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Variability and characteristics of recycled asphalt shingles sampled from different sources

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VARIABILITY AND CHARACTERISTICS OF RECYCLED ASPHALT SHINGLES SAMPLED FROM DIFFERENT SOURCES

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Abstract

Recent literature studies have demonstrated depletion in natural resources; therefore, making resources needed for the pavement industry is more costly. There is a need to minimize cost and to try to reduce the depletion of natural resources. While the recycling of asphalt shingles is beneficial in reducing the consumption of virgin materials, pavement performance should not be compromised. One major concern with recycled asphalt shingles (RAS) relates to the variability in the properties of the recycled materials originating from different sources. In addition, the rheological properties of RAS have not been evaluated as well as its influence on the virgin binder when used in asphalt mixtures. Therefore, the objectives of this study were to characterize the rheological properties and molecular fractions of RAS materials sampled from different sources around the country. In addition, the influence of RAS on the Superpave Performance Grade (PG) of the binder was investigated. Results of the experimental program indicated that the asphalt cement (AC) content in tear-off shingles was consistent among different RAS sources across the country. However, AC content in manufacturer waste shingles was noticeably lower than in tear-off shingles. Furthermore, all extracted RAS binders were graded as PG 118 or higher using the Superpave binder specification system but the low temperature grade was not measurable due to the high stiffness of the binder. This stiff behavior is due to the binder used in shingle manufacturing, which is an air-blown asphalt binder with stiff characteristics and low elongation properties. Results showed that at a RAS content of up to 5%, the high temperature grade of the blends was increased by one to seven grades and the low temperature grade was increased by one grade. The use of binder blending charts is recommended to account for the influence of RAS in the mix design. At a RAS content of 10%, the binder blends did not pass the Superpave criterion at low temperature.

Chapter 1 – Introduction

The asphalt paving industry is responsible for building motorways, highways, streets, airports runways, parking areas, driveways, coastal protection, canal linings, reservoirs, footpaths and cycle paths, and sport and play areas (NAPA, 2011). Asphalt also plays a vital role in the global transportation infrastructure and drives economic growth and social well-being in developed as well as in developing countries (Mangum, 2006). The U.S. public investment in highway, street, and bridge construction is around $80 billion per year, which does not include private sector investments in this area (NAPA 2011). Therefore, because of the importance of the infrastructure and the need to ensure quality and performance of asphalt roads, the materials that are designed and constructed must result in an end product that has high standards. According to the asphalt industry, 85 percent of all asphalt that is used worldwide is in asphalt pavements (Asphalt Institute and Eurobitume, 2008). In 2007, 1.6 trillion metric tons of asphalt was produced worldwide and the U.S. has roughly 4,000 asphalt production sites and produced approximately 410 million metric tons per year (NAPA, 2011). To this end, it is very important for the U.S. to save money and look into more eco-friendly alternative to construct roads in this country. By taking advantage of new recycling methods in constructing hot-mix asphalt (HMA), roads, time, natural resources, and money can be saved. Also, by using different methods of recycling in HMA, waste can be prevented from going into the landfills. Thus, this will not only improve the bottom line for companies, but it will also have a positive impact on the environment.

With the increase in energy prices and the gradual depletion of natural resources, there is a need to save energy in highway construction activities and to use new methods that will also be beneficial to the environment, the users, and the industry. While the recycling of by-product materials is beneficial by reducing the consumption of virgin materials, the performance of the road should not be compromised. Therefore, it is important to research and analyze these new methods of recycling. HMA roads are a very important part of the infrastructure of the U.S. because in the U.S. more than 92 percent of the roads are surfaced with asphalt (NAPA, 2011).

Two strategies may be employed in the processing of tear-off asphalt shingles (CMRA, 2007). First, the tear-off shingles are separated by the roofing contractor before it gets transferred to the recycling plant. Second, mixed roofing materials are taken to the recycling facility, where non-shingle debris is taken from the material. RAS is usually processed to be ground to a uniform particle size ranging from 12.5 to 19.0 mm.

1.1 Problem Statement

Blending asphalt shingles with HMA has promising benefits, but there are a number of concerns too. Researchers have started evaluating how recycled asphalt shingles will affect HMA. It is generally recognized that recycled shingles in different parts of the country will have different properties. Shingles that are from a certain region of the country might age faster than some shingles from other parts of the country. Therefore, there is a critical need to determine the different characteristics of recycled shingles sampled from different regions of the country. There are also several unanswered questions including what is the Performance Grade (PG) that is obtained from blending recycling (or recycled) shingles with virgin binder? What are the characteristics of the asphalt binder in the shingles? In this study, these questions have been addressed.

1.2 Objectives

The objectives of this study were to characterize the rheological properties of RAS materials sampled from different sources around the country and to determine the variability in Asphalt Cement (AC) content among different Recycled Asphalt Shingles (RAS) sources. In addition, the influence of RAS on the Superpave Performance Grade (PG) of the binder in the blend was investigated.

1.3 Research Methodology

Laboratory testing activities in this study assessed the properties of RAS sampled from different sources around the country and investigated the effects of RAS modification on the binder rheological properties. The adopted research approach consisted of four main research tasks:

Task 1: Collect the recycled asphalt shingles from different recycling plants around the country. RAS were collected from various states including Michigan, Missouri, Minnesota, Texas, Connecticut, Oregon, South Dakota, and Virginia.

Task 2: Extract the asphalt binder from the shingles, according to AASHTO T 164-11 – Test Method B (Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt HMA). This method was based on the reflux test method using trichloroethylene (TCE). Once extracted from RAS, rotary evaporation was used to recover the asphalt from the TCE solvent.

Task 3: Evaluate AC content variation among the different RAS sources and measure particle size distribution of the RAS aggregates by means of AASHTO T 27.

Task 4: Conduct Superpave testing of the extracted asphalt binder according to AASHTO MP-1 (Specification for Performance Graded Asphalt Binder). In addition to the RAS binders, the properties of binder blends prepared with the binders extracted from RAS and virgin asphalt binder, classified as PG 64-22, were evaluated.

1.4 References

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Chapter 2 – Literature Review

2.1 Introduction

Asphalt shingles are the most popular roofing materials in the US making up to two-thirds of the residential roofing market (NAHB, 1998). Asphalt has been used as a building construction material for thousands of years (Blanchford and Gale, 2002). In 1893, the forerunner of the asphalt shingle, asphalt-prepared roofing, was first manufactured (Blanchford and Gale, 2002). In 1901, the first asphalt shingles appeared with slate granules as surface protection (Cullen, 1992). With time, asphalt shingles became more and more popular in the roofing industry due to ease of installation, light weight, low cost, and low maintenance requirements (Blanchford and Gale, 2002). By the late 1930s, 32 manufacturers produced over 11 million squares of asphalt shingles, enough to cover about 45% of U.S. residential homes (Cullen, 1992). Now, approximately 12.5 billion square feet of asphalt shingles are manufactured annually, which is enough to cover about five million homes (ARMA 2007). Currently, 80% of homes are covered with asphalt shingles in the U.S. (Townsend et. Al, 2007). They are manufactured as two main types (Roof Types, 2010): organic and fiberglass, which are illustrated below in figure 2.1. Organic shingles are composed of 30 to 35% asphalt, 5 to 15% mineral fiber, and 30 to 50% mineral and ceramic-coated granules. Fiberglass shingles are the most popular type and consist of 15 to 20% asphalt, 5 to 15% felt, 15 to 20% mineral filler, and 30 to 50% mineral and ceramic-coated granules. While glass fiber shingles have a fiberglass reinforcing backing that is coated with asphalt and mineral fillers, organic shingles have a cellulose-felt base made with paper.

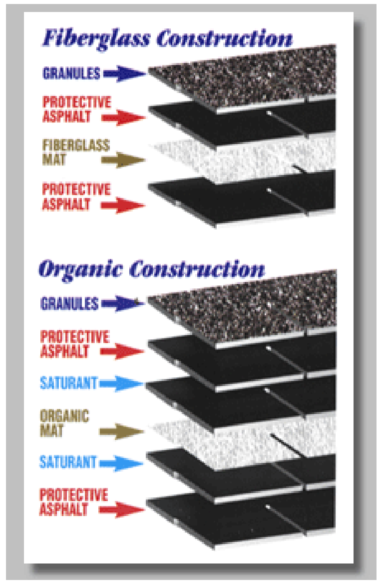

Figure 2.1 Fiberglass and Organic Shingle (Obtained at WWW.Roofingislandny.com)

The average life of asphalt shingles vary with the environment and in-service conditions. For example, they can last from around 14 years in Arizona to about 21 years in Pennsylvania. The weathering of asphalt shingles seems to accelerate in hot temperatures and they may be damaged easily because of high temperature fluctuations, also known as thermal shock, or infiltration of water. Tear-off shingles have a greater percentage of asphalt because they lose part of the surface granules during service due to weathering (Davis, 2009). The cost of disposing waste shingles in landfills can reach as high as $90 to $100 per ton in large cities (Malik et al., 2000). Before the early 1970s, asbestos was sometimes used in the manufacturing of fiberglass asphalt shingles. However, a survey on 27,000 samples revealed that only 1.5% of shingles used asbestos (Gevrenov, 2008). Another study on 1,791 shingles samples found no harmful materials (CMRA, 2010). It is worth noting that the EPA does not allow any materials containing greater than 1% asbestos to be used in road construction (Marks and Petermeier, 1997).

Another concern relates to the emission of polycyclic aromatic hydrocarbons (PAHs) (Gevrenov, 2008). While early results show that RAS do not readily emit PAH, current research is evaluating the effects of adding discarded shingles on PAH emissions during HMA production. Asbestos testing is conducted occasionally during recycling and processing of tear-off shingles based on the Polarized Light Microscopy (PLM) method, which can detect an asbestos content of 1%.

2.2 Overview of Shingles

Asphalt roofing shingles constitute nearly two-thirds of the roofing market for both new homes and roof replacements (NAHB, 1998). Annually, roof installation generates an estimated 7 to 10 million tons of shingle tear-off waste and instillation scrap plus another 60 manufacturing plants across the U.S. generate 750,000 to 1 million tons of manufacturing shingle scrap (NAHB, 1998). The reason why there is a focus on asphalt shingles to be recycled is because of its recycling potential. Asphalt shingles are plentiful in the construction and demolition waste stream. They are also generated separately from other waste, therefore, they are easy to isolate. With the advances in recycling technology, the use of recycled shingles in pavement can be economic. However, there are concerns among shingles recyclers because they have to deal with different issues. For example, potential asbestos content, differences in shingle properties between manufacturing scrap and tear-off waste, and equipment and collection needs are important factors to be addressed (NAHB, 1998). Asphalt shingle roof replacement can generate waste at rates of at least 2 to 5 pounds per square foot of roof area, which vary by the number of layers and the type of shingle (NAHB, 1998).

The composition of the shingle depends on the manufacturer and the roofing application; however, the manufacturing process is similar. The process of making shingles starts with a layer of organic (cellulose or wood fiber) or fiberglass backing felt (Austin, 2011). The felt is then covered with liquid asphalt and is then coated on both sides with additional asphalt. The asphalt used on the felt is harder than the asphalt that is used in pavement applications. This type of asphalt is air blown during production, which forces oxygen into the asphalt to help increase the viscosity of the material. After the felt paper has been coated with the appropriate amount of asphalt, then granules are placed on it for protection against physical damage as well as damage from the sun. The granules that are on top of the felt paper are made of crushed rock and the granules are coal slag. The aggregate is uniform in size, which ranges from 0.3 – 2.36 mm and is hard and granular (Austin, 2011). At the end of the process, a light coating of fine sand is put on the back surface of the shingle to prevent the individual shingles from sticking to each other during packaging and transport.

Tear-off shingles and manufactured shingles are the type of shingles that are present in RAS; however, the shingles that mostly get used are the tear off shingles. Tear off shingles are torn off houses and other structures, which means that when they first get to a recycling facility they are contaminated with nails, paper, wood, and other debris. Tear-off shingles have a higher percentage of asphalt than manufactured shingles, because of the loss of a portion of the granules that are on the surface due to weathering. The asphalt on the tear off shingles gets hardened from oxidation and the volatilization of the lighter organic compounds (Austin, 2011).

2.3 Sources and Generation of Asphalt shingles

Approximately 11 million tons of RAS are produced annually in the U.S., of which approximately 5 to 10% is from manufacturer scrap (Sengoz and Topal, 2005; VANR, 1999; Zickell, 2003). Post manufactured scrap is generally more uniform and homogeneous than tear-off shingles (NAHB, 1998).

Most of the RAS originate from tear-off (post-consumer) waste. The lifetime of an asphalt shingle roof can range between 12 to 25 years. Ultimately, the service life depends on the shingle manufacturing technology (Cullen, 1992). Approximately 7 to 9 million tons of discarded post-consumer asphalt shingle waste is generated in the U.S. (VANR, 1999). Most of the waste from post-consumer shingles comes from residential sites during construction, demolition, and renovation. Unlike the post-manufacture shingles, tear-off shingles may have shingles of varying asphalt and aggregate compositions and may originate from multiple manufactures. It has also undergone weathering and aging from exposure to ultraviolet sunlight (Foo et al., 1999; NAHB, 1998).

Post-manufacture shingle scrap is normally unused, clean, and sometimes bundled. Post-manufactured shingle is often the most desired shingle scrap because it does not contain any other materials as potential contaminants like nails (Townsend, 2007). The post-manufacture asphalt shingle consists of a combination of remnants and scraps from the manufacturing process as well as damaged or off specification shingles (Townsend, 2007).

The majority of asphalt shingle waste is managed by landfilling (Zickell, 2003). Some landfills will separate waste shingle loads (and charge a lower tipping fee) and use them as a road base material or pads for trucks (Townsend, 2007). Since the materials in asphalt shingles are similar to those materials used in HMA and other road applications, discarded asphalt shingles have been identified as a material that may be diverted from landfill disposal and reused (Townsend, 2007).

2.4 Processing Shingle Waste

There are generally three steps in the asphalt shingle recycling process: 1) Removal of non-shingle waste that interferes with processing or end uses; 2) Grind shingles to ¼” – 2½”, depending on the end use; and 3) Use processed shingles materials. Asphalt shingles are recycled at dedicated recycling or processing facilities (which are those that only accept asphalt shingles) or at a mixed construction and demolition debris recycling facility, which accepts multiple construction and demolition waste. Construction contractors commonly provide separate bins for different waste components as part of an effort to recycle construction debris (Townsend, 2007). One main goal with shingle separation at construction and demolition facilities is to ensure compliance with regulations that have been put on material that may contain asbestos, which is normally accomplished by that facility following an approved sampling protocol (Townsend, 2007). When the shingles get to the recycling facility, they are large in size because they have just been torn off from an old roof. Therefore, the shingles must be ground down to a smaller size to be used in HMA. As illustrated in figure 2.2, when the shingles are ground, they are ground down to a size that is smaller than 1/2", and preferably smaller than ¼". There are also different requirements for how much of the RAS has to pass a specific size of sieve. For example, in Texas, 100% of the shingle shreds must pass 19 mm (3/4") sieve, and 95% must pass the 12.5 mm (1/2") mm sieve (RAS APP, 1999). The machines that have been used to crush shingles are crushers, hammer mills, and rotary shredders. RAS are often put through these machines twice to reduce the size of the material. For example, one machine illustrated in figure 2.3 known as the Rotochopper, is a specialized piece of equipment that is manufactured specifically to process asphalt shingles. This machine has an inclined belt, rotating anvil, clamshell screen, water spray bar (used to keep the ground shingles cool and prevent agglomeration), and a belt magnet (to remove metals such as nails). One operator is required to run this grinder.

Figure 2.2 Ground Shingle Example (Obtained from www.recycling.about.com)

Figure 2.3 Rotochopper (From www.Rotochopper.com)

Tear-off roofing is easier to shred as opposed to manufacturer scrap because factory scrap tends to become plastic from the heat and mechanical action of the shredding process; therefore, tear off roofing is hardened with age and is less likely to agglomerate during processing (Grodinsky, 2002). Water is added sometimes during the shredding process to keep the shingles cool and to limit dust; however, the added moisture is undesirable in processing HMA. The shreds may also be blended with up to 20% sand, as an alternate to water, which would normally be added later in the production of HMA (Grodinsky, 2002).

HMA is currently the largest recycling market for waste asphalt shingles (Townsend, 2007). There are two ways asphalt shingles are used in HMA production as a binder and as an aggregate (Foo et al., 1999; FVD, 2006). Asphalt has good adhesive characteristics, flexibility, and an ability to form strong cohesive mixtures with mineral aggregates (Townsend, 2007).

From 1940 to 1973, asbestos containing materials were used in shingle production as a fiberglass paper backing (Austin, 2011). Since asbestos is very toxic, any shingles with this material in it is prohibited from use in paving mixes. As this is a very critical issue with roofing shingles, precautions need to be taken to help catch any asbestos containing materials in the shingle. For example, the Iowa Department of Transportation has developed a method of identifying asbestos in shingles (Austin, 2011). They place a small sample of shingles in a furnace at 500 degrees for two hours, and then after it cools the sample is examined under a microscope for the presence of asbestos fibers (McGraw, 2010).

As stated earlier, tear-off shingles are torn off from houses and have roofing nails, wood, paper, and other debris in them. Therefore, when being processed, a blower and a magnet are used to catch the unwanted debris. The magnet attracts the metallic waste, while the blower eliminates waste like paper (Austin, 2011). The shingles then have to be stockpiled correctly, which means the manufactured waste shingles must be isolated from the tear-off shingles. The tear-off shingles must also be protected from excessive precipitation and weathering (Foth & Van Dyke and Associates, 2006).

2.5 Challenges to Recycling RAS in Asphalt Pavements

Testing is one challenge for shingle recyclers. Laboratory test for asbestos can costs between $15 and $25 and could take up to 24 hours. While recycling companies in Massachusetts, Maine, Maryland, and Washington have tested hundreds of loads, they have detected asbestos in only a handful of instances (NAHB, 1998). Another challenge can be some of the regulations that are required. OSHA regulates workplace exposure to asbestos and EPA regulates handling and disposal issues. Therefore, shingle recycling may require siting, waste handling, and/or processing permits and, thus, recyclers agencies need to acquire proper permits and ensure good testing for and handling of potential hazardous materials. It is also a challenge to find paving companies that will be willing to use recycled shingles. As virgin asphalt prices increase, recycled shingles may become a very attractive option. Another challenge can be the equipment that is necessary to process recycled shingle waste. Recycling of shingles normally requires modification of standard grinding, screening, and dust control equipment in order to process shingles waste for the desired end use products (NAHB, 1998). There have been recent advances in equipment design that have overcome previous problems with blade wear and dust control. Many machines have been designed to process roofing and other construction waste. Location, landfills, and tip fees are other challenges that roofers face. Transportation is a large portion of disposal costs; therefore, roofers cannot afford to haul waste long distances. Local landfill capacity and tip fees can also affect roofers' disposal choices. Recycling companies typically must charge at least $30 per ton to cover the processing costs. The difference between what the recyclers charge and the landfill tip fee must be large enough to provide an economic incentive to generators to change their practice of landfill disposals (NAHB, 1998).

2.6 Economic Benefits of using RAS in HMA

Recycling of asphalt shingles in HMA is a very valuable approach for technical, economical, and environmental reasons. The EPA has estimated that about 11 million tons of asphalt shingles are placed in landfills annually in the U.S. In addition, the EPA estimates that 170 million tons of construction and demolition (C&D) debris are generated every year with asphalt shingles making up to 15% of this waste. While C&D debris have increased by 25% from 1996 to 2003, the recovery rate has increased from 25% to 48% during that period (CMRA, 2012). Recent studies show that recycled tear-off asphalt shingles contain 15 to 35% of asphalt binder, which can provide an annual saving of $1.1 billion and will also reduce non-renewable energy consumption in the U.S. (NERC, 2007; Gevrenov, 2008). Furthermore, the use of RAS also allows a decreasing amount of produced waste and helps resolve disposal problems especially in the neighborhood of large cities. Another benefit is that there can be an increase in the strength and stiffness of HMA due to the fibers and polymers in RAS (C&D World, 2011). Roofing contractors can also reduce their disposal expenses by tipping roofing waste for a lower fee at a recycler, which is typically $5 to $20 less than landfills (NAHB, 1998).

2.7 Use of Asphalt shingles in Construction

The use of RAS in hot-mix asphalt reduces the amount of virgin asphalt binder that is added to the mixture and it is expected to provide significant benefits to the asphalt industry and highway agencies. Recycled asphalt shingles can be used as an aggregate base course, where course-ground shingles (2½" minus) can be added to the mix as part of the lower pavement layers for the subbase, base, or binder courses (NAHB, 1998). Recycled asphalt shingles can also be used in HMA, where fine ground shingles (½" minus) can be added at 5% by weight of HMA for use in wear/surface course (NAHB, 1998). When this is done, shingles are added to HMA in a similar way that recycled asphalt pavement (RAP) is. However, this requires the use of a softer virgin asphalt to offset the effect of adding the harder asphalt in recycled shingles (NAHB, 1998). Another good use for RAS is in the construction of temporary roads, driveways, or parking lots. In this situation, course ground shingles (2½" minus) can be used for dust control on bare ground, which may be an economical alternative to ground covers such as gravel, stone, or wood chips in low traffic areas. It can also be used on farm lanes, rural roads, or temporary construction surfaces. Recycled asphalt shingles can be used for a cold patch mix, which would require it to be ground down to ½" minus size and used alone or combined with virgin asphalt or other materials for use as a cold patch material (NAHB, 1998). A cold patch generally consists of asphalt, aggregate, and a solvent (Townsend, 2007). In the cold patch application, ground asphalt shingles will typically be mixed with aggregates and an emulsion to produce a patching mix (Townsend, 2007). By using recycled asphalt shingles in a cold patch, the performance can be improved because of the fiberglass and /or cellulose fibers in the shingles. There are also potential economic savings due to longer life and decreased maintenance costs relative to non-shingle containing cold patch (Townsend, 2007). Recycled asphalt shingles can also be used for expansion joints for concrete pavement. The fibrous shingle base (organic or fiberglass) also contains valuable fibers that may enhance the performance of asphalt mixtures (CMRA, 2007). Since the early 1990s, a number of research studies evaluated the use of this recycled material and its influence on the mix mechanical behavior. Air blown asphalt is typically used in the manufacturing of asphalt shingles; this type of asphalt binders has a greater viscosity than regular asphalt binder used in HMA (Foo et al., 1999). Button et al. (1995) evaluated the influence of adding 5 to 10% of asphalt shingles on the mechanical properties of asphalt mixtures as compared to untreated mixes. The use of RAS resulted in a decreased tensile strength and creep stiffness of the mixture but it improved the mix resistance to moisture damage. Ultimately, the use of recycled asphalt shingles in construction improves pavement resistance to wear, increases resistance to moisture, decreases deformation and rutting, and decreases thermal and fatigue cracking (NAHB, 1998).

The influence of RAS content was evaluated in the range from 0 to 7.5% as well as its influence on the mechanical properties of two types of asphalt mixtures (Gardiner et al., 1993). The use of RAS decreased the amount of virgin binder that was needed and improved the resistance of the mixture to permanent deformation. However, mixture resistance to low temperature cracking appears to decrease when asphalt shingles are used. Similar results were reported by other investigators (Grzybowski, 1993; Ali et al., 1995; Sengoz and Topal, 2004). Foo et al. (1999) compared the properties of two HMA mixtures prepared with conventional materials and using one source of fiberglass shingles at a content of 5 and 10%. Results of the experimental program showed that this particular source of shingles had a high percentage of aggregates passing the 0.075 mm sieve (~35.5%). This may limit the content of asphalt shingles that can be used in the mix using the dry blending process. However, the use of asphalt shingles improved the rutting resistance of the mixture but the mix had lower fatigue and low temperature cracking resistance. The use of RAS at a content ranging from 3 to 5% by weight of the aggregate in the preparation of Warm-Mix Asphalt (WMA) significantly improved the moisture resistance of the mixture (Xiao et al., 2011). Field evaluation of HMA constructed with 5% shingle waste shredded to a particle size of 12.5mm revealed acceptable performance (Watson et al., 1998).

2.8 Status of Shingle Recycling in the U.S.

As the cost of natural resources increases, more states are authorizing the use of shingles in paving mixes. The Georgia Department of Transportation has an approved specification for the use of both manufacturer's shingle scrap and tear-off shingle scrap pavement (NERC, 2012). The RAS in the asphalt mixture cannot be more than 5% of the total weight of the hot-mix asphalt mixture. Recyclers that use tear-off RAS are also required to provide test results for bulk sample analysis (polarized Light Microscopy) to certify the RAS material does not contain any asbestos (NERC, 2012). Indiana has a standard specification that allows the use of recycled asphalt shingles in HMA. The 2012 Standard Specifications were revised to allow tear-off shingle scrap but it cannot contribute more than 25% by weight of the total binder content for any HMA mixture (NERC, 2012). The Maryland Department of Transportation has specifications that allow the use of up to 5% manufacturers shingle scrap into pavement (NERC, 2012). In the state of Minnesota, DOT has recently adopted new specifications that allow the use of post-consumer reclaimed asphalt shingles in pavement. The pre and post-consumer RAS in the recycled mixture are limited to no more than 5% of the total weight of HMA (NERC, 2012). In Missouri, DOT has specifications that allow the use of up to 7% recycled asphalt shingles, which can be manufactured shingles or tear-off in HMA (NERC, 2012). The Texas Department of Transportation has specifications and procedures to allow the use of both pre-and post-consumer asphalt shingles in paving projects. The one barrier with the spread of recycled asphalt shingles being used in road construction is the concern of asbestos, which was used in the shingle fiber mat in the 1960s and 1970s. Therefore, it is feared that it might be found in shingle waste. However, there was a study that was done for the Chelsea Center in Massachusetts in 2000 and found only very small amounts of asbestos, which seems to be the same result that other studies have reported (NERC, 2012). Recycling asphalt shingles has definitely been a trending topic around the country among researchers and different organizations and as stated earlier this is something that will continue to increase as prices of natural resources continue to increase.

2.9 Use of Trichloroethylene to Extract Asphalt

Extracting the asphalt from the shingles is a very important part of the process in this study. Trichloroethylene (TCE) has many different uses in industry such as degreasing, cleaning solvents, aerosol propellants, extraction of organic compounds and refrigerants. As illustrated in Figure 2.4, TCE was used in this study in the reflux apparatus and heated to a temperature of 110 degrees Celsius. The top of the reflux was cooled such that when the heated TCE would evaporate, it would go up to the cool top of the reflux and would condensate. At this point, the TCE would drip down on to the grounded shingle dissolving the asphalt to a liquid state, thus, extracting the asphalt from the RAS.

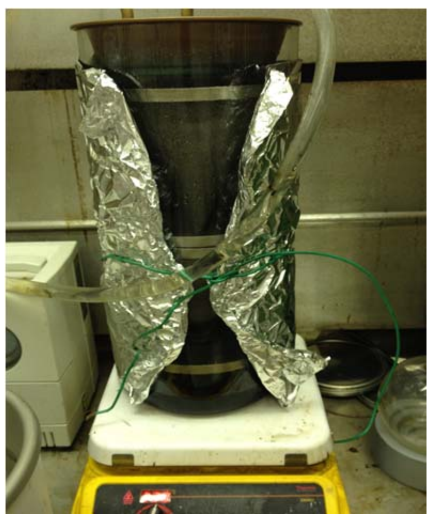

Figure 2.4 Reflux Used to Extract Asphalt

TCE can be a very dangerous chemical if not handled properly. Safety glasses and gloves had to be worn at all times when dealing with this material. It was also imperative that TCE be handled under a hood that pulled the air at a rate of at least 85 feet per minute. People who are exposed to large amounts of TCE can become dizzy, sleepy, or unconscious at high levels of exposure (Public Health Statement, 1997). Another dangerous side effect of this material is that test studies have proven that it may cause cancer when high doses of exposure happen. There were studies done where high doses of TCE were exposed to rats and mice. Tumors developed in their lungs, liver, and tests on these animals provided some evidence that high doses of TCE can cause cancer in experimental animals (Public Health Statement, 1997). Therefore, the International Agency for Research on Cancer (IARC) has made the determination that TCE is probably carcinogenic to humans too (Public Health Statement, 1997). With all of this being said, much care was taken when TCE was used in this project.

When TCE was being used to extract the asphalt from the shingles, it then had to be extracted from the asphalt. The apparatus, which is illustrated in Figure 2.5, was used to extract the TCE from the asphalt and is known as the rotovapor. The TCE, which at this point was mixed with asphalt after the extraction, was pored into a flask. The glass flask was then attached to the rotovapor and lowered down into a heating bath, which heated the material to a temperature of 60 degrees Celsius while rotating the material in the heated bath. Suction from a vacuum was used and pulled the TCE vapors out of the flask up to tubes that were filled with a cooled solution down to a low temperature. The vapors would then condensate and drip down into another flask giving recycled TCE that was extracted from the asphalt. At the end of this process, a flask was filled with TCE and another flask was filled with asphalt.

Figure 2.5 Rotovapor used to extract asphalt from TCE

2.10 Advantages and Disadvantages of Using Reflux Method

There are advantages and disadvantages to using the Ruflux. Trichloroethylene TCE is the solvent that is used in the reflux to extract the asphalt form the shingle. Unfortunately TCE has been identified as a carcinogen (Garcia, 2000). It has also been known to cause headaches, dizziness, tremors and high exposures have been known to cause death (ASDR, 1993). TCE is also hazardous to the environment and contributes to the depletion of the earth's ozone layer (Garcia, 2000). There are five different methods of extraction in ASTM D 2172, which are Centrifuge (Method A), reflux (Method B, C, and D), and vacuum (Method E) extraction. The most common method which was also used in this paper is Method B (Reflux). This method has been shown to cause aging on the asphalt binder because it is exposed to high temperatures for a long time during the extraction process (Garcia, 2000). However, these disadvantages are mostly about normal asphalt and not roofing asphalt. Tear off roofing asphalt has already been aged because it has been on a roof for up to 20 years. Therefore, the rate of aging tear off roofing asphalt is slower than the rate of aging for normal asphalt. Thus, using the reflux to extract the asphalt in this project did not have the same effects that it would have had on normal asphalt.

It is also important to note that there can only be less than 1% of TCE left in the asphalt at the end of this process because any higher concentration will change the outcome of the grading of the asphalt. Therefore, tests were done at Entek Lab to ensure that this did not happen. One sample of material was submitted to Entek Lab on 2/27/12 to test the tear-off from Virginia asphalt sample (TOVA). The test was completed on 3/09/12 and gave 0.2% TCE in the sample. Therefore, this sample was handled properly and the adopted procedure was applied to all other samples in this project.

2.11 Superpave Binder Testing

It is important to understand the behavior of asphalt as it pertains to binder testing and performance. Asphalt cement behavior depends on two things, which are, temperature and time of loading (McGennis, 1994). The flow behavior of one asphalt could be the same for one hour at 60°C or 10 hours at 25°C, which means that time and temperature are interchangeable, therefore, high temperature and short time is equivalent to lower temperature and longer times (McGennis, 1994). At high temperatures, asphalts act like viscous liquids and flow and at lower temperatures asphalt behave like elastic solids (McGennis, 1994). Another characteristic that is important about asphalt is its aging behavior. Asphalt is composed of organic molecules; therefore, they react with oxygen from the environment, which is called oxidation (McGinnes, 1994). When oxidation starts, the asphalt becomes more brittle and hard. This happens normally at a slow rate in the pavement; however, this can happen at a faster rate in a hot climate when compared to cool climate (McGinnes et al., 1994). Since asphalt behaves as a viscoelastic material, it is important to characterize its performance at different temperatures. Asphalt needs to meet a certain performance grade (PG Grade) before it is used in road construction because it will behave differently at different temperatures. Viscosity testing is used for testing asphalt at high temperature and penetration test is used for testing asphalt at intermediate temperature but asphalt also needs to pass other test criteria to meet a performance grade, which is why Superpave (Superior Performing Asphalt Pavement) testing was introduced.

In 1987, the Strategic Highway Research Program (SHRP) started to develop new test for measuring the physical properties of asphalt (McGinnes, 1994). This research, which cost $50 million, resulted in a new asphalt specification along with a new set of test methods. The new test methods that were added at that time were the Dynamic Shear Rheometer (DSR), Rotational Viscometer (RV), Bending Beam Rheometer (BBR), Direct Tension Tester (DTT), Rolling Thin Film Oven (RTFO), and Pressure Aging Vessel (PAV) (McGennis, 1994).

The (DSR), which is illustrated in Figure 2.6, is used to measure the resistance of permanent deformation such as rutting and fatigue cracking at high and intermediate temperatures. This machine has been used in the plastic industry for many years (Brown et al., 1994). The DSR measures the complex shear modulus G* (G star) and phase angle (delta) of the asphalt binders at the desired temperatures and frequency of loading (Brown et al., 1994). The complex G* modulus is considered to be the total resistance of the binder to deformation when it is repeatedly sheared, which means that the G* consists of two components: (a) storage modulus G' (G prime) or the elastic (recoverable) part, and (b) loss modulus G" (G double prime) or the viscous (non-recoverable) part (Brown et al., 2009). The asphalt binder sample is sandwiched between a fixed plate and an oscillating plate. When torque is applied to the oscillating plate, it starts from point A then moves to point B (Brown et al., 2009). Then from point B, the plate moves back and goes to point C passing point A (Brown et al., 2009). This is considered one oscillation. If three oscillations occur in one second, then the frequency of oscillation is three hertz (Hz) (Brown et al., 2009). The oscillation frequency can also be expressed as the circumferential distance (radians) traversed by the oscillating plate in one second (Brown, 1994). Superpave test methods are all performed at a frequency of 10 radians per second, which is equivalent to about 1.59 Hz (Brown et al., 2009).

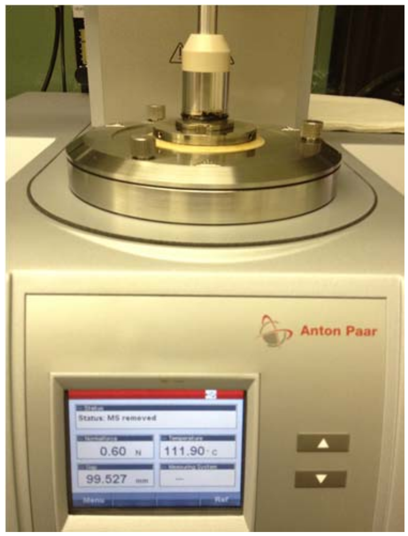

Figure 2.6 Dynamic Shear Rhoemeter

The RTFO is, which is illustrated in Figure 2.7, is mainly used to simulate the asphalt binder aging during the manufacture and construction of HMA pavements (Brown et al., 2009). This machine is a suitable aging tool because, (a) it continually exposes fresh binder to heat and air flow during rolling, (b) modifiers, if used, usually remain dispersed in the asphalt binder due to rolling action, (c) unlike Thin film oven (TFO) test where binder does not move, it does not allow any surface skin to be formed, which can inhibit aging, and (d) it takes only 85 minutes to perform rather than five hours required for the TFO test (Brown et al., 2009). The RTFO test provides an aged asphalt binder that can be used for more testing by the DSR, BBR, and other machines. This test also gives the amount of volatiles lost from the binder during the test and some asphalt binders gain weight during the RTFO aging because of the oxidative products that can be formed during the test (Brown et al., 2009).

Figure 2.7 Rolling Thin Film Oven

The BBR, which is illustrated in Figure 2.8, measures the resistance of the asphalt to permanent deformation at low temperature for thermal cracking. When the temperature drops rapidly at cold temperatures the pavement will start to contract and can be susceptible to thermal cracking. When the pavement contracts, stresses will begin to build up within the HMA pavement layers and if this happens too fast the stresses can build and eventually exceed the stress relaxation ability of the HMA pavement (Brown et al., 2009). When this happens, the HMA pavement will develop cracks in order to relieve stress. This kind of cracking can result from critically low temperature or from the temperature cycling up and down, but remaining above the critically low temperature (Brown et al., 2009). The BBR uses a creep load, which is applied to the bending mode, to load an asphalt beam specimen held at a constant low temperature (Brown et al., 2009).

The temperature is maintained by a fluid bath that is filled with a mixture of ethylene glycol, methanol, and water. The BBR has a loading mechanism, temperature control bath, and a data acquisition system. The binder beams are formed by pouring heated binder into aluminum or silicone molds. The asphalt binder beams have a height with a measure of 125 mm in length, 6.25 mm in width, and 12.5 mm in height (Brown et al., 2009). The beams are removed from the mold by putting them into a freezer or ice water for 5-10 minutes, then the beam is kept in the test bath at the desired temperature for 60 $\pm$ 5 minutes before testing. After the preloading procedure is performed, a load of 100 grams is applied to the beam for 240 seconds (Brown et al., 1994). The deflection of the beam is recorded during the testing period and the load deflection versus time plots are also shown on the computer screen. The BBR software will then calculate creep stiffness and m-value. The formula used to calculate the creep stiffness of the asphalt binder beam at 60 seconds loading time is $S(t) = PL^3/4bh^3\delta(t)$ (Brown et al., 2009).

Figure 2.8 Bending Beam Rheometer

The DTT measures binder properties at low service temperatures for the resistance to thermal cracking. The creep stiffness of the asphalt that is measured by the BBR is not sufficient to completely characterize the low temperature behavior of asphalt in terms of thermal cracking (Brown et al., 2009). There are some asphalt binders that might be modified and have a high creep stiffness, however, they do not crack because they can stretch further before breaking (Brown et al., 2009). That is why the DTT was introduced so that these stiff ductile asphalt binders can be tested. The DTT measures the tensile strain of the asphalt binder, usually in the temperatures of 0°C to -36°C. The asphalt binder will have already been aged through the PAV and RTFO aging, and then it will be poured as a dog-bone shaped specimen. Once the asphalt has been placed in the specimen, then tension is applied at a constant rate of (1mm/min.) until it breaks (Brown et al., 2009). The failure strain in the asphalt is the change in length divided by the effective gauge length (Brown et al., 2009). Therefore, the failure strain in the DTT represents where the load on the specimen reaches its maximum value, not the load when the specimen breaks (Brown et al., 2009).

The (PAV), which is illustrated in Figure 2.9, has been used in asphalt testing for many years and was developed by Dr. D. Y. Lee at Iowa State University for long-term aging of asphalt cements (Brown, 2009). The advantages of the pressure aging vessel are: (a) limited loss of volatiles, (b) the oxidative process is accelerated without resorting to high temperatures, (c) an adequate amount of asphalt binder is can be aged at one time for further testing, and (d) the test is practical for routine laboratory testing (Brown et al., 2009). The (PAV) simulates 5-10 years of binder aging (hardening and oxidation) during HMA service life and measures its resistance to aging during service life. Since the asphalt binder will have already undergone short-term aging during production and construction, the PAV is used to age RTFO residue (Brown et al., 2009). The

PAV is composed of stainless steel and has to be able to operate under the pressure of (2070 kPa). The temperature conditions for this test must be performed under the temperature of (90, 100, 110°C) (Brown et al., 2009). The sample rack, which holds ten sample pans, can be placed in the vessel. The lid of the PAV can then be shut and secured quickly to minimize heat loss. When the PAV reaches within 2°C of the desired temperature, a pressure of 2070 kPa will be applied using the valve on the air cylinder. After a period of 20 hours, air pressure is released slowly (usually over a period of 8-10 minutes) using the bleed valve (Brown et al., 2009). The samples are then placed into another machine, which maintains a temperature of 163°C for 30 minutes and places the sample under a vacuum. This machine then vacuums the air out of the sample, which is stored for further testing.

Figure 2.9 Pressure Aging Vessel (Obtained from www.pavementinteractive.org)

The (RV), illustrated in Figure 2.10, rotational viscometer has been used in Superpave for determining the viscosity of asphalt binder at high construction temperatures (above 100°C) to ensure that the binder is sufficiently fluid for pumping and mixing (Brown et al., 2009). The RV is suitable for measuring the viscosity of the asphalt instead of the capillary viscometer because the capillary viscometer can get clogged if it has a modified binder (such as crumb rubber modified binder) in it. The Superpave binder specification limits the viscosity to 3 Pa.s at 135°C (Brown et al., 1994). The machine that was used to measure the viscosity of the binder in this study was the Brookfield Viscometer, which consists of a viscometer and a thermosel. The rotational viscosity of the binder is determined by measuring the torque required to maintain a constant rotational speed of 20 RPM of cylindrical spindal while submerged in asphalt binder at a constant temperature (Brown et al., 2009). The Brookfield viscometer has a motor, spindle, control keys, and a digital readout. Most of the asphalt binders can be tested with only one of two spindles, which are No 21 and 27; however, the latter is used most frequently (Brown et al., 2009). The Thermosel system has a stainless steel sample chamber, a thermo container with electric heating elements, and a temperature controller that controls the test temperatures (Brown et al., 2009). Binder is placed in the oven to be heated until it is sufficient enough to pour. No more than 11 grams of binder is poured into each tube, which will vary depending on the size of the spindle that is used (Brown et al., 2009). At this point, the sample tube that contains the binder is placed in the thermo container and is ready for testing when the desired temperature of 135°C stabilizes. Then the spindle, which has hot binder in it, is lowered into the chamber and is coupled with the viscometer. Once the temperature has stabilized again, the motor on the RV is turned on at 20 RPM (Brown et al., 2009). The digital reading of the viscosity of the binder will be in centipoise (cP); however, Superpave binder specification uses Pa.s. Therefore, the factor of 1000 cP = 1Pa.s is used to convert centipoise to Pa.s. Most agencies measures viscosity at the temperature for mixing and compaction during HMA mix design, which means that the RV will be measured at one more temperature other than 135°C, then the temperature viscosity curve will be plotted (Brown et al., 2009).

Figure 2.10 Rotational Viscometer

2.12 Use of RAS in Asphalt Pavements

Use of RAS in pavements is not widely used around the country as of yet, but as stated earlier it is becoming more popular. The state of Illinois has been using recycled asphalt shingles in their roads and has found it to be very favorable. In May 2011, the 97th Illinois General Assembly passed House Bill 1326, which amended the Environmental Protection Act (Lippert and Brownlee, 2012). The bill was signed into law by Governor Pat Quinn on August 12, 2011. This act addresses the desire to collect shingles from waste and recycle the material into the Illinois Department of Transportation (IDOT) hot-mix paving projects (Lippert and Brownlee, 2012). This was very beneficial to their state and can be beneficial to other states that follow this same path because a new industry was created and new jobs were created. Another benefit was that the potential for savings were realized on state highway projects (Lippert and Brownlee, 2012). In addition to 13 other recycled materials, IDOT has found RAS to perform well as a supplement or substitute for conventional materials (Lippert and Brownlee, 2012).

Even though the IDOT is fairly new in using RAS, the Illinois Tollway has more experience. In 2011, the city of Chicago and the Illinois Tollway used 4,440 and 14,054 tons of RAS, which represents a significant increase from the year before (Lippert and Brownlee, 2012). The Illinois Tollway also expects another increase in RAS use in the future years to satisfy the large amount of anticipated HMA production (Lippert and Brownlee, 2012).

IDOT met with the Illinois Environmental Protection Agency (IEPA) in 2010 to discuss adoption of RAS into HMA on IDOT projects (Lippert and Brownlee, 2012). The tear-off or post-consumer shingles are part of the waste stream and are designated to be disposed of at approved landfill facilities. In Chicago, in order for some materials that are part of the waste stream to get diverted from it, it must have a valid use and have an established condition of acceptance by a new owner who wants to use the waste stream material. This is called Beneficial Use Determination (BUD), which is outlined in Section 22.54 of the Illinois Environmental Protection Act (Lippert and Brownlee, 2012).

Like other states, one concern that Illinois had about using old tear-off shingles was the threat of asbestos. Before the early 1980s, some manufactures may have used asbestos as a fiber as the base mat of the shingle (Lippert and Brownlee, 2012). Asbestos was never banned from being used in construction; however, because of litigation businesses that were using it went out of business from health claims and incurred cost. Determining if shingles containing asbestos is difficult (Lippert and Brownlee, 2012). That is why the National Emission Standards for Hazardous Air Pollutants (NESHAP) requires asbestos screening when shingles are taken from commercial buildings and also on apartment complexes with four or more units (Lippert and Brownlee, 2012). This requirement mainly focuses on large structures and on multiple family apartments instead of single family homeowners. Hence, the primary source for tear-off shingles, which are non-commercial facilities, apartment houses of three units or less and single-family homeowner are not controlled by NESHAP (Lippert and Brownlee, 2012).

Another use for asphalt shingles is surface treatment on unpaved roads. In 1995, the Iowa Department of Transportation performed a study on the use of ground shingles as a surface treatment on an unpaved road (Marks et al., 1997). In this study, 300 tons of tear-off shingles were ground to pieces less than 1 inch in size and 600 tons of tear off shingles were ground to less than 2 inch pieces. Both sizes of shingles were mixed together before being used. Then 500 tons of the shingles were applied to newly laid crushed limestone and graded back and fourth to achieve a uniform shingle/limestone mixture of about 2.5 inch in thickness (Grodinsky et al., 2009). Then after two years of observations, the study concluded that shingles are very effective for dust control on rural roads, it also resulted in better lateral control of vehicles, reduced the loss of granular materials into ditches, and resulted in a quicker smoother roadway (Grodinsky et al., 2009). Also recycling the shingles cost less than having them processed at a local landfill. Processing the shingles cost $30 per ton, which is $10 less than the tipping fee at the local landfill (Grodinsky et al., 2009).

Recycled shingles have also been used as an ingredient for cold applied maintenance mixtures, or cold patch (Grodinsky et al., 2009). At least two New England firms, Commercial Paving, Inc., Scarborough, Maine, and American Reclamation Corporation, Charlton, Massachusetts, produce cold patch in amounts good for municipal and State use (Grodinsky et al., 2009). The use of recycled asphalt shingle use seems to be promising. The combination of hard asphalt, uniform and angular aggregate, and the entrained cellulose or glass fibers apparently make for a quality product that may rival the standard performance of cold mixes that are used in roads (Grodinsky et al., 2009).

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Chapter 3 – Variability and Characteristics of Recycled Asphalt Shingles

3.1 Introduction

While the national transportation network is a critical component of the US economy, there is a growing recognition that highway construction and maintenance both have major environmental impacts, (EPA 1994, World Bank 1996). Highway construction impacts the environment, the cost, and the energy use associated with these processes. Since no slowdown in freight transportation growth is in sight in the near future, it is imperative to introduce innovative technologies that can reduce the environmental impacts of highway construction.

The asphalt industry has experimented with sustainable alternatives since the 1970s. This has led to the implementation of various construction and recycling techniques that are thought to reduce the environmental impacts of highway construction and positively assist in the reduction of waste disposed in landfills. A recent survey identified as many as 19 different byproduct materials that have been considered for recycling in highway construction applications (Recycled Materials Resource Center 2007). In hot-mix asphalt (HMA) production, the recycling of Reclaimed Asphalt Pavement (RAP) has been noticeably successful as the residual asphalt binder in the RAP material blends with the virgin binder during mixing and contributes positively to the properties of the blend (Zhou et al. 2012). The use of RAP in HMA production also allows a reduction in the amount of virgin asphalt binder required in the mix. Other byproducts such as blast furnace slag, coal fly ash, kiln dusts, scrap tires, roofing shingle scrap, and waste glass have been incorporated in HMA production with various degrees of success.

Recycling of asphalt shingles in HMA has received considerable interest in recent years for technical, economical, and environmental reasons. The EPA estimates that about 11 million tons of asphalt shingles are placed in landfills annually in the US with 10 million tons of asphalt shingles coming from construction and demolition (C&D) and one million tons originating from asphalt shingle manufacturers (National Association of Home Builders (From Roofs to Roads 1998). Over 1.2 million tons of recycled asphalt shingle (RAS) has been used in HMA in 2010 by 15 states, which currently allow its use in asphalt paving construction. Recent studies show that recycled asphalt shingles (RAS) contain 15 to 35% of asphalt binder, which can provide an annual savings of $1.1 billion and also reduce non-renewable energy consumption in the US (Northeast Recycling Council 2007). The use of RAS also allows decreasing amounts of produced waste and helps resolve disposal problems, especially issues facing many landfills that are reaching their full capacity.

While the recycling of RAS is beneficial by reducing the consumption of virgin materials, road performance should not be compromised. One major concern with RAS relates to the variability in the properties of the recycled materials originating from different sources. In addition, the rheological properties of RAS have not been evaluated as well as its influence on the virgin binder when used in asphalt mixtures. Therefore, the objectives of this study were to characterize the rheological properties and molecular fractions of RAS materials sampled from different sources across the country. In additional, the influence of RAS on the Superpave Performance Grade (PG) of the binder in the mix was investigated.

3.2 Background

Two main types of asphalt shingles are used in roof construction (Roof Types 2010): organic (cellulose) and fiberglass. Organic shingles consist of 30 to 35% asphalt, 5 to 15% mineral fiber, and 30 to 50% mineral and ceramic-coated granules. Fiberglass shingles are the most popular types and consist of 15 to 20% asphalt, 5 to 15% felt, 15 to 20% mineral filler, and 30 to 50% mineral and ceramic-coated granules. The average life span of asphalt shingles widely varies with the environment from around 14 years in Arizona to 21 years in Pennsylvania. Weathering of asphalt shingles appears to accelerate in hot weather and they may easily be damaged due to daily high temperature fluctuations (thermal shock) or infiltration of water. Tear-off shingles would have a greater Asphalt Cement (AC) content as they lose part of the surface granules during service due to weathering (Davis 2009). The disposal fee of waste shingles in landfills may reach as high as $90 to $100 per ton in some areas around the country (Malik et al 2000). Prior to the early 1970s, asbestos was sometimes used in the manufacturing of fiberglass asphalt shingles. However, a survey of 27,000 samples tested revealed that only 1.5% of shingles used asbestos (Gevrenov 2008). Another study tested 1,791 shingles for asbestos and none were found to contain this harmful material (Asbestos in Asphalt Shingles 2010). The EPA does not allow any material containing greater than 1% asbestos to be used in roadway construction (Marks et al. 1997). Another concern relates to the emission of Polycyclic aromatic hydrocarbons (PAHs) (Gevrenov 2008). While preliminary results show that RAS do not readily emit PAHs, current research is evaluating the effect of adding discarded shingles on PAHs emissions during HMA production. Asbestos testing is occasionally conducted during recycling and processing of tear-off asphalt shingles based on the Polarized Light Microscopy (PLM) method, which can detect asbestos content of 1%.

Two strategies may be adopted in the recycling and processing of tear-off asphalt shingles in HMA (CMRA 2007). In the first strategy, the roofing contractor separates tear-off shingles before transferring to the shingle recycling plant. RAS is usually processed to be ground to a maximum particle size ranging from 12.5 to 19.0mm. Similar to RAP, RAS is added to the mix during production through a dry process as an aggregate source. Due to high temperature during production, aged binder in RAS is assumed to become available in the mixture and to effectively contribute to the blend between virgin and aged binder. A second approach was recently introduced in which RAS is ground to ultra-fine particle sizes (more than 80% passing sieve No. 200 – 0.075 mm) and blended with asphalt binder through a wet process (Elseifi et al. 2012). In the proposed wet process, the ground recycled material is blended with the binder at high temperature prior to mixing with the aggregates. This study only dealt with the first approach (i.e., dry blending of RAS). In this process, RAS is expected to reduce the amount of asphalt binder that is added to the mixture and to contribute as a source of aggregates to the mix. Fibrous shingle base (organic or fiberglass) also contains valuable fibers that may enhance the performance of asphalt mixtures (Foo et al. 1999).

Since the early 1990s, a number of research studies evaluated the use of this recycled material and its influence on the mix mechanical behavior. Air blown asphalt is typically used in the manufacturing of asphalt shingles; this type of asphalt binder has a greater viscosity than regular asphalt binder used in hot-mix asphalt (Foo et al. 1999). Button et al. evaluated the influence of adding 5 to 10% of asphalt shingles on the mechanical properties of asphalt mixtures as compared to untreated mixes (Button et al. 1995). The use of RAS resulted in a decreased tensile strength and creep stiffness of the mixture but it improved the mix's resistance to moisture damage.

3.3 Experimental Program

3.3.1 Test Materials

The experimental program was designed to evaluate a wide range of RAS materials from contrasting sources. Eight sources of RAS were collected from recycling plants around the country, see Table 1. The majority of the sources were from tear-off shingles, which represent the majority of the RAS around the country. During processing, mixed roofing materials were loaded to the recycling facility, at which non-shingle debris were removed from the recycled material. At the recycling facility, RAS was ground to a maximum particle size of 12.5 mm. A virgin shingle source was also collected from a major shingle manufacturer (referred to as SHIN), Table 1. These shingles were never installed on the roof and did not experience any aging due to service. Therefore, this sample may be considered an acceptable representation of RAS originating from manufacturer waste shingles, which consist of crumb shingles during production. The AC content in these shingles was set by the manufacturer at 20.3% during production. As shown in Table 1, a manufacturer waste source was also sampled from Minnesota, MWMN. However, this source was only evaluated in the molecular fractions testing conducted using HP-GPC.

Table 1. Descriptions of the RAS Materials and Sources

ID	Label ID	Source	Type
1	TOTX	Texas	Tear-off
2	TOMI	Michigan	Tear-off
3	TOR	Oregon	Tear-off
4	TOVA	Virginia	Tear-off
5	TOMO	Missouri	Tear-off
6	TOSD	South Dakota	Tear-off
7	TOMN	Minnesota	Tear-off
8	TOCT	Connecticut	Tear-off
9	SHIN	Virgin Shingle	Waste

(Table 1. continued)

ID	Label ID	Source	Type
10	MWMN	Minnesota	Waste

3.3.2 Laboratory Testing

3.3.2.1 Asphalt Extraction

Laboratory testing activities in this study determined the variation in the binder rheological properties extracted from RAS materials. Extraction of asphalt binder from RAS was conducted, according to AASHTO T 164-11 – Test Method B (Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)), based on the reflux test method using trichloroethylene (TCE). A high-speed centrifuge rotating at 11,000 rpm was used to recover mineral fillers from the extracted asphalt binder/solvent solution. Rotary evaporation was used to recover the asphalt from TCE. A water bath, heated at a temperature of $60^{o}C$, was used in the rotary evaporator to minimize aging during binder recovery. Analysis of the recovered binder using Thermo-Gravimetric Analyzer (TGA) indicated no traces of TCE in the recovered binder. It is noted that Test Method A was evaluated to recover the binder from the RAS but proved to be impractical due to the high content of asphalt in RAS and the large quantities of fines. This required a large of quantities of TCE for each RAS extraction, which was costly and impractical for disposal reasons.

3.3.2.2 High Pressure Gel Permeation Chromatography (HP-GPC)

HP-GPC was conducted on the first four RAS sources and the manufacturer waste source (MWMN) (shown in Table 1) in order to identify the variability in the molecular fractions of RAS materials. A gel permeation chromatograph Agilent 1100 equipped with an auto injector and a Hitachi differential refractive index detector was used. The separation of the asphalt components was performed with three columns connected in series with pore sizes of 500 angstrom (Å), 10-4 Å, and mix beads. The column set was calibrated with narrow molecular weight polystyrene (PS) standards using 1wt% in tetrahydrofuran (THF). The elution volume observed for polystyrene standards with each given molecular weight was used to build a calibration curve. All asphalt samples for HP-GPC were prepared at a concentration of 3 wt% in THF, injected through a 0.45μ filter into 150 μL vials, and inserted in an automatic sample injector. Samples were eluted with THF at 1 ml/min. at room temperature, and the species concentration in the eluent was recorded using a differential refractometer. The molecular weight distribution was divided into three fractions, a high molecular weight fraction (HMW), low molecular weight fraction (LMW), and others. The expected error in the measured molecular fractions is around 0.2% or less. Two replicates were measured for each binder blend and the average was used in the analysis.

3.3.2.3 Particle Size Distribution

Particle size distribution of the sampled RAS materials was measured by means of AASHTO T 27. Sample size in the shingle gradation test ranged from 700 to 1000g. AASHTO PP53-09 (Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in New Hot-Mix Asphalt (HMA)) provides a standard gradation for RAS, which may be used instead of measuring shingle aggregate gradation. Results of the sieve analysis for the different sources of RAS were calculated and compared to the standard gradation recommended by AASHTO PP53-09.

3.3.2.4 Properties of Binder Blends

In addition to the RAS binders, the properties of binder blends prepared with the binders extracted from RAS and virgin asphalt binder, classified as PG 64-22, were evaluated. The blends were prepared by mixing 500 g of virgin asphalt binder with the corresponding content of extracted binder from RAS at a mixing temperature of 180°C using a mechanical shear mixer

rotating at a speed of 1500 rpm for 30 minutes. Table 2 presents the RAS content in the blends, which ranged from 0 to 10.0%. These contents represent the RAS contents in the mix, from which the proportion ratios between virgin and RAS binder were calculated assuming a total binder content of 5% in the mix. This approach assumes total contribution of the RAS binder in the mix; however, other levels of contribution should be evaluated in future studies. Currently, around 15 states allow RAS content in the mix ranging from 5 to 7.5% using a dry blending process to which the RAS are added as a source of aggregates. The amount of virgin asphalt binder in the mix is reduced by the estimated level of replacement from RAS. Prepared blends were characterized using fundamental rheological tests (i.e., dynamic shear rheometry, rotational viscosity, and bending beam rheometer) and by comparing the Superpave Performance Grade (PG) of the RAS-modified blend to the unmodified binder as per AASHTO M 320-09 (Standard Specification for Performance-Graded Asphalt Binder).

Table 2. Descriptions of the Binder Blends

ID	RAS ID	RAS Source	Virgin Binder	RAS Content (%)
1	TOTX	Texas	PG 64-22	0, 2.5, 5.0, 10.0
2	TOMI	Michigan	PG 64-22	0, 2.5, 5.0, 10.0
3	TOR	Oregon	PG 64-22	0, 2.5, 5.0, 10.0
4	TOVA	Virginia	PG 64-22	0, 2.5, 5.0, 10.0

3.4 Results and Analysis

3.4.1 Asphalt Content in RAS

Figure 3.1 presents the AC content variation among the different RAS sources. As shown in this figure, AC content in tear-off shingles ranged from 24% to 31% with an average of 26.6% and a coefficient of variation (COV) of 8.9%. A 95% confidence interval around the mean shows that the AC content in RAS materials from tear-off shingles would range between 24.6 and 28.6%. Based on these results, it is observed that AC content did not substantially vary among the different sources around the country. However, past research found that the use of the ignition oven would result in erroneous estimation of binder content in RAS by about 5%, as many of the fibers and mineral components burn during testing and are assigned in the calculations to be part of the AC (Maupin 2010). Results presented in Figure 1 also show that the AC content in the virgin shingle source (SHIN) was 20.4%, which matched closely to the content provided by the shingle manufacturer. The noticeably lower AC content in the virgin shingle source as compared to the RAS from tear-off was expected as shingles lose surface granules during service due to weathering, which results in a higher AC content in RAS (Davis 2009).

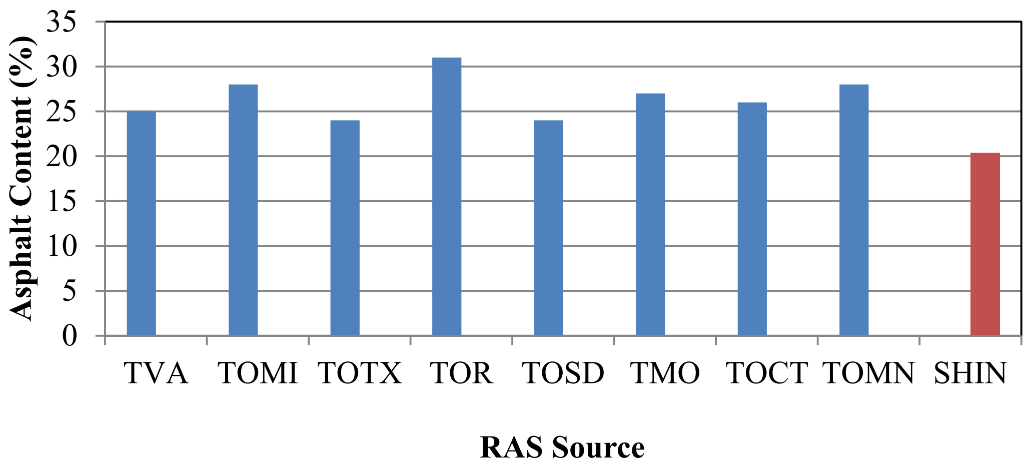

Figure 3.1. Variation of Asphalt Content in RAS Sources

3.4.2 Superpave PG Grading of RAS Binders

Tables 3 and 4 present the measured rheological properties of the extracted RAS binders as well as their final PG grades based on laboratory testing conducted using rotational viscometer, dynamic shear rheometer, and bending beam rheometer. As shown in these tables, binders in RAS were very stiff and brittle and could not be graded at low temperature even when tested at

0°C. In addition, the extracted binders were too stiff at 135°C for testing using rotational viscometer. Temperature was gradually increased in the viscosity test until a valid reading was obtained. This temperature is indicated in Tables 3 and 4. This stiff behavior was expected as the binder, used in shingle manufacturing and present in RAS materials, is an air-blown asphalt binder with stiff characteristics and low elongation properties. It is also noted from these tables that the properties of the binders from RAS sources sampled from different recycling plants around the country did not substantially change. In fact, all RAS binders were graded as PG 118 + - xx using the Superpave binder specification system. Stiffening of the binder during service was also observed in these results by comparing the measurements of the virgin binder (SHIN) to the binders from RAS sources.

Table 3. Results of the Superpave PG Testing on Extracted RAS Binders

Binder Testing	Spec	Test Temp	SHIN	TVA	TOMI	TOTX	TOR
Test on Original Binder							
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	1.00^{+}	112°C	25.7	51.1	47.6	155	32
	1.00^{+}	118°C	18.65	36.25	33.7	114	22.4
Rotational Viscosity (Pa·s), AASHTO T316	3.0^{-}	135°C	135°C N/A (195°C) 5.2	135°C N/A (225°C) 3.8	135°C N/A (195°C) 9.1	135°C N/A (225°C) 3.4	135°C N/A (195°C) 4.4
Tests on RTFO							
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	2.20^{+}	112°C	87.9	211.5	81.9	201.5	58.45
	2.20^{+}	118°C	67.8	160.5	60	147	41.5
Tests on (RTFO+ PAV)							
Dynamic Shear, G*Sin(δ), (kPa), AASHTO T315	5000^{-}	34°C	5610	5280	(43°C) 4740	(25°C) 5100	43°C 5540
		37°C	4720	4500	(40°C) 5530	(28°C) 4550	46°C 4680

(Table 3. continued)

Binder Testing	Spec	Temp Test	SHIN	TVA	TOMI	TOTX	TOR
BBR Creep Stiffness, (MPa), AASHTO T313	300⁻	0°C	81.3	135	99.7	127	113
Bending Beam M – Value AASHTO T313	0.300	0°C	0.198	0.146	0.183	0.159	0.199
Actual PG Grading			**PG +118 - xx**	**PG +118 - xx**	**PG +118 - xx**	**PG +118 - xx**	**PG +118 –xx**

Table 4. Results of the Superpave PG Testing on Extracted RAS Binders

Binder Testing	Spec	Test Temp	TMO	TOSD	TOMN	TOCT
Test on Original Binder						
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	1.00^{+}	112°C	56.4	19.3	46.2	129
		118°C	39.8	13.95	35.3	100.7
Rotational Viscosity (Pa·s), AASHTO T316	3.0^{-}	135°C	135°C N/A (195°C) 9.1	135°C N/A (165°C) 13.8	135°C N/A[1] (165°C) 13.8	135°C N/A (195°C) 13.75
Tests on RTFO						
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	2.20^{+}	112°C	189	59.6	87	122
	2.20^{+}	118°C	143.5	45.3	66.4	89.5
Tests on (RTFO+ PAV)						
Binder Testing	**Spec**	**Test Temp**	**TMO**	**TOSD**	**TOMN**	**TOCT**
Dynamic Shear, G*Sin(δ), (kPa), AASHTO T315	<=5000	46°C	5460	(37°C) 5910	(37°C) 5270	(40°C) 5320
		49°C	4850	(40°C) 4920	(40°C) 4590	(43°C) 4720
BBR Creep Stiffness, (MPa), AASHTO T313	300^{-}	0°C	146	62.1	106.3	114
Bending Beam m-value AASHTO T313	0.300^{+}	0°C	0.184	0.211	0.184	0.187
Actual PG Grading			**PG +118 - xx**	**PG +118 - xx**	**PG +118 - xx**	**PG +118 - xx**

[1] N/A: binder too stiff at 135°C.

3.4.3 High-Pressure Gel Permeation Chromatography Analysis

Table 5 presents the molecular size distribution obtained from the HP-GPC test results for the four RAS sources from tear-off and the manufacturer waste source (i.e., MWMN). Fractional composition of the binders were divided into three main groups: (1) high molecular weight (HMW), which represents the molecular fraction in the binder associated with asphaltenes; (2) low molecular weight (LMW), which represents the molecular fraction in the binder associated with maltenes; and (3) others, which may indicate the presence of polymers or rubber in the RAS. Past research has shown that an increase in the binder content of LMW results in an increase in its elongation properties at intermediate and low temperatures (Shen 2006). Results presented in Table 5 show the variation in the binders' molecular compositions extracted from different RAS sources. The extracted binder from Texas tear-off (i.e., TOTX) had the highest content of HMW followed by the binder extracted from Virginia tear-off (i.e., TOVA). The increase in the content of HMW in RAS sources from tear-off would cause the binder from these sources to be more brittle and stiffer, which was expected as binders from tear-off age and stiffen during service. It is noted from the results presented in Table 5 that the content of HMW and LMW in the other RAS sources did not vary substantially with the exception of Texas tear-off. It is possible that the RAS source sampled from Texas originated from a different shingle manufacturing process, as it had substantially different molecular compositions than the other RAS materials.

Table 5. Molecular Fraction Compositions of RAS Materials

RAS	Others %	HMW %	LMW %
TOMI	4.78	28.02	67.20
TOTX	11.58	34.52	53.90
TOR	6.59	28.52	64.89
TOVA	5.26	30.32	64.42

(Table 5. continued)

RAS	Others%	HMW%	LMW%
MWMN	6.29	29.87	63.84

3.4.4 Properties of Asphalt Binder Blends

Tables 6 and 7 present the measured rheological properties of the binder blends, as well as their final PG grades based on laboratory testing conducted using rotational viscometer, dynamic shear rheometer, and bending beam rheometer. As shown in these results, consistent trends were observed in the final PG grade of the blends for RAS sampled from different sources. At a RAS content of 2.5%, the high temperature grade of the binder was increased due to RAS by one grade and the low temperature grade was also increased by one grade as compared to the virgin binder (i.e., PG 64-22).

Table 6. Results of the Superpave PG Testing on Binder Blends

Binder Blends	Spec	Test Temp	TOTX 2.5%	**TOTX 5%**	TOTX 10%	TOMI 2.5%	TOMI 5%	TOMI 10%
Test on Original Binder								
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	1.00+	70°C	1.80	(82°C) 1.30	(106°C) 1.41	(70 °C) 1.93	(76)°C 1.93	(106)°C 1.31
Rotational Viscosity (Pa·s), AASHTO T316	3.0-	135°C	0.900	1.863	10.804	.879	1.350	11.671
Tests on RTFO								
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	2.20+	70°C	4.02	(82°C) 3.80	(100)°C 3.92	(70)°C 6.07	(76)°C 4.97	(106°C) 3.28
	2.20+	76°C	1.91	(88°C) 1.94	(106)°C 2.08	(76)°C 2.94	(82)°C 2.46	(112°C) 1.87
Tests on (RTFO+ PAV)								
Binder Lends	**Spec**	**Test Temp**	TOTX 2.5%	TOTX 5%	TOTX 10%	TOMI 2.5%	TOMI 5%	TOMI 10%
Dynamic Shear, G*Sin(δ), (kPa), AASHTO T31	5000-	25°C	5640	(28°C)5280	(31°C)6130	(25°C)5943	(25)°C 6160	(25)°C 5740
		28°C	4080	(31°C) 3975	(34°C) 4895	(28°C)4297	(28)°C 4510	(28)°C 4235
BBR Creep Stiffness, (MPa), AASHTO T313	300-	-6°C	99.7	127	118	97.85	97.5	70.35
		-12°C	126	258	243	207	205	127
Bending Beam m-value AASHTO T313	0.300+	-6°C	.359	.307	.306	.336	.320	.272
		-12°C	.292	.263	.244	.285	.268	.244
Actual PG Grading			**PG 70-16**	**PG 82-16**	**PG 100-16**	**PG 70 - 16**	**PG 76 - 16**	**PG 106-xx**

At a RAS content of 5.0%, the high temperature grade of the blends was increased due to RAS by three grades (except for TOMI 5%, which was increased by two grades) and the low temperature grade was increased by one grade as compared to the virgin binder (i.e., PG 64-22). At a RAS content of 10.0%, the high temperature grade of the blends was increased due to RAS by seven grades (except for TOTX 10%, which was increased by six grades). However, the blends with 10% RAS were not graded at low temperature as they did not pass the m-value criterion in the BBR even when tested at 0°C. From these results, it is noted that the use of RAS at up to 5% results in substantial changes in the PG grade of the blends and these changes should be accounted for in the mix design process possibly through the use of blending charts. At a RAS content of 10%, the blends did not pass the Superpave criterion at low temperature and may indicate that these blends are unsuitable for road applications.

Table 7. Results of the Superpave PG Testing on Binder Blends

Binder Blends	**Spec**	**Test Temp**	TOR 2.5%	TOR 5%	TOR 10%	TOVA 2.5%	TOVA 5%	TOVA 10%
Test on Original Binder								
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	1.00^+	70°C	1.62	(82°C) 1.79	(106°C) 1.66	(76°C) 1.01	(82°C) 1.44	(106°C) 1.60
Rotational Viscosity (Pa·s), AASHTO T316	3.0^-	135°C	0.846	1.775	12.121	.912	1.713	(165°C) 1.663
Tests on RTFO								
Dynamic Shear, G*/Sin(δ), (kPa), AASHTO T315	2.20^+	70°C	4.49	(82°C) 4.62	(106)°C 2.58	(76°C) 2.65	(82°C) 3.63	(106°C) 3.04
	2.20^+	76°C	2.11	(88°C) 2.34	(112)°C 1.46	(82°C) 1.31	(88°C) 1.86	(112°C) 1.75
Tests on (RTFO+ PAV)								
Dynamic Shear, G*Sin(δ), (kPa), AASHTO T315	5000^-	25°C	5760	(28°C) 5880	(31°C) 6255	(25°C) 6340	(28°C) 5425	(31°C) 6080
		28°C	4105	(31°C) 4330	(34°C) 4950	(28°C) 4530	(31°C) 4035	(34°C) 4865
BBR Creep Stiffness, (MPa), AASHTO T313	300^-	-6°C	108	120	162	103	117	144
		-12°C	213	243	----	234	239	----
Bending Beam m-value AASHTO T313	0.300^+	-6°C	0.349	.306	.263[1]	.345	.323	.251[1]
		-12°C	0.286	.263	----	.288	.259	----
Actual PG Grading			**PG 70-16**	**PG 82-16**	**PG 106-xx**	**PG 70 - 16**	**PG 82 - 16**	**PG 106-xx**

[1] Blends also failed at 0°C.

3.4.5 RAS Particle Size Distribution

Figure 2 presents the gradation curves for the different RAS sources as well as the standard gradation curve recommended by AASHTO PP 53-09. As shown in this figure, seven of the eight RAS sources had similar particle size distributions, while one source (TOTX) had a different distribution. It is also noted that the gradation curve recommended by AASHTO PP 53-09 does not agree or resemble the particle size distributions of the different RAS sources. The percentage passing No. 200 in the standard curve is extremely high (25%) as compared to what was measured for the different RAS sources. Based on the particle size distribution curves obtained for the seven RAS sources with similar gradation curves, an average gradation is provided in Table 8, which may be used if sieve analysis of RAS is not conducted as part of the mix design.

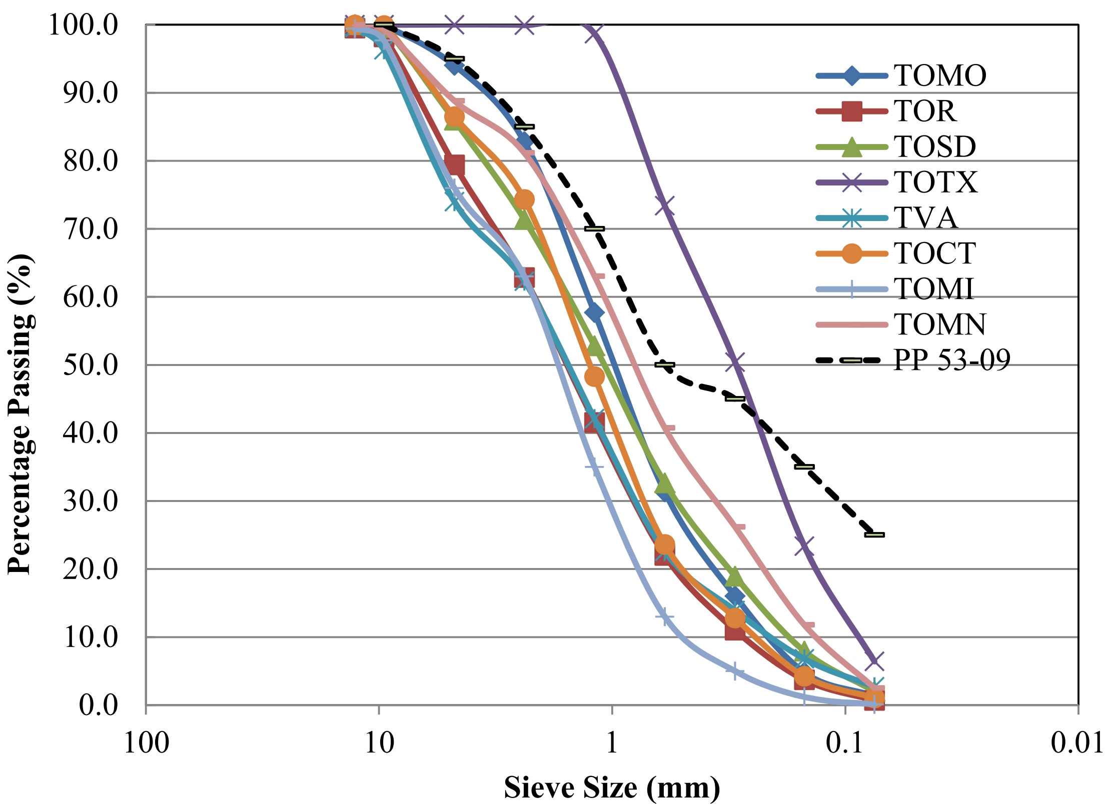

Figure 3.2. Variations of Particle Size Distributions for the RAS Sources

Table 8. Standard Gradation Curve for RAS

Sieve Size (mm)	Percent Passing (%)
12.7	99.8
9.5	98.7
4.75	83.5
2.36	71.1
1.19	48.6
0.60	26.6
0.30	14.8
0.15	5.8
0.075	1.5

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Chapter 4 – Summary and Conclusions

This study evaluated the effects of RAS modification on the rheological properties of asphalt binder. In addition, variability of RAS characteristics sampled from different sources around the country was investigated. Based on the results of this analysis, the following conclusions may be drawn:

- AC content in tear-off shingles was consistent among different RAS sources around the country. A 95% confidence interval around the mean show that the AC content in RAS materials from tear-off shingles would range between 24.6 and 28.6%. AC content in manufacturer waste shingle was 20.4%, which was noticeably less than in tear-off shingles.
- The standard gradation curve recommended in AASHTO PP 53-09 for RAS does not agree with the size distributions of the different RAS sources. The percentage passing No. 200 in the standard curve is extremely high (25%) as compared to what was measured for the different RAS sources.
- All extracted RAS binders were graded as PG 118 + - xx using the Superpave binder specification system. This stiff behavior is due to the binder used in shingle manufacturing, which is an air-blown asphalt binder with stiff characteristics and low elongation properties.
- With the exception of one source, the content of HMW and LMW in RAS sources did not vary substantially.
- At a RAS content of up to 5%, the high temperature grade of the blends was increased by one to seven grades and the low temperature grade was increased by one grade. The use

of binder blending charts is recommended to account for the influence of RAS in the mix design. At a RAS content of 10%, the binder blends did not pass the Superpave criterion at low temperature.

4.1 Future Work

Based on the results of this study, further research is needed to investigate different levels of binder contribution from RAS and to evaluate the effects of different RAS sources on mix design and performance. Mix design is a very important part of testing the effects that RAS can have on HMA. The next step in this research is to use asphalt blends on a Superpave mix design and evaluate and analyze its effectiveness. It is very important to determine what the variability will be with RAS that comes from different areas around the country and its effects on mix performance. It is also not known how the moisture susceptibility, air voids, and compaction will be affected. Furthermore, it is important to evaluate how the bulk specific gravity, bulk density, voids in the total mix, and voids filled with asphalt will be affected with the use of RAS.

Vita

Aaron Lodge was born in Baton Rouge, Louisiana on December 4, 1987. After graduating from Woodlawn High School in Baton Rouge as a scholar, he chose to attend Southeastern Louisiana University. During his tenure at Southeastern, he studied business management, with a concentration in entrepreneurship. In the fall of 2011, Aaron Lodge was presented with a Bachelor of Science Degree in Business Management.

After Graduating College Aaron Lodge continued working in the construction industry on the construction project of the $150M+ New Woman's Hospital in Baton Rouge, Louisiana. After his participation in this project was done, he then started working for his dad's landscaping and irrigation company, where he learned the basics of how to manage a crew and how to track materials. He worked on landscaping projects that ranged in size from $5,000 to $25,000. Working in the construction industry and in the landscaping industry is what influenced Aaron Lodge to get a Masters with a focus in Construction Management. After receiving his Masters in Engineering Science from Louisiana State University, he plans to move to Houston, Texas to work for a Fortune 500 company who has already given him a job offer as a Construction Manager.