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Assessing the effectiveness of recycling agents on reclaimed asphalt pavements

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To my family.

Abstract

Reclaimed Asphalt Pavements (RAP) are a significant resource for environmentally friendly road building techniques. RAP is obtained from millings when the pavement loses its quality by aging, and it needs to be removed when brand-new asphalt is needed. The use of RAP lowers the costs and environmental impact along with conserving natural resources. However, the aging of the asphalt binders in the reclaimed material affects the pavement's functionality. Recycling agents, sometimes referred to as rejuvenators, have become a popular way to increase RAP's performance in asphalt mixtures and improve its qualities.

There is still more work to be done on the use of RAP in hot-mix asphalt pavements. There are many challenges on any form of recycling agent in order to restore the aged asphalt binder in RAP, despite the growing interest in its use. Even so, there is still no agreement on how to employ RAP and rejuvenators. It is crucial to have an in-depth understanding of how they affect the rheological characteristics and performance of pavements to use recycling agents in asphalt mixtures at their fullest potential.

This study investigates the use of rejuvenators (recycling agents) in RAP applications. To improve the adoption of sustainability in the construction of roads, especially with a special focus on asphalt pavements, we need to have a full understanding of recycling agents and their behaviors on reclaimed asphalt pavements. The research aims to shed light on the potential advantages and difficulties connected to recycling agents with their use together with RAP. In order to understand the effects of recycling agents on asphalt pavements, the Laboratory of Road Materials at Politecnico di Torino brings a new methodology, called Model System (MS).

Model System consists of two main structures. It focuses on single-size aggregate (sieve No.4, 4.75 mm) to limit the finer fractions and clumps in RAP MS samples. Secondly, MS has the target of 30% Voids in Mineral Aggregate (VMA), No.4 RAP materials from two different sources in the United States are collected. After sieving to the No.4 (4.75mm), compacted to cylindrical shape (62 mm height, 150 mm diameter) in its original state or cold treated with two different types of recycling agents. By using the single-size aggregate and 30% VMA volumetric properties, it is anticipated that the binder phase will have a major impact on the eventual response, aggregate interlocking having minimal impact on the response. 3 different Model

Systems are constructed. Model Systems with 100% RAP so-called Black System, Model Systems with two different recycling agents called Rejuvenated System, and Model Systems with extracted aggregate (by ignition oven) and treated with virgin binder called White System. Each model system was tested and analyzed to have a broader understanding of the effect of recycling agents by comparing the Black, Rejuvenated, and White Systems. Also, this paper focused on the earlier research, especially the tests conducted at Politecnico di Torino, where we used Model Systems as a practical approach to evaluate the application of recycling agents in RAP.

According to analysis, recycling agents have demonstrated potential in improving the properties of aged asphalt binders. Rejuvenators improve the workability and distress resistance of RAP-containing asphalt mixes. However, depending on variables like RAP source, granular gradation, binder grade, and environmental conditions, certain recycling agents may not always be as effective as others.

Keywords: RAP, recycling agents, aging

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List of Notations/ Acronyms

RAP	reclaimed asphalt pavement
RA	recycling agent (rejuvenator)
VMA	voids in mineral aggregate
CT_{index}	cracking tolerance index
ITS	indirect tensile strength
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
HMA	hot mix asphalt
BS	black system
RS	rejuvenated system
WS	white system
PG	penetration grade

Introduction

Road construction and maintenance are essential for maintaining transportation networks while supporting growth. Flexible pavements have become more and more popular because they provide performance, cost reduction, and the ability to adjust to increasing traffic demands. Due to its outstanding capacity to disperse loads and endure dynamic pressures generated by moving vehicles, flexible pavements, also known as bituminous pavements, have become increasingly preferred on a global scale. Since its high availability, it makes flexible pavements more attractive to the agencies/authorities. The Federal Highway Administration (FWHA) reports that 2.78 million miles, or almost 67% of all public roads, were paved in the United States in 2017, and asphalt pavements represent a significant portion of the transportation infrastructure in the US.

Hot mix asphalt (HMA) is a composite material that is made of aggregates such as crushed stone, sand, or gravel that are mixed with asphalt binder. Asphalt binder is also called bitumen in the literature. While the asphalt binder serves as a binder, binding the aggregates together and giving the pavement flexibility, the aggregates give the mixture strength and stability. During the manufacturing process, temperature, mixing duration, and aggregate gradation must be precisely controlled if high-quality HMA is to be achieved. Different HMA varieties, such as dense-graded, open-graded, and gap-graded mixes, are created to meet the requirements of various applications and traffic conditions. Instead of using virgin materials for each construction, HMA can help to promote sustainability by using recycled materials.

A sizable amount of asphalt material goes to waste because pavements deteriorate by aging and need to be repaired or rebuilt. Asphalt material that has been taken out of old pavements and prepared (removal of unwanted materials and/or fractionation) for reuse is known as reclaimed asphalt pavement (RAP). Hot mix asphalt (HMA), new asphalt pavements, and other products like roofing materials can all be made from asphalt binder. Even though it is not common to use reclaimed asphalt shingles (RAS) in Europe, the use of RAP and RAS in the construction of new asphalt pavements is extremely increasing in the United States.

The amount of waste that is disposed of in landfills would be decreased when RAP is used, among many other advantages. By recycling old asphalt pavements, we can protect the environment and cut down on the quantity of material that ends up in landfills. Recycling asphalt materials in the pavement industry will save lots of money and bring the design of environmentally friendly perspective.

The use of the RAP can reduce the price of brand-new asphalt roads' materials and, consequently be cost-effective. RAP often costs a lot less than brand-new asphalt does. RAP recycling can also cut down on the demand for fresh raw material extraction, which can result in cost savings in terms of materials, workmanship, and logistics.

Recycling RAP improves the performance of asphalt pavements: RAP-modified (100% RAP or partially included) asphalt pavements can have improved properties, such as strength. By implementing more effective methods and approaches, the use of RAP in asphalt pavements will continue to give satisfactory results.

The use of RAP is becoming increasingly common in the United States as greater numbers of organizations become aware of the advantages of the use of recycled asphalt pavements, and it is believed that this trend is going to continue its growth. However, RAP recycling is not without its difficulties. The quality of RAP might vary depending on the age and condition of the pavement location, gradation, etc., which is something to consider. Mixing RAP with virgin asphalt to produce a consistent product may be an adapted approach and surely challenging. RAP recycling can be difficult since it often requires specific demands and expertise. Recycled asphalt pavement must meet a certain standard of quality requirements and meet the requirements of the designed road. Despite these difficulties, recycling RAP is an effective strategy for lowering trash, saving money, and enhancing the life expectancy of asphalt pavements. RAP recycling is expected to become even more significant in the future as demand for environmentally friendly construction materials rises.

Objectives and aim

This research aims to analyze and optimize the effectiveness of recycling agents in improving the performance of asphalt pavements containing reclaimed asphalt pavement (RAP). In order to give useful information for the use of RAP in road construction and maintenance, the study will examine the effects of various recycling agents on the mechanical characteristics and performance of asphalt pavements.

The main motivation in this research is to evaluate the improvement in the performance of RAP-containing asphalt pavements, investigate the effects of recycling agents on the mechanical properties of RAP-modified asphalt pavements (such as strength), examine the effects of various types of recycling agents on different levels of aged asphalt pavement. The motivation to carry out the tests and analysis is to have a wider perspective to understand the impact of the recycling agents on Reclaimed Asphalt Pavements (RAP).

This research will evaluate the use of different sources of RAP and compare the different types of recycling agents by using a new methodology called Model System (MS). Model System will be explained in detail in the following chapters.

Literature Review

This chapter reviews reclaimed asphalt pavements in detail in past research. The importance of recycling the old millings and addressing various aspects related to RAP. As a starting point, the aging of the asphalt binder and its inevitable results are discussed. Previous studies on the aging of the asphalt binder and their key findings have been taken into account. The utilization of recycling agents was examined, covering aspects like how they are accepted in the industry. It's unraveled that many states/countries have their way of using the recycling agents on the old pavements including dosage or the treatment way. However, it is observed that standardized anti-aging approaches have yet to be established. This section delves into the most widely accepted methods and research in this regard.

Reclaimed Asphalt Pavements

The application of Reclaimed Asphalt Pavement (RAP) in road construction and maintenance has become a practical and sustainable option without any doubt. Asphalt pavements are one of the few things that we can construct with the possibility of using 100% recycled materials and this process can be done forever. An overview of the main characteristics of RAP, as well as its advantages and disadvantages, is given in this literature review.

The use of RAP minimizes waste and cuts down on the requirement for virgin materials by recycling and reusing existing asphalt materials from millings. Instead of using virgin materials, the utilization of RAP has several benefits in terms of economic and environmental. The figure below shows that 100% RAP reduces the cost per ton of asphalt by up to 70%. (Zaumanis, Mallick, & Frank, 2014). Although it is not mandatory, it is possible to make sustainable and economical mixtures with additional virgin materials combined with RAP, still eco-friendly compared to conventional methodology.

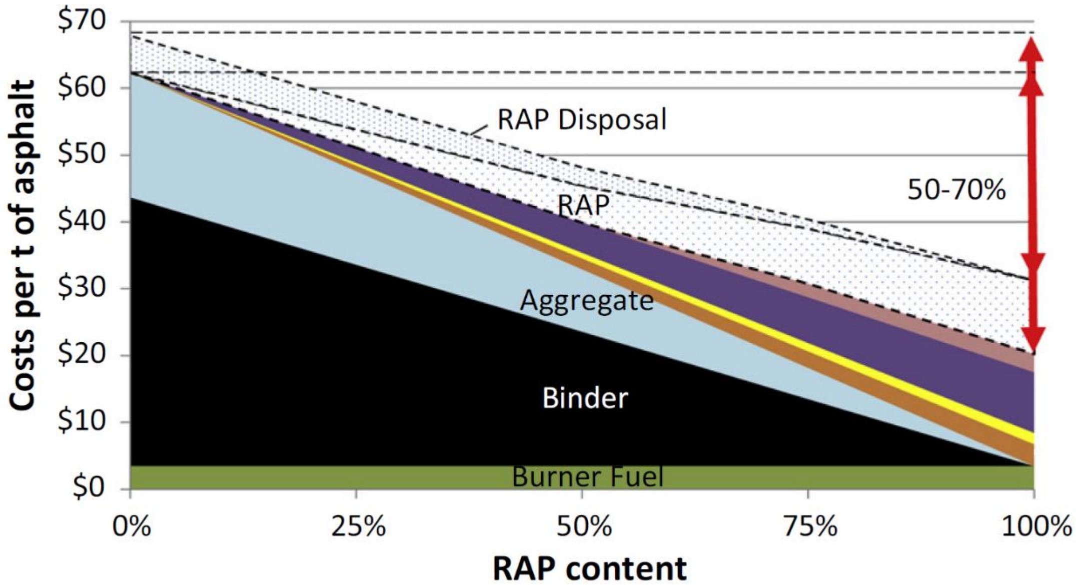

Figure 1. Cost analysis of hot mix asphalt (Zaumanis et al., 2014)

Also, many supporting studies show the historical price change of asphalt paving over the years. This increase in the price leads contractors to invest in affordable solutions while maintaining the desired quality as conventional methodologies do.

5485.3 million tons of asphalt were produced between 2008 and 2015 among the 32 nations. Therefore, the cost of producing asphalt would have been lowered by 270.5 billion dollars if other sources of bitumen (like Crumb-rubber binder (CRM) and/or rejuvenators) had been used instead of normal asphalt. Additionally, this decrease corresponds to 32 countries, and the amount of money saved would increase if the manufacturing of asphalt globally were included. Therefore, it may be believed that utilizing waste materials in pavement applications helps to preserve the environment and significantly lowers production costs. (Jahanbakhsh et al., 2020)

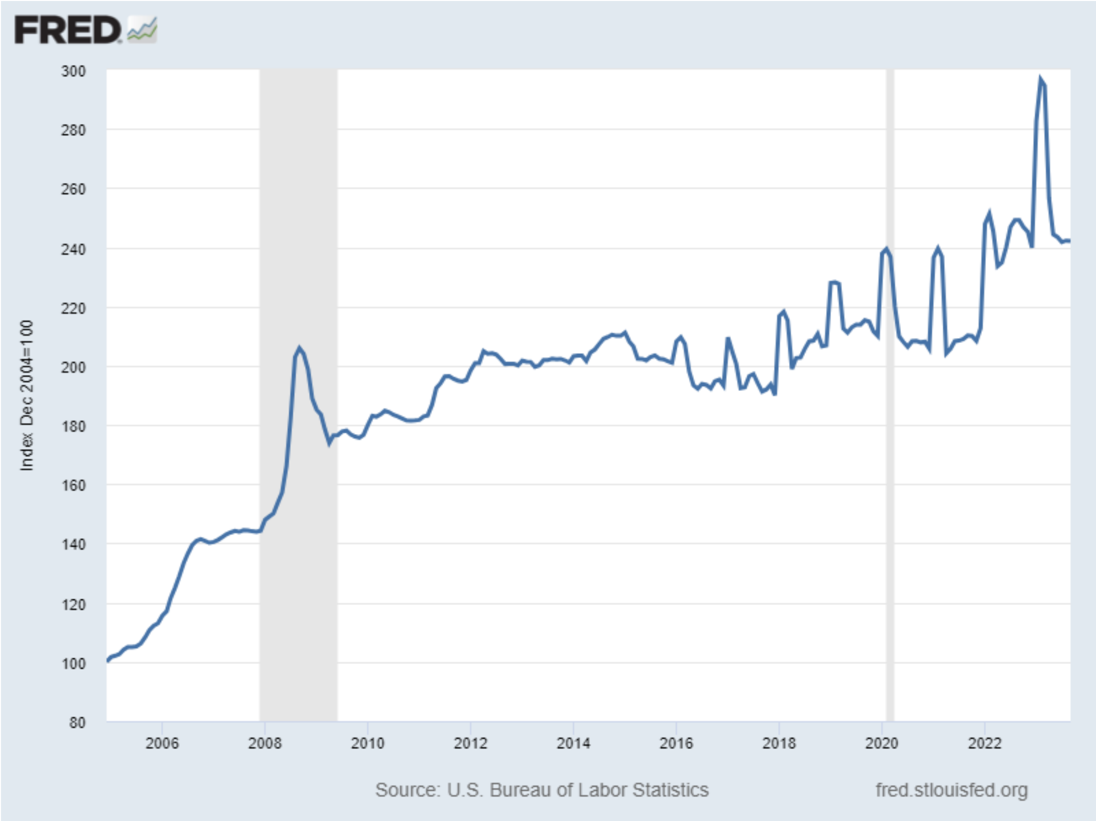

Figure 2. Producer Price Index by Industry: Asphalt Paving Mixture and Block Manufacturing (Source: U.S. Bureau of Labor Statistics)

When we compare conventional paving with virgin materials and the use of reclaimed asphalt by considering environmental factors, we see that recycling the old millings is a more suitable option. Pavement construction requires a significant amount of energy, water, and raw materials, most of which come from natural resources. Also, emissions are another unavoidable component of pavement construction operations. The industry is facing difficulties in maintaining economic and technological advancement in the face of population expansion and the widespread use of non-renewable natural resources (Mallick & El-Korchi, 2018). The comparison includes each step of the life cycle assessment of asphalt from cradle to grave for both scenarios. Life Cycle Assessment (LCA) is an internationally standardized methodology (ISO 14040-14044) to criticize the environmental burdens and resources involved along the life of products, in our case asphalt pavements. To compare the environmental effect of both approaches Zaumanis estimated and plotted down the kg of CO_2 equivalent per ton of paved mix. For the sake of simplicity, the transport distance was divided into two parts: the 50 km from the asphalt plant to the paving site and the 50 km from the asphalt plant to the quarry/RAP site. The process's main variables are the amount of energy used to produce the component materials. The computation findings show that using 100% recycled material to produce asphalt can save 18 kg of CO_2 equivalent and 20% of energy for every ton of paved mixture (Zaumanis, Mallick, & Frank, 2014).

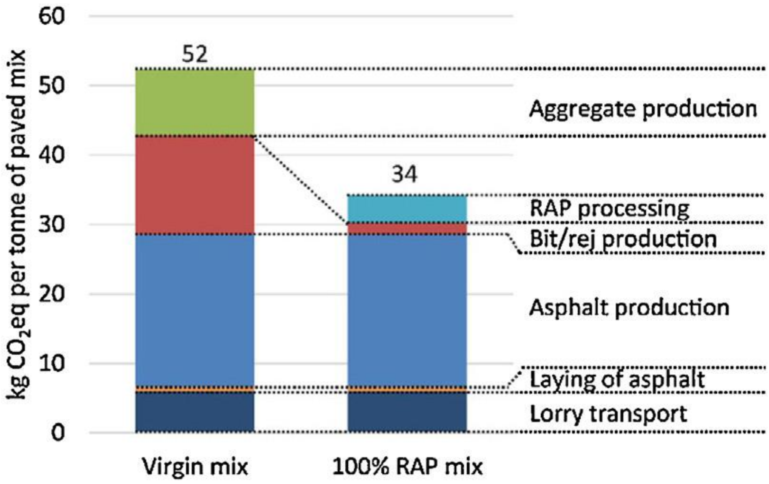

Figure 3. Carbon emissions (Zaumanis et al., 2014)

However, the use of RAP does not mean that it’s perfect and satisfies all the requirements for sufficient performance we expect. There is one major problem that we face, especially when we use high-content RAP in road construction. NCHRP 9-12 runs research and their goal was to answer if RAP binder blends with fresh asphalt binder in the hot mix. RAP consists of two elements, asphalt binder and aggregates. To ensure the quality of the mix there are questions we must ask. What is the level of blending in RAP mixtures between aged and fresh binder? Do I expect the same level of blending in each RAP mixture? Explaining the level of blending scenarios focused on three possible outcomes (Bowers, 2013).

To find out how RAP mixes behaved, three scenarios representing potential interactions between the old and new binders were considered:

1. Black rock: that means RAP does not interact with virgin binder. There is no blending between aged and fresh binder. The behavior is like an aggregate since it’s only a rocky particle. This is not the desired scenario when we mix them.

2. Partial Blending: obtaining the partially blended mixture that we face in the field/lab. Thin bitumen later interacts with virgin binder, not totally but in some measure.
3. Total blending: the case where we consider 100% blending the aged binder with a virgin binder. It is the optimum case where we mostly consider the mixtures but sometimes not all the binder content is available to mix. Binder availability refers to the amount of RAP binder that is available to blend with the virgin asphalt (Pape & Castorena, 2022).

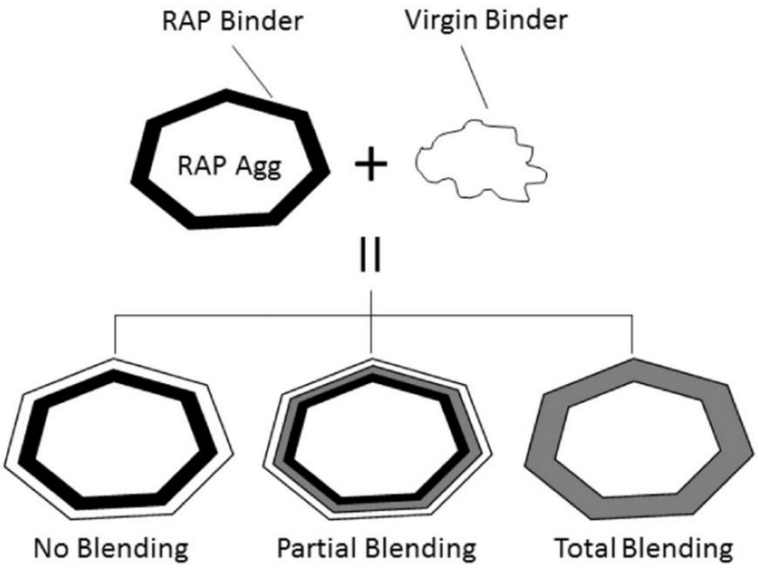

Figure 4. Binder blending scenarios (Bowers, 2013)

Pavement engineers should take into account the above-mentioned blending scenarios in the fields. In the case of considering the RAP as black rock but having a total blend in reality would lead to an unexpected stiffness in the mixture. On the contrary, considering your mixture has a total blending while your RAP behaves as black rock would end up with lower binder content may result in premature cracking issues (Zaumanis & Mallick, 2015). As a final thought, as stated in NCHRP 9-12 research, we obtain that in most cases partial blending or total blending depending on RAP content. Expecting the black rock case would be misleading since research shows that actual practice is between total blending and partial blending.

Recycling Agents

As asphalt binder begins to age, the ratio of its constituent components begins to change (Kaseer et al., 2019; Petersen et al., 2002). Regarding this change, the asphalt binder loses its ductility and becomes stiffer as asphalt ages. Aging by the time of construction is generally considered as short-term aging. This period includes from the beginning of the mixing up until the paving of the asphalt mixture. The aging while in the service life of the pavement is considered as long-term aging. During this period, both the influence of sunlight (UV radiation, temperature) and traffic load continue to affect asphalt pavement. After an investigation of the road, if any rehabilitation is needed, engineers decide to whether keep the old pavement with repair or construct the new pavement.

Recycling agents or so-called rejuvenators are such additives that enhance aged binder’s qualities and qualify it for use in fresh asphalt mixtures. To repair the properties of RAP, rejuvenators are usually liquid materials added to the mixtures, or extracted and recovered binders. Chemical modifiers, rejuvenators, and softening agents are examples of common recycling agents for now in the industry. Based on the type of the liquid, they have different applications and properties. Recycling agents can soften RAP's aged stiff binder, making it more workable and effective in asphalt mixtures.

Increasing the amount of RAP in asphalt mixes can result in economic savings, but having a stiffer mixture we will have (Petersen et al., 2002). The utilization of the rejuvenators can help us to overcome this issue. By lowering the demand for fresh asphalt production and preserving natural resources, RAP and recycling agents enhance sustainability. Additionally, construction expenses can be drastically decreased by using RAP with the aid of recycling agents. The virgin asphalt binder to be utilized and the RAP gradation should work well together when selecting a recycling agent. RAP must be properly mixed and blended with the virgin binder and recycling agent to get the necessary qualities. The utilization of recycling agents is mainly related to the possibility of rutting damage, which is caused by the rejuvenator not being fully integrated with the reclaimed asphalt pavement (RAP) and the resultant development of a low-stiffness micro-layer on the RAP's surface. Rutting-related problems are still concerns of many authorities related to the use of recycling agents and their implementation (Mogawer et al., 2015).

This emphasizes the significance of selecting the rejuvenator carefully. (Zaumanis, Mallick, Poulikakos, et al., 2014) In order to give the pavement the desired qualities in the short and long term, as listed below, this thorough selection is essential:

In the short term: In order to achieve uniformly wrapped mixtures, rejuvenators must accelerate the diffusion into the RAP binder and activate against aging. Recycling agents should make the RAP softer and workable to obtain the desired material that can be easily applied and compacted to the required density. Most of the diffusion process must be finished before traffic is permitted since the vehicles might not feel the friction.

In the long term: Rejuvenators must be able to restore the aged binder's chemical and physical properties efficiently, guaranteeing its stability over many years of use. Recycling agents should keep the same quality of effects on aged binders without fatigue and low-temperature cracking potential, The rheology of the binder must be restored. In order to prevent moisture-related damage and raveling, the mixture should also provide sufficient stiffness without over-softening.

Theoretical Framework

This chapter will provide a detailed explanation of the starting point of the Model System (MS). It will include a discussion of reference research and its key parameters, an overview of the background of related work, and a demonstration of the methodology employed in the current work.

Model System (MS) Structure

The Model System (MS) is an approach developed by the Road Materials Laboratory at the Department of Environment, Land, and Infrastructure Engineering (DIATI) of Politecnico di Torino. It is used for investigating the effectiveness of rejuvenators on reclaimed asphalt pavements. (Dalmazzo et al., 2022). This approach is based on creating Model Systems with single-sized materials and high voids in the mineral aggregate (VMA). Each created structure is called a Model System. Model systems are created single-sized and extremely high VMA (30%) that is because this structure is thought to provide model systems where response to indirect tensile stresses is mostly determined by the binder phase, eventually representing the used recycling agent with aggregate interlocking having minimal effect on the response. Eliminating the finer materials and clumps on the sample may provide more reliable results, in order to prevent any confusion that can happen during the production process. To clarify, the fundamental of this approach is not to create the response of 100% RAP standard asphalt mixtures or any asphalt mixtures by any means. The goal of this research is to determine the effectiveness of recycling agents by creating single-sized and high VMA Model Systems to monitor the response of Model Systems on the binder phase while eliminating the other effects that may be triggered by sample production.

This approach consists of three main model systems. As mentioned earlier, the Model System uses single-size aggregates. In earlier studies, the model system used 5/8 aggregates that is RAP stockpiles are sieved, and aggregate sizes between 5 mm and 8 mm are used. Simply, aggregates passing through 8 mm sieves but retained on 5 mm sieves are used to create model systems. In this research, due to the availability problem of European standard sieves in the USA, slightly different sieve sizes were adopted. In this regard, only sieve No. 4 (4.75 mm) materials are used.

Selected RAP aggregates were passed through the sieve 3/8in (9.5 mm) and retained on sieve No. 4.

The one Model System that is created by 100% RAP is called the ''Black System (BS)''. Model Systems created by using recycling agents called the ''Rejuvenated System (RS)''. Rejuvenated systems are basically Black Systems treated with recycling agents during the production phase. Rejuvenators are applied to RAP materials during the mixing phase, before compaction. Finally, model systems that are created by using the extracted aggregates (by using an ignition oven) and mixing with the virgin binder are called ''White System (WS)''.

Differently from the previous studies, curing time was not implemented in this research since there was not a significant effect of curing time on the model systems found (Dalmazzo et al., 2022).

Recycling agents on different levels of aged RAP

Another question comes to mind, do recycling agents respond the same to all aging levels? Is it possible to have different effects of the same recycling agent? To investigate the aging sensitivity of recycling agents, in other words -to investigate the effectiveness of recycling agents on different aging levels- the model system approach was implemented in the new system. In this step, virgin materials were used. By using the same gradation of aggregates concerning the one selected plant (Plant Y), mixed with PG64-22 binder. This binder was selected since it is the most probably used binder on the selected RAP sources. It is believed that most likely the RAP has a similar grade asphalt binder. Mixtures were aged on different levels after mixing (not aged, 3 days, 6 days, and 11 days) at 95 ºC, and at the end of each aging level samples were cooled down at room temperature, then heated up to the compaction temperature as done earlier to create Black System and Rejuvenated Systems.

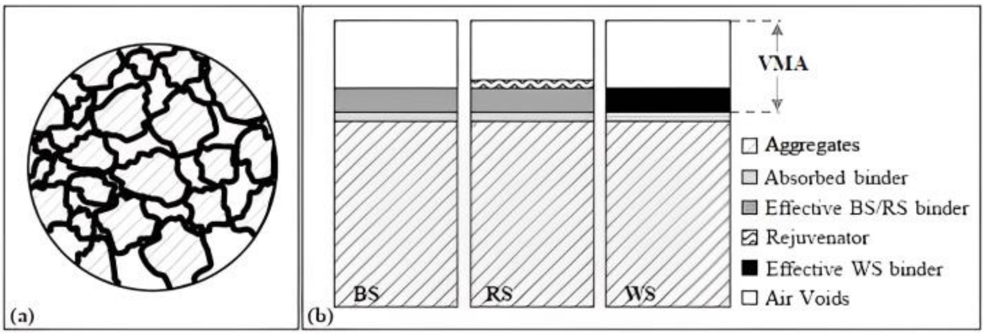

Figure 5. Model System representation ((Dalmazzo et al., 2022)

Mixtures were set to wait in the oven at 95 ºC and everyday pans inside the oven were rotated and placed randomly to have uniform effects and minimize the upside and downside difference if there is any in the oven. Set temperature and durations were inspired by an NCHRP research report 973 (Kim et al., 2021).

Material Characterization and Methodology

Firstly, the current study started with the material investigation. The amount of the required material based on the experimental plan is determined. It is important to differentiate the similarities and differences between different sources of RAP to understand the mechanical properties and the test findings. Since this study aims to better understand the effects of recycling agents on reclaimed asphalt pavements, it is essential to characterize the initial materials we have. Characteristics of each material, like the source of the RAP or gradation, play a significant role in the final response. Any differences among the materials may be the real difference between the final test findings.

Reclaimed Asphalt Pavement

As mentioned earlier, reclaimed asphalt pavements (RAP) are recycled old asphalt pavements that are typically crushed and adapted for application in fresh asphalt mixtures.

In this study, there are two different asphalt plants selected. Those two plants are located in North Carolina (NC) and Virginia (VA) and are named X and Y respectively in the United States of America. Each source is different from each other for many perspectives. There was not much information about how long the stockpiles of RAP were waiting for. Obviously, each source differs in terms of gradation, asphalt content, age, binder type, etc.

Figure 6. Plant X, RAP stockpile being processed.

Enough amount of material was obtained from both plants and stacked into the 5-gallon buckets.

As a first step, RAP materials are dumped into the large pans so that the thickness does not exceed 5 cm. Pans waited in an oven at 60 °C until the RAP reached a constant mass. This step took between 12-15 hours mostly. However, some pans require as long as 18 hours, depending on the moisture content of the stockpile. Right after removing the pans from the oven, pans are stirred to prevent clumps.

Dried RAP split with mechanical splitters to separate into buckets of RAP to homogenize and reduce to the required amount of the RAP by following the AASHTO R 76 (formerly T 248).

Figure 7. Aggregate/RAP drying oven

Sieve Analysis

In civil engineering and materials testing, sieve analysis of aggregates is a frequently used technique to determine the particle size distribution of granular materials. Given that the characteristics of RAP/aggregates, and other building materials can be greatly impacted by the particle size distribution of the aggregates, this investigation is essential for many kinds of engineering and construction applications.

Engineers and materials scientists can use this knowledge to develop asphalt mixtures with the workability and strength they want. It also helps ensure quality control and specification compliance in road construction projects.

Figure 8. RAP sieved to No. 4

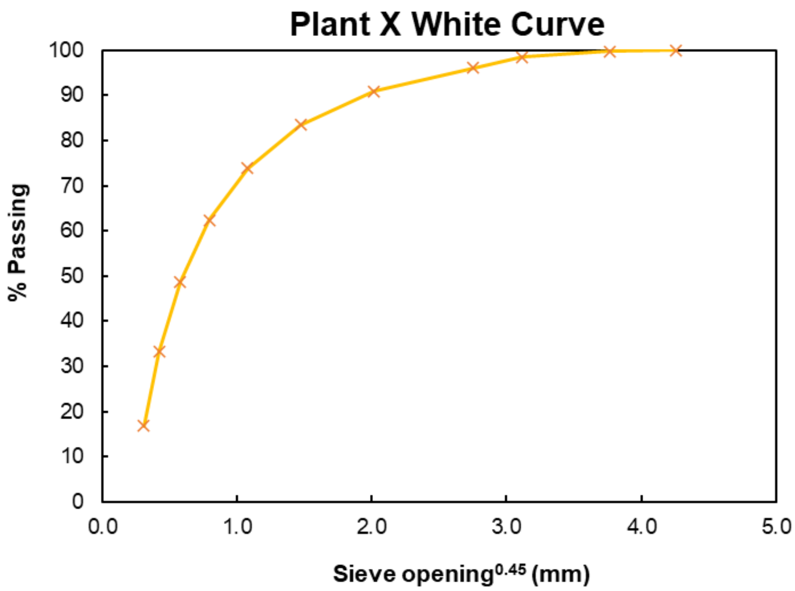

Figure 9. Plant X White Curve

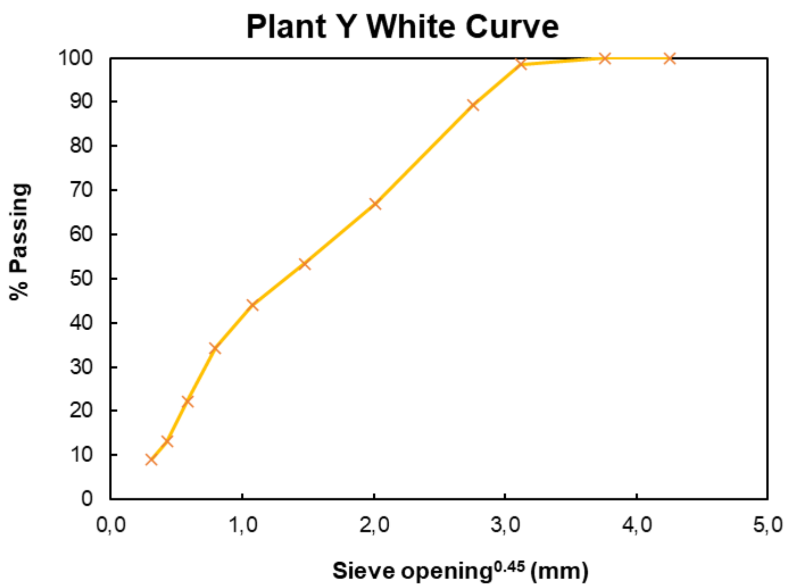

Figure 10. Plant Y White Curve

White curves are obtained from the sieve analysis of aggregates that were obtained after the elimination of the asphalt binder by ignition oven. The filler part (< No. 200 sieve, smaller than 0.075 mm aggregates) was eliminated by wash sieve analysis by following the standards AASHTO T27, and AASHTO T11.

The material that was maintained in the No. 200 sieve was dried at 110 ºC until the constant mass was achieved.

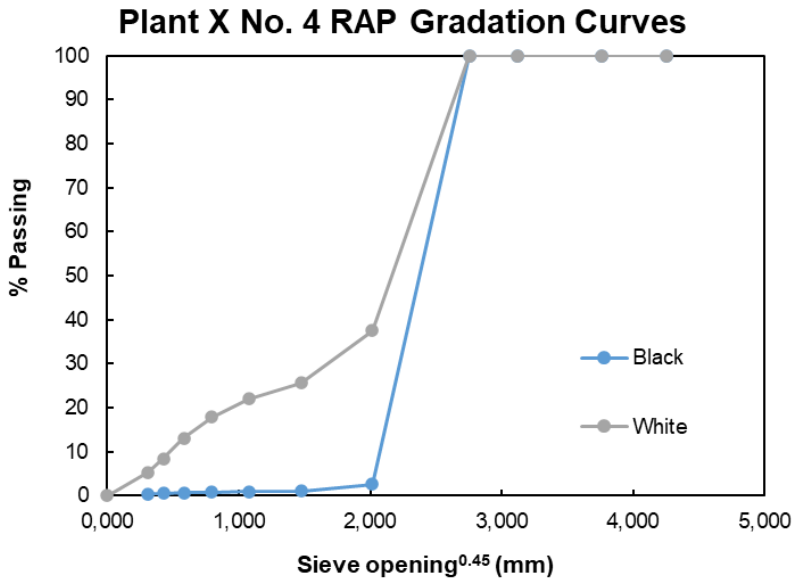

Figure 11. Plant X No. 4 Gradation Curves

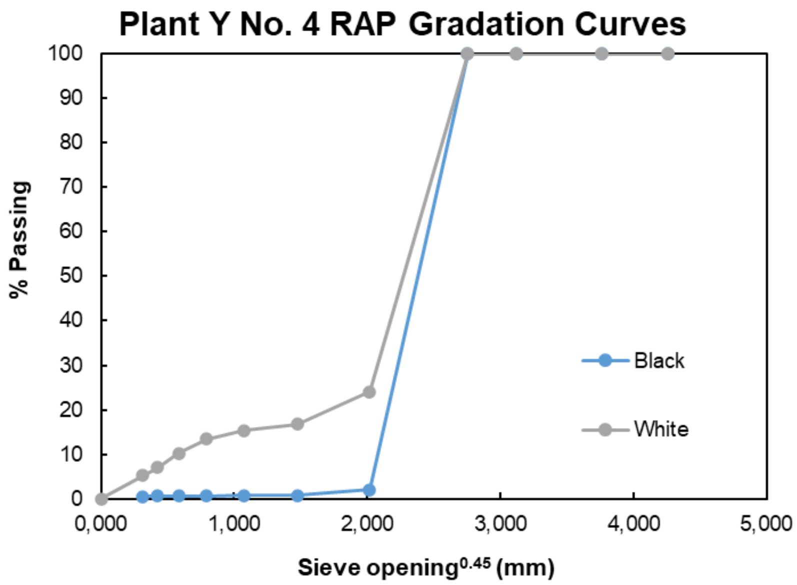

Figure 12. Plant Y No. 4 Gradation Curves

Binder content by ignition oven

The binder content of the RAP (including stockpile and No. 4 RAP) is determined by following the standard AASHTO T308. The required amount of the material was placed into the metal box and run the test at 540 ºC. Binder content is determined by the following formulation.

$$P_b = \frac{M_i - M_f}{M_i} * 100 - MC - C_f \quad \text{Eq. 1}$$

where

P_b = the corrected asphalt binder content as a percent by mass of the asphalt mixture sample

M_f = the final sample mass after ignition [g]

M_i = the initial mass of the asphalt mixture before ignition [g]

MC = moisture content of the companion asphalt mixture sample [%] (MC = 0 if oven-dried sample).

C_f = correction factor as a percent by mass of the asphalt mixture sample, C_f considered as 0 in this study.

Table 1. Binder content of RAP

Binder content (P_b) [%]			
Plant X Stockpile	Plant X No. 4	Plant Y Stockpile	Plant Y No. 4
4.8	3.5	4.8	3.2

Determination of volumetric properties of aggregates and RAP

Volumetric properties of aggregates and RAP are essential for understanding the behavior of the mixture, especially in the design and assessment of asphalt mixtures. Understanding the behavior of aggregates and RAP materials in the construction of asphalt pavement requires an understanding of these qualities.

The development and manufacturing of desired excellent-quality asphalt pavements depend heavily on an understanding of the volumetric properties of asphalt mixtures. These characteristics provide additional detail about the volumes and ratios of the various parts that make up an asphalt mixture. It is essential to understand these characteristics of the asphalt mixture to meet the required quality specifications.

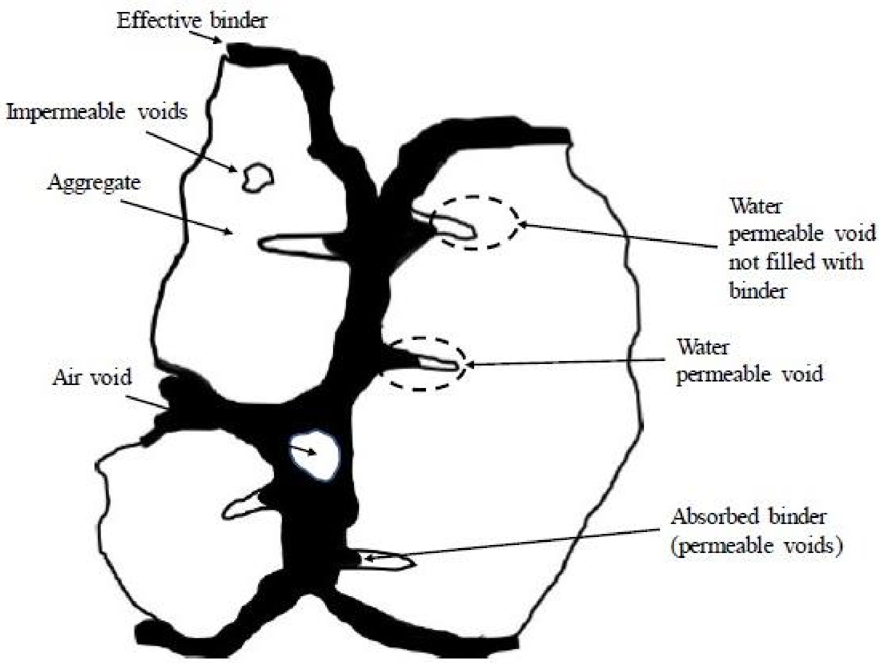

Figure 13. Representative microscale view of asphalt mix (Urbano, 2022)

The following are some significant features of volumetric properties:

Apparent Specific Gravity (G_{sa}): It represents the weight of the oven dry aggregate to the equivalent volume of water. It is a measurement of the aggregate particles' solid density.

Effective Specific Gravity (G_{se}): It is the ratio of the mass of oven-dry aggregate particles to the volume of aggregate particles including the pores not filled with asphalt.

Bulk Specific Gravity: The weight of a certain volume of aggregate, including the voids in the particles that are both permeable and impermeable, divided by the weight of an identical volume of water is known as bulk specific gravity. Since bulk specific gravity of aggregate is needed to compute VMA, it is important information for constructing HMA. It might vary in terms of compaction of a sample or density of the aggregate material depending on the gradation and form of the aggregates.

Maximum Specific Gravity of Asphalt Mixtures (G_{mm}): It represents the maximum specific gravity that can be reached, theoretically the highest possible density of an asphalt mixture when there is no air inside.

Samples were reduced to the required amount to measure the maximum density of the asphalt mixture (G_{mm}) by following the standard ASTM D6857-09. At least two samples were prepared, and the result should be satisfactory by standard criteria for judging the accuracy of density test results. Bulk specific gravity and apparent specific gravity of coarse aggregates (recovered from RAP) are determined by following the standard ASTM C127. Due to the availability of special types of equipment in the laboratory, the test was conducted for aggregates sieve No. 8 and above (coarser).

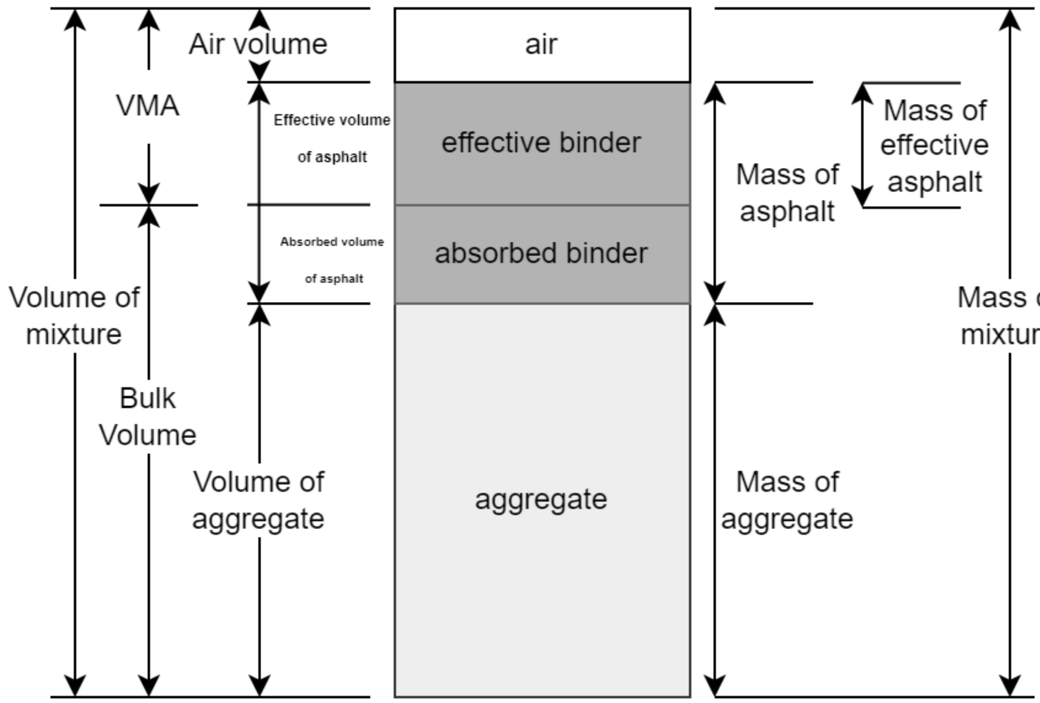

Figure 14. Components of compacted asphalt specimen (adopted from Hislop, 2000; Al-bayati et. al, 2018)

Table 2. Volumetric properties of RAP

	G_{sa} [-]	G_{se} [-]	G_{sb} [-]	G_{mm} [g/cm^3]
Plant X No.4	2.693	2.679	2.594	2.536
Plant Y No.4	2.689	2.683	2.607	2.552

Recycling Agents

In this study, there were two different types of recycling agents employed. They are named RA1 and RA2. The dosage was selected by suggestion from the supplier by considering the previous study at NCSU asphalt laboratory. RA1 and RA2 were employed as a cold spray during the mixing procedure at 4% and 8% by weight of RAP binder respectively. This dosage was selected to have a similar effect of restoring since they showed similar rheological properties when mixed with asphalt binder from a previous study at the lab. Detailed implementation will be provided in the methodology section. Characteristics of the recycling agents are shown in the table below.

Table 3. Recycling agents' properties

Name	Type	Specific gravity	Color	Flashpoint	Odor	Viscosity
RA1	Triglycerides and Fatty Acids	0.92	Dark	>150 ºC	Slight	Dynamic 150 CPS (138 mm^2/s) at 25 °C
RA2	Aromatic Extracts	0.98	Dark	210 ºC	Slight	Kinematic 40°C: 375 mm^2/s

Virgin Binder

In order to construct the White System (WS), PG 64-22 virgin asphalt binder was used. It is commonly used in the construction and maintenance of roads and highways. It is believed that most likely to represent the reality in the USA roads. PG 64-22 is considered a versatile binder grade that can be used in various regions, including areas with both hot summers and cold winters. There is no testing carried out on the asphalt binder. Asphalt binder was provided from a plant located in Roanoke, VA, USA.

The splitting process of the asphalt binder into the small binder cans is explained as follows. 5-gallon metal binder bucket placed into the oven at 70 ºC for 8 hours. After 8 hours, the temperature is set to 125 ºC for 2 hours to fully liquefy the binder. 5-gallon binder bucket stirred with a metal rod and then poured into the 1-gallon bucket. A 1-gallon bucket is poured into the small cans while a 5-gallon bucket waits inside the oven to keep the remaining binder liquefied. The process repeated until the 5-gallon bucket emptied. Small cans are stored in the shelf to construct white systems.

Figure 15. Asphalt binder in a can

Testing and Execution Methodology

The followed approach and major steps in this study are visualized in the diagram below.

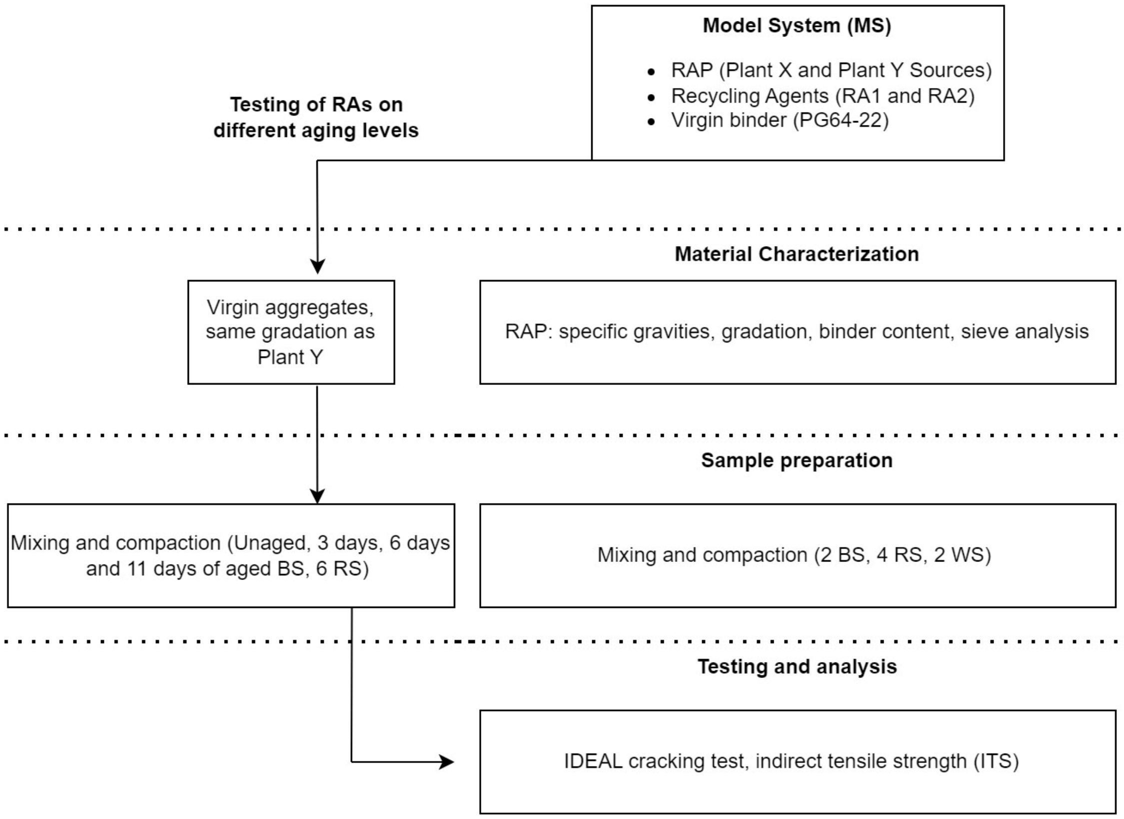

Figure 16. Experimental program

The main goal of this study, Model System (MS), is to investigate the effectiveness of recycling agents on reclaimed asphalt pavements (RAPs). In order to reach the desired investigation, the Model system has a unique philosophy. Every model system consists of single-sized No.4 RAP and high VMA (30%). The main structure of this approach enables us to obtain the final response on the binder phase and gives the potential idea of the comparison of different model systems among each other. Model systems, the ones that were prepared as 100% RAP, and the ones that have recycling agents show reasonable indications. As a reference, also white systems were constructed with the virgin binder.

Once the characterization of the materials was complete, an experimental plan was pursued. In the study, two different sources of RAP, and two different types of recycling agents were used. To investigate the effectiveness of recycling agents, the Indirect Tensile Cracking Test was performed by following the standard ASTM D8225-19 ''Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature''. Also, ITS parameters were observed and compared to the previous study performed at Politecnico di Torino since it is the same procedure for both the Indirect tensile strength test (ITS) and IDEAL cracking test.

As stated earlier, Model Systems have a structure of single-sized RAP material and target 30% VMA to get the response on the binder phase, by eliminating the additional side effects of clumps and aggregate interlocking.

Sample Preparatory Procedures

A certain number of samples were prepared. Five samples for each model system are prepared in order to guarantee the least number of required samples by standards. Many organizations expect at least three samples to have trustable results. Constructed three model systems explained below.

- Black System (BS) built with 100% RAP No. 4
- Rejuvenated System (RS) constructed as 100% RAP mixed with recycling agents RA1 or RA2.
- White System (WS) constructed with recovered aggregates from RAP No. 4 material and mixed with virgin PG64-22 asphalt binder.

Cylindrical samples with 150 mm diameter and 62 mm height were prepared. The required amount of mass can be found by the following formulation below to satisfy the 30% VMA.

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}} \qquad \text{Eq. 2}$$

$$G_{mb} = \frac{M}{V_{geo}/\rho} \quad \text{Eq. 3}$$

$$M = \frac{V_{geo}}{\rho} * (100 - VMA) * \frac{G_{sb}}{P_s} \quad \text{Eq. 4}$$

where

VMA	= voids in mineral aggregates
G_{mb}	= bulk specific gravity of compacted specimen
P_s	= percentage of aggregate in the total mix weight
ρ	= water density
V_{geo}	= volume of the specimen
G_{sb}	= bulk (dry) specific gravity of the aggregate
M	= mass of the sample

Each model system followed the same approach in the mixing. The compaction temperature was set to 150 ºC. To construct the BS, RAP waited in the preheated oven for 2 hours. After heating up, the material is mixed in an automatic rotating steel bucket (5-gallon volume). All mixing equipment is also heated up to the mixing temperature in another oven. Mixed in the steel bucket for 3 mins. Once the mixing was complete, the sample waited in the oven for another 30 minutes to prevent heat loss during the mixing procedure. After 30 minutes, the loose mixture was compacted with a gyratory compactor.

RS samples were treated the same as BS except RA1 or RA2 employed by spraying cold into the sample by weight of the RAP binder 4% and 8% respectively after 1 minute of mixing.

Concerning the WS, recovered aggregates and binders were put in the oven two hours earlier than the compaction time. Aggregates and fresh binder were mixed into the bucket and mixed for 3 minutes, waited 30 minutes in the oven at the compaction temperature, and the loose mix compacted later.

Verification of the compacted samples was done by following the standard ASTM D6752. Among the five samples, those that fail to meet the requirements or yield results that deviate from the expected range after testing are removed. The final results are derived from the three samples with the lowest coefficient of variation (COV) based on the collected data.

Figure 17. Mixing bucket

Figure 18. Compacted samples

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

This test is similar to the conventional indirect tensile strength test. During the Ideal-CT testing, the ASTM D8225-19 standard was followed. A cylindrical specimen (150 mm diameter and 62 mm height) is placed under testing by applying a monotonic vertical load that slowly lowers the load-applying point at a rate of 50 mm per minute. When the load falls to 0.1 kN, it is over. The crosshead's displacement is continuously monitored and recorded during the test. The relationship between the load and displacement—which determines the CT_{Index}, a test parameter, is the basis for the data analysis. The slope of the post-peak curve at a 25% drop from the peak load and the total fracture energy is used to calculate the CT_{Index}. Compacted asphalt mixtures were conditioned at an intermediate temperature of 25 ºC in the chambers for 2 hours and tested immediately within 2 mins.

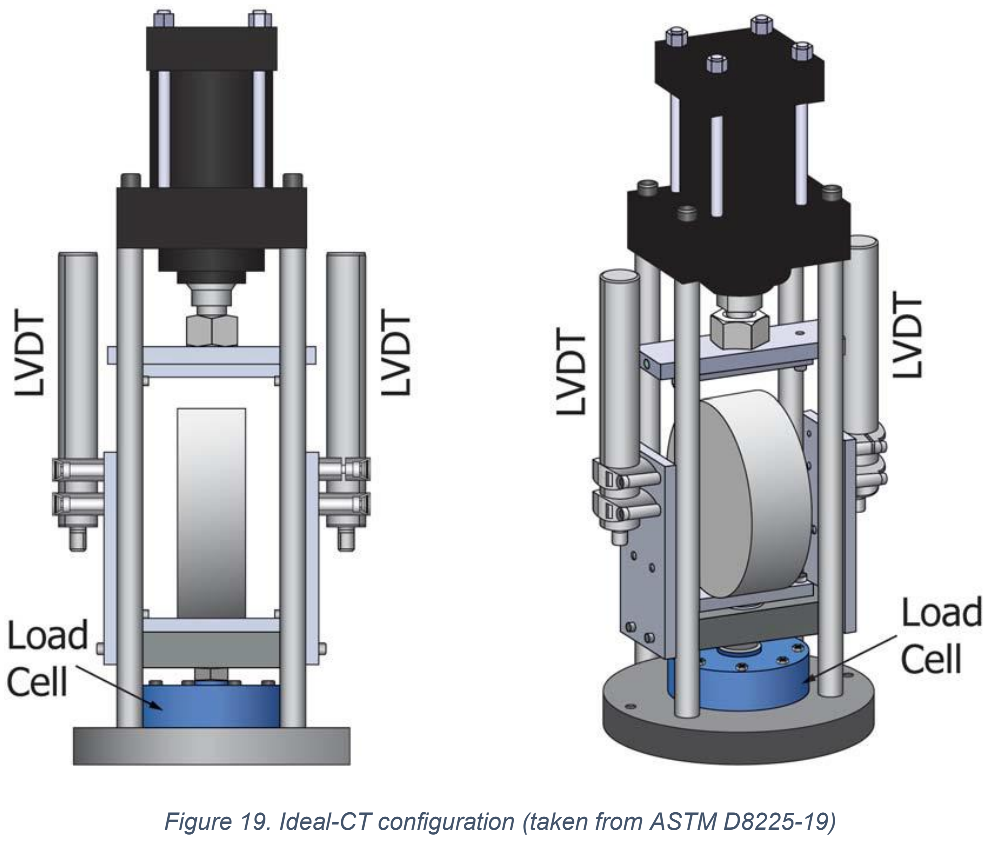

Figure 19. Ideal-CT configuration (taken from ASTM D8225-19)

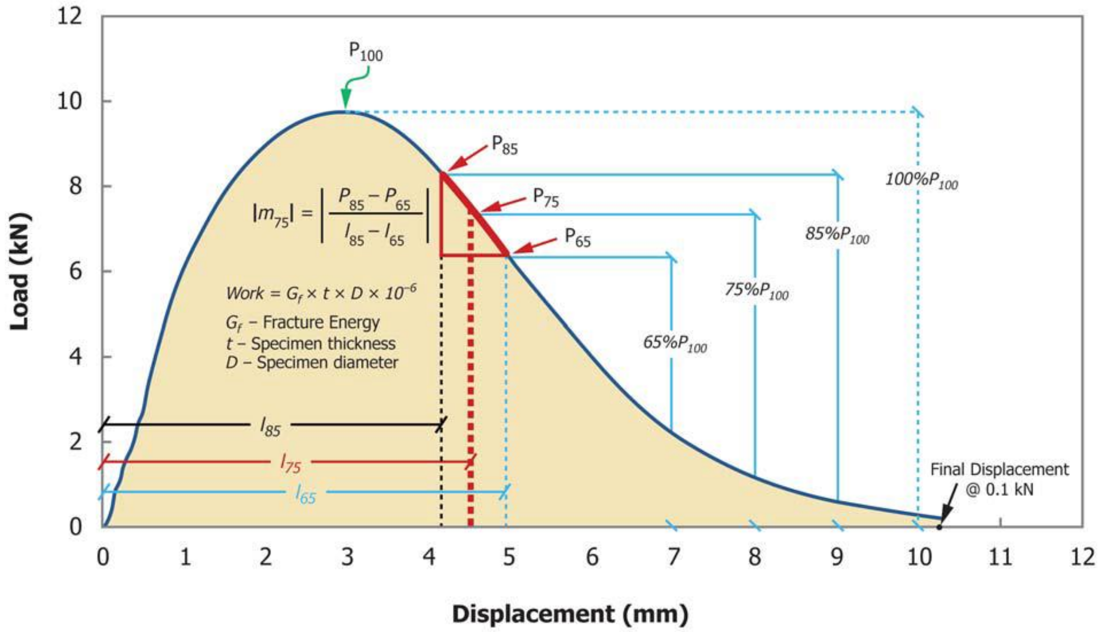

Figure 20. Recorded Load-Displacement graph (taken from ASTM D8225-19)

CT_{index} calculated as shown below:

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \qquad \text{Eq. 5}$$

$$G_f = \frac{W_f}{D * t} * 10^6 \qquad \text{Eq. 6}$$

$$|m_{75}| = \left|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right| \qquad \text{Eq. 7}$$

where

CT_{index} = cracking tolerance index,

G_f = fracture energy (kN/mm),

W_f = work of fracture (area under the force-displacement curve) (kN.mm),

$|m_{75}|$ = absolute value of slope at 25% drop from peak load (N/m),

l_{75} = displacement at 25% drop from peak load (mm),

D = specimen diameter (mm),

t = specimen thickness (mm).

$\frac{t}{62}$ is the unitless correction factor, would not have any effect in the case of a 62 mm specimen. 10^6 is the unit conversion multiplier in the equation.

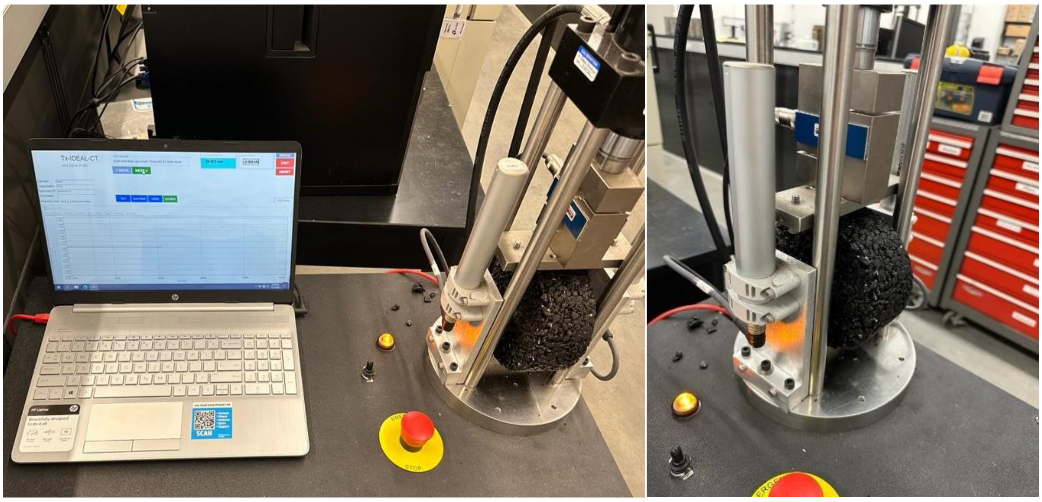

Figure 21. Testing and data acquisition

Since it is the same technique as the Indirect tensile strength test, ITS parameters were obtained by following the formulation below.

$$ITS = \frac{2 * P}{\pi * D * H} * 1000$$ Eq. 8

where

ITS = indirect tensile strength (kPa)

P = peak load (N)

D = specimen diameter (mm)

H = specimen height (mm)

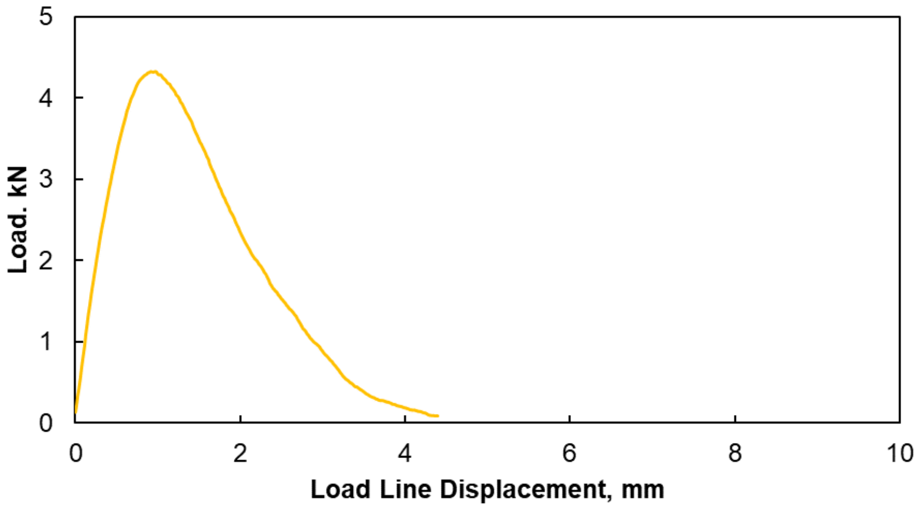

Figure 22. Example of obtained force-displacement graph

Figure 23. Failure surface of a specimen

Analysis of results

The findings of the experimental tests that were previously discussed are presented and analyzed in this chapter. The chapter starts by summarizing the results of the carried-out tests of the compacted samples and then looks at the outcomes.

Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and ITS

As explained earlier, 150 mm diameter and 62 mm thickness samples were tested. Force–displacement graph obtained. CT_{Index} of model systems were compared as shown below.

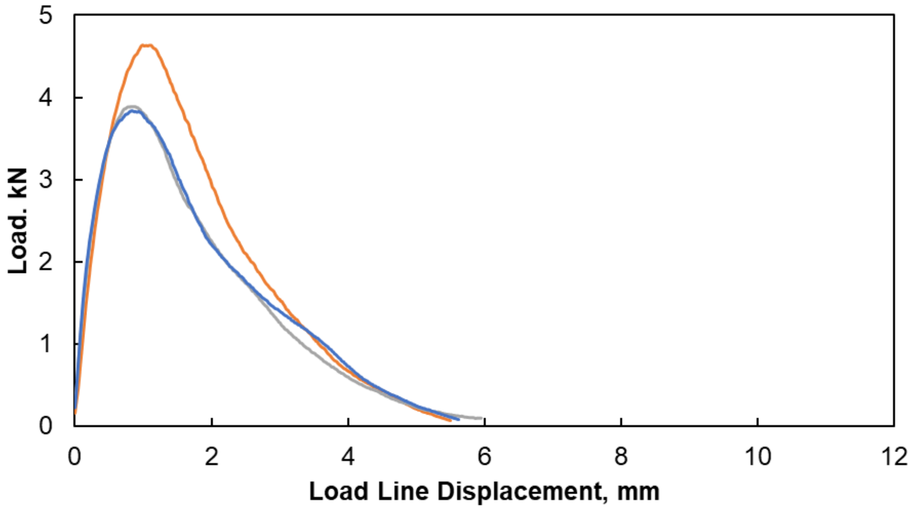

Figure 24. Force-displacement graph of plant x black system

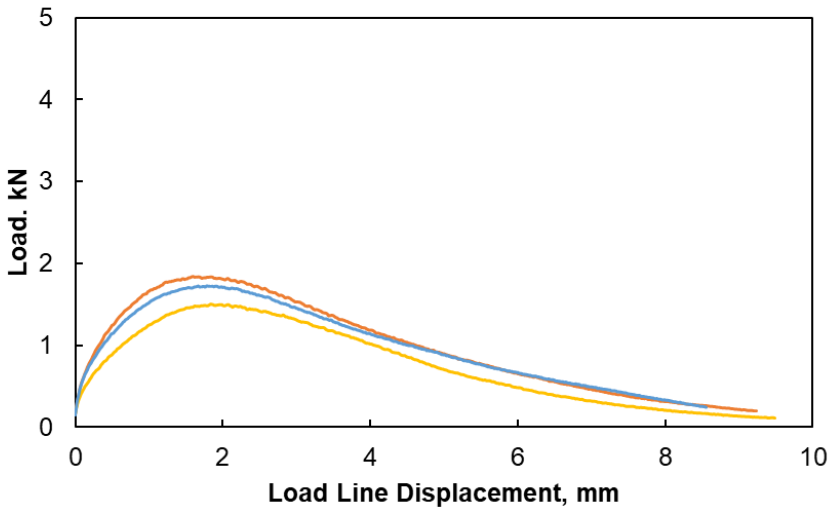

Figure 25. Force-displacement graph of plant x white system

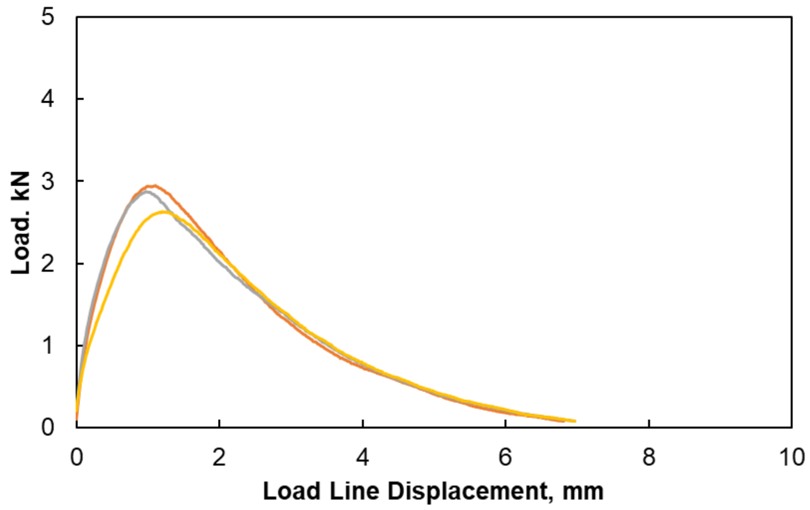

Figure 26. Force - displacement graph of plant x rejuvenated system (RA1)

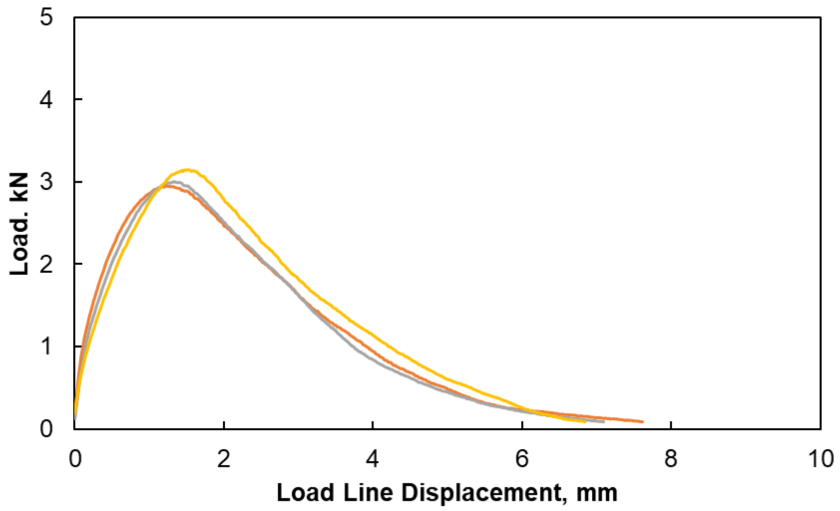

Figure 27. Force - displacement graph of plant x rejuvenated system (RA2)

Force and displacement graphs for only plant x are shown above since it would be quite repetitive to present. Black systems were facing a higher peak load since its stiffer binder, but failure happened dramatically because of its low ductility. As can be seen, the force-displacement graphs were more wavily in the black system while white systems observed more smooth results. This is because in Black Systems asphalt binder was not able to fully cover all the RAP particles. Some particles were like a ‘’black rock’’ and not interacting with other particles when the mixing process taking place. This explains the phenomenon that ‘’black rock’’ does not interact with other materials and ends up with a thinner layer of asphalt binder or the absence of the binder. Old RAP particles sometimes may lose their binder outside and RAP behaves like an aggregate.

Recycling agents show some change in the slope after the peak load achieved in the testing. Rejuvenated systems had smaller absolute slopes while black systems had steep slopes after the peak load. This shows the impact of the recycling agents, even if it was quite small to consider. Recycling agents showed that they help the black systems to gain their ductility.

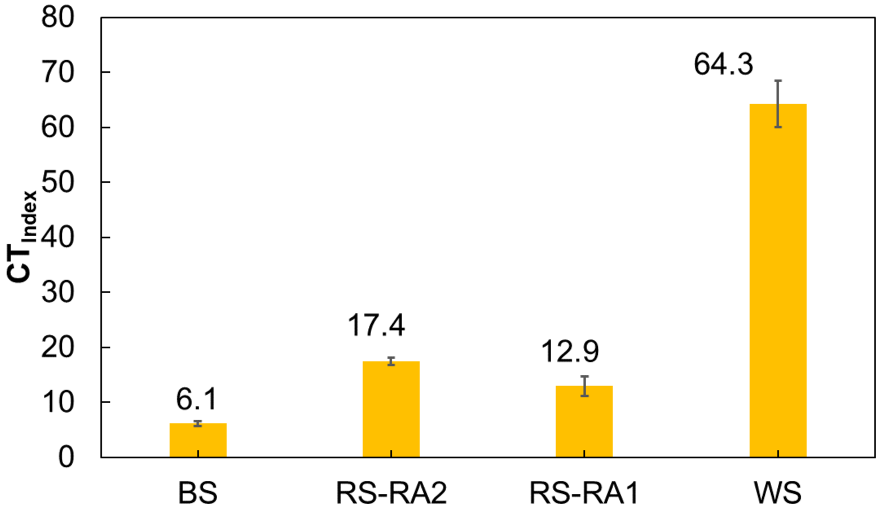

Figure 28. CT_{Index} comparison of plant x

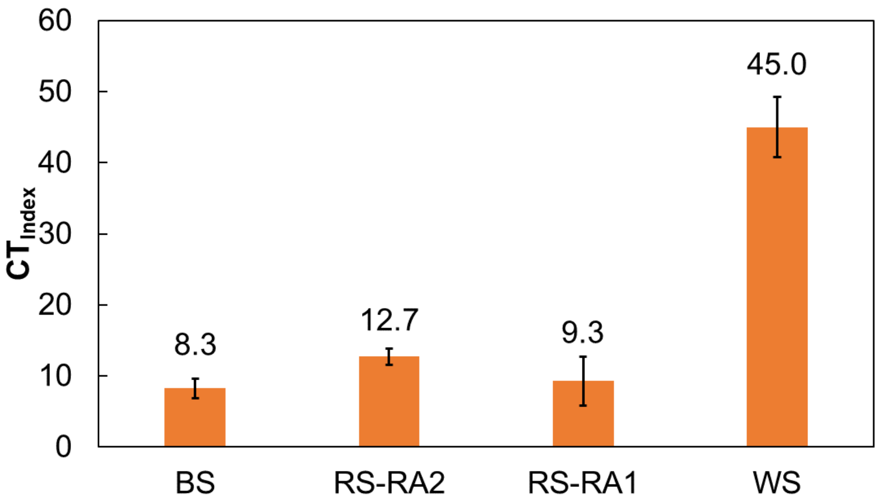

Figure 29. CT_{Index} comparison of plant y

Recycling agents were showing some improvements for sure in terms of CT_{Index}, but nothing too considerable to compare with the white systems. In some cases, the CT_{index} jumped to the double value of Black System for the Rejuvenated System. It is still far away from the reference point which is White System. White systems had way higher CT_{Index} than any other rejuvenated systems. It was obtained that Rejuvenated Systems were able to restore the ductility and the performance of the aged binder. Whereas it was not close to the target point. In most cases, RA2 showed better results compared to RA1. RA2 showed it was the better fit in this study compared to RA1. Error bars represent the one standard deviation distance from the shown median value.

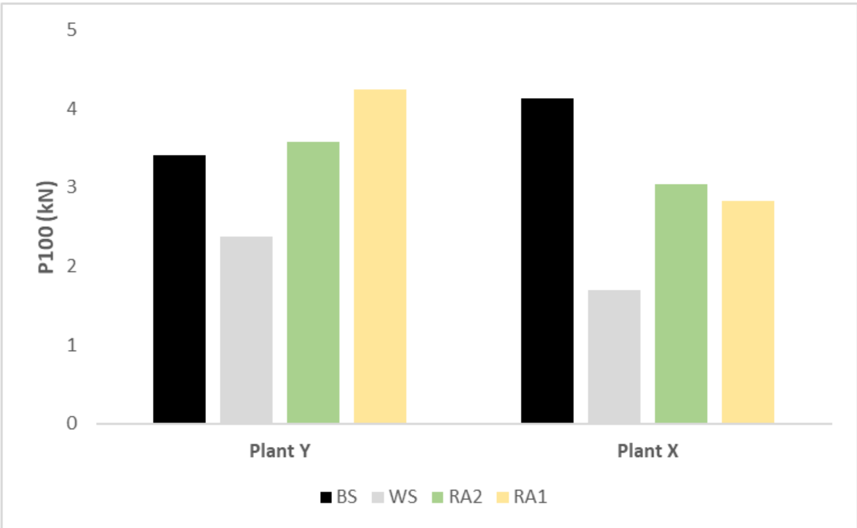

Figure 30. Peak load, P100 for both plants

The peak load observed after the testing is shown above. It is notable that Black Systems showed a higher peak load. It was not the expected outcome since it is known that peak load to failure would drop with the aging. This behavior may be explained as the hardening of the asphalt binder. The harder the asphalt binder, the harder to break it.

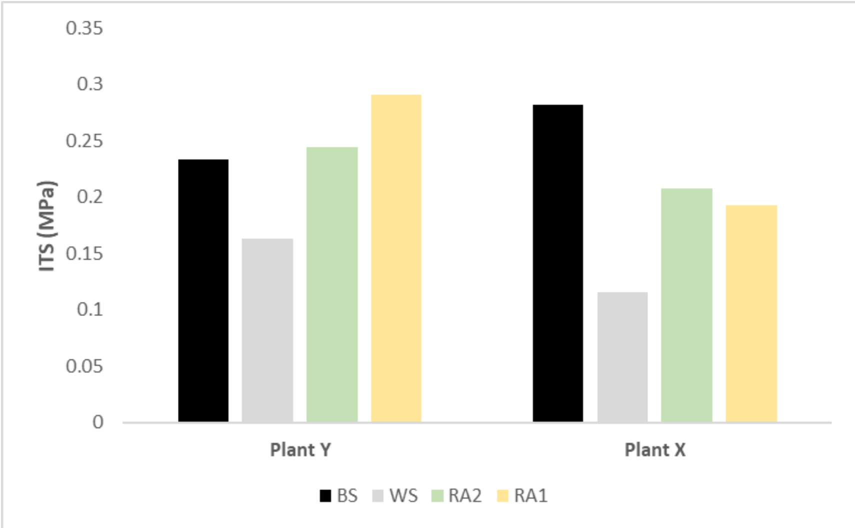

Figure 31. ITS parameter for both plants

As proportional to the peak load, ITS values are shown above. All the samples were compacted to the same geometric dimensions. It is expected to observe a higher ITS value for WS since a fresh binder could provide better results. As noted for the two different sources of RAP, the behavior was not stable to compare. Different model systems showed unusual results than expected for plant y. The results above for two different sources show different trends.

Different aging levels and recycling agent response

In order to investigate the response of recycling agents on different aging levels, the Virgin System (VS) was constructed. VS consists of only virgin materials, the same gradation as Plant Y mixed with virgin same binder content (3.2%) PG64-22 grade binder. Rejuvenated systems are named the same as used recycling agents. Once mixing was completed, the aging process started in the ovens at 95 ºC. After removing the material from the oven according to the aging day, samples cooled down and considered RAP, and RAP went through the same process as other model systems did.

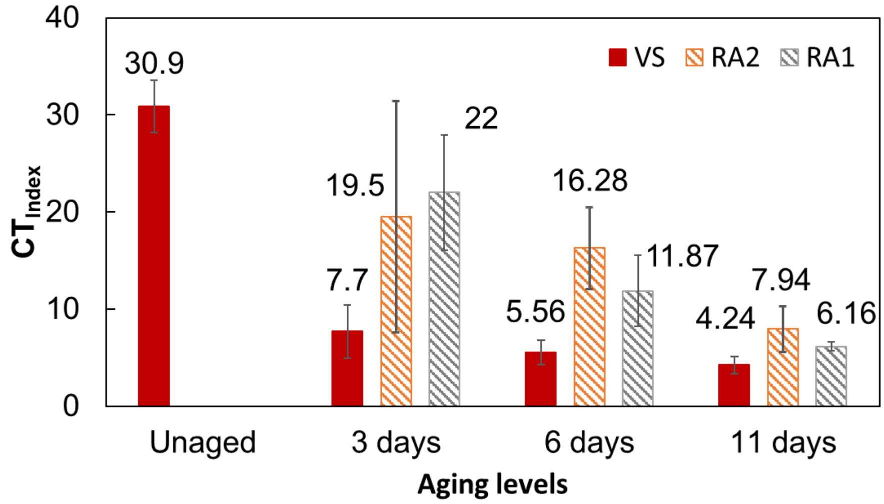

Figure 32. CT_{index} of different aged materials

The graph above shows the decrease in CT_{index} by aging as expected. The sudden drop starts with 3 days of aging and keeps the slightly decreasing. The high standard deviation error bars are not the desired result but are kept in the graph to represent at least the trend. It is believed that the high variability of 3 days of aging is related to unexpected behavior of oven or testing-related problems.

Another key takeaway from this study is that recycling agents were able to restore the RAP properties when aging is at the beginning of the process. In other words, when RAP ages more, restoring the RAP properties.

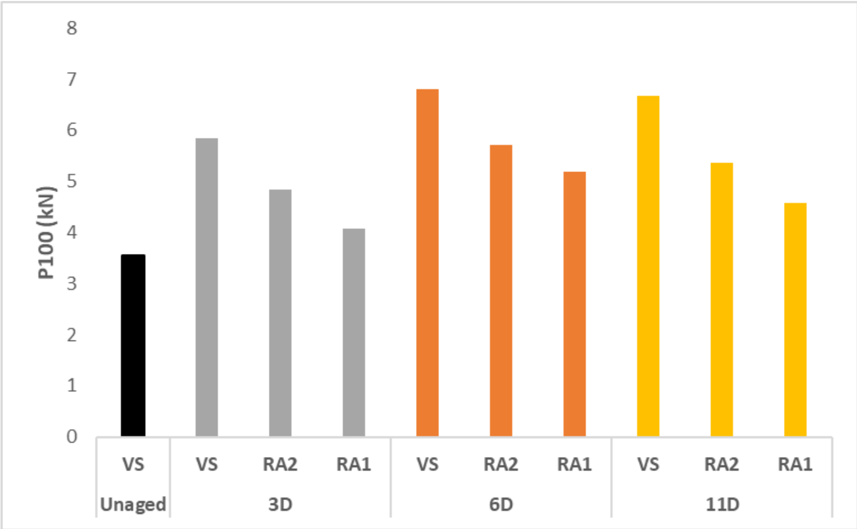

Figure 33. Peak load change by aging

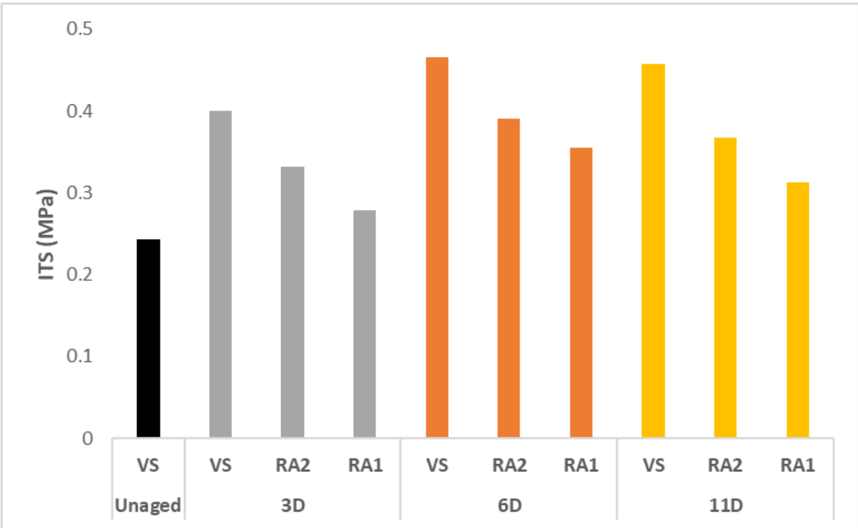

Figure 34. ITS comparison

The peak load increased by the aging of the material and the use of the recycling agents showed a considerable decrease in peak load to failure and ultimately ITS as well. It illustrates that the amount of force that needs to be applied to the specimen increases with the aging process. It is believed that due to the hardening increased in the binder phase. It was expected to see low gluing and lower tensile strength of the binder by aging, but the unaged system showed the lowest ITS value.

Conclusion and recommendations

This study aims to look in detail at the use of recycling agents and show their effectiveness. For the road building industry, the use of recycling agents in the production of recycled asphalt pavements (RAP) presents an eco-friendly option for sure. It has been demonstrated that adding recycling agents to recycled asphalt materials improves their qualities, resulting in pavements with better performance compared to RAP without any additives. While black system samples were shown to weakest findings, white system samples were able to maintain good quality. It was expected to observe rejuvenated systems show close behavior to the white systems because white systems were the reference point.

It must be noted that the use of recycling agents still needs to be standardized and implemented. Recycling agents need to improve their efficiency since it is not the desired point as yet. The results are promising, and the industry of road construction could undergo a significant transformation if recycling agents are successfully included in asphalt pavements. As discussed in the earlier chapters, recycling agents were not that impactful in gaining the desired performance. But it must not be ignored since rejuvenated systems were able to show better results compared to the black systems. The target is always to have a great impact of the recycling agents same as use of the virgin materials. Inevitably virgin materials show better results and rejuvenated systems need detailed further investigations. The utilization of the recycling agents has the potential to result in better findings considering increased sustainability, cost-effectiveness, and infrastructure sustainability. The standardization of the RAP, as well as the use of recycling agents, should be encouraged.

Continued studies should include various recycling agents, figuring out how much to use, and evaluating how well recycling agents and RAP work considering various asphalt mixture types. Further investigations should pay special attention to the use of recycling agents and their long-term effects, fatigue, and rutting resistance. Also, it should be noted that even the same types of recycling agents may show different behavior since the production process may differ from company to company. Recycling agents are unique and mostly formed as a liquid. More studies on this material considering the application process will be favorable.

For each RAP source, three different Model Systems were built to have a desired VMA with a desired gradation (sieve No. 4 only) and tested. These were the two main structures of the model system. Consequently, the final response of the sample would be in the binder phase thanks to the model system approach. This approach aims to eliminate additional effects of any forms of clusters and aggregate interlocking that mixtures may experience by selecting single-sized RAP and high VMA (30%). As stated earlier, model system mixtures do not represent conventional asphalt mixtures by any means. It only allows us to test and observe the asphalt binder thanks to its structure.

In the study, two different sources of RAP and two different types of recycling agents were investigated. All the components of the materials were not connected. Two sources of reclaimed asphalt pavements from two different states in the USA. Climate conditions or different state standards of asphalt may be implemented in the RAP. They are all unique and different from each other.

To highlight the outcomes shown in this study is rejuvenating additives work quite well to consider. As shown in the comparison of the CT_{index}, rejuvenated systems were able to heighten the performance compared to the black system results. Still, it is not feasible to implement the recycling agents by looking at the given data since the increase was not that strong to consider. White systems were able to obtain the highest CT_{index} thanks to their fresh binder. Fresh material showed superior results compared to black and rejuvenated systems as expected. Black systems showed the lowest CT_{index}, and the failure of the samples was something to notable. Black system samples failed under the testing load so quickly. This supports the knowledge of aged binder loses its ductility. Scattering of particles (like sand) took place after the failure of the samples. This explains the how low bonding black systems have. Also, it shows the limited aggregate interlocking thanks to the model system. This behavior was more visible in the black system samples.

In most of the cases, RA2 showed better restoring performance on the model system compared to RA1. While none of the recycling agents were able to reach the reference level, as white systems. However, it should be noted that this comparison does not represent the final decision since those recycling agents might show different responses under different circumstances. Further detailed investigations with different types of recycling agents under different circumstances might be useful.

Definitely, further detailed investigations are needed to highlight the exact effects of recycling agents for different mixtures under divergent conditions. A detailed study of different types of recycling agents is recommended to have a broader understanding of rejuvenators. The selection of recycling agents, according to their types and dosage also plays a significant role in the performance of the asphalt since different types of rejuvenators have different effects as shown in the outcomes of the test. The result obtained from the test is not enough to recommend a kind of recycling agent specifically. Additionally, it should be noted that model systems do not represent traditional asphalt mixtures. So, further investigations should include asphalt mixtures to obtain mixture response, not only have a response on the binder phase.

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