the study was compared 1%, 2%, 3% of crumb rubber to 0% crumb rubber which is controlled sample to determine which percent closely to controlled sample. Based on the overall findings, the addition of 1% crumb rubber content which is close to the controlled sample was suggested in modifying the HMA mixes. Hence, 1% of crumb rubber content was determined as an optimum crumb rubber content. Thereby, the usage of crumb rubber in road construction should be put into consideration in order to provide pavement design with better durability and strength for further studies in the future. Finally, usage of crumb rubber as an alternative material will reduce cost by recycling waste material.

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LIST OF SYMBOLS

mm	Millimeter
ºC	Celcius
µm	Micrometer
g/cm^3	Gram per centimeter square
g	Gram
kg	Kilogram
s	Second
dmm	Deci-millimeter
MPa	Mega pascal
N	Newton

LIST OF ABBREVIATIONS

ASTM	American Standard Testing for Materials
BS	British Standard
HMA	Hot Mix Asphalt
AC14	Asphaltic Concrete with Nominal Maximum Aggregate Size of 14mm
JKR	Jabatan Kerja Raya
CR	Crumb rubber
CRM	Crumb rubber modifier
RMB	Rubberized Modified Bitumen
SPT	Simple Performance Test
PEN	Penetration

CHAPTER 1

INTRODUCTION

1.1 Background

Recently, numerous studies have evaluated formulations design asphalt mixture to improve the environmental benefits and pavement performance using crumb rubber. In Malaysia, waste crumb rubber still being studied and may be will be major issue if nobody take action to recycle the scrap tire since the number of scrap tires steadily increased from year to year when millions scrap tire were generated. The use of crumb rubber modified bitumen in asphalt mixture will beneficially in economy especially in Malaysia as we know that increment of waste crumb rubber will become serious issue over the world. Several states in US and countries around the world have used, or in the process of using crumb rubber modifier in new pavement design. The inflation cost of bitumen and polymer modifiers and the lack of resources have motivated highway engineers to explore new material for the construction of new roads.

Crumb rubber is recycled rubber produced from truck scrap tire and automotive. During the recycling process, steel and tire cord are removed and leaving tire rubber with a granular consistency. The process is continued with a cracker mill or rubber grinding, reduce the size of particle further. One day, the usage of crumb rubber will be the one of main material in the road construction with sufficient quality raw material compared to existing conventional method.

1.2 Problem Statement

In road construction, fractures or crack on pavement are more complicated problem faced by highway engineer. It causes the road to become damaged and not suitable for use. There are two main factors that cause cracking and slack roads in

Malaysia. The first factor is the temperature and weather while the second factor is the increasing number of vehicles on the roads is too high. Hot weather will make asphalt in road surface becomes hard and brittle as a result of the reaction the aging process. Asphalt is hard and brittle and fracture easily crack when heavy load traffic on the pavement road. When it rains, water will enter through cracks and damage pavement that will cause potholes (Junus, 2003). Invention of modified bitumen has been study in order to improve the performance of pavement mixes. Crumb rubber acquired from waste rubber tire and has been concentrate on the target to overcome those pavement problems. It also helps in recycling waste rubber tire from polluted environment such as illegal dumping tires at landfill (Hasan, 2007).

In Malaysia, road construction using crumb rubber modifier as bitumen in asphalt mixture is currently analysing the performance of road pavements by Public Work Department (PWD) cooperated with Malaysian Rubber Road in several locations (Junus, 2003). However, the level of improvement and actual cost of using crumb rubber modifier in asphalt mixes still under observation of Ministry of Public Works. (Ministry of Public Work, 2016) reported that study of location has been completed it is Jalan Gemas-Rompin, Negeri Sembilan and another project at Kedah, Pahang, Kelantan and Selangor will be construct in this year. Moreover, many studies have been carry out to investigate the effectiveness using crumb rubber modifier in hot mix asphalt mixes, give the differentiation result have been recognized. Therefore, there is requirement to study to analyse and evaluate the performance of asphalt mixture by using crumb rubber as crumb rubber modified bitumen.

1.3 Objectives of the Study

The main objective of this project is to investigate the performance of asphalt mixture using crumb rubber as modified bitumen. The specific objectives for the project are:

i. To determine the contribution of crumb rubber to the performance of asphalt mixes toward Indirect Tensile Test (Matta Test).
ii. To determine the optimum percentage of crumb rubber by substituting modified bitumen in asphalt mixes.

1.4 Scope of Study

Crumb rubber modified bitumen will be prepared for each sample according to ASTM or BS specifications using Marshall Design Procedure and Indirect Tensile Test procedure using MATTA machine. For material preparation we get the crumb rubber from supplier rubber tire to meet requirement in order to conduct the tests. Additionally, each type of mixes, the numbers of samples prepared were divided into four categories which are percentage of crumb rubber used were assorted from 1 to 3 percent by total weight of modified crumb rubber. These categories consist of unmodified samples, samples added with 1 percent crumb rubber, samples added with 2 percent crumb rubber and samples added with 3 percent crumb rubber in order to identify which mixes that meet the necessary performance. Thus, for each sample we divide to three classifications which are from 4 until 6 percent.

Crumb rubber modifier was added in the mixes using ‘Wet Process’ method where the crumb rubber modifier was added to unmodified bitumen as binder component before it was blended with aggregate and asphalt mixes formed. However, modified crumb rubber in asphalt mixture was not going to substitute unmodified bitumen but they react as an additive to improve properties of asphalt mixes.

1.5 Significant of the Study

This research is important to solve the pavement problem and environmental problem which are majority come from waste rubber tire. From the observation, the performance of asphalt mixes with different mixes with various percentage of crumb rubber added can be achieved. If the performances of asphalt mixture were found to be affected by the addition of modified crumb rubber, the optimum percentage of crumb rubber that enhances the properties of HMA mixes was determined. In addition, the laboratory test that should be conducted is Indirect Tensile Test which are focus on determine the optimum percentage of crumb rubber by substituting modified bitumen in hot mix asphalt. Furthermore, the test also was conducted to determine the contribution of crumb rubber in term of performance. Usage of crumb rubber in road construction should be put into consideration in order to provide pavement design with better durability and strength for further studies in the future. Finally, usage of crumb rubber as an alternative material will reduce cost by recycling waste material.

1.6 Limitation of Study

This research covers on the topic of modified HMA mixes with crumb rubber by using "wet process" method. The preparation of HMA samples and tests were conducted using Marshall Design Procedures according to the JKR specifications, which were usually used for Malaysian pavement design. However, most of the research conducted on crumb rubber modified mixes basically based on Marshall Design method but using Indirect Tensile Test (Matta test). From the test, the study was compared 1%, 2%, 3% of crumb rubber to 0% crumb rubber which is controlled sample to determine which percent closely to controlled sample.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nowadays, the road pavement in construction has grown from year to year in Malaysia and other countries. The usage of crumb rubber from recycle tires may contribute to sustainable development as well as environment protection since it involves the appreciation of waste materials, then provides a solution to the waste disposal problem, and implies a reduction of the utilization of natural resources in road construction. Moreover, the utilization of natural resources in this country tend to weakening from time to time. The government has spending a lot of money to give better road construction and maintenance of roadways. It would be advantages to the nation's economy if age of service life of the roads be longer. In order to adequate the pavement performance, the materials involved in pavement construction are important to understand. Hence, recycled material such as crumb rubber could be one of the alternative material in improving the performance of the quality of hot mix asphalt.

2.2 Background of Crumb Rubber

Waste materials, are being generated and accumulated in vast quantities causing an increasing threat to the environment. The scrap tires can be considered as a non-decaying material and it disturb the surrounding environment. It is positive method to reuse this non-decaying material for a better environment. Some research has been reported that the United States alone has 1 billion tires stockpiled, and with an annual increase of 300 million tires generated per year (Malek KB, 2008). Most researchers or country is continuously progressing towards finding new and innovative techniques to recycle waste materials. In 1997, U.S federal government mandate required all fifty states to use waste tire modified asphalt in 20% of their total mix asphalt (Nejad F, 2012).Scrap tire rubber has been used in asphalt mixtures for several decades. In 1960, Charles McDonald is the first highway engineer to use crumb rubber (CR) in asphalt mixtures to improve the performance of pavement (Daryl M, 2007). In the last decades, many researchers indicated that the blends of asphalt pavement's resistance of permanent deformations and cracking.

Four types of scrap tire particles have been classified by the study carried out by (Siddique, 2004) which were graded according to particle size. These types consisted of slit tires (the tire is split into two halves), shredded/chipped tires (the particle size is 300–400 mm long by 100–230 mm wide), ground rubber (19–0.15 mm), and crumb rubber (4.75–0.075 mm). The crumb rubber has been reported to have a nominal size between 4.75 mm (No. 4 sieve) and 0.075 mm (No. 200 sieve). Fine crumb rubber (grinding from truck tyres) was added in a form of powder where the size was between 0.3mm to 0.6mm. The amount of crumb rubber modifiers added into the mixes was expressed in the percentages which vary from 1%, 2% and 3% of the total weight of bitumen. The waste tire particles used in this study were crumb rubber, was supplied by Jingyun Crumb Product Recycle Industries Indera Mahkota 1, Kuantan.

Figure 2.1 Crumb rubber powder (0.3mm – 0.6mm)
Source: Wikipedia (2016)

Since crumb rubber is made in a form of loose granules, it is practical to incorporate crumb rubber into asphalt mix whether to function as 'rubber-filler', 'asphalt-rubber' or as an additive. Modified asphalt pavement containing high air porosity due to crumb that take place in the mixture will certainly increase the sound absorption capability in comparison with conventional asphalt pavement. Additionally, crumb rubber is recycled material, if consume more it will help to reduce scrap tire pollution (Hasan, 2007).

2.3 Crumb Rubber for Civil Engineering Applications

In order to reduce the utilization of natural resources and recycle the scrap tyre to be crumb rubber, it has been considered as suitable material for the use in civil engineering applications. The strength and physical properties of crumb rubber itself make this material attractive for these types of applications. There are variety of commercial applications which are:

i. Flooring for pavements, athletic fields and industrial facilities
ii. Rail crossings, ties and buffers
iii. Acoustic barriers
iv. Partition wall
v. Sidewalks

Some of the benefits of using crumb rubber in asphalt in highway construction include:

i. Longer lasting roads and reduced maintenance due to improved durability of the mix.
ii. Lower road noise.
iii. Increased elasticity and resilience at high temperatures.
iv. Reduced temperature susceptibility.
v. Shorter breaking distances.
vi. Long term cost effectiveness.
vii. Improved aging and oxidation resistance due to higher binder contents.

2.4 Crumb Rubber as Modified Bitumen

Crumb rubber (CR) is the recycled waste rubber obtained by mechanical shearing or grinding of tyres into small particles. The use of crumb rubber modifier (CRM) in hot mix asphalt (HMA) can be traced back to the 1840s when natural rubber was introduced into bitumen to increase its engineering performance Since the 1960s, researchers and engineers have used shredded automobile tyres in HMA mixes for pavements (Heitzman, 1992).

With a lot of research being done in this field, there are many terminologies associated with rubber tyre modified asphalt concrete mixes. Some of the terminologies that are commonly used are crumb rubber modifier and asphalt rubber. CRM is a general term used to classify concepts that incorporate scrap tyre rubber into paving materials (Hasan, 2007).

Currently, there are two technologies method which are different process. There are two processes by which this waste is applied to bituminous mixes: the wet process and the dry process. In the wet process, the crumb rubber is added directly to the bitumen, and its properties are modified. It is then added to the mix as a modified binder. In the dry process, the crumb rubber is added directly to the aggregate as another ingredient in the mix. The bitumen is then modified when it come in contact with the rubber. For this study, we are using ‘wet process’ method.

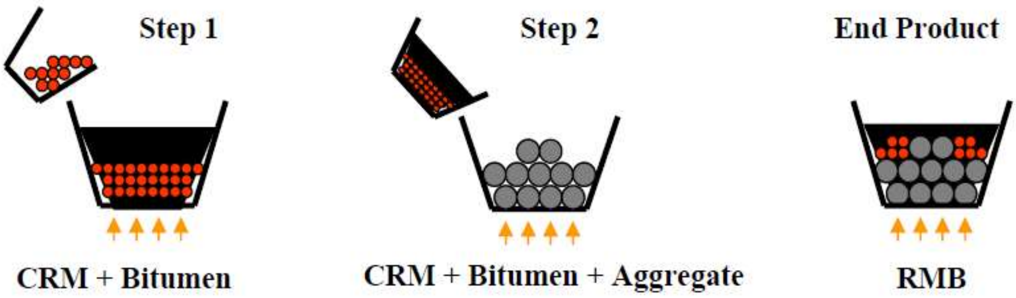

Figure 2.2 Wet process
Source: Hasan (2007)

2.5 Mix Production

The raw materials used for the preparation of the asphalt mix consist of crumb rubber, natural fine aggregate, coarse aggregates taken from crushed limestone, all of which were supplied from highway & transport laboratory except for crumb rubber. Besides, unmodified bitumen was taken from oven at temperature 160°C at highway & transport laboratory. For three proportion mixes, which are 4%, 5% and 6%, each crumb rubber which are 1%, 2% and 3% from total weight of bitumen were prepared two samples each. Marshall mix sample with no additives of crumb rubber was designated as the control mix. From that we use the samples for two tests which are Marshall Stability Test and Indirect Tensile Test. For the clear illustration, see Table 2.1 below.

Table 2.1 The samples for tests.

Indirect Tensile Test			
%	% of total weight of bitumen		
4	0	Sample 1	Sample 2
	1	Sample 1	Sample 2
	2	Sample 1	Sample 2
	3	Sample 1	Sample 2
5	0	Sample 1	Sample 2
	1	Sample 1	Sample 2
	2	Sample 1	Sample 2
	3	Sample 1	Sample 2
6	0	Sample 1	Sample 2
	1	Sample 1	Sample 2
	2	Sample 1	Sample 2
	3	Sample 1	Sample 2

There are two types of mix productions can be used to combine crumb rubber into hot mix asphalt which are wet process and dry process. The wet process has the advantage that the binder properties are better controlled, meanwhile the dry process is frequently easier for an asphalt manufacturer to use (Hasan, 2007). For this research, we are used wet process.

2.5.1 Preparation of CRM Mixes

Based on the research, the raw material which is bitumen was prepared in the oven at temperature 160°C overnight to use next day. Then, the percentage of crumb rubber was added into bitumen by following the total weight of the bitumen. The mixes of crumb rubber and bitumen was prepared for 4%, 5% and 6% to use for Marshall Mix Design. Hence, after preparation it called crumb rubber modified mixes (CRM mixes).

2.6 Volumetric Properties Performance

Most of the research conducted on crumb rubber modifier mixes were based on mixes designed using Marshall method. In addition, we use the same method by producing the samples to conduct Indirect Tensile Test (Matta Test) and not only for Marshall Stability Test. Crumb rubber modified asphalt has several advantages such as the increased viscosity and softening point, improved penetration index and preferable low-temperature ductility, which means superior rutting resistance at the high temperatures, intensive crack resistance at the low temperatures and fatigue resistance of road pavement (Bahia HU, 1994). But in this case, we narrow down the research by consider the characteristic of Marshall Stability Test and Indirect Tensile Test properties.

Numerous literatures reported that preparation conditions and characters of rubber particles as well as asphalt are crucial factors in order to obtain the desired properties of crumb rubber modifier asphalt, including crumb rubber particles diameters, processing temperatures and blending time (Moreno F, 2013). According to (Navarro FJ, 2004), the effects of rubber particles on linear viscoelastic behavior and emphasized that particle sizes lower than 0.35 mm to modify asphalt are recommended for the manufacturing operations. Since we are using 0.30 mm crumb rubber size, it is recommended by focused on performance of asphalt mixes with limited scope related with Indirect Tensile Test. The CRM used can range from 1% to 6% by weight of the bitumen. However, 1% to 3% CRM is commonly being used (Chehovits, 1993).

In term of wet process, the materials included such as fine crumb rubber and bitumen for early preparation before Marshall mix design. In addition, after 1981, (Esch, 1984) stated that 20% of the originally used coarse rubber was replaced with fine crumb rubber (passing 850 µm sieve). Most of the studies on rubber- bitumen interaction has verified that during the mixing period, crumb rubber does swell and the amount of bitumen absorb by crumb rubber was significantly increased. These will cause the residual bitumen become stiffer, elastic and subsequently affect the performance of the asphalt mixes (Singleton, 2000). On the other hand, performance evaluation on Marshall properties is significantly dependent on the crumb rubber gradation, air voids, aggregate gradation, mixing temperature and curing conditions stressed out by (Takkalou, 1985).

2.7 Evaluating of CRM Mixes Performance

The main objective of this study is to determine the contribution of crumb rubber to performance of asphalt mixes toward Indirect Tensile Test (Matta Test). A major consideration for this evaluation is performance related to rutting, stability and resilient modulus, horizontal deformation, and peak loading. The primary purpose of using crumb rubber modifiers in hot mix asphalt (HMA) is to obtain an optimum percentage of crumb rubber that enhance HMA properties. It will also cover the elasticity of HMA based on Malaysia's weather and long term of service life of the pavement. The awareness of using crumb rubber (CRM) as a modifier in HMA can be classified into two components system. Foremost, the bitumen was replaced by crumb rubber based on the total weight of the bitumen then reacts with the HMA mixes. Otherwise, another assumption is to replace a portion of the aggregates in the HMA mixes and acts as an elastic aggregate. The modified CR mixes tested will be compared to unmodified or control samples.

2.7.1 Rutting Performance

Rutting is a flexible pavement distress caused by the accumulation of permanent deformation in the pavement layers due to the repeated application of traffic. (Heitzman, 1992) and (Epps, 1994) claimed that incorporation of crumb rubber modifier into asphalt mixes will make the mixes more elastic at higher service temperature hence enhancing their rutting resistance. There are four tests commonly used in monitoring rutting resistance of asphalt mixture such as repeated-load creep test, wheel tracking, indirect tensile test and Simple Performance Test (SPT). In this study, we use indirect tensile test.

According to JKR, the asphalt tends to strengthen and become hard at the primary stage of the procedure, in storage, during the process of mixing and in service. On the other hand, (Koh, 2006) pointed out that rutting of asphalt mixes at 2,000 load cycles was reduced by 22% with the addition of 3% crumb rubber. Most of the previous research shows a general trend about Marshall mixes, that wet process of incorporating CRM into the mixes enhanced the rutting resistance. Nevertheless, CRM pavement sections done in Louisiana exhibit similar or lower rut depth than the control sections after five to seven years discovered by (Troy, 1996).

2.8 Summary

The use of crumb rubber in HMA in order to improve their performance has become a technique of great potential in recent years. In this sense, highway engineering has opted for the application of new techniques that contribute to a development that is more environmentally friendly. For example, pavement recycling and use of waste material in bituminous mixes. Therefore, by conducting study performance of asphalt mixes by adding crumb rubber as crumb rubber modified bitumen in asphalt mixture can be evaluated whether a certain combination will yield improvements in the desired properties or not.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses several tests that were conducted in achieving the objectives of the study. The procedures used for the laboratory works were referred to American Society for Testing and Material (ASTM) and JKR specifications. The laboratory works can be divided into several stages beginning with the aggregates preparation and distribution into different particle sizes through sieve analyses. Firstly, the quarry aggregates were dried sieve and blended meeting the gradation limit fulfilling the JKR standard specification. Washed-sieve analysis that was to determine the proportion of mineral filter content required in the aggregates gradation. The determination of specific gravity for coarse and fine aggregates was done according to ASTM C 127 and ASTM C 128. For this study, fine crumb rubber (grinding from truck tyres) was added in a form of powder where the size was between 0.3mm to 0.6mm called as 30 mesh. The amount of crumb rubber modifiers added to the mixes was expressed in the percentage (1%, 2% and 3%) of the total weight of modified bitumen. Next, performing the Marshall sample for both mix designs as referred to ASTM or BS (British Standard). The method used in preparing the crumb rubber modified asphalt mixes was wet process. The samples of Marshall were prepared including both modified and unmodified.

3.2 Operational Framework

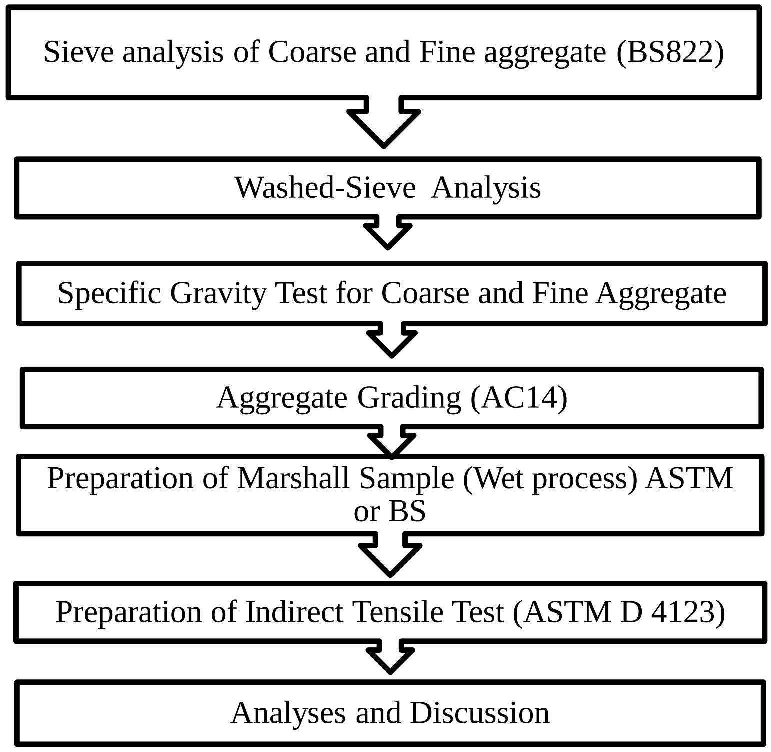

Figure 3.1 Flow chart for laboratory process and analyses

3.3 Sieve Analysis of Fine and Coarse Aggregate

Sieve analysis was carried out on dry aggregate taken from highway and traffic laboratory. Sieve analysis is the process of separating dry aggregate into different sizes through a series of sieves of progressively smaller openings for determination of particle size distribution. The coarse aggregate then wash after sieve and oven dry for 24 hours in laboratory oven.

3.3.1 Apparatus

i. Sieves – Sieves were mounted on substantial frames that were constructed in a manner that will prevent loss of material during sieving.
ii. Mechanical sieve shaker – A mechanical sieve shaker is imparting a vertical and/or lateral, motion to the sieve, causing the particles there on to bounce and turn to present different orientations to the sieving surface.

iii. Oven - An oven of appropriate size capable of maintaining a uniform temperature of 110-130°C.

3.3.2 Procedures

i. The sieves were nested in order of decreasing size of opening, from top to bottom and the samples were placed on the top sieve. The sieves were stirred up by the mechanical apparatus for 10 minutes.
ii. The quantity of material was limited on given sieve so that all particles have opportunity to reach sieve openings a few times during the sieving operation.
iii. The sieve process was continued for 10 minutes as usual.
iv. In order to prevent the overloading of individual sieve, the portion of the sample finer than 4.75mm was distributed among two or more sets of sieves.
v. After repeated the step until get enough aggregates, the coarse aggregate then was washed to remove dust stick to the aggregate.
vi. The samples were dried to constant weight at a temperature of 110-130°C.

Figure 3.2 Sieve shaker

Figure 3.3 Washed-sieve analysis

3.4 Aggregate Gradation

The percentages of aggregates required for every sieve size were determined according to JKR specification. Then the mass retained were calculated using the percent passing for every sample size.

Table 3.1 Gradation limit for AC14

Sieve size (mm)	Gradation Limit	Percentage Passing
14	90-100	95
10	76-86	81
5	50-62	56
3.35	40-54	47
1.18	18-34	26
0.425	12-24	18
0.150	6-14	10
0.075	4-8	6

3.5 Specific Gravity of Aggregate

Specific gravity test was performed to determine the absorption rate of the aggregate and the volume of water in the aggregate. Coarse aggregate is defined as the aggregate retained on sieve size 4.75mm while fine aggregate is defined as the aggregate passing sieve size 4.75mm and retain on sieve size 75 µm. The specific gravity of aggregate is useful in making weight-volume conversions and in calculating the void content in compacted hot mix asphalt. However, average specific gravity of aggregate was taken from Highway and Traffic Laboratory which is 2.603.

3.6 BITUMINOUS BINDER

Bitumen with penetration grade 80/100 PEN was used for this study. The bitumen contents for these samples were ranged as in Table 3.2 according to JKR specification.

Table 3.2 Design bitumen content

Mix Type	Bitumen content
AC14	4%-6%

3.7 Crumb Rubber Modifier (CRM)

Fine crumb rubber (grinding from truck tyres) was added in a form of powder where the size was between 0.3mm to 0.6mm. The amount of crumb rubber modifiers added into the mixes was expressed in the percentages which vary from 1%, 2% and 3% of the total weight of bitumen. Crumb rubber was supplied by Jingyun Crumb Product Recycle Industries Indera Mahkota 1, Kuantan.

Figure 3.4 Crumb rubber powder 0.3mm-0.6mm (30 mesh)

3.7.1 Specific Gravity of Crumb Rubber

The size of crumb rubber used for this study can be categorized as fine crumb rubber or powder type. In addition, (Moreno, Rubio, & Martinez-Echevarria, 2012) stated that density of crumb rubber is 1.15 g/cm^3 from table properties and composition of the crumb rubber. Specific gravity of rubber is approximately 1.15.

3.8 Marshall Mix Design

The basic concepts of the Marshall mix design method were originally developed by Bruce Marshall of the Mississippi Highway Department around 1939 and then refined by the U.S Army. Currently, the Marshall method is used in some capacity by about 38 states. The Marshall method seeks to select the asphalt binder content at a desired density that satisfies minimum stability and range of flow values. For this study, Marshall samples were prepared for mix designs of AC14 (Roberts, Kandhal, Brown, & Lee, 1996).

The method of wet process, fine crumb rubber powders fully react with asphalt binders (called ‘‘asphalt–rubber’’) and improve the binder properties. Specifications outlined by the Highway & Transportation Laboratory and past researchers were adopted along with Marshall design method in incorporating crumb rubber in Marshall samples.

3.8.1 Marshall Sample Preparation (Compacted sample)

The Marshall method uses standard test specimens of 64mm thickness x100mm diameter. All the samples were prepared using a specified procedure for heating, mixing and compacting the asphalt aggregate mixes. The equipment, tools and procedures for preparing the Marshall sample were based on ASTM or BS. Additionally, the modified samples were prepared using wet process that was recommended from past researchers.

3.8.1.1 Apparatus

i. Pans, metal, flat bottom for heating aggregate.

ii. Pans, metal, round, approximately 4 litres capacity for mixing asphalt and aggregate.

iii. Oven and hot plate, electric for heating aggregate, asphalt and equipment as required.

iv. Scoop for batching aggregates.

v. Containers, gill types tins, beakers, pouring pots or sauce pans for heating asphalt.

vi. Thermometers, armored, glass, or dial type with metal stem, 10°C to 232°C for determining temperature of aggregates, asphalt and asphalt mixtures.

vii. Balance – to the nearest 0.1g.

viii. Mixing spoon, large or trowel, small.

ix. Spatula.

x. Compaction pedestal.

xi. Compaction mould, consisting of a base plate, forming mould and collar extension.

xii. Compaction Hammer, consisting of a flat circular tamping face 98.4mm in diameter and equipped with a 4.5kg weight constructed to obtain a specified 457mm height of drop.

xiii. Mould holder.

xiv. Oil grease for extruding compacted specimens from mould.

xv. Gloves.

xvi. Marking crayons for identifying test specimens.

xvii. Filter paper.

3.8.1.2 Procedures

i. Aggregates were dried in the oven at temperature of 190ºC to 218ºC for at least 12 hours before blending process.

ii. Crumb rubber modified bitumen was melted at minimum temperatures 170°C at least 5 hours.

iii. Mould was heated at 135°C to 150°C before use. Filtration paper was cut as mould size and put at the base of mould before it was filled with premix sample.

iv. The heated aggregates were placed in pot with the required crumb rubber modified bitumen was added to blend together. Then, mixed until having a uniform distribution of asphalt throughout at 135°C to 160°C.

v. Oil grease was spread on the inner surface of the mould and the filter paper was put at base of mould. While waiting for asphalt mix uniformly, the mould is placed in the oven.

vi. The blended mixes were put inside the mould and flat using the spatula by penetrating it 15 times at around mould.

vii. Then, the filter paper was put at the top of sample and the compaction was performed.

viii. The compaction was performed at 75 blows (modified AC14) for both top and the bottom surface of the samples. Then samples were cooled or maintained at room temperature for 24 hours before extrusion.

Figure 3.5 Materials were mixed together

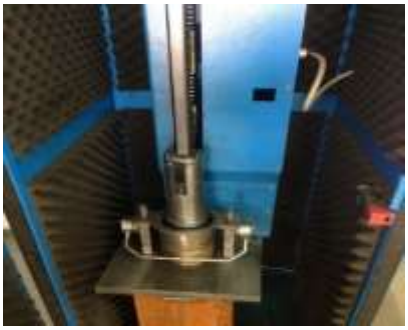

Figure 3.6 Automatic Marshall Compactor machine

3.8.2 Softening Point of Bitumen (ASTM D36-95)

The softening point is defined as the mean of the temperatures at which the bitumen disks soften and sag downwards a distance of 25 mm under the weight of a steel ball.

3.8.2.1 Apparatus

i. Steel balls-two numbers each of 9.5 mm diameter weighing 3.5 ± 0.05 g.
ii. Ball guide and ring holder
iii. Thermometer
iv. Beaker
v. Burner

3.8.2.2 Procedures

i. Melted the bitumen and pour the liquid into a pair of ring placed on plate. The process same goes to the 1%, 2% and 3% of crumb rubber to place into a pair of ring each.
ii. After specimen has cool, rings is suspended in the distilled water in the bath/beaker at 5°C ± 2°C. Bath temperature is maintained at that temperature for 15 minutes.
iii. Put the steel balls on the surface of the bitumen in the ring.
iv. Stirred and heated the bath liquid to 5°C ± 2°C per minutes.
v. Temperature is noted just after the ball is passed and dropped into the base plate.

Figure 3.7 Four pairs of rings were placed into the plate

which are unmodified bitumen, 1% of CR, 2% of CR and 3% of CR

3.8.3 Penetration of Bituminous Materials (ASTM D5-97)

The bituminous materials used in highway construction are either asphalt or tars. All bituminous material consists of primarily of bitumen, have strong adhesive properties, and have colors ranging from dark brown to black. These hydrocarbons found in natural deposits or are obtained as a product of the distillation of crude petroleum. The penetration test gives us an empirical measurement of the consistency of a material in terms of the distance a standard needle sinks into that material under a prescribed loading and time. This test is important in pavement of construction because the consistency at a specified temperature will indicate the grade of the material. Consistency of a bituminous material expressed as the distance in tenths of a millimeter that a standard needle vertically penetrates a sample of the material under known conditions of loading, time, and temperature.

3.8.3.1 Apparatus

i. Penetration
ii. Water bath
iii. Penetration Container
iv. Asphalt Sample
v. Thermometer
vi. Penetrometer

3.8.3.2 Procedures

i. Specimens are prepared in sample containers as specified (ASTM D5-97) and placed in a water bath at the prescribed temperature of test for 1 to 1.5 hours before the test.
ii. Clean the penetration needle and fix it into the needle holder and guide. For normal test the precisely dimensioned needle, loaded to 100 ± 0.05g.
iii. Keep the container on the stand of the penetration apparatus.
iv. Adjust the needle to make contact with the surface of the sample.
v. Adjust the dial reading to zero.
vi. Release the needle holder to penetrate the bitumen for 5± 0.1s, while the temperature of the specimens is maintained at 25± 0.1°C. The penetration measured in tenths of a millimeter (deci-millimeter, dmm).
vii. Read and record the depth of penetration.
viii. Make at least three determinations on the specimen. A clean needle is used for each determinations start each with the tip of needle at least 10mm apart.

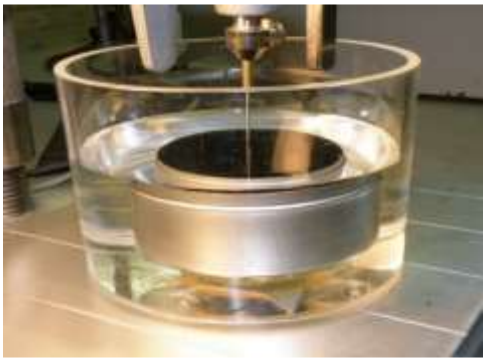

Figure 3.8 Needle holder is ready to penetrate

3.9 Indirect Tensile Test

3.9.1 Introduction

After the sample of Marshall have been done, the indirect tensile modulus will be testing for each sample to determine resilient modulus values of bituminous mixtures by repeated load indirect tensile testing using the Universal Testing Machine (UTM) developed by Industrial Process Controls (IPC Global) Limited. For the resilient modulus sample was tested at temperature room 25°C.

The modulus test would usually be used to gauge the relative performance of asphalt mixes for road pavement design. However, with the standard supplied and calibrated transducers, any bound material with a moduli range from approximately 500-20,000 MPa could be tested.

The test sequence consists of a user selected number (minimum of five for both the Australian and British test methods) of conditioning loading pulses followed by five test loading pulses from which the final data are calculated and tabulated. During the test the following test properties are calculated and displayed.

i. Specimen resilient modulus (stiffness modulus for the British test method)
ii. Total recoverable horizontal strain (Australian test method only)
iii. Horizontal Deformations (summed total and individual transducers)
iv. Peak (repeated) loading force
v. Rise time, Load time and Phase delay (Australian test method only)
vi. Load factor (British test method only)
vii. Vertical deformations (summed total and individual transducers) (American test methods only)

In addition, using the data from the final five loading pulses, the mean, standard deviation (SD) and coefficient of variance (CV%) are calculated. For controlled temperature testing, the specimen's skin and core temperatures are estimated by transducers inserted in a dummy specimen and located near the specimen under test. Test results are archived in a system generated data file, which is generally identified by name with the specimen. In this research, we use Australian Test Method for total recoverable horizontal deformation because there is no vertical deformation.

3.9.2 Apparatus

i. Specimens
ii. Metal moulds for placing of specimens
iii. Matta machine (UTM-25)
iv. Personal computer using UTS003 software

Figure 3.9 Matta machine

Figure 3.10 Sample on the Matta machine

3.9.3 Procedures

i. Specimens were kept in the MATTA machine at the temperature of 40°C for at least 1 hours and the pressure adjusted to 1000 N. A direct compressive load is to be applied through a 12mm wide loading strips along the vertical diameter of the specimens. The linear variable differential transducers (LVDTs) are used to monitor the resultant indirect tensile stress and strain along the horizontal diameter.

ii. The rise and the rest time in between the initial application and the peak value of the load are arbitrarily specified at 100 milliseconds. Observe that this rise time gives a load-time relationship with a clearly defined peak at 40°C for all the specimens tested. The test conditions as described above are essentially maintained throughout the test, as the elastic stiffness was dependent on these conditions.

iii. For each specimen, the test is repeated after rotating the specimen through approximately 90°. Provided the difference is about 10% or less, the mean of the two test results is taken as the elastic stiffness of the specimen.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Recently, the past research was conducted by adding certain portion of bitumen with crumb rubber in order to modify the mixture. However, for this project the modifying concept was investigated by adding several portions of crumb rubber which are 1% crumb rubber, 2% crumb rubber and 3% crumb rubber as an additive into the mixture and they were functioning as part of the modified bitumen.

4.2 Material Preparation

Main materials used for this study were aggregate, asphalt cement and crumb rubber. All properties of the materials used were measured for further analysis consideration. Several tests were conducted in order to measure their properties according to the specifications referred which were JKR specifications and ASTM 1992. These materials were prepared for mixes AC14.

4.3 Marshall Sample

The equipment and procedures for preparing the Marshall sample were outlined in ASTM D 1559. All the samples were prepared using a specified procedure for heating, mixing and compacting the asphalt aggregate mixes. The Marshall samples were compacted for each side is 75 blows/side. Additionally, the modified samples were prepared using wet process that was recommended from past researchers. Various percentages of crumb rubber used to modified bitumen which are 0% crumb rubber (controlled sample), 1% crumb rubber, and 2% crumb rubber and 3% crumb rubber. The samples also be prepared for each binder content which are 4%, 5% and 6%.

4.4 Softening Point Test

The softening point is defined as the temperature at which the asphalt reaches the degree of the softening when an asphalt sample can no longer support the weight of steel ball. The bitumen is needed to heat up to for mixing purposes. As the crumb rubber content increased, it showed strong effects of increasing softening point depending on the amount of crumb rubber content that was added to bitumen (Adil AL Tamimi, 2014). Table 4.1 presents the result of modified and unmodified crumb rubber for softening point.

Table 4.1 Softening Point for unmodified and modified bitumen

Crumb Rubber	0%	1%	2%	3%
Softening Point	47.05 ˚C	51.5 ˚C	56 ˚C	59.2 ˚C

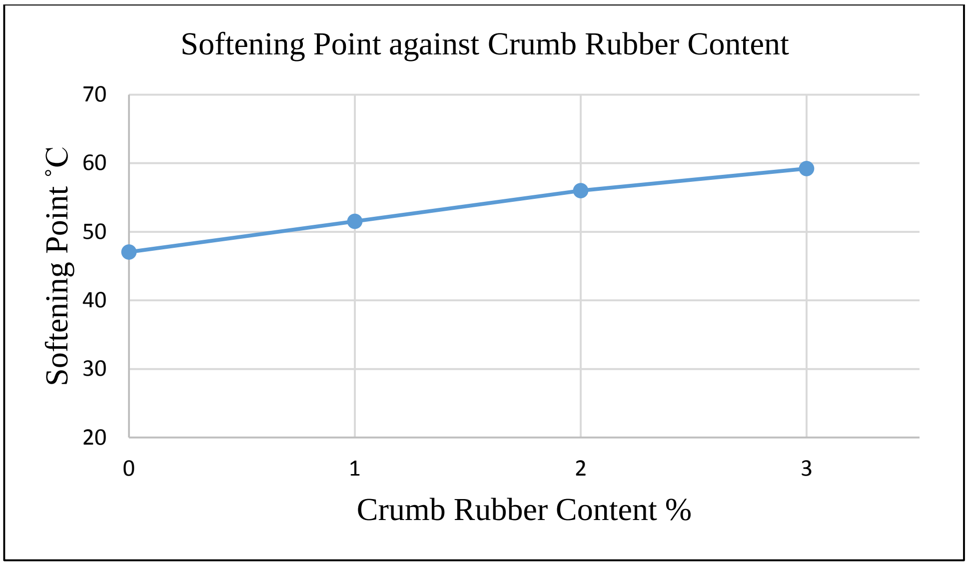

Figure 4.1 Summary of Softening Point Test

As indicated in Figure 4.1, the softening point increases with increasing crumb rubber content. The increase in softening point values of modified asphalt with addition of 1%, 2% and 3% of crumb rubber is by substituting of virgin asphalt. As mentioned before in the literature, higher softening point is required for better resilience of asphalt pavements.

4.5 Penetration Test

The penetration test gives us an empirical measurement of the consistency of a material in terms of the distance a standard needle sinks into that material under a prescribed loading and time. This test is important in pavement of construction because the consistency at a specified temperature will indicate the grade of the material.

4.5.1 0% crumb rubber (controlled sample)

Table 4.2 Penetration for unmodified bitumen

No. of Penetration	Penetration (mm)
1	84
2	89.3
3	86.3
Average	**86.5**

(Note: Grade of Bitumen 40/50, 60/70, 80/100, 120/150 and 200/300)

Calculation:

Average = (Total penetration recorded in test) / (Number of test)

= (84+89.3+86.3) / 3

= 86.5

4.5.2 1% crumb rubber

Table 4.3 Penetration for modified 1% crumb rubber

No. of Penetration	Penetration (mm)
1	70
2	70.4
3	69
Average	**69.8**

Calculation:

Average = (Total penetration recorded in test) / (Number of test)

= (70+ 70.4 + 69) / 3

= 69.8

4.5.3 2% crumb rubber

Table 4.4 Penetration for modified 2% crumb rubber

No. of Penetration	Penetration (mm)
1	69
2	64
3	62.3
Average	**65.1**

Calculation:

Average = (Total penetration recorded in test) / (Number of test)

= (69+64+62.3) / 3

= 65.1

4.5.4 3% crumb rubber

Table 4.5 Penetration for modified 3% crumb rubber

No. of Penetration	Penetration (mm)
1	58.3
2	67
3	56.3
Average	**60.5**

Calculation:

Average = (Total penetration recorded in test) / (Number of test)

= (58.3+67+56.3) / 3

= 60.5

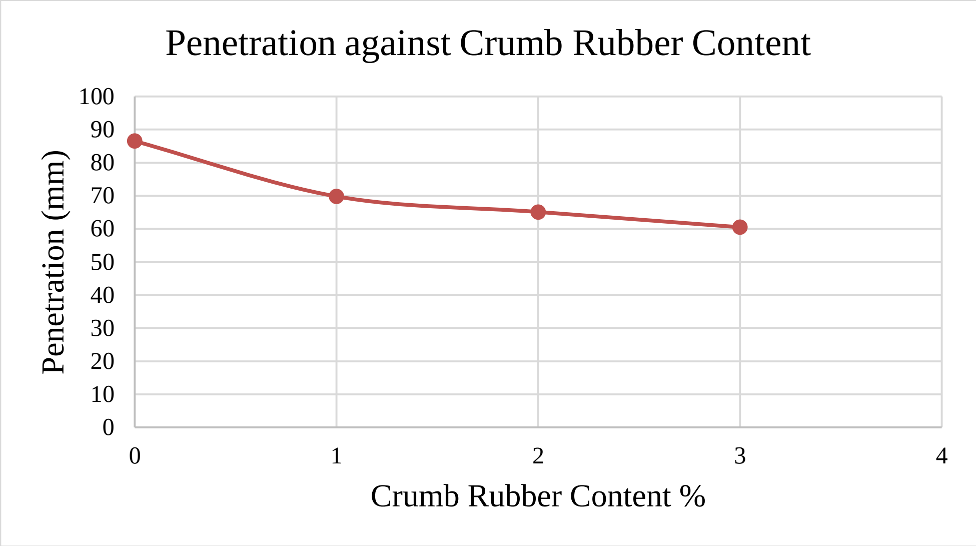

Figure 4.2 Summary of Penetration Test

From the results in Figure 4.2, for the unmodified sample of bitumen, we had obtained the average of penetration is 86.5. From the experiment, the bitumen grade that we get is 80/100. Each reading had nearest number, so it has sub-standard difference between the highest and the lowest reading. A grade of 80/100 bitumen means the penetration value is in the range 80 to 100 at standard test conditions follow ASTM D5-97. (Mahrez, 1999) investigated the properties of rubberized prepared by physical blending of bitumen 80/100 penetration grade with different crumb rubber content and various aging phases. The average penetration is decreased in values for 1%, 2% and 3% crumb rubber are 69.8, 65.1 and 60.5 which is 60/70 below than 80/100 penetration. For the results of penetration values decreased over the aging as well as before aging by increasing the rubber content in the mix. In the penetration, the modified binders have lower penetration values than the unmodified binders. This is a clear indication of increasing binder stiffness as a result of addition of crumb rubber. This will contribute to the rutting resistance of the binder. Thus, the consistency of the base asphalt changes and becomes harder.

4.6 Indirect Tensile Result (Matta Result)

The results for 0% CR, 1% CR, 2% CR and 3% CR was obtained from test to determine resilient modulus values, horizontal deformation and peak loading force of bituminous mixtures by repeated load indirect tensile testing using the Universal Testing Machine (UTM 25).

4.6.1 0% of CR (controlled samples)

i. Resilient Modulus result against Binder Content

The graph shows the plotted data of resilient modulus data against binder content for two sample of 0% of crumb rubber content. The pattern of the graph of the two sample is similar but with different values. However, the graph shows that the resilient modulus is decrease to the binder content. The higher the binder content results in lower resilient modulus result. The higher the binder content would affect the strength of the sample. The optimum binder content is 4% for the control sample. The higher the percentage of the binder content can cause bleeding, rutting and failure to the performance of the pavement.

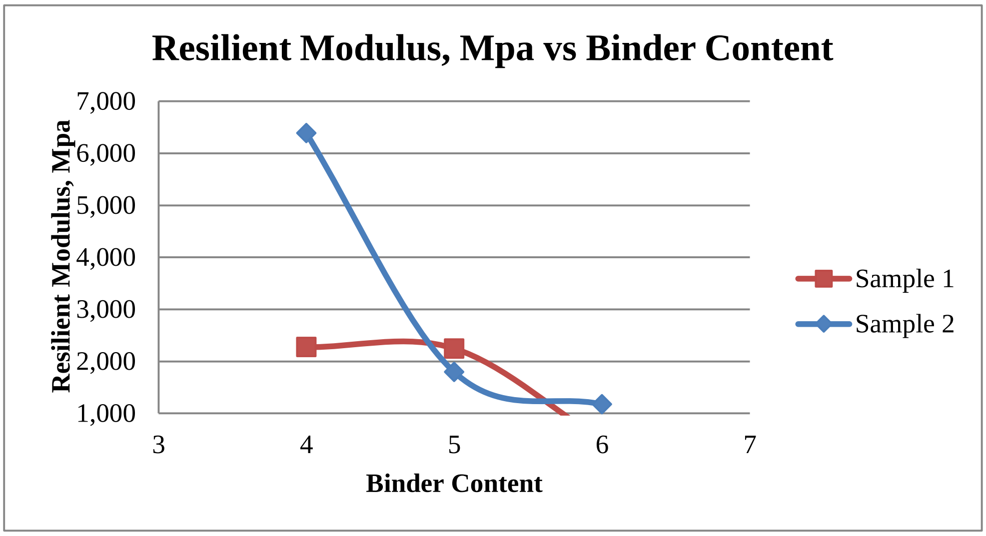

Figure 4.3 Resilient Modulus for 0% crumb rubber content

ii. Horizontal Deformation result against Binder Content

This graph is the results of the horizontal deformations against the binder content. Generally, the horizontal deformation increase as the binder content increases for both samples. The pattern for both samples of the horizontal deformation increases slowly within the number of binder content because the higher binder content would increase the viscosity factor of the sample properties. This results in the lower strength of the sample and rutting effect. In the normal pavement, this will contribute to the pavement failure as the road will become wavy with higher loading capacity of traffic. Even though the value between the samples varies and produced the different graph but the patterns are still similar to each other.

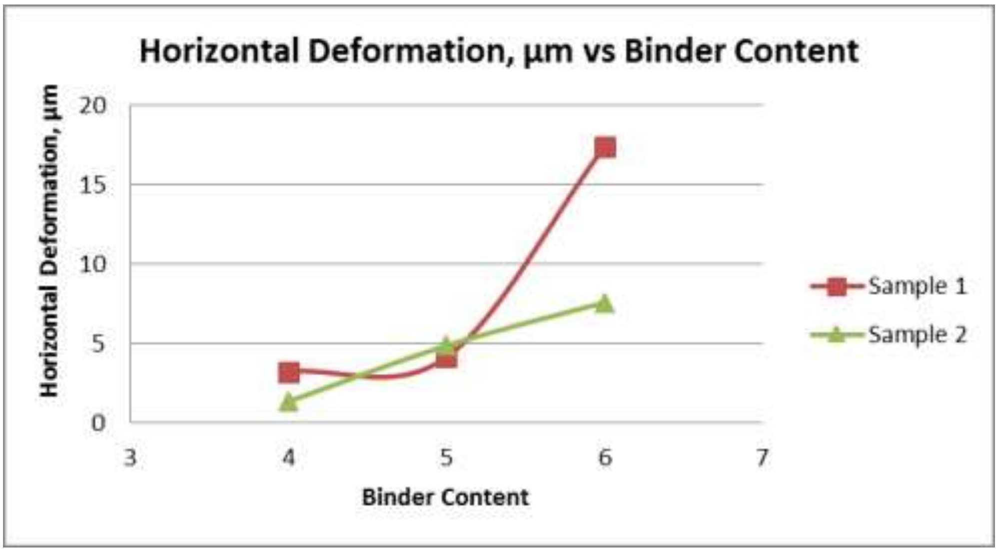

Figure 4.4 Horizontal Deformation for 0% crumb rubber content

iii. Peak Loading result against Binder Content

The graph shows the result of peak loading against the binder content for the same two samples. For sample 1, the graph shows that the peak loading increases gradually from 4% and achieve its optimum strength at 5%, then the peak loading decreases for 6%. Meanwhile for sample 2, the results show that the peak loading force is higher than the sample 1 at 4% and the peak loading force is consistence and slightly increase at 6% which is still higher than the sample 1. Both sample shows different optimum peak loading as it's has different strength which result is slightly different in properties. However, the behaviour of both samples stills same as the resilient modulus and the horizontal deformation produced the similar pattern. Therefore, the optimum binder content is 4% for 0% crumb rubber as binder content in asphalt mixture.

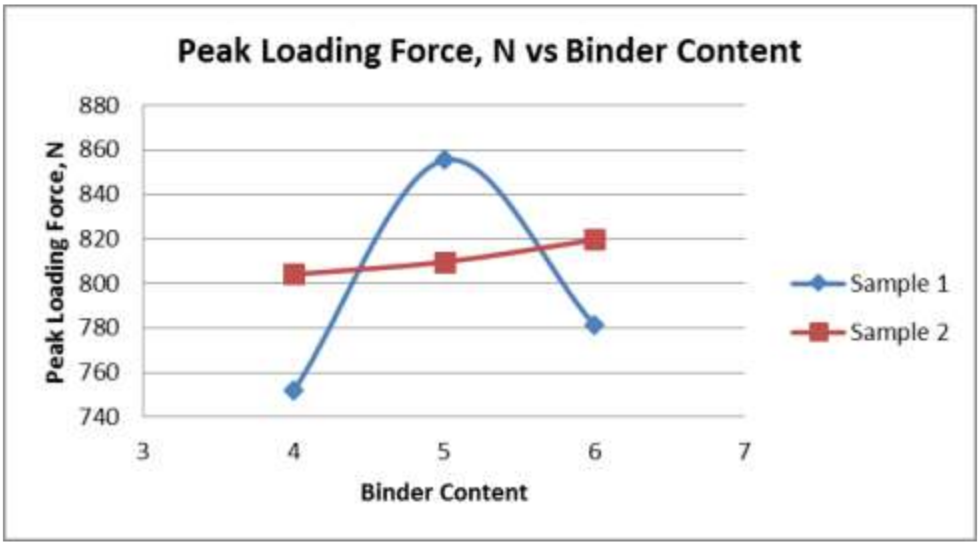

Figure 4.5 Peak Loading for 0% crumb rubber content

4.6.2 1% of CR

i. Resilient Modulus result against Binder Content

The graph shows the plotted data of resilient modulus data against binder content for sample 1 and sample 2 of 1% crumb rubber content. For both samples, the pattern of the graph is similar from 4% to 5% binder content which is steadily declined. However, after 5% binder content, sample 1 and sample 2 acts diversely proportional to different directions. For sample 1, the graph shows that the resilient modulus is slowly decrease to the binder content. But at 5% binder content it starting to climbed up which is resilient modulus can achieve at 6% binder content. Meanwhile, for sample 2 the resilient modulus gradually decrease from 4% to 6% binder content shows the result affect the strength of the sample with the higher binder content. However, the optimum binder content is 4% for the both sample randomly. For 1% crumb rubber content, the higher the percentage of the binder content can cause bleeding, rutting and failure to the performance of the pavement.

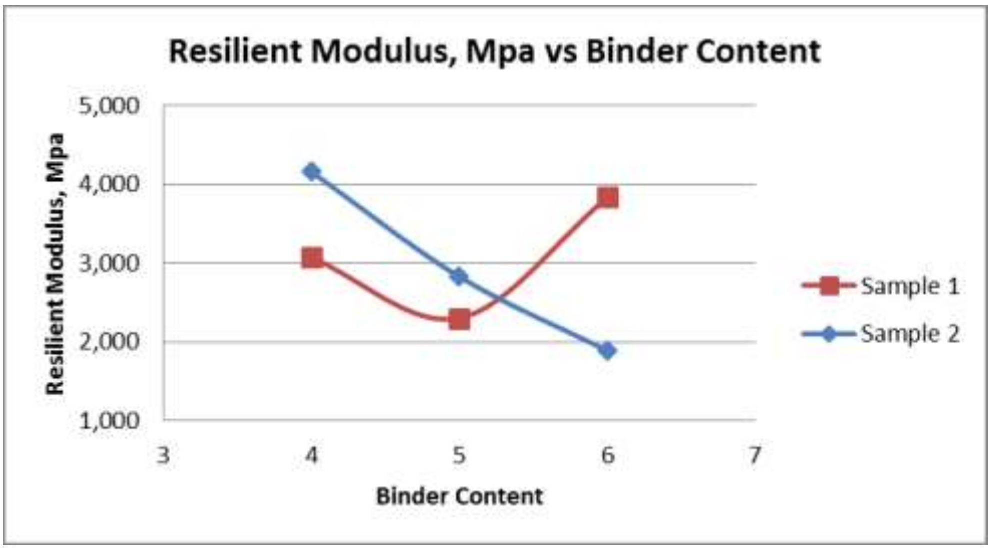

Figure 4.6 Resilient Modulus for 1% crumb rubber content

ii. Horizontal Deformation result against Binder Content

This graph is the results of the horizontal deformations against the binder content. Mostly, the horizontal deformation increase as binder content increase for both samples. The pattern for both samples of the horizontal deformation increases slowly within the number of binder content because the higher binder content would increase the viscosity factor of the sample properties. This result would have tendency to the lower strength of the sample and rutting effect. From the graph shown above, the results for both samples slowly increased from 4% to 5% binder content. On the other hand, sample 1 and sample 2 acts diversely proportional to different directions at 6% binder content. In the normal pavement, this will contribute to the pavement failure as the road will become wavy with higher loading capacity of traffic due to higher viscosity. Even though the values between the samples varies from 4% until 5% binder content for 1% crumb rubber content.

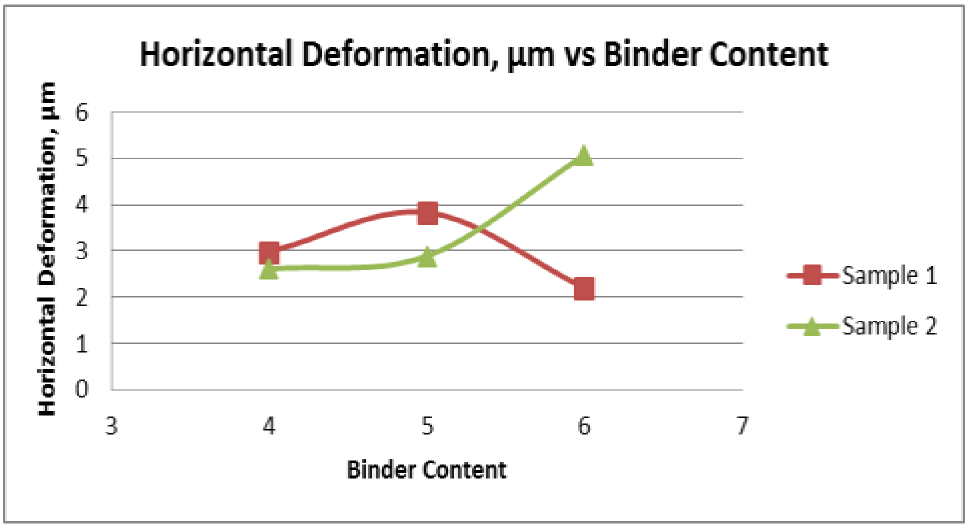

Figure 4.7 Horizontal Deformation for 1% crumb rubber content

iii. Peak Loading result against Binder Content

The graph shows the result of peak loading against the binder content for the same two samples. For sample 1, the graph shows that the peak loading increases gradually from 4% binder content and achieve its optimum strength at 5% binder content, then the peak loading decreases for 6% binder content. Meanwhile for sample 2, the results show that the peak loading force is higher than the sample 1 at 4% binder content and the peak loading force is fluctuated from 4% until 6% binder content. Both sample shows different optimum peak loading as it's has different strength which result is slightly different in properties. However, the behaviour of both samples stills same as the resilient modulus and the horizontal deformation produced the similar pattern. Therefore, the optimum binder content is 4% for 1% crumb rubber as binder content in asphalt mixture.

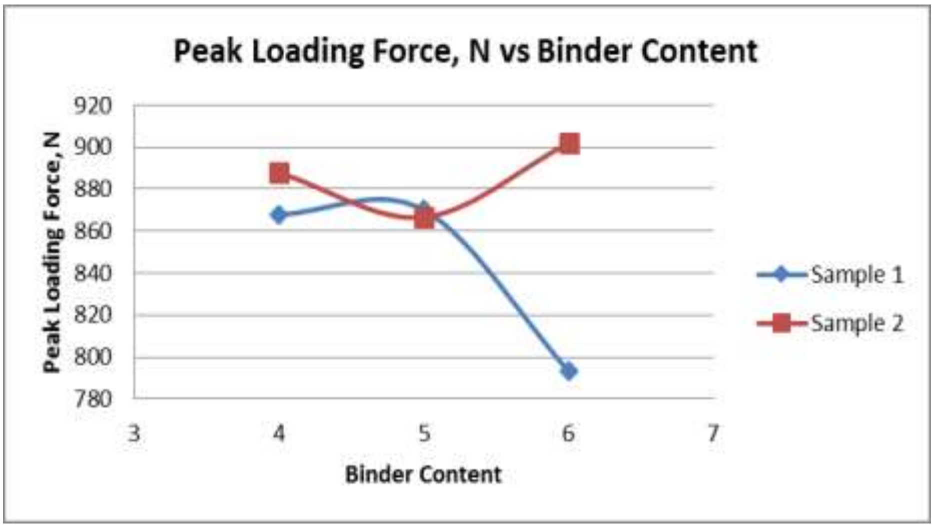

Figure 4.8 Peak Loading for 1% crumb rubber content

4.6.3 2% of CR

i. Resilient Modulus result against Binder Content

The graph shows the plotted data of resilient modulus data against binder content for sample 1 and sample 2 of 2% crumb rubber content. For both samples, the pattern of the graph is similar from 4% to 6% binder content which are gradually declined and increase within the percentage of binder content. The graphs for both samples shows that the resilient modulus is slowly decrease to the binder content means at 5% binder content gives lower result. However, at 5% binder content it starting to climbed up which is resilient modulus can achieve at 6% binder content which is sample 1 is higher than sample 2. For 2% crumb rubber content, the higher the percentage of the binder content can affect the higher resilient modulus. Hence, the optimum binder content is 6% for the both sample randomly.

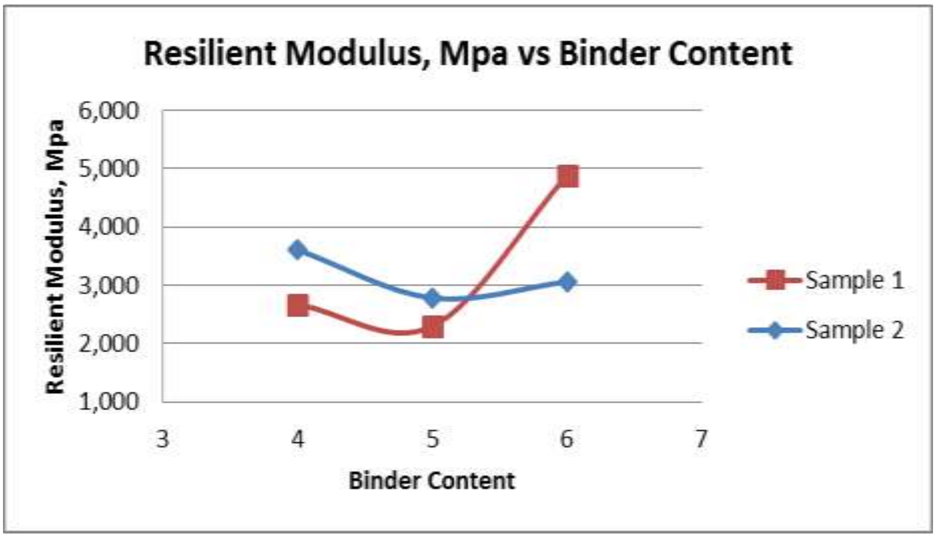

Figure 4.9 Resilient Modulus for 2% crumb rubber content

ii. Horizontal Deformation result against Binder Content

This graph shows the results of the horizontal deformations against the binder content. In general, the horizontal deformation increases as binder content increase for both samples. The pattern for both samples of the horizontal deformation increases slowly within the number of binder content because the higher binder content would increase the viscosity factor of the sample properties. This result would have tendency to the lower strength of the sample and rutting effect. However, at 5% binder content the horizontal deformation starting steadily declined towards 6% binder content. Therefore, horizontal deformation at 6% binder content will contribute to the pavement performance due to decreasing for 2% crumb rubber content.

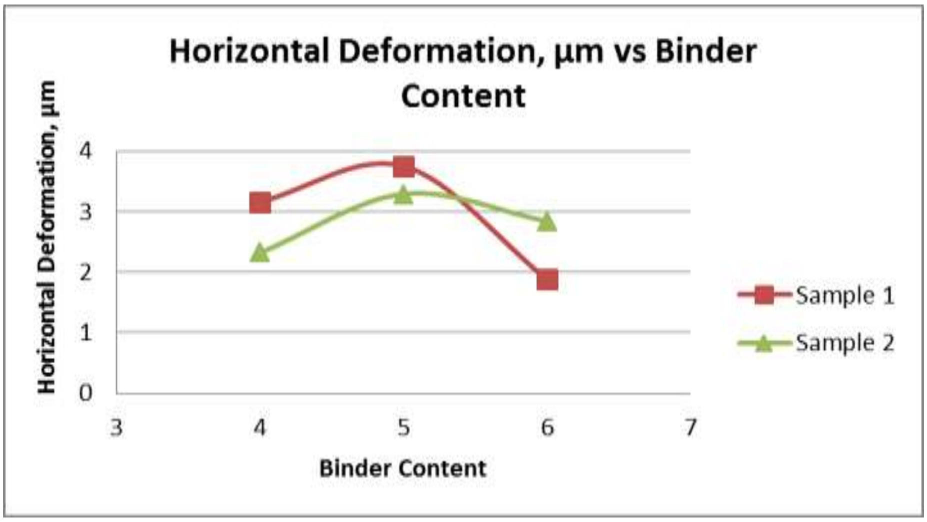

Figure 4.10 Horizontal Deformation for 2% crumb rubber content

iii. Peak Loading result against Binder Content

The graph shows the result of peak loading against the binder content for two samples. For sample 1, the graph shows that the peak loading increases gradually from 4% and achieve its optimum strength at 6% binder content. Meanwhile for sample 2, the results show that the optimum strength is higher than the sample 1 at 5% binder content and slightly decrease at 6% binder content. Both sample shows different optimum peak loading as it's has different strength which result is slightly different in properties. However, the behaviour of both samples stills same as the resilient modulus and the horizontal deformation produced the similar pattern. Therefore, the optimum binder content is 6% for 2% crumb rubber as binder content in asphalt mixture.

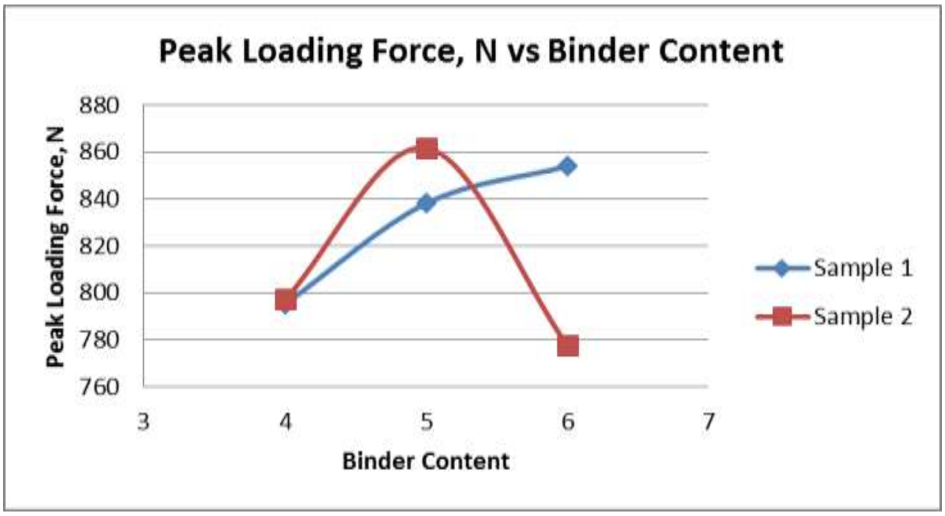

Figure 4.11 Peak Loading for 2% crumb rubber content

4.6.4 3% of CR

i. Resilient Modulus result against Binder Content

The graph shows the plotted data of resilient modulus data against binder content for sample 1 and sample 2 of 3% crumb rubber content. For both samples, the pattern of the graph is quite similar from 4% to 6% binder content. For sample 1, the graph shows that the resilient modulus is slightly fell to the binder content. Meanwhile, for sample 2 the resilient modulus rapidly dropped shows the result affect the strength of the sample with the higher binder content. However, the optimum binder content is 4% for the both sample randomly. For 3% crumb rubber content, the higher the percentage of the binder content can cause bleeding, rutting and failure to the performance of the pavement.

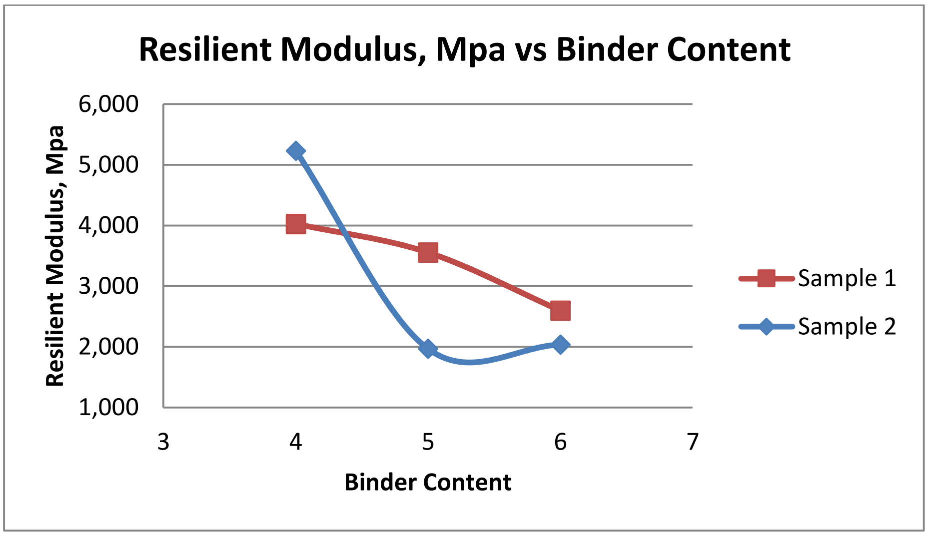

Figure 4.12 Resilient Modulus for 3% crumb rubber content

ii. Horizontal Deformation result against Binder Content

This graph shows the results of the horizontal deformations against the binder content. Generally, the horizontal deformation increase as binder content increase for both samples. The pattern for both samples of the horizontal deformation are similar within the number of binder content because the higher binder content would increase the viscosity factor of the sample properties. This result would have tendency to the lower strength of the sample and rutting effect. From the graph shown above, sample 1 is steadily increased from 4% to 6% binder content. On the other hand, sample 2 shows the horizontal deformation dramatically increases from 4% to 5% binder content. However, at 5% to 6% binder content the graph shows the value dropped slowly. In the normal pavement, the increasing horizontal deformation will contribute to the pavement failure as the road will become wavy with higher loading capacity of traffic due to higher viscosity. Hence, 4% binder content for 1% crumb rubber content will have good performance.

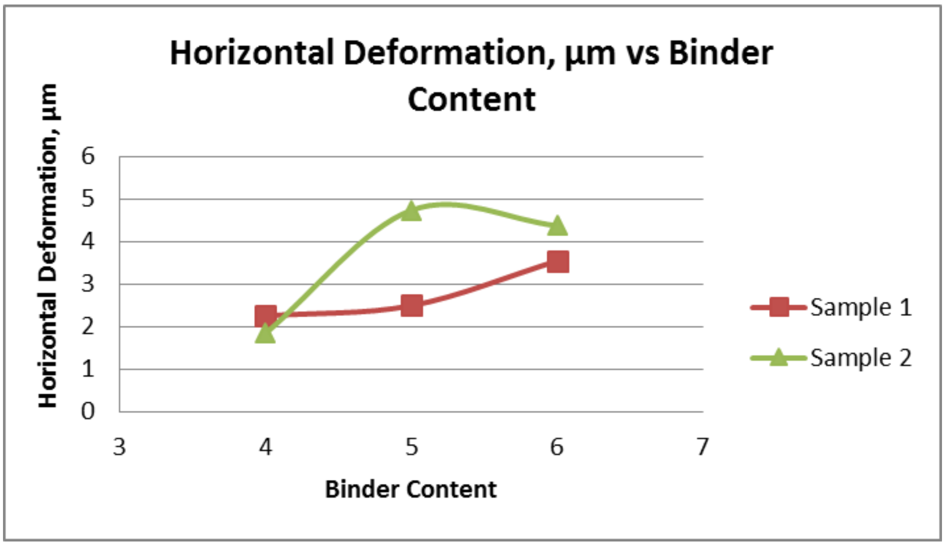

Figure 4.13 Horizontal Deformation for 3% crumb rubber content

iii. Peak Loading result against Binder Content

The graph shows the result of peak loading against the binder content for two samples. For both samples, the graph shows that the peak loading decrease gradually from 4% to 5% binder content. Meanwhile, starting from 5% to 6% binder content the results show that the peak loading acts diversely proportional to different directions. Both sample shows same optimum binder content and produced the similar pattern which is at 4% binder content. Therefore, the optimum binder content is 4% for 3% crumb rubber as binder content in asphalt mixture.

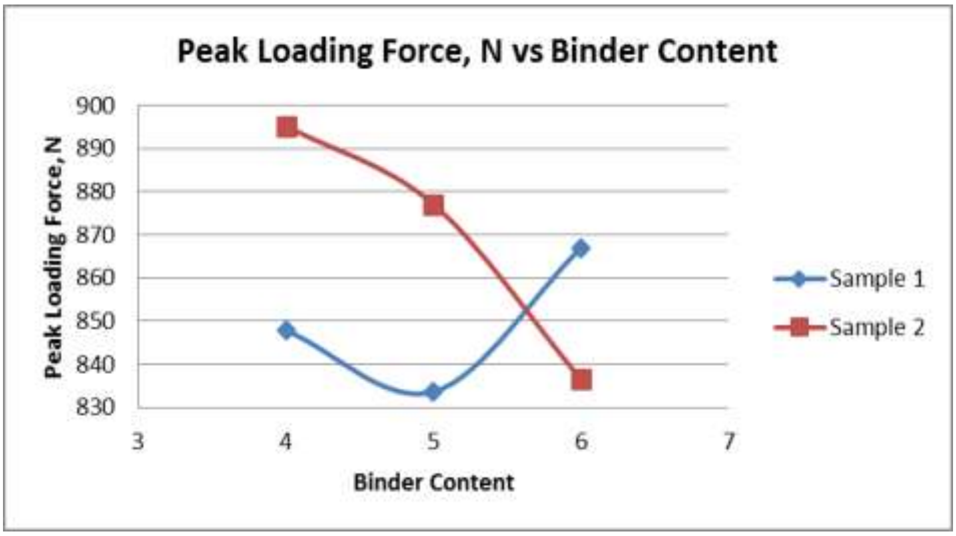

Figure 4.14 Peak Loading for 3% crumb rubber content

4.6.5 Comparison between 0% (controlled sample) and 1-3% CR

i. Resilient Modulus result against Binder Content

The graph shows the plotted data of resilient modulus data against binder content for 0% (controlled sample), 1%, 2% and 3% of crumb rubber. For 1% and 3% of crumb rubber, the pattern of the graph is conforms and follow to the controlled sample from 4% to 6% binder content. Meanwhile, 2% crumb rubber is slightly differ from others. As shown above, the graph of the resilient modulus is slightly dropped with the higher binder content. Moreover, the resilient modulus for 0% crumb rubber (controlled sample) at 4% binder content is choose for the optimum binder content. For 1% crumb rubber content, it is closely similar to the controlled sample which is resilient modulus have optimum binder content at 4% binder content and it is recommended to use. While for 2% crumb rubber, the pattern does not follow the controlled sample because starting 5% to 6% binder content the trend start to increase which is the optimum binder content for 2% crumb rubber is 6% binder content. The 2% crumb rubber is not recommended due to the higher the percentage of the binder content can cause bleeding, rutting and failure to the performance of the pavement.

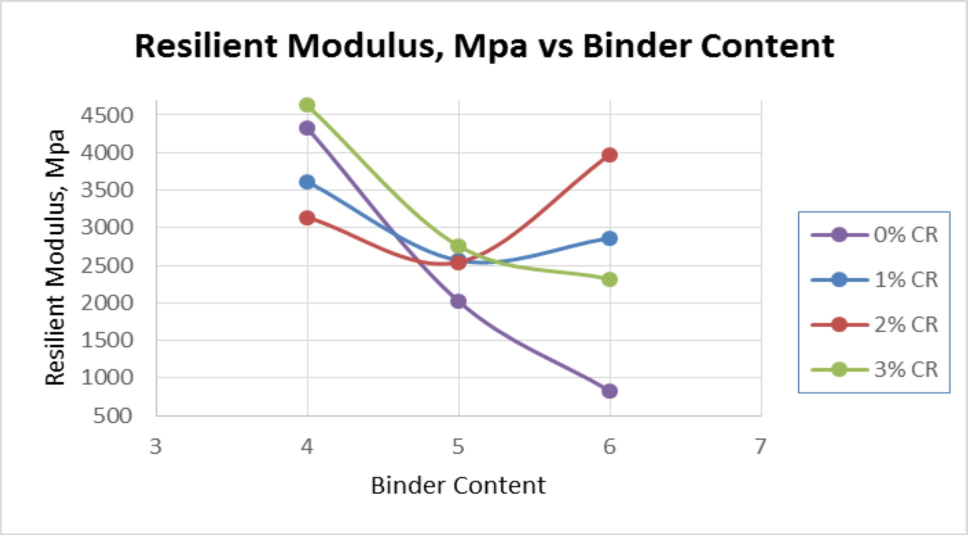

Figure 4.15 Resilient Modulus for all crumb rubber content

ii. Horizontal Deformation result against Binder Content

This graph shows the results of the horizontal deformations against the binder content for 0% (controlled sample), 1%, 2% and 3% of crumb rubber. For 1% and 3% of crumb rubber, the pattern of the graph are conforms and follow to the controlled sample from 4% to 6% binder content. Meanwhile, 2% crumb rubber is slightly differ and fell slowly compare to others. The graph of the horizontal deformation for controlled sample is rapidly increase with the higher binder content. In addition, for 1% crumb rubber content, it rather closely to the controlled sample even though steadily incline. The higher percentages of binder and crumb rubber content may be tend to increase the viscosity factor of the sample properties. This result would have tendency to the lower strength of the sample and rutting effect. Hence, the horizontal deformation against binder content is choose 1% crumb rubber content for the optimum crumb rubber content.

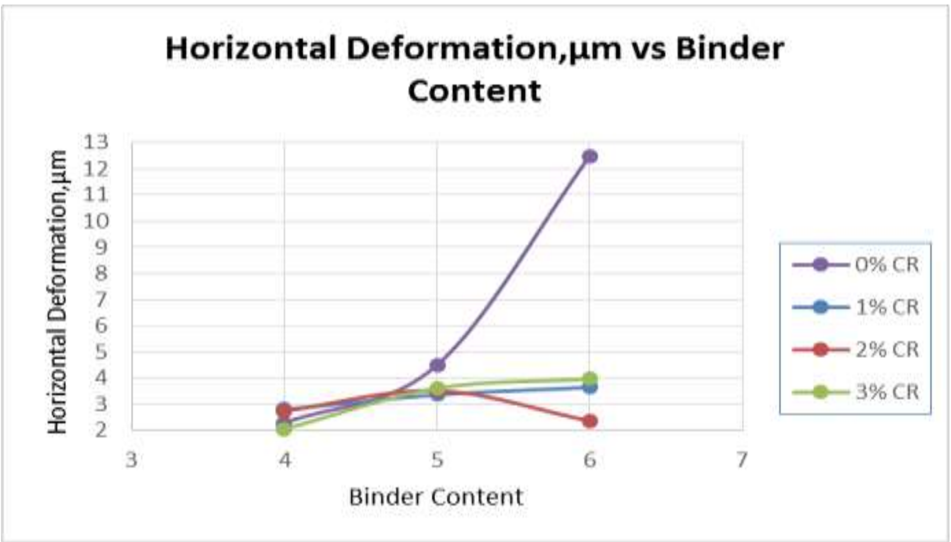

Figure 4.16 Horizontal Deformation for all crumb rubber content

iii. Peak Loading result against Binder Content

The graph shows the result of peak loading against the binder content for 0% (controlled sample), 1%, 2% and 3% of crumb rubber. For controlled sample and 2% crumb rubber, the graph shows that the peak loading increases gradually from 4% and achieve its optimum strength at 5% binder content, then the peak loading decreases for 6%. Meanwhile for 1% and 3% crumb rubber, the results show that the peak loading force is higher than 0% and 2% crumb rubber at 4% and the peak loading force is consistence and slightly decrease at 6% which is still higher than 0% and 2% crumb rubber. The percentages of crumb rubber shows different optimum peak loading as it's has different strength which result is slightly different in properties. However, the behaviour of both samples stills same as the resilient modulus and the horizontal deformation produced the similar pattern. Therefore, the optimum crumb rubber content is 1% crumb rubber due to higher peak loading force than others that can sustain high load applied on the road.

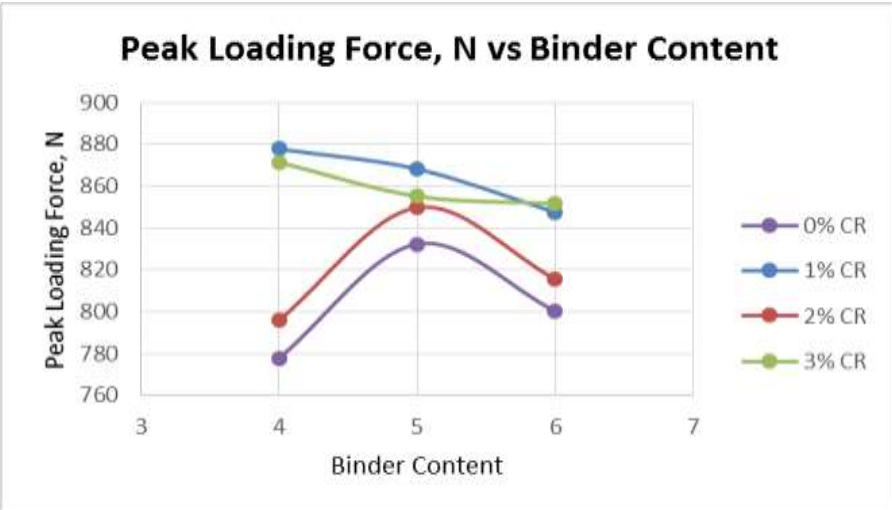

Figure 4.17 Peak Loading for all crumb rubber content

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

In this chapter, the conclusion and recommendation are based on the comparison and evaluation on the properties between mixes which are 0% CR, 1% CR, 2% CR and 3% CR. The conclusion made from the indirect tensile test using Marshall samples. Based on this study, it was observed that the performance of asphalt mixes using crumb rubber as binder in HMA was significantly affected with the addition of crumb rubber using wet process. Optimum crumb rubber content was found with the higher the binder content.

5.2 Conclusion

Table 5.1 Optimum crumb rubber content

Indirect Tensile properties	**4% binder content**	**5% binder content**	**6% binder content**
	Optimum crumb rubber content (%)		
Resilient Modulus (MPa)	1	1	2
Horizontal deformation (μm)	1	1	2
Peak Loading (N)	1	1	2

From the observation, 4%, 5% and 6% binder content give result in term of resilient modulus, horizontal deformation and peak loading for optimum percentage of crumb rubber content is 1% CR. On the other hand, 2% CR was differ from others because the optimum binder content get from the observation was 6% binder content. The effect of crumb rubber content was found to be the dominant factor in the resilient modulus, horizontal deformation and peak loading where an increase in rubber content in the mixes increase the viscosity and rutting resistance due to the highly elastic nature of the rubber particles. Based on the overall findings, the addition of 1% crumb rubber content was suggested in modifying the HMA mixes.

The conclusions that can be drawn based on the objective of this study are:

i. After modified AC14 mix properties with crumb rubber as an additive, the parameter still follow the controlled sample even though there is slight different for the parameter value.

ii. The result for optimum binder content for controlled and modified sample were similar.

iii. The result for optimum crumb rubber content in modified sample was 1% crumb rubber content in modifying in HMA mixes.

iv. The performance of the resilient modulus, horizontal deformation and peak loading will have good performance due to percentage of crumb rubber and binder content.

v. From this research, it is recommended that crumb rubber as binder in HMA can be used for road pavement as surface course that previously called wearing course.

5.3 Recommendations

It is recommended that further studies can be conducted on a variety of crumb rubber types, sizes and percentages and laboratory testing that are related to the research. Instead of rutting, other pavement deterioration due to fatigue, long term aging, skid resistance and stripping can be studied for next research. In addition, the most important effort is to compile all the results obtained from all research that are related and revised in order to make substance of it in improving the hot mix asphalt performance according to Malaysian condition.

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APPENDIX A
RESULTS FOR 0% CRUMB RUBBER (INDIRECT TENSILE TEST)

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 1a(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 1:40:45 PM
Project: Marshall Mix Design
Operator: control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1a(4%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	69.4	69.2	69.4				69.4	0.1
Diameter (mm)	101.1	101.1	101.1				101.1	0.0

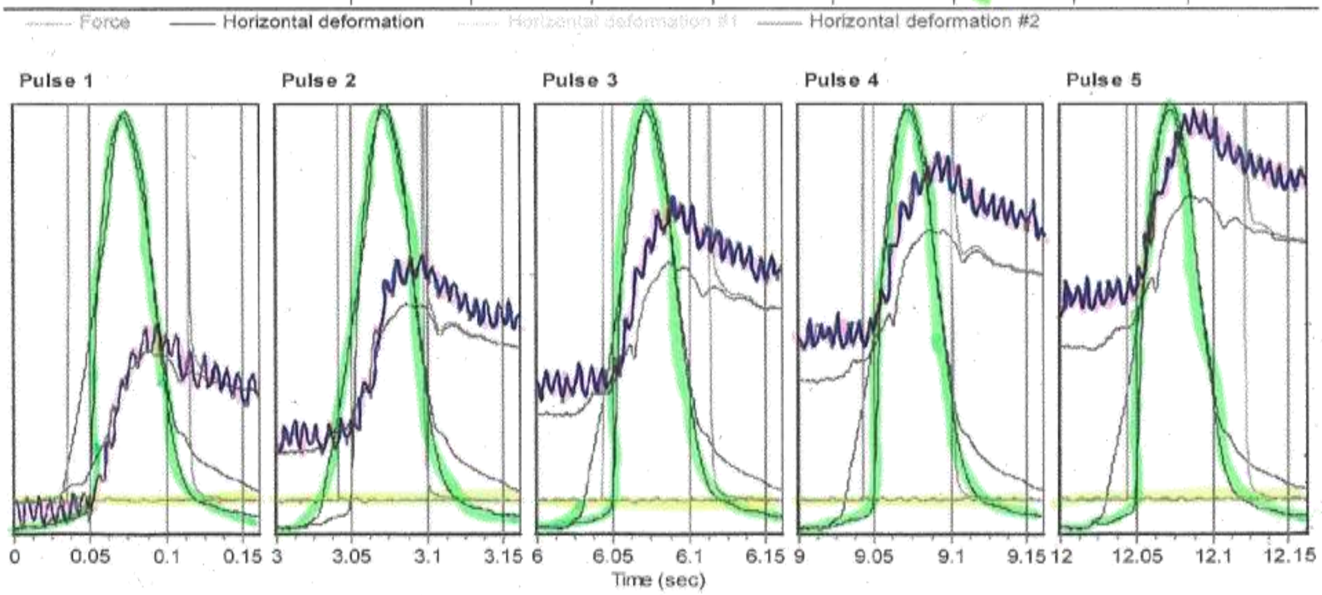
Cross-sectional area (mm²): 8026.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.6
Skin temperature (°C): 37.4

Perm't horiz'l def'n/pulse (μm): 2.262000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2571	2432	2231	1976	2157	2274	208.54	9.17
Total recoverable horiz. deform. (μm)	2.79	2.99	3.26	3.71	3.37	3.22	0.31	9.76
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	743.9	752.1	752.8	758.5	751.7	751.8	4.66	0.62
Recoverable Horiz. deform. #1 (μm)	0.02	0.02	0.04	0.02	0.01	0.02	0.01	37.56
Recoverable Horiz. deform. #2 (μm)	2.78	2.97	3.22	3.68	3.35	3.20	0.31	9.74
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	18.2	21.5	20.1	18.3	22.6	20.1	1.75	8.68



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 2a(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/4/2016 12:42:23 PM
Project: Marshall Mix Design
Operator: control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 2a(4%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.0	63.4	63.2				63.2	0.2
Diameter (mm)	101.3	101.3	101.3				101.3	

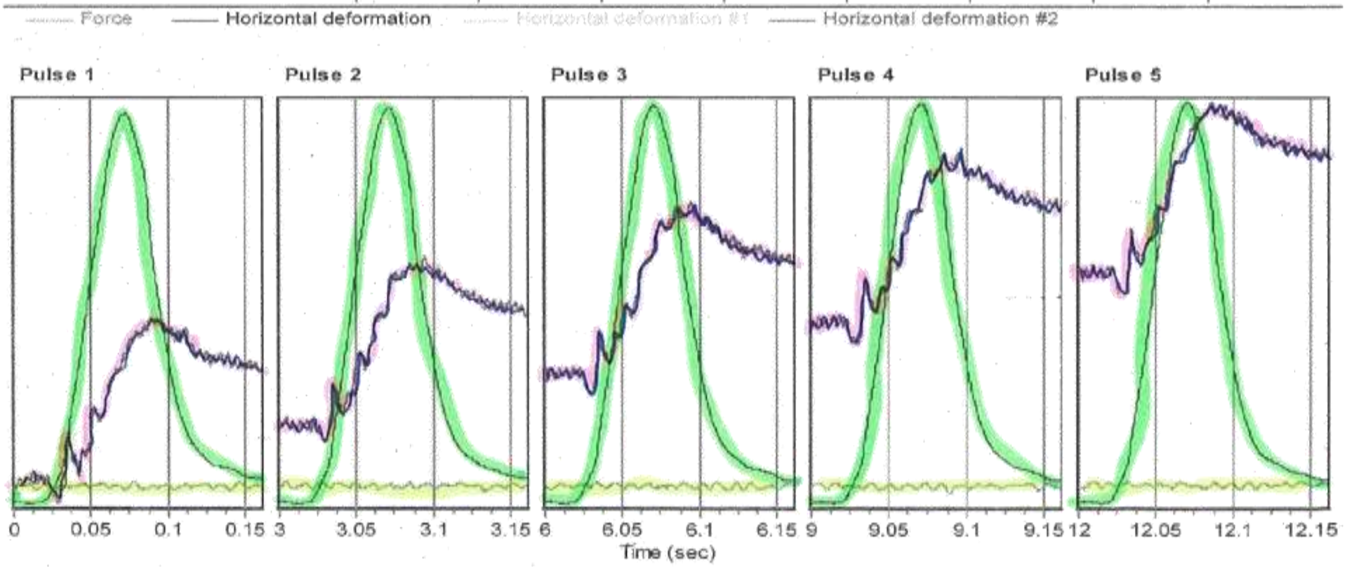
Cross-sectional area (mm²): 8054.7

Test Results

Conditioning pulses: 5
Core temperature (°C): 44.0
Skin temperature (°C): 39.1

Perm't horiz'l def'n/pulse (µm): 1.239000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6841	6421	6114	6293	6254	6385	248.56	3.89
Total recoverable horiz. deform. (µm)	1.22	1.32	1.40	1.37	1.38	1.34	0.06	4.71
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	788.3	801.2	805.8	811.2	813.6	804.1	8.96	1.11
Recoverable Horiz. deform. #1 (µm)	0.01	0.03	0.00	0.00	0.02	0.01	0.01	87.96
Recoverable Horiz. deform. #2 (µm)	1.21	1.30	1.39	1.37	1.36	1.33	0.07	4.90
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	21.5	21.7	21.2	20.1	19.8	20.9	0.77	3.68



Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 2a(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/4/2016 2:40:14 PM
Project: Marshall Mix Design
Operator: Control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2a(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	62.2	62.0	61.8				62.0	0.2
Diameter (mm)	101.6	101.6	101.6				101.6	

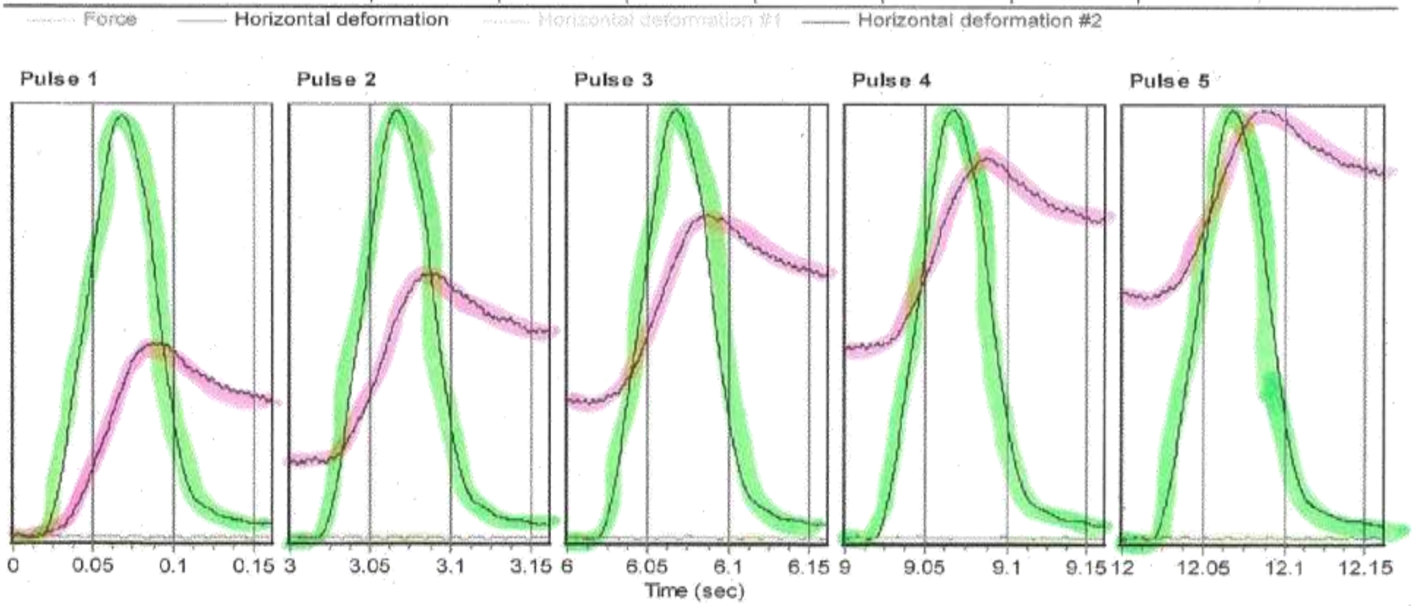
Cross-sectional area (mm²): 8100.9

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.9
Skin temperature (°C): 38.9

Perm't horiz'l def'n/pulse (μm): 3.636000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2420	2319	2205	2168	2126	2247	107.38	4.78
Total recoverable horiz. deform. (μm)	3.77	3.99	4.21	4.29	4.38	4.13	0.22	5.33
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	843.1	855.8	857.7	859.3	860.6	855.3	6.31	0.74
Recoverable Horiz. deform. #1 (μm)	0.01	0.00	0.04	0.01	0.01	0.02	0.01	74.87
Recoverable Horiz. deform. #2 (μm)	3.75	3.99	4.17	4.27	4.37	4.11	0.22	5.29
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	22.1	21.0	20.2	19.4	18.0	20.1	1.41	6.99



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 3a(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/4/2016 2:56:25 PM
Project: Marshall Mix Design
Operator: control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 3a(5%)
Remarks...

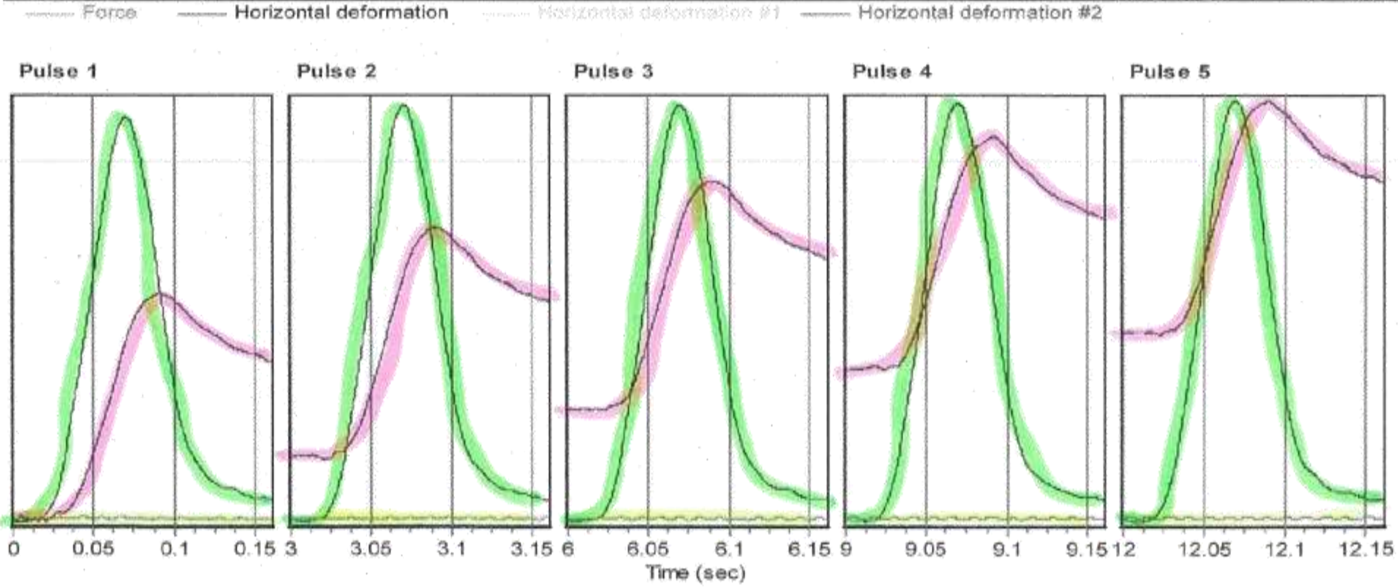
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	62.0	62.6	62.8				62.5	0.4
Diameter (mm)	101.1	101.1	101.1				101.1	0.0

Cross-sectional area (mm²): 8026.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.3
Skin temperature (°C): 38.5
Perm't horiz'l defn/pulse (µm): 2.291000
Perm't vert'l defn/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	1999	1829	1772	1703	1682	1797	113.55	6.32
Total recoverable horiz. deform. (µm)	4.24	4.76	4.93	5.13	5.23	4.86	0.35	7.13
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	790.6	811.1	813.4	813.7	819.3	809.6	9.88	1.22
Recoverable Horiz. deform. #1 (µm)	0.01	0.03	0.02	0.04	0.01	0.02	0.01	61.90
Recoverable Horiz. deform. #2 (µm)	4.24	4.73	4.90	5.09	5.22	4.84	0.34	7.09
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	18.3	21.3	19.2	22.6	22.4	20.8	1.73	8.33



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 1a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/4/2016 3:16:22 PM
Project: Marshall Mix Design
Operator: control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1a(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.1	63.2	62.9				63.1	0.2
Diameter (mm)	101.3	101.3	101.3				101.3	

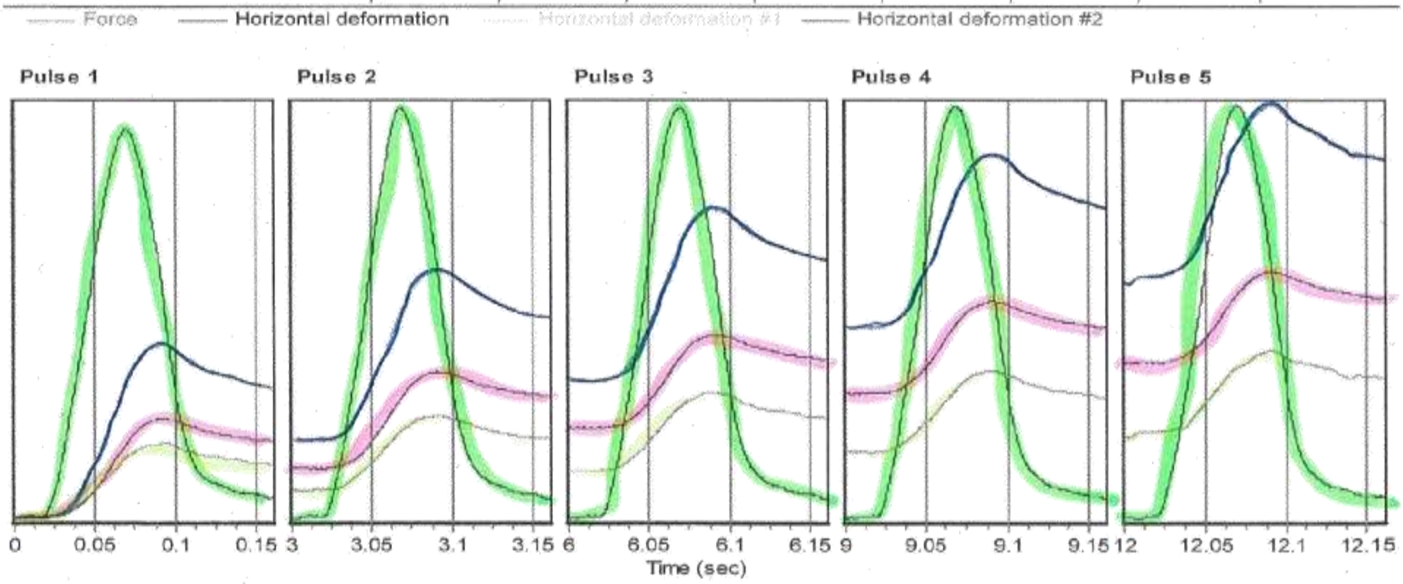
Cross-sectional area (mm²): 8064.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 43.0
Skin temperature (°C): 37.6

Perm't horiz'l defn/pulse (µm): 17.390000
Perm't vert'l defn/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	548	501	474	439	443	481	40.60	8.44
Total recoverable horiz. deform. (µm)	14.51	16.71	17.69	19.12	18.99	17.41	1.70	9.75
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	748.5	788.5	789.4	789.2	790.9	781.3	16.42	2.10
Recoverable Horiz. deform. #1 (µm)	7.05	8.31	8.90	9.86	9.46	8.72	0.98	11.28
Recoverable Horiz. deform. #2 (µm)	7.46	8.40	8.79	9.26	9.53	8.69	0.73	8.36
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	17.4	17.5	17.6	19.4	21.1	18.6	1.44	7.75



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\0%\Sample 2a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/4/2016 3:39:17 PM
Project: Marshall Mix Design
Operator: control sample
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 2a(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	61.5	61.7	61.6				61.6	0.1
Diameter (mm)	101.2	101.2	101.2				101.2	

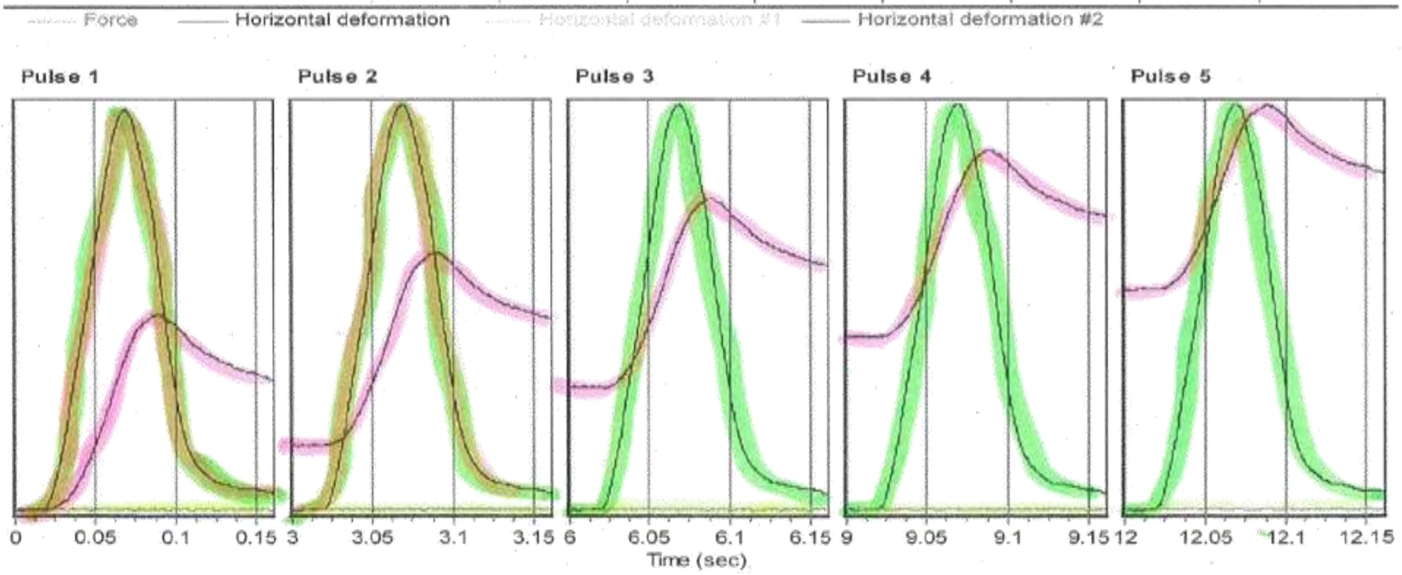
Cross-sectional area (mm²): 8042.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.9
Skin temperature (°C): 38.2

Perm't horiz'l def'n/pulse (µm): 5.829000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	1230	1191	1166	1157	1137	1176	32.00	2.72
Total recoverable horiz. deform. (µm)	7.18	7.51	7.66	7.72	7.85	7.58	0.23	3.05
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	811.7	822.5	821.4	821.8	820.5	819.6	4.00	0.49
Recoverable Horiz. deform. #1 (µm)	0.03	0.00	0.03	0.03	0.02	0.02	0.01	51.61
Recoverable Horiz. deform. #2 (µm)	7.15	7.51	7.63	7.69	7.83	7.56	0.23	3.06
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	19.2	18.3	18.7	19.6	20.7	19.3	0.83	4.30



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APPENDIX B

RESULTS FOR 1% CRUMB RUBBER (INDIRECT TENSILE TEST)

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\1%\Sample 2a(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 12:03:48 PM
Project: Marshall Mix Design
Operator: 1%(Dee)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2a(4%)
Remarks...

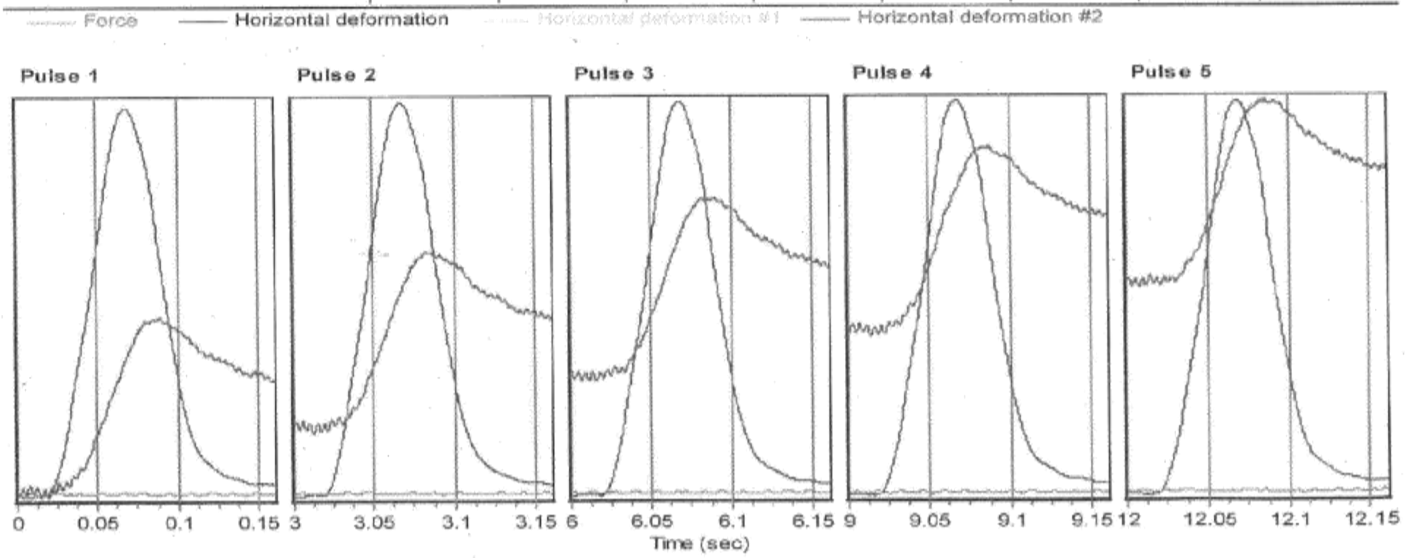
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.1	64.1	64.2				64.1	0.0
Diameter (mm)	101.2	101.2	101.2				101.2	

Cross-sectional area (mm²): 8042.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.8
Skin temperature (°C): 39.3
Perm't horiz'l defn/pulse (µm): 2.369000
Perm't vert'l defn/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	3601	3190	2902	2915	2747	3071	300.96	9.80
Total recoverable horiz. deform. (µm)	2.49	2.85	3.14	3.12	3.30	2.98	0.28	9.53
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	858.5	870.7	871.1	871.2	867.8	867.9	4.84	0.56
Recoverable Horiz. deform. #1 (µm)	0.01	0.03	0.00	0.01	0.09	0.03	0.03	127.29
Recoverable Horiz. deform. #2 (µm)	2.48	2.82	3.14	3.12	3.21	2.95	0.27	9.13
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	20.4	17.8	17.5	20.3	21.0	19.4	1.47	7.55



Industrial Process Controls Global Ltd UTS003 Ver:1.25 (1.25)
Printed 11/9/2016 11:54:16 AM

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\1%\Sample 1a(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 12:31:44 PM
Project: Marshall Mix Design
Operator: 1%(DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1a(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	66.3	66.2	66.2				66.2	0.1
Diameter (mm)	101.0	101.0	101.0				101.0	

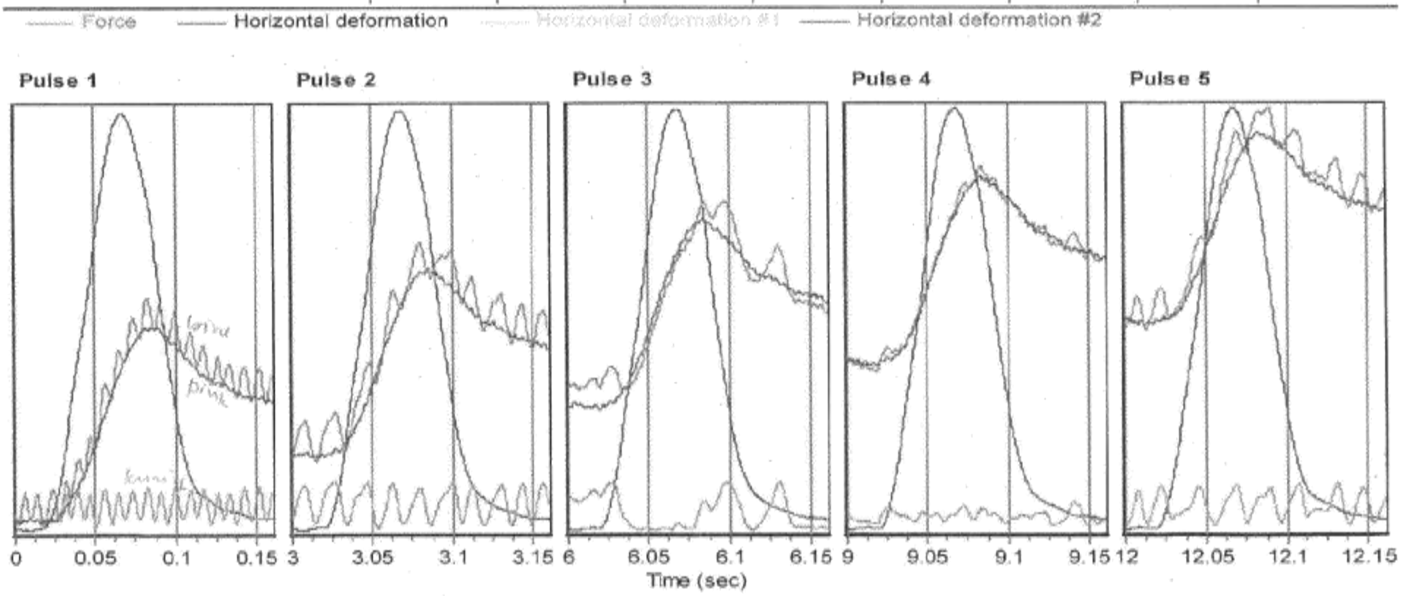
Cross-sectional area (mm²): 8011.8

Test Results

Conditioning pulses: 5
Core temperature (°C): 45.1
Skin temperature (°C): 39.6

Perm't horiz'l def'n/pulse (µm): 2.819000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2223	2413	2188	2158	2543	2305	148.57	6.44
Total recoverable horiz. deform. (µm)	3.92	3.64	4.03	4.10	3.48	3.83	0.24	6.16
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	861.1	868.0	871.7	874.2	874.8	870.0	5.06	0.58
Recoverable Horiz. deform. #1 (µm)	0.73	0.19	0.80	0.42	0.03	0.43	0.30	68.88
Recoverable Horiz. deform. #2 (µm)	3.19	3.45	3.23	3.68	3.45	3.40	0.18	5.17
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	21.4	19.2	18.8	18.5	17.9	19.2	1.20	6.24



Industrial Process Controls Global Ltd UTS003 Ver:1.25 (1.25) Printed 11/9/2016 11:53:00 AM

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\1%\Sample 3a(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 12:55:01 PM
Project: Marshall Mix Design
Operator: 1%(DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 3a(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	72.2	71.5	72.0				71.9	0.3
Diameter (mm)	101.0	101.0	101.0				101.0	

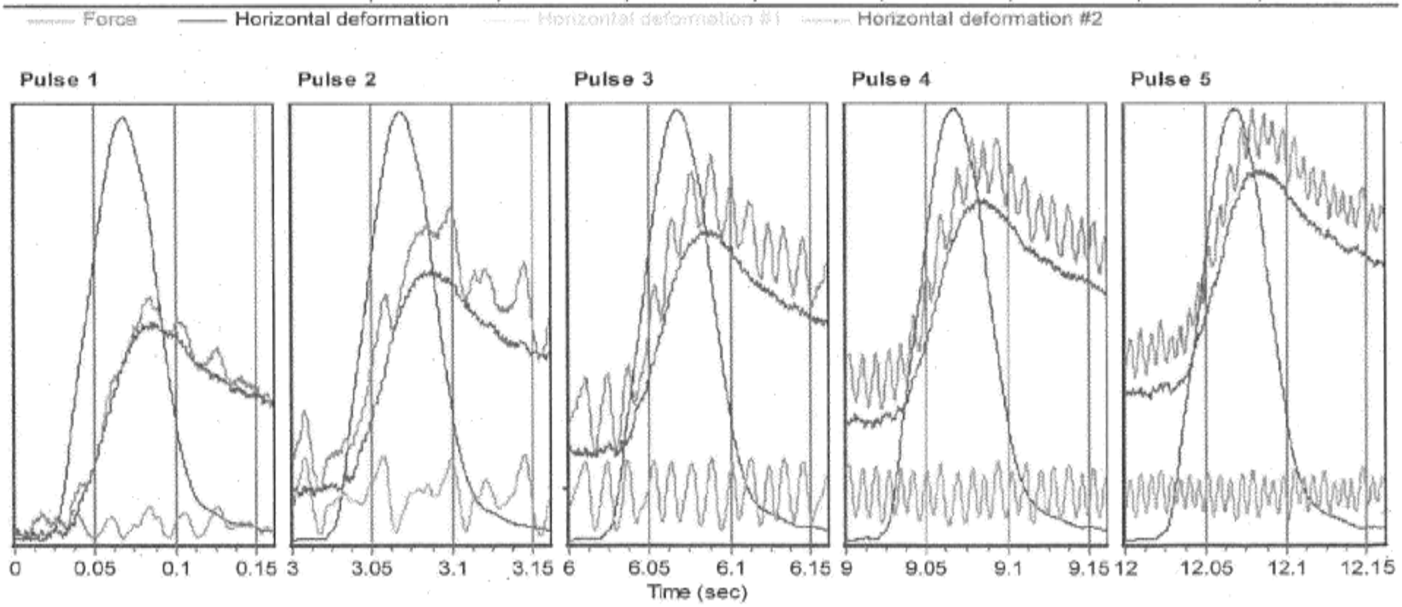
Cross-sectional area (mm²): 8015.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 43.2
Skin temperature (°C): 39.5

Perm't horiz'l def'n/pulse (µm): 1.089000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	3417	2694	2898	2592	2538	2828	319.32	11.29
Total recoverable horiz. deform. (µm)	2.33	3.00	2.80	3.14	3.20	2.89	0.31	10.83
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	853.6	866.7	870.2	872.3	870.4	866.6	6.77	0.78
Recoverable Horiz. deform. #1 (µm)	0.04	0.66	0.13	0.54	0.52	0.38	0.25	64.90
Recoverable Horiz. deform. #2 (µm)	2.29	2.34	2.67	2.60	2.68	2.51	0.17	6.67
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	20.1	18.1	18.1	18.0	18.2	18.5	0.80	4.32



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\1%\Sample 1a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 1:05:55 PM
Project: Marshall Mix Design
Operator: 1%(Dee)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 1a(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.8	63.4	63.8				63.7	0.2
Diameter (mm)	101.0	101.0	101.0				101.0	

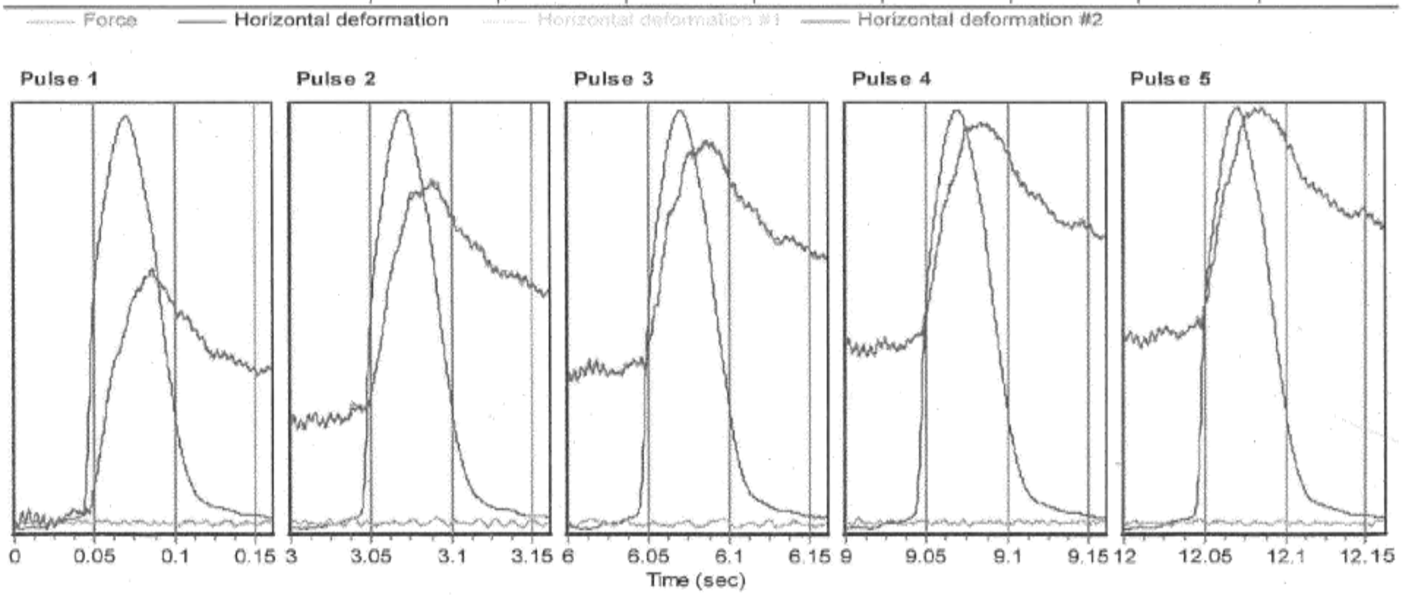
Cross-sectional area (mm²): 8018.2

Test Results

Conditioning pulses: 5
Core temperature (°C): 43.5
Skin temperature (°C): 38.6

Perm't horiz'l def'n/pulse (μm): 0.973600
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	4658	3805	3646	3422	3639	3834	429.71	11.21
Total recoverable horiz. deform. (μm)	1.77	2.20	2.29	2.44	2.32	2.20	0.23	10.42
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	784.4	794.2	792.2	794.5	801.7	793.4	5.54	0.70
Recoverable Horiz. deform. #1 (μm)	0.03	0.03	0.03	0.02	0.02	0.02	0.01	21.69
Recoverable Horiz. deform. #2 (μm)	1.74	2.17	2.26	2.43	2.30	2.18	0.23	10.69
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	18.8	19.7	22.2	20.0	17.9	19.7	1.44	7.28



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\1%\Sample 2a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/8/2016 1:21:07 PM
Project: Marshall Mix Design
Operator: 1%(DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2a(6%)
Remarks...

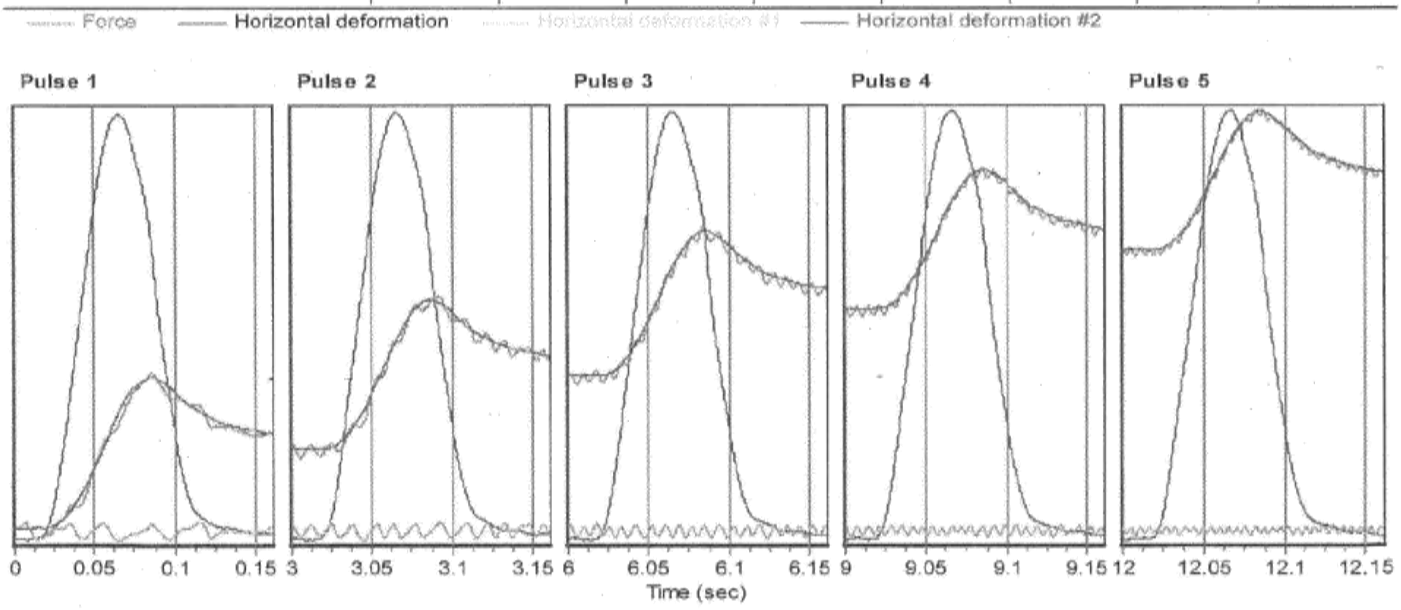
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.4	63.2	63.2				63.3	0.2
Diameter (mm)	101.0	101.0	101.0				101.0	

Cross-sectional area (mm²): 8010.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 42.4
Skin temperature (°C): 38.3
Perm't horiz'l def'n/pulse (µm): 8.303000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2074	1954	1857	1833	1743	1892	113.13	5.98
Total recoverable horiz. deform. (µm)	4.57	4.88	5.15	5.24	5.51	5.07	0.32	6.31
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	895.2	899.5	902.2	906.8	906.0	901.9	4.28	0.47
Recoverable Horiz. deform. #1 (µm)	0.09	0.23	0.22	0.23	0.27	0.21	0.06	29.32
Recoverable Horiz. deform. #2 (µm)	4.48	4.65	4.93	5.01	5.24	4.86	0.27	5.50
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	21.9	21.3	20.6	17.8	18.1	19.9	1.67	8.35



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APPENDIX C
RESULTS FOR 2% CRUMB RUBBER (INDIRECT TENSILE TEST)

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 1a(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:05:33 PM
Project: Marshall Mix Design
Operator: 2% (DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1a(4%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.2	63.2	63.2				63.2	0.0
Diameter (mm)	101.2	101.2	101.2				101.2	0.0

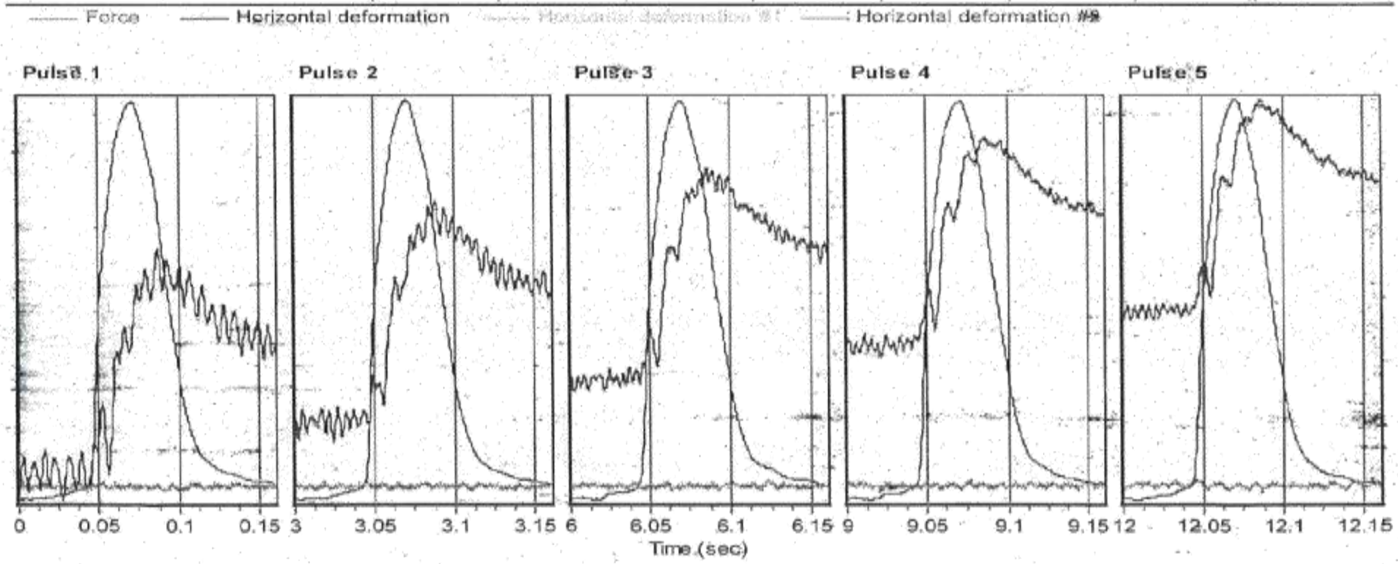
Cross-sectional area (mm²): 8046.8

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.3
Skin temperature (°C): 38.8

Perm't horiz'l def'n/pulse (µm): 1.432000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2741	2641	2687	2627	2661	2671	40.25	1.51
Total recoverable horiz. deform. (µm)	3.07	3.21	3.14	3.20	3.17	3.16	0.05	1.59
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	793.1	798.6	795.5	792.5	796.1	795.2	2.21	0.28
Recoverable Horiz. deform. #1 (µm)	0.03	0.08	0.03	0.05	0.00	0.04	0.02	65.87
Recoverable Horiz. deform. #2 (µm)	3.04	3.13	3.10	3.15	3.17	3.12	0.04	1.43
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	19.9	18.9	19.1	21.3	21.5	20.1	1.06	5.28



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 2a(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:14:27 PM
Project: Marshall Mix Design
Operator: 2% Dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 2a(4%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.0	64.0	63.9				64.0	0.0
Diameter (mm)	101.5	101.5	101.5				101.5	0.0

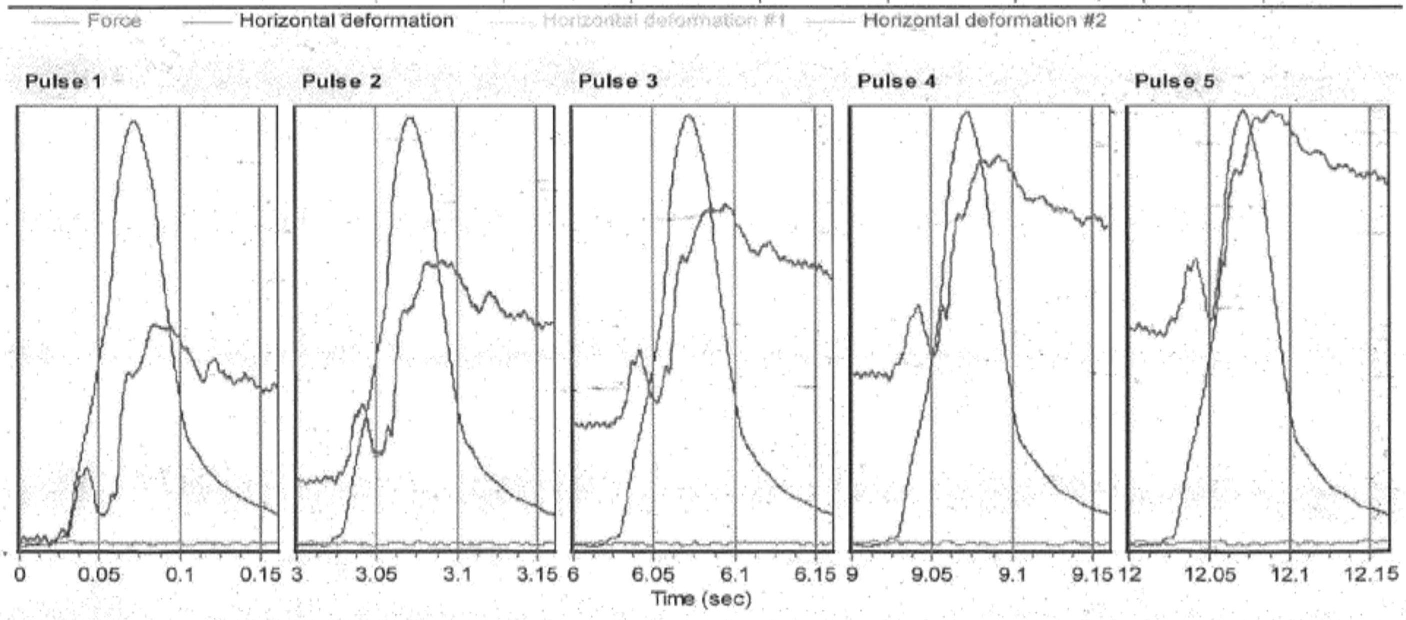
Cross-sectional area (mm²): 8086.6

Test Results

Conditioning pulses: 5
Core temperature (°C): 41.2
Skin temperature (°C): 38.8

Perm't horiz'l def'n/pulse (µm): 1.399000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	3860	3697	3581	3470	3436	3609	155.50	4.31
Total recoverable horiz. deform. (µm)	2.14	2.25	2.33	2.41	2.46	2.32	0.11	4.91
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	788.7	794.5	796.5	799.9	805.9	797.1	5.72	0.72
Recoverable Horiz. deform. #1 (µm)	0.01	0.00	0.00	0.02	0.00	0.01	0.01	86.74
Recoverable Horiz. deform. #2 (µm)	2.13	2.25	2.33	2.40	2.46	2.31	0.12	5.00
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	17.9	19.2	21.0	22.0	19.0	19.8	1.46	7.38



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 1a(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:27:22 PM
Project: Marshall Mix Design
Operator: 2% (DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 28

Specimen Information

Identification: Sample 1a(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	65.6	65.4	64.8				65.2	0.4
Diameter (mm)	101.0	101.0	101.0				101.0	

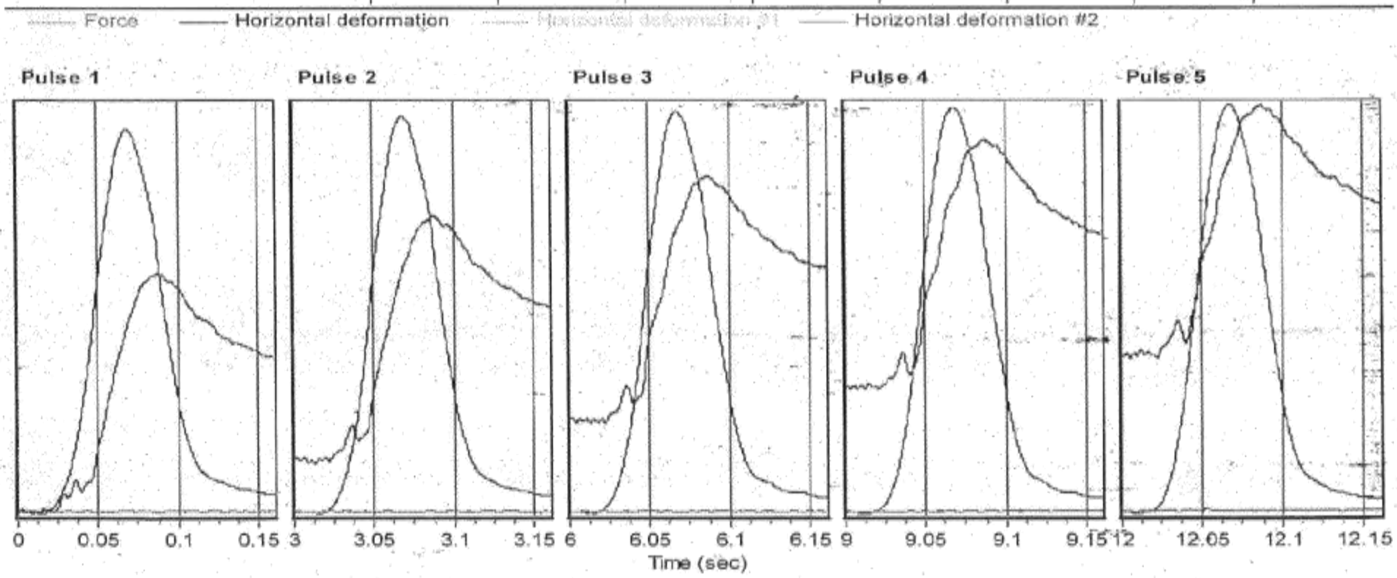
Cross-sectional area (mm²): 8015.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.6
Skin temperature (°C): 37.8

Perm't horiz'l def'n/pulse (µm): 1.332000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2466	2333	2268	2229	2204	2300	93.56	4.07
Total recoverable horiz. deform. (µm)	3.36	3.67	3.82	3.91	3.99	3.75	0.22	5.88
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	807.8	833.2	844.3	849.4	855.8	838.1	16.85	2.01
Recoverable Horiz. deform. #1 (µm)	0.02	0.01	0.02	0.01	0.00	0.01	0.01	61.20
Recoverable Horiz. deform. #2 (µm)	3.34	3.66	3.81	3.90	3.99	3.74	0.23	6.08
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	19.4	20.7	21.2	21.7	22.2	21.0	0.97	4.60



Industrial Process Controls Global Ltd UTS003 Ver:1.25 (1.25)
Printed 5/16/2017 4:39:41 PM

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 2a(5%).D003
Template file name: C:\IPCglobal\UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:37:53 PM
Project: Marshall Mix Design
Operator: 2%Dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2a(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.4	63.5	63.2				63.4	0.1
Diameter (mm)	101.5	101.5	101.5				101.5	

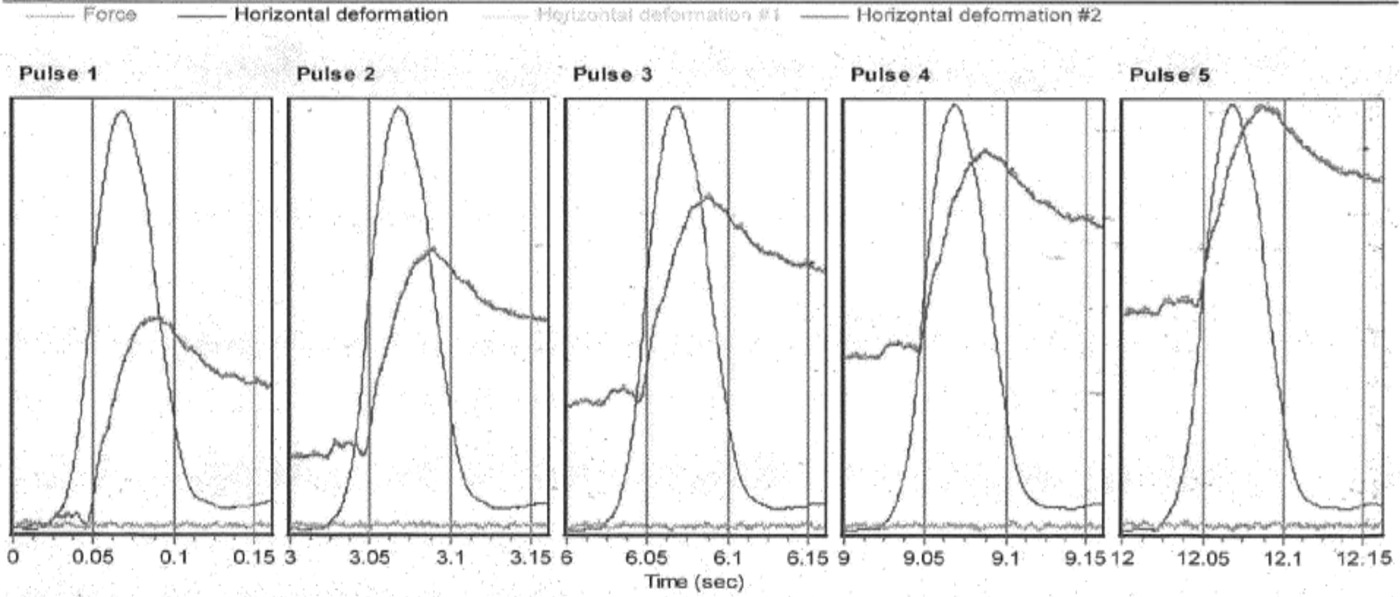
Cross-sectional area (mm²): 8083.4

Test Results

Conditioning pulses: 5
Core temperature (°C): 41.1
Skin temperature (°C): 38.0

Perm't horiz'l defn/pulse (µm): 2.127000
Perm't vert'l defn/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	3113	2752	2691	2685	2674	2783	167.34	6.01
Total recoverable horiz. deform. (µm)	2.89	3.30	3.39	3.42	3.44	3.29	0.21	6.24
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	850.0	859.0	862.5	868.0	869.2	861.7	6.93	0.80
Recoverable Horiz. deform. #1 (µm)	0.02	0.12	0.07	0.03	0.05	0.06	0.03	56.52
Recoverable Horiz. deform. #2 (µm)	2.86	3.18	3.32	3.38	3.38	3.23	0.20	6.08
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	22.4	21.6	19.8	18.7	18.8	20.2	1.49	7.37



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 1a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:45:49 PM
Project: Marshall Mix Design
Operator: 2% (DEE)
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1a(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.1	63.5	63.7				63.4	0.3
Diameter (mm)	101.5	101.5	101.5				101.5	

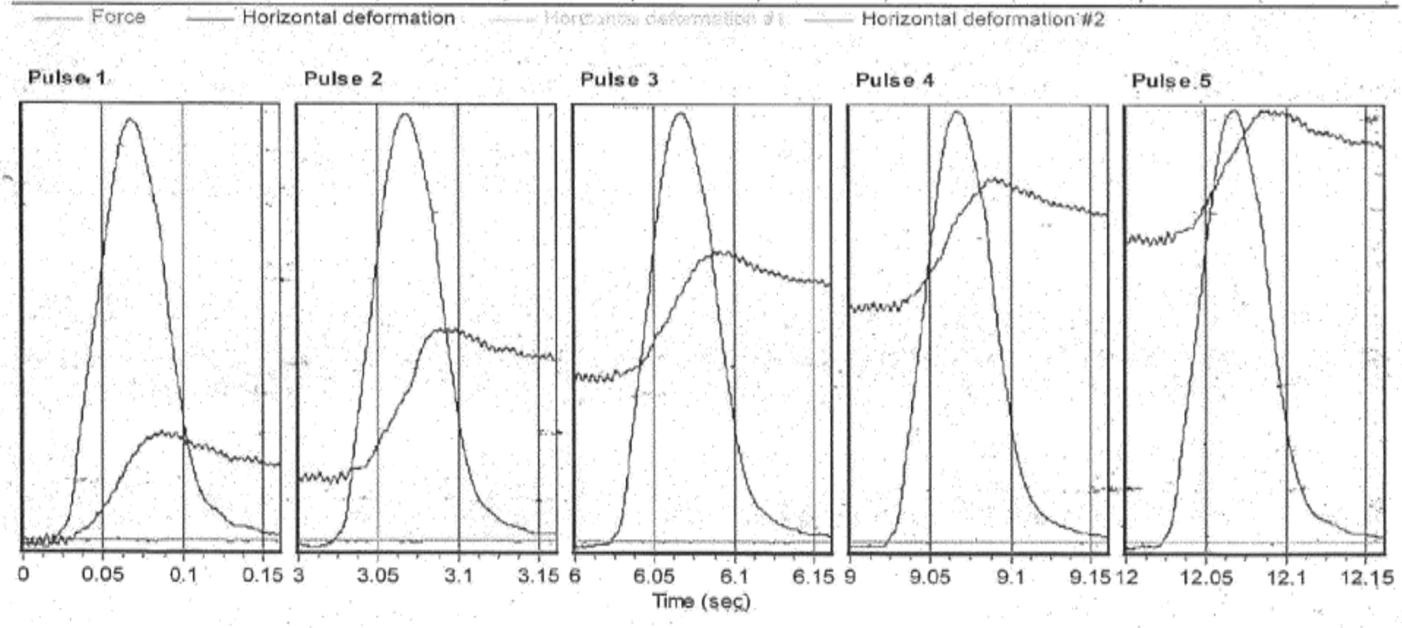
Cross-sectional area (mm²): 8089.8

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.7
Skin temperature (°C): 37.3

Perm't horiz'l def'n/pulse (μm): 4.831000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5745	5287	4948	4324	4122	4885	600.31	12.29
Total recoverable horiz. deform. (μm)	1.54	1.70	1.83	2.10	2.21	1.88	0.25	13.27
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	839.5	848.8	857.0	860.8	863.7	854.0	8.79	1.03
Recoverable Horiz. deform. #1 (μm)	0.00	0.02	0.01	0.02	0.01	0.01	0.01	55.24
Recoverable Horiz. deform. #2 (μm)	1.54	1.67	1.82	2.06	2.21	1.86	0.25	13.29
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	21.2	22.6	19.6	18.8	18.7	20.2	1.48	7.33



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\2%\Sample 2a(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/11/2016 4:53:59 PM
Project: Marshall Mix Design
Operator: 2%Dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2a(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.4	63.7	63.6				63.6	0.1
Diameter (mm)	101.0	101.0	101.0				101.0	

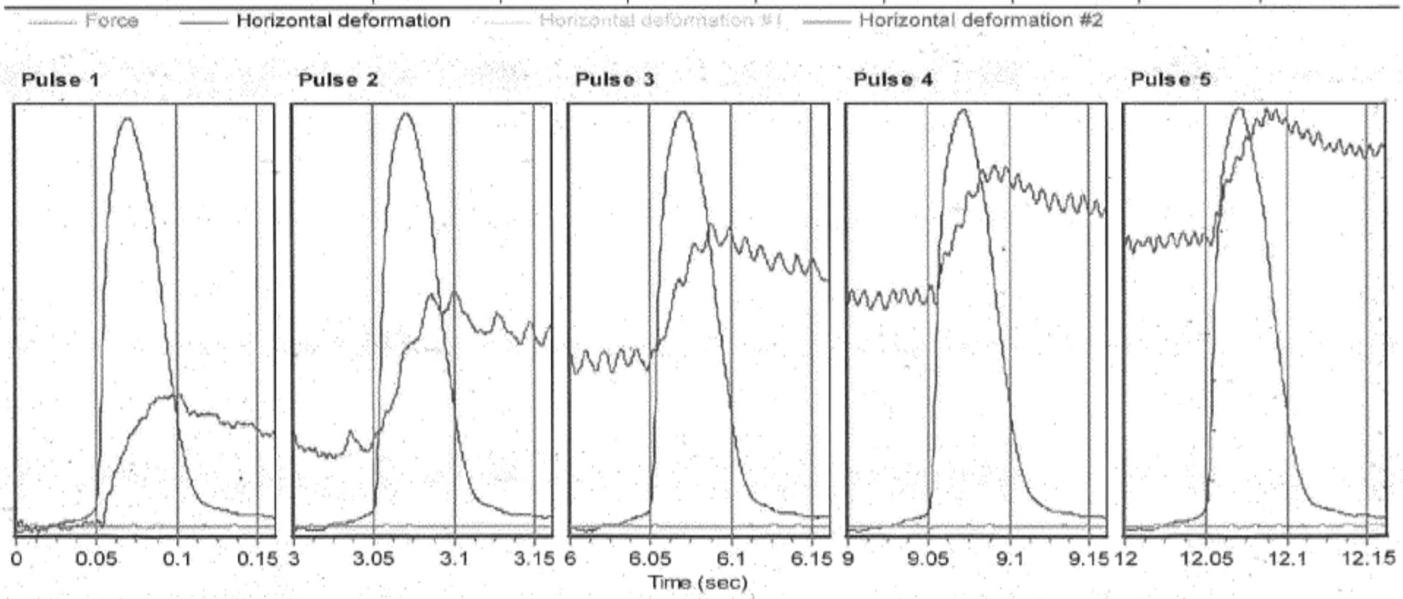
Cross-sectional area (mm²): 8011.8

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.7
Skin temperature (°C): 37.3

Perm't horiz'l def'n/pulse (µm): 5.580000
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	4683	3057	2521	2536	2511	3062	837.04	27.34
Total recoverable horiz. deform. (µm)	1.73	2.67	3.25	3.25	3.29	2.84	0.60	21.15
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	768.6	775.4	777.4	781.3	784.9	777.5	5.54	0.71
Recoverable Horiz. deform. #1 (µm)	0.02	0.03	0.03	0.02	0.03	0.03	0.01	24.77
Recoverable Horiz. deform. #2 (µm)	1.71	2.64	3.22	3.23	3.27	2.81	0.60	21.33
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	17.6	20.5	21.8	20.0	19.0	19.8	1.40	7.08



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APPENDIX D
RESULTS FOR 3% CRUMB RUBBER (INDIRECT TENSILE TEST)

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\3%\Sample 2(4%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/16/2016 4:10:33 PM
Project: Marshall Mix Design
Operator: 3% Dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 2(4%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.4	64.6	64.3				64.4	0.2
Diameter (mm)	100.7	100.7	100.7				100.7	

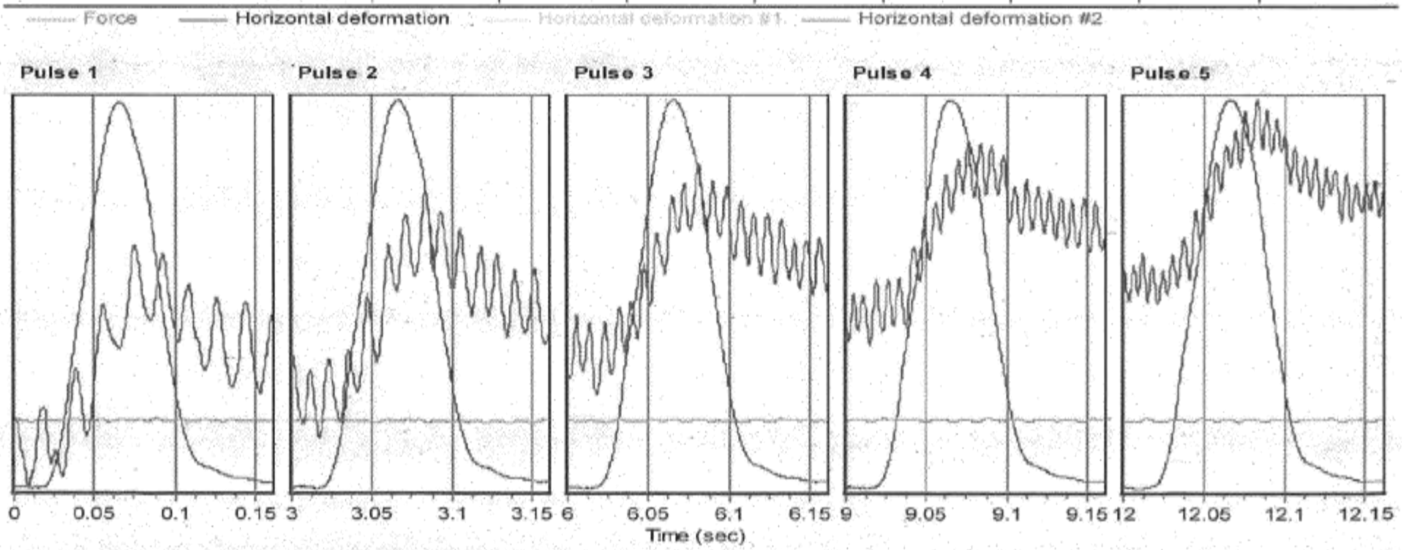
Cross-sectional area (mm²): 7964.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.5
Skin temperature (°C): 38.5

Perm't horiz'l def'n/pulse (μm): 0.813400
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6793	4094	4581	5779	4916	5233	954.72	18.25
Total recoverable horiz. deform. (μm)	1.36	2.28	2.04	1.61	1.89	1.84	0.32	17.44
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	891.0	897.0	897.7	895.5	895.0	895.2	2.32	0.26
Recoverable Horiz. deform. #1 (μm)	0.00	0.02	0.00	0.01	0.02	0.01	0.01	67.61
Recoverable Horiz. deform. #2 (μm)	1.36	2.26	2.03	1.60	1.87	1.82	0.32	17.30
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	19.7	20.4	21.1	21.4	22.1	20.9	0.82	3.90



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\3%\Sample 1(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/16/2016 4:19:30 PM
Project: Marshall Mix Design
Operator: 3% Dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.5	63.4	63.1				63.3	0.2
Diameter (mm)	100.6	100.6	100.6				100.6	

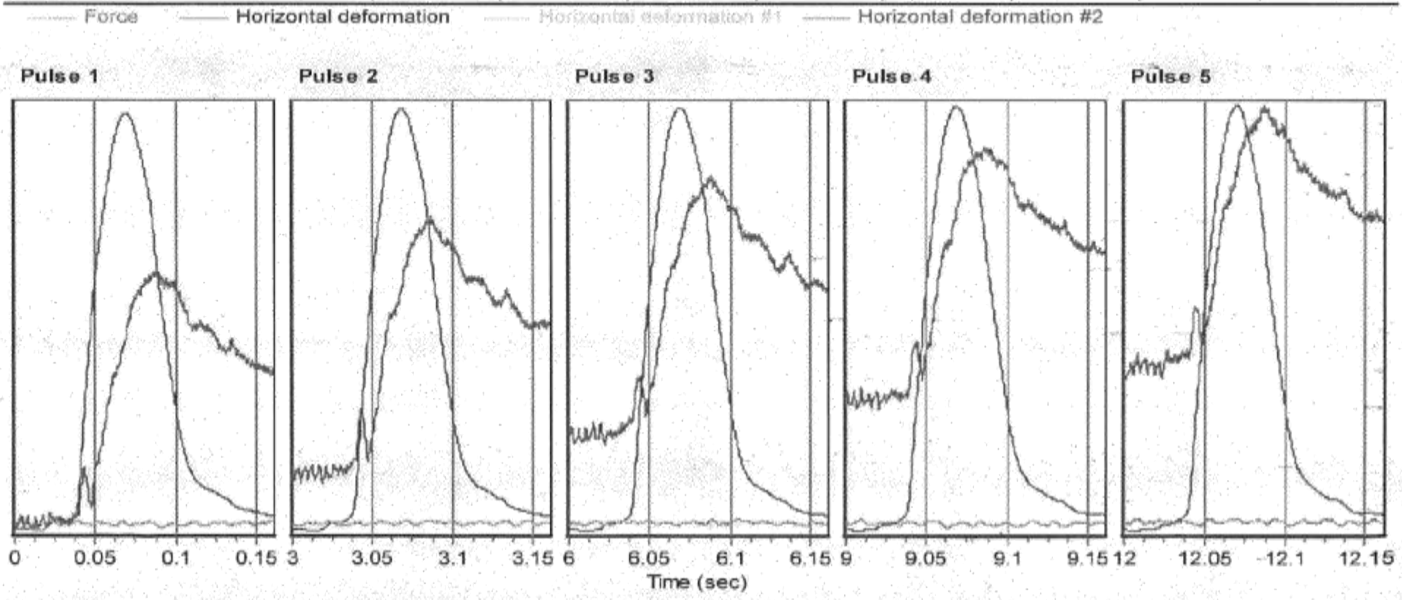
Cross-sectional area (mm²): 7943.8

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.0
Skin temperature (°C): 38.3

Perm't horiz'l def'n/pulse (µm): 0.804200
Perm't vert'l def'n/pulse (µm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	3749	3631	3617	3452	3322	3554	149.92	4.22
Total recoverable horiz. deform. (µm)	2.33	2.43	2.44	2.56	2.68	2.49	0.12	4.85
Total recoverable vert. deform. (µm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	825.2	832.8	833.6	836.2	840.3	833.6	4.98	0.60
Recoverable Horiz. deform. #1 (µm)	0.03	0.04	0.04	0.00	0.01	0.02	0.01	61.71
Recoverable Horiz. deform. #2 (µm)	2.30	2.38	2.40	2.56	2.66	2.46	0.13	5.32
Recoverable Vert. deform. #1 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (µm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	20.3	21.0	21.7	20.8	20.3	20.8	0.52	2.50



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\3%\Sample 2(5%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/16/2016 4:24:25 PM
Project: Marshall Mix Design
Operator: 3%
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2(5%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.3	63.6	63.3				63.4	0.2
Diameter (mm)	100.8	100.8	100.8				100.8	

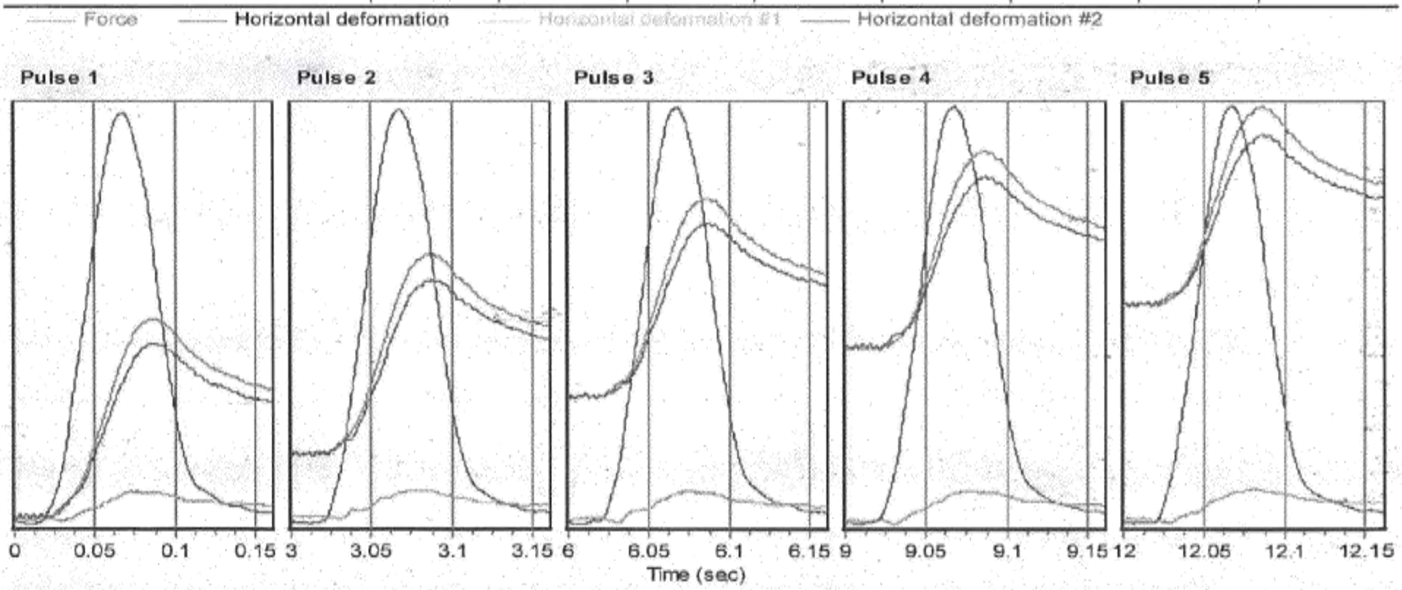
Cross-sectional area (mm²): 7983.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 41.5
Skin temperature (°C): 38.0

Perm't horiz'l def'n/pulse (μm): 3.248000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2144	1991	1944	1888	1864	1966	99.12	5.04
Total recoverable horiz. deform. (μm)	4.27	4.64	4.79	4.93	5.01	4.73	0.26	5.58
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	865.3	873.7	880.2	881.4	884.4	877.0	6.79	0.77
Recoverable Horiz. deform. #1 (μm)	0.72	0.90	0.88	0.87	0.94	0.86	0.08	8.83
Recoverable Horiz. deform. #2 (μm)	3.55	3.74	3.91	4.07	4.08	3.87	0.20	5.19
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	23.2	22.6	20.7	21.1	19.5	21.4	1.33	6.20



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\3%\Sample 1(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/16/2016 4:28:53 PM
Project: Marshall Mix Design
Operator: 3% dee
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4

Contact force (N): 20

Specimen Information

Identification: Sample 1(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.4	63.5	63.4				63.4	0.1
Diameter (mm)	104.5	104.5	104.5				104.5	

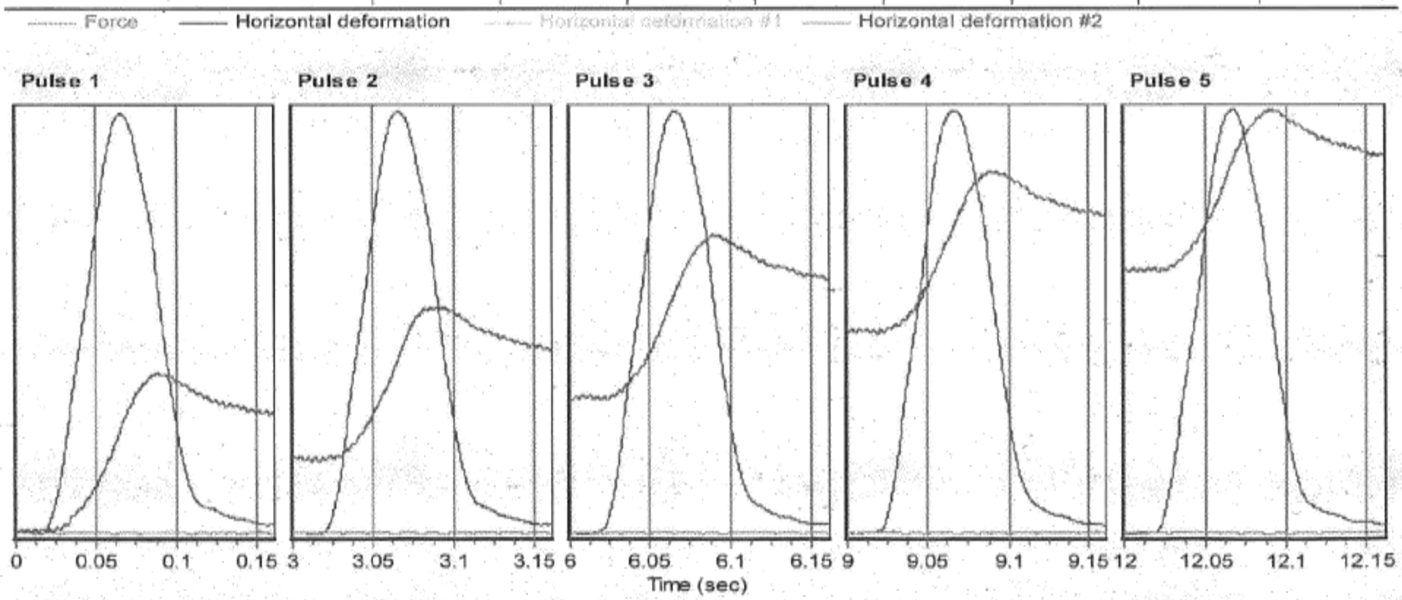
Cross-sectional area (mm²): 8580.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 41.6
Skin temperature (°C): 38.7

Perm't horiz'l def'n/pulse (μm): 4.779000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2905	2642	2511	2477	2448	2597	167.94	6.47
Total recoverable horiz. deform. (μm)	3.14	3.47	3.65	3.70	3.76	3.54	0.23	6.38
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	862.3	866.5	866.8	868.1	871.4	867.0	2.93	0.34
Recoverable Horiz. deform. #1 (μm)	0.01	0.00	0.03	0.03	0.02	0.02	0.01	58.96
Recoverable Horiz. deform. #2 (μm)	3.13	3.46	3.62	3.67	3.74	3.52	0.22	6.21
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	21.3	20.5	21.5	20.6	19.3	20.6	0.77	3.73



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Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. & vert. lvdts, assumed Poisson's ratio)
Data fileName: C:\Users\UMP\Desktop\Crumb rubber\3%\Sample 2(6%).D003
Template file name: C:\IPCglobal UTS\003 IT Modulus Test\Templates\default wani.P003
Test date & time: 11/16/2016 4:33:24 PM
Project: Marshall Mix Design
Operator: 1% Areesa
Comments:

Setup Parameters

Target temperature (°C): 40
Loading pulse width (ms): 100
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 1000
Estimated Poisson's ratio: 0.4
Contact force (N): 20

Specimen Information

Identification: Sample 2(6%)
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.5	63.4	63.1				63.3	0.2
Diameter (mm)	101.2	101.2	101.2				101.2	

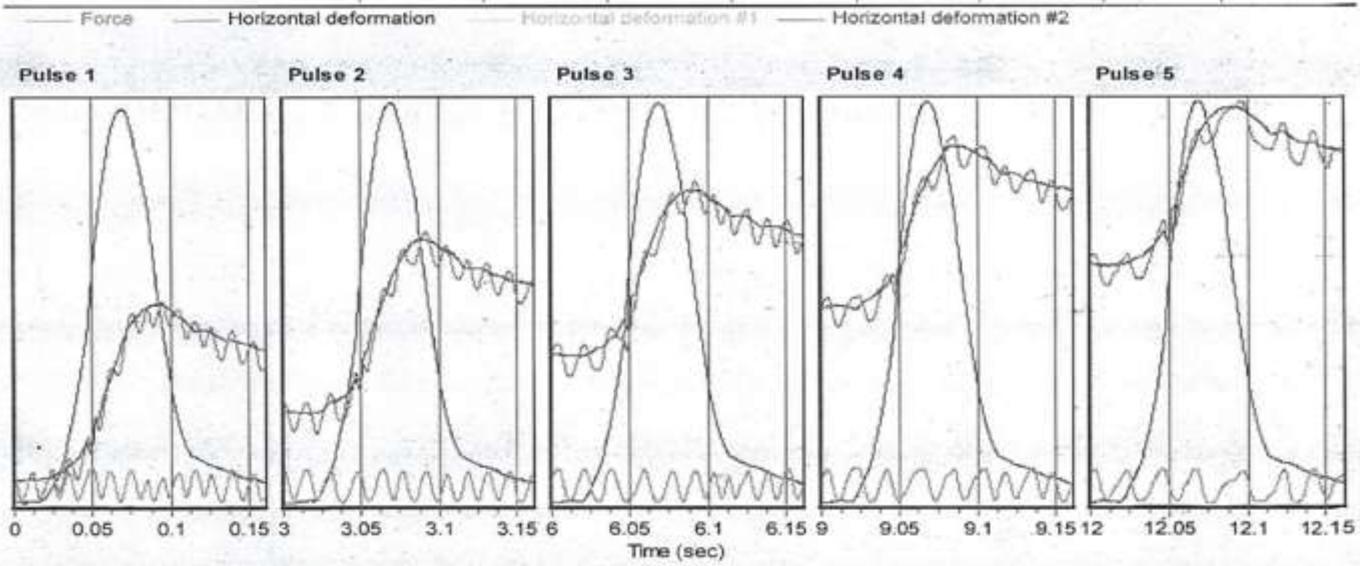
Cross-sectional area (mm²): 8048.4

Test Results

Conditioning pulses: 5
Core temperature (°C): 40.2
Skin temperature (°C): 38.3

Perm't horiz'l def'n/pulse (μm): 3.414000
Perm't vert'l def'n/pulse (μm): 0.000000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	2182	2096	2005	2089	1809	2036	126.69	6.22
Total recoverable horiz. deform. (μm)	3.99	4.23	4.43	4.26	4.92	4.37	0.31	7.13
Total recoverable vert. deform. (μm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak loading force (N)	823.2	837.4	838.5	841.4	841.7	836.4	6.80	0.81
Recoverable Horiz. deform. #1 (μm)	0.18	0.15	0.24	0.07	0.74	0.28	0.24	85.62
Recoverable Horiz. deform. #2 (μm)	3.81	4.08	4.18	4.19	4.19	4.09	0.15	3.57
Recoverable Vert. deform. #1 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Recoverable Vert. deform. #2 (μm)	Error	Error	Error	Error	Error	0.00	0.00	0.00
Seating force (N)	19.7	18.5	18.4	18.3	17.9	18.6	0.60	3.23



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APPENDIX E
0% OF CR (CONTROLLED SAMPLES)

Sample		Resilient Modulus, Mpa
4%	1	2274
	2	6385
5%	1	2247
	2	1797
6%	1	481
	2	1176

Sample		Horizontal Deformation, µm
4%	1	3.22
	2	1.34
5%	1	4.13
	2	4.86
6%	1	17.41
	2	7.58

Sample		Peak Loading, N
4%	1	751.80
	2	804.10
5%	1	855.30
	2	809.60
6%	1	781.30
	2	819.60

APPENDIX F
1% OF CR

Sample		Resilient Modulus, Mpa
4%	1	3071
	2	4158
5%	1	2305
	2	2828
6%	1	3834
	2	1892

Sample		Horizontal Deformation, µm
4%	1	2.98
	2	2.61
5%	1	3.83
	2	2.89
6%	1	2.20
	2	5.07

Sample		Peak Loading Force, N
4%	1	867.90
	2	887.80
5%	1	870.00
	2	866.60
6%	1	793.40
	2	901.90

APPENDIX G
2% OF CR

Sample		Resilient Modulus, Mpa
4%	1	2671
	2	3609
5%	1	2300
	2	2783
6%	1	4885
	2	3062

Sample		Horizontal Deformation, µm
4%	1	3.16
	2	2.32
5%	1	3.75
	2	3.29
6%	1	1.88
	2	2.84

Sample		Peak Loading Force, N
4%	1	795.20
	2	797.10
5%	1	838.10
	2	861.70
6%	1	854.00
	2	777.50

APPENDIX H
3% OF CR

Sample		Resilient Modulus, Mpa
4%	1	4027
	2	5233
5%	1	3554
	2	1966
6%	1	2597
	2	2036

Sample		Horizontal Deformation, µm
4%	1	2.25
	2	1.84
5%	1	2.49
	2	4.73
6%	1	3.54
	2	4.37

Sample		Peak Loading Force, N
4%	1	847.80
	2	895.20
5%	1	833.60
	2	877.00
6%	1	867.00
	2	836.40

APPENDIX I
COMPARISON BETWEEN 0% AND 1-3% CR

Sample	Resilient Modulus, Mpa			
	0%	**1%**	**2%**	**3%**
4%	4329.50	3614.50	3140.00	4630.00
5%	2022.00	2566.50	2541.50	2760.00
6%	828.50	2863.00	3973.50	2316.50

Sample	Horizontal Deformation, µm			
	0%	**1%**	**2%**	**3%**
4%	2.28	2.80	2.74	2.05
5%	4.50	3.36	3.52	3.61
6%	12.50	3.64	2.36	3.96

Sample	Peak Loading Force, N			
	0%	**1%**	**2%**	**3%**
4%	777.95	877.85	796.15	871.50
5%	832.45	868.30	849.90	855.30
6%	800.45	847.65	815.75	851.70

APPENDIX J
SOFTENING POINT OF BITUMEN

Timer Reading (Minutes)	**Temperature (Deg. Celcius**
0	22.1
1	22.3
2	22.8
3	22.9
4	23.1
5	23.4
6	23.6
7	24.1
8	24.4
9	24.8
10	25.2
11	25.6
12	26.2
13	26.7
14	27.2
15	27.9
16	28.7
17	29.3
18	30.0
19	30.8
20	31.6
21	32.5
22	33.3
23	34.2
24	35.1
25	36.2
26	37.2
27	38.2
28	39.1
29	40.1
30	41.0
31	41.9
32	42.9
33	43.9
34	44.9
35	45.9
36	46.9
37	47.2

Timer Reading (Minutes)	Temperature (Deg. Celcius	Timer Reading (Minutes)	Temperature (Deg. Celcius
0	22.2	41	45.2
1	22.3	42	46.3
2	22.5	43	47.1
3	22.7	44	48.2
4	22.9	45	50.9
5	23.2	46	51.5
6	23.3	47	52.3
7	23.5	48	53.5
8	23.9	49	54.4
9	24.3	50	55.3
10	24.5	51	56.0
11	24.8		
12	25.3		
13	25.5		
14	25.9		
15	26.3		
16	26.5		
17	26.9		
18	27.3		
19	27.8		
20	28.1		
21	28.4		
22	28.9		
23	29.3		
24	29.7		
25	30.2		
26	30.5		
27	31.2		
28	31.6		
29	31.9		
30	32.6		
31	33.2		
32	33.9		
33	34.5		
34	35.7		
35	37.8		
36	38.5		
37	39.4		
38	41.5		
39	42.9		
40	43.1		

Timer Reading (Minutes)	Temperature (Deg. Celcius	Timer Reading (Minutes)	Temperature (Deg. Celcius
0	22.0	41	45.1
1	22.3	42	46.4
2	22.5	43	47.2
3	22.8	44	48.1
4	22.9	45	49.3
5	23.4	46	50.4
6	23.3	47	51.3
7	23.5	48	52.2
8	23.9	49	53.3
9	24.3	50	54.2
10	24.5	51	55.1
11	24.8	52	56.2
12	25.3	53	57.3
13	25.5	54	58.1
14	25.9	55	59.2
15	26.3		
16	26.5		
17	26.9		
18	27.3		
19	27.8		
20	28.1		
21	28.4		
22	28.9		
23	29.3		
24	29.7		
25	30.2		
26	30.5		
27	31.2		
28	31.6		
29	31.9		
30	32.6		
31	33.2		
32	33.9		
33	34.5		
34	35.7		
35	37.8		
36	38.5		
37	39.4		
38	41.5		
39	42.9		
40	43.1		