Beneficial Reuse of Reclaimed Asphalt Pavement in Geotechnical Infrastructure

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16. Abstract

Reclaimed Asphalt Pavement (RAP) has been extensively studied for potential use as a recycled material in infrastructure construction. There is consensus that utilization of RAP provides environmental and economic benefits for most projects. However, impacts to engineering performance are less known, due to the highly variable nature of RAP sources with different asphalt pavement mixtures and milling processes, which has limited the adoption of RAP as fill material in geotechnical infrastructure. This study conducted a comprehensive review of geotechnical properties reported for RAP in the experimental literature. Additionally, experimental testing was conducted on six sources of RAP from Pennsylvania's District 6 to determine the geotechnical properties and to identify potential reuse opportunities. The gradation, specific gravity, density, moisture content, hydraulic conductivity, leaching, shear strength, and creep properties of different RAP sources from literature and District 6 were summarized and compared. These geotechnical properties, as well as recent investigations into the effects of temperature and aggregate mixing, were used to identify the potential reuse of RAP in highway transportation applications beyond just asphalt mixture design, such as embankments or fill, shoulder backfill, pipe bedding, and reinforced fill for MSE walls. Additionally, a correlation between the coefficient of uniformity and the geotechnical properties of maximum dry density and saturated hydraulic conductivity was identified.

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Statement of Credit

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1. INTRODUCTION

Reclaimed Asphalt Pavement (RAP), as defined by the Federal Highway Administration, is reprocessed pavement material containing asphalt and aggregate that is generated when asphalt pavements are removed for construction purposes (FHWA 2016). RAP contains high-quality, well-graded aggregates coated by asphalt cement (FHWA 2016). RAP is a commonly used material throughout the United States, with the most frequent application being in recycled pavement mixtures (Copeland 2011; FHWA 2020; FHWA 2021; PennDOT 2020; Williams et al. 2020) While PennDOT currently uses RAP in recycled pavement applications, excess RAP is being generated that is not being utilized. At the end of each construction season in Pennsylvania, significant amounts of RAP are being placed in stockpiles (Williams et al. 2020). In a survey conducted by Wen et al. (2022), PennDOT cited that legal barriers were limiting the reuse of RAP in non-pavement applications. The abundance of RAP in stockpiles has led to investigations into revising specifications to allow for reuse. PennDOT is interested in finding new and innovative ways to utilize RAP beyond just pavement applications and it was determined that the benefits of reusing RAP include cost-savings, environmental improvement, reduced demand on non-renewable resources, and reduced landfill space (PennDOT 2020). The purpose of this report is to provide guidance on alternative uses of RAP in transportation infrastructure, beyond pavement applications. Based on a comprehensive literature review and an experimental testing program, the Villanova University research team summarizes recommendations on alternative uses of RAP in non-pavement applications such as embankment or fill, shoulder backfill, pipe bedding, and reinforced fill for mechanically stabilized earth (MSE) walls.

1.1 Objectives and Scope of the Report

This report provides a comprehensive literature review that encompasses the state of the art (SOA) of research on the engineering properties of RAP. Additionally, this report provides the results from experimental laboratory testing that evaluated the geotechnical properties of six sources of RAP from Pennsylvania's District 6. The results from the literature review and the experimental testing were compiled to provide practical recommendations on the reuse of RAP in non-pavement highway transportation applications. Roadmaps for the implementation of RAP and the broader use of the results from this project are reported.

1.2 Organization of the Report

The report is organized in the following manner:

- Chapter 2: This chapter provides background information on the creation process of RAP, as well as the current state of the practice (SOP) of RAP reuse throughout the United States and in the state of Pennsylvania. Additionally, the state of the art (SOA) of research on the geotechnical properties of RAP are evaluated to provide recommendations on the use of RAP in highway transportation infrastructure. This was accomplished by performing a comprehensive literature review on the following topics: (a) case histories of beneficial reuse of RAP; (b) review of PennDOT RAP usage; (c) measured geotechnical properties of RAP; and (d) recent developments of RAP reuse. The geotechnical properties that were evaluated are as follows: (1) gradation; (2) specific gravity; (3) maximum dry density; (4) hydraulic conductivity; (5) leaching; (6) shear strength; and (7) creep.

- Chapter 3: This chapter includes an experimental laboratory investigation of the geotechnical properties of RAP obtained from six locations in PennDOT District 6. The laboratory testing program included the evaluation of hydraulic conductivity, shear strength, maximum dry density, leaching, and most importantly creep behavior of the RAP and RAP mixtures with aggregate (No. 57 Stone). The effects of temperature were evaluated on RAP that was compacted to a temperature of 35°C (95°F), and these results are also included in the testing program. In addition, standard geotechnical classification testing was performed to thoroughly characterize RAP and RAP mixtures (e.g., particle-size distribution and specific gravity). Both the RAP and the RAP mixtures were compared with typical materials used for embankment fills and other non-pavement transportation infrastructure.

- Chapter 4: This chapter summarizes the literature review and laboratory testing, and it provides recommendations for the future reuse of RAP for PennDOT. Guidance for reuse of RAP in non-pavement applications is provided in the form of flowcharts for the following applications: (1) embankment or fill material, (2) shoulder backfill (3) pipe bedding, (4) and reinforced fill for MSE walls.

- Chapter 5: This chapter concludes the findings of this report, and provides details on the broader use of the results of this project.

2. LITERATURE REVIEW

2.1 Introduction

RAP is a commonly used material in recycled pavement applications throughout the world, however there is substantial excess RAP that is not being utilized. At the end of each construction season, significant amounts of RAP are left in stockpiles (Copeland 2011; FHWA 2020; Tarsi et al. 2020; Williams et al. 2020). For example, in the 2019 construction season, an estimated 138 tons of RAP was stockpiled in the United States (Williams et al. 2020). Eventually, when stockpiles become overwhelmed, more RAP will have to be placed in landfills. Landfilling is costly, and it can be detrimental to the environment. Therefore, there has been growth in recent research investigating new and innovative ways to utilize RAP beyond just pavement applications for highway infrastructure applications.

Numerous experimental studies have focused on measuring and evaluating geotechnical properties of RAP. Most of the existing literature on RAP is in reference to the further processed, smaller particle-sized material (Arulrajah et al. 2013; Bejarano 2001; Bennert and Maher 2005; Cleary 2005; Cooley 2005; Cosentino et al. 2003; Hajj et al. 2012; Kalpacki et al. 2018; Locander 2009; Ma et al. 2015; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Solaimanian et al. 2011; Thakur et al. 2013; Titi et al.2019; Yin et al. 2017; Yousefi et al. 2021). While processed RAP has been extensively studied by researchers worldwide, the properties such as the gradation, maximum dry density, hydraulic conductivity, and leaching of RAP can vary based on location due to the make-up of the initial asphalt pavement mixtures, the milling process, the use over a lifetime, and the stockpile management of the material (Gao et al. 2021; Zhou et al. 2010). For example, in Mijic et al. (2020), RAP from seven highways in Maryland was evaluated, and it was found that there was variability within the same state between the gradation, the maximum dry density, the saturated hydraulic conductivity, and the concentrations of chemicals that leached out of RAP.

Due to challenges associated with the reuse of RAP, such as excessive creep, researchers have also investigated options to improve RAP's engineering properties. For example, research into mixing RAP with other aggregate materials such as sand and gravel has been conducted (Cosentino et al. 2003; Dikova 2006; Kalpacki et al. 2018; Mousa and Mousa 2017). Also, the effects of elevated temperatures on RAP's engineering behavior have been investigated (Abedalqader et al. 2021; Soleimanbeigi and Edil 2015; Wen et al. 2022). RAP research has primarily focused on processed RAP, thus future research on unprocessed RAP is needed to identify how the variability could lead to different conclusions.

This chapter summarizes the geotechnical properties of RAP that are commonly considered in construction specifications for materials used non-pavement highway transportation applications. The properties evaluated were gradation, specific gravity, maximum dry density/optimum moisture content, hydraulic conductivity, leaching, shear strength, and creep properties of RAP, as well as recent developments into the effects of temperature and aggregate mixing. **Table 2.1** shows a compilation of studies used to evaluate the differences present in RAP properties throughout the world.

Table 2.1. Studies considered in this literature review, organized by the RAP geotechnical properties that were reported.

Source	Location	RAP Type	Gradation	Specific Gravity	MDD/OMC	Hydraulic Conductivity	Leaching	Shear Strength	Creep
Bejarano et al. (2001)	California	Processed	X		X			X	
Morse et al. (2001)	Texas	Not Reported					X		
Rathje et al. (2002); Rathje et al. (2006); Viyanant (2006); Viyanant et al. (2007)	Texas	Processed [a]	X	X	X	X		X	X
Cosentino et al. (2003); Cosentino et al. (2008); Cleary (2005); Dikova (2006)	Florida	Processed [a]	X	X	X	X	X	X	X
Bennert and Maher (2005)	New Jersey	Processed	X			X			
Cooley (2005)	Utah	Processed	X	X	X				
Locander (2009)	Colorado	Processed	X	X	X				
Zhou et al. (2010)	Texas	Processed	X						
Solaimanian et al. (2011)	Pennsylvania	Processed	X						
Bleakley and Cosentino (2012)	Florida	Not Reported							X
Hajj et al. (2012)	Multiple [c]	Processed	X	X					
Shedivy et al. (2012)	Multiple [d]	Not Reported		X	X	X	X		
Arulrajah et al. (2013)	Australia	Processed	X		X	X		X	
Rahardjo et al. (2013)	Singapore	Processed [b]	X	X	X	X		X	
Thakur et al. (2013)	Kansas	Processed	X	X	X				X
Ma et al. (2015)	China	Processed	X					X	

Soleimanbeigi and Edil (2015); Yin et al. (2016); Yin et al. (2017)	Wisconsin	Processed	X		X				X
Aydilek et al. (2017); Mijic et al. (2020); Seybou-Insa et al. (2021)	Maryland	Processed	X	X	X	X	X		
Mousa and Mousa (2017)	Egypt	Processed	X		X				
Kalpakci et al. (2018)	Iraq	Processed	X		X				
Herrara (2019)	Multiple [e]	Not Reported					X		
Titi et al. (2019)	Wisconsin	Processed	X	X					
Abedalqader et al. (2021)	Jordan	Unprocessed	X	X	X			X	
Gao et al. (2021)	China	Processed	X						
Mousa et al. (2021)	Egypt	Processed	X	X	X	X		X	
Wen et al. (2022)	Illinois	Both	X		X	X		X	X
Yang et al. (2020)	New Jersey	Not Reported					X		
Yousefi et al. (2021)	Iran	Processed	X	X					X

a. Initial RAP was processed to be coarse-grained ($\geq$ 25 mm), but a finer, well-graded reference gradation was created for laboratory testing
b. RAP was processed, however, fractionating occurred which created both a uniform coarse gradation and a uniform fine gradation
c. RAP sourced from Alabama, Nevada, California, and Florida
d. RAP sources from Ohio, Wisconsin, California, New Jersey, Colorado, and Wisconsin
e. RAP sources from Maryland, France, New Jersey, Denmark, Sweden, Minnesota, and Florida

2.2 Background and Current RAP Use

Understanding how RAP is created, stored, and utilized is critical when investigating alternative uses for RAP beyond pavement applications. This information can be used to develop testing programs and provide recommendations for RAP reuse.

2.2.1 RAP Creation Process

RAP is created by the grinding or milling of an asphalt roadway to a specific depth, typically the top 2 inches of roadway (FHWA 2016). The initial roadway milling creates RAP of variable size and quality, with some RAP particles exceeding 2 inches in size. The RAP in this initial state is considered unprocessed. Once roadway milling is complete and unprocessed RAP is created, RAP can be further processed (i.e., screened, crushed, and ground down) to the desired gradation envelope. The particle size of RAP is highly dependent upon the desired use/application of the material (Tarsi et al. 2020). In some applications where large particle sizes are desirable, it may be acceptable to use unprocessed RAP that has been directly milled from the roadway. More commonly, however, processed RAP of smaller particle sizes (typically less than 1 inch) is used (Tarsi et al. 2020; Zhou et al. 2010). Processed RAP is commonly created due to its frequent application in hot and cold recycled asphalt mixes (FHWA 2016). **Figure 2.1** compares processed RAP to unprocessed RAP, and **Figure 2.2** provides a flowchart highlighting the process of creating RAP.

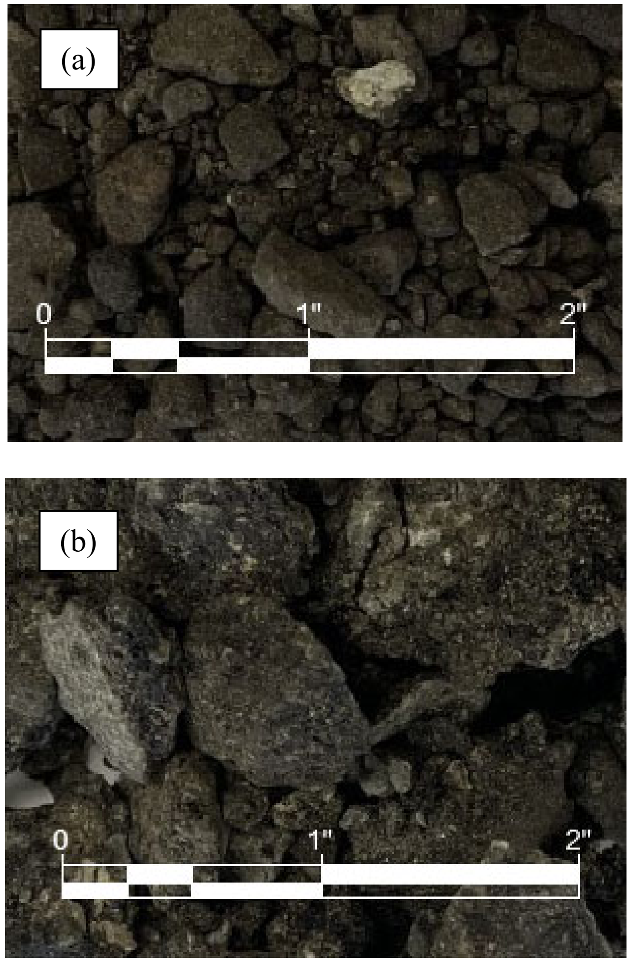


Figure 2.1 Photographs of two types of RAP: (a) processed and (b) unprocessed.

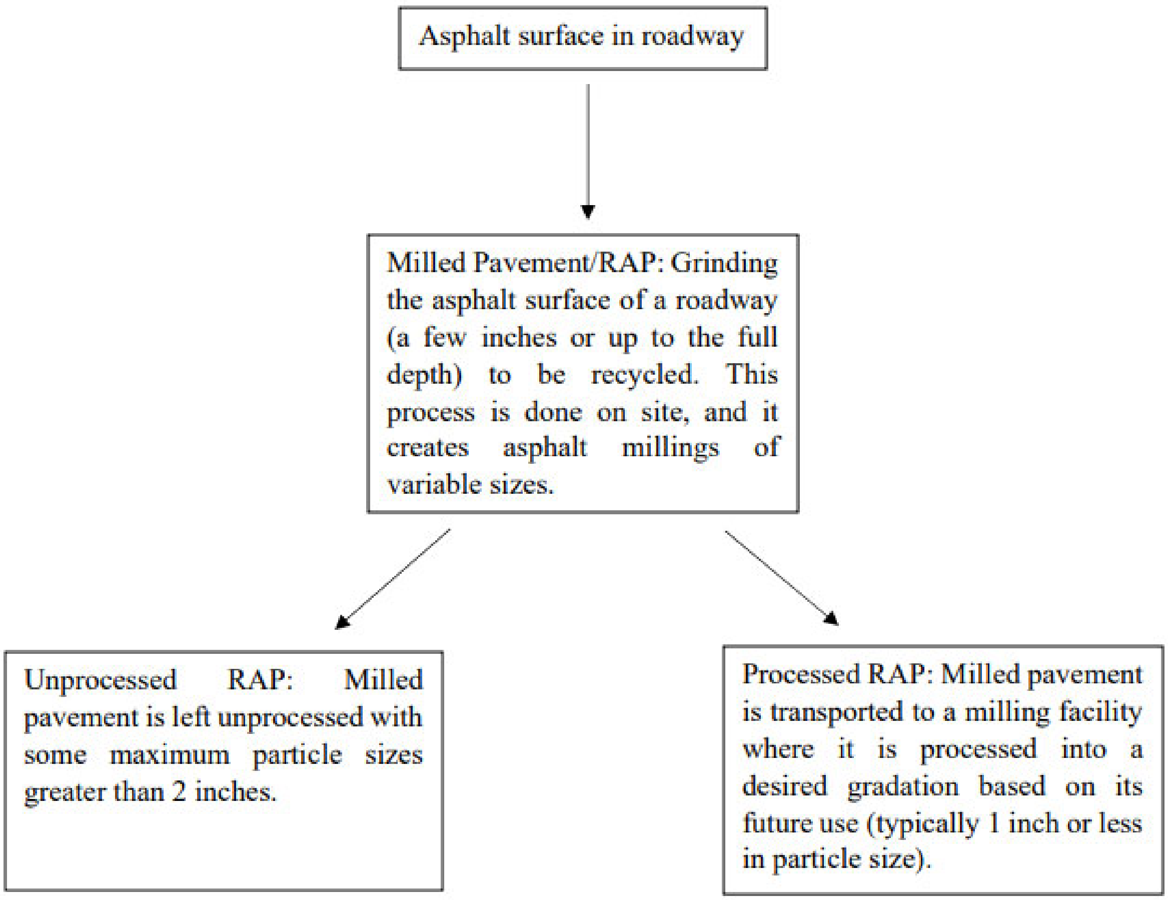


Figure 2.2. Process of creating RAP.

A study conducted by West (2010) provided guidance on the processing of RAP, and the advantages and disadvantages of the processing procedure were identified. The advantages to leaving RAP unprocessed are cost savings and minimal dust content. The disadvantages include stockpile space limitations and quality control from multiple sources of RAP (West 2010).

When RAP is processed, there are many different techniques that are used, and those techniques include screening, crushing, and fractionating (West 2010). The advantages to processing include quality control and decreased variability between multiple sources of RAP. The disadvantages to processing RAP include increased costs and an increase in dust content (West 2010). **Table 2.2** details the advantages and disadvantages of the processing procedure.

Table 2.2 Advantages and disadvantages of processing RAP (West 2010).

Process	Possible Advantages	Possible Disadvantages
Use of Millings Without Further Processing	• Avoids further crushing of aggregate particles in RAP, which may allow for higher RAP content in mixes. • Lowest cost RAP processing option. • Millings from large projects are likely to have a consistent gradation and asphalt content	• Requires multiple RAP stockpiles at the plant. • Millings from individual projects are different; therefore, when a particular millings stockpile is depleted, new mix designs must be developed with other RAP.
Screening RAP Before Crushing	• Limits crushing of aggregate particles in RAP, which reduces dust generation.	• Few RAP crushing and screening units are set up to pre-screen RAP.
Crushing all RAP to a Single Size	• Allows processed RAP to be used in many different mix types. • Generally provides good uniformity from RAP materials obtained from multiple sources	• Increases the dust content of RAP stockpiles, which will tend to limit how much RAP can be used in mix designs
Fractionating RAP	• Using different sized RAP stockpiles provides much greater flexibility in developing mix designs. Fine RAP fraction is ideal for Thinlay mixes. • Heat transfer to fine RAP may be efficient during plant mixing.	• Requires the most space for multiple smaller stockpiles. • Most expensive processing option (cost of fractionation unit plus additional RAP feed bins). • Due to higher asphalt contents, fine fractionated RAP stockpiles tend to have agglomerations, which may not feed well through the plant.

While variability arises from the processing procedure of RAP, the way in which RAP is stockpiled also has an effect on its characteristics. At the end of the construction season in 2019, an estimated 94.8 million tons of RAP was used in the United States, whereas an estimated 138 million tons of RAP was stockpiled in that year (Williams et al. 2020). Due to the large amounts of stockpiled RAP, it is important to understand the stockpiling process.

A study by Zhou et al. (2010) evaluated the state of practice of RAP stockpile management and processing in Texas. The researchers found that while it is best practice to separate stockpiles from different sources, more commonly contractors separate RAP based on whether it is unprocessed or processed (Zhou et al. 2010). It was found that the stockpiles containing processed RAP were generally better managed then stockpiles with unprocessed RAP. Processed RAP stockpiles are typically uncontaminated with foreign materials, and are placed on paved slopes to aid in drainage (West 2010; Zhou et al. 2010). It is common for unprocessed RAP stockpiles to contain contamination such as plant waste, site soil, and construction debris (West 2010; Zhou et al. 2010). **Figure 2.3** shows an unprocessed RAP stockpile and **Figure 2.4** shows a processed RAP stockpile.

Figure 2.3. Unprocessed RAP stockpile (Zhou et al. 2010).

Figure 2.4. Processed RAP stockpile (Zhou et al. 2010).

Additionally, West (2010) and Zhou et al. (2010) found that it is common for RAP to be fractionated within different stockpiles. In 2019, RAP producers from 30 states reported that they fractionate RAP, and 21% of RAP nationwide was fractionated (Williams et al. 2020). Fractionating is the process of splitting up the overall gradation into two or three distinct particle sizes and placing them into separate stockpiles (West 2010; Zhou et al. 2010). This is done to better control the gradation of RAP that is used in recycled asphalt mixture design. Additionally, it allows for more uniform RAP properties and it lessens the impact of combining stockpiles from multiple sources (Zhou et al. 2010).

Also, RAP that is greater than 6 months old may require further processing in order to retain its properties. When RAP is stockpiled for long periods of time, the particles tend to clump together, forming a crust on the surface of the stockpiles. If this occurs, re-crushing and re-screening of the particles may be necessary to break up the agglomerated particles (FHWA 2016). Additionally, because stockpiles of RAP are generally exposed to the elements, the moisture content of RAP may increase during long storage lengths (FHWA 2016). In order to prevent lengthy stockpiling times, the Pennsylvania Department of Environmental Protection's (DEP) Special Conditions General Permit WMGR101 states that RAP cannot be stored for more than two consecutive construction seasons (DEP 2020).

2.2.2 RAP Usage in the United States

A study conducted by the National Asphalt Pavement Association (NAPA) in accordance with the Federal Highway Administration (FHWA) conducted a nationwide survey to gather information on the use of recycled materials in the asphalt paving industry (Williams et al. 2020). The survey, completed in 2019, compiled results from 48 states, one U.S territory, and the District of Columbia. The findings on RAP usage from 2018 and 2019 is shown in **Table 2.3**. The reported values represent tonnage reported by survey respondents. The estimated values represent compiled information from State Asphalt Pavement Associations (SAPA). For the 2019 construction season, the national survey responses equated to 38 percent of the estimated total tons from the SAPA report (Williams et al. 2020).

Table 2.3. Survey results on RAP usage (Williams et al. 2020).

National Summary	**Reported Values**		**Estimated Values**	
	2018	2019	2018	2019
RAP	Tons (Millions)		Tons (Millions)	
Accepted	46.8	40.2	101.1	97.0
Used in HMA/WMA Mixtures	41.1	36.5	82.2	89.2
Used as Aggregate	2.9	1.7	6.4	3.8
Used in Cold-Mix Asphalt	0.1	0.1	0.3	0.3
Used in Other	0.9	0.6	2.0	1.4
Landfilled	0.0	0.1	0.0	0.1
Total Tons of RAP Stockpiled at Year-End	54.9	58.8	110.3	138.0

Overwhelmingly, the most common use of RAP is incorporating it back into the pavement by hot or warm recycling, with an estimated 89.2 million tons of RAP being used in that way. Another common use of RAP is as coarse aggregate in subbase or base construction; however, this was nowhere near as common as hot mix asphalt (HMA)/warm mix asphalt (WMA) applications, with only 3.8 million tons of RAP being utilized in this manner. There was an increase in the estimated amount of RAP used in asphalt mixes from 82.2 million tons in 2018 to 89.2 million tons in 2019. Additionally, there was an increase in the estimated amount of RAP stockpiled at the end of 2019 construction season from 110.3 million tons to 138.0 million tons (Williams et al. 2020). If the trend of increased RAP stockpiling continues, this would indicate the need for new applications of RAP to be developed. If stockpiles become overwhelmed and new uses of RAP are not developed, more RAP is likely to be placed in landfills.

While the values found in **Table 2.2** were averaged from the entire United States, there is variability of RAP usage state-by-state. A study by Wen et al. (2022) surveyed 32 DOTs to identify how RAP is used throughout the United States. From the survey responses, 11 states use RAP as embankment fill and 17 states do not use RAP in this way (Wen et al. 2022). The most common reasons DOTs do not use RAP as embankment fill was because it was deemed that RAP was more valuable in pavement or base/subbase applications. Additionally, some states cited compaction and environmental concerns (Wen et al. 2022).

The survey also investigated the use of RAP as a structural backfill material. Only 6 state DOTs use RAP in this manner, and the most common reason RAP was not used as structural backfill was because of difficulty compacting the material and creep concerns (Wen et al. 2022). **Figure 2.5** provides a pie chart showing the reasons RAP was not used as structural backfill. The numbers in the pie chart represent the amount of survey responses.

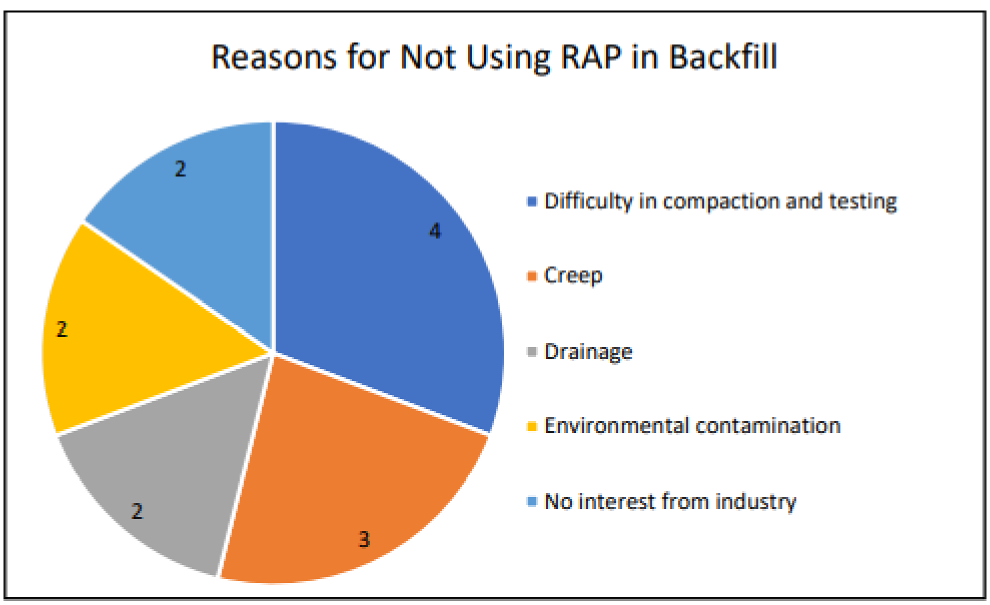


Figure 2.5 Reasons given by state DOTS for not using RAP as structural backfill (Wen at al. 2022).

The Federal Highway Administration (FHWA) was also interested in the use of RAP in the United States, and how various states use RAP in different applications. FHWA created user guidelines for waste and byproduct materials in pavement construction, and these guidelines provide valuable information on the use of RAP throughout the United States. FHWA (2016) states that RAP can be used in many highway applications, with those applications being:

- Aggregate substitute and asphalt cement supplement in recycled asphalt paving (hot mix or cold mix)
- Granular base or subbase
- Stabilized base aggregate
- Embankment or fill material

The reuse of RAP as an embankment or fill material is the only non-pavement application that FHWA (2016) identifies. FHWA (2016) found that the use of RAP as an embankment or fill material would be most beneficial if RAP had been stockpiled for long periods of time or if it had been mixed with other materials. Additionally, when RAP is being used in embankment or fill applications, minimal processing is required, with some states allowing unprocessed or more coarse-grained RAP to be used (FHWA 2016). In fact, FHWA (2016) found that at least nine states: Connecticut, Indiana, Kansas, Montana, New York, Tennessee, California, Illinois, and Louisiana; have used RAP in some capacity during embankment construction. In general, RAP is permitted for reuse as embankment or fill material if its geotechnical properties are similar to typical coarse aggregate material it would be replacing (FHWA 2016).

2.2.3 Pennsylvania RAP Usage

The nationwide NAPA survey by Williams et al. (2020) broke down the use of RAP in asphalt pavement applications state-by-state. In Pennsylvania, in the 2019 construction season, an estimated 3.3 million tons of acceptable RAP was generated, with 2.7 million tons being used in HMA/WMA mixtures. It was estimated that less than 100,000 tons of RAP was used as an aggregate material (Williams et al. 2020). This is likely due to the commonality of RAP reuse in recycled pavement mixtures, and the need for additional guidance on the reuse of RAP in non-pavement applications.

PennDOT Publication 408 provides specifications for construction projects throughout the state of Pennsylvania. In Publication 408, the current approved applications for RAP reuse are as follows (PennDOT 2022):

- Cold Recycled Asphalt Base Course, Cold-In-Place
- Cold Recycled Asphalt Base Course, Central Plant Mix
- Full Depth Reclamation
- Superpave Mixture Design, Standard and RPS Construction of Plant-mixed Asphalt Courses with Percent Within Limits and LTS Testing (PWL-LTS)

- Pervious Asphalt Pavement Systems
- Asphalt Seal Coat Using Aggregate From RAP
- Asphalt Material

Currently, RAP is used extensively in pavement applications, however, there is limited guidance on the reuse of RAP for non-pavement applications. PennDOT Publication 23 – Chapter 5 approves the use of RAP in gravel shoulder applications; however, no specifications are provided for other non-pavement applications (PennDOT 2019; DEP 2020). Identifying other reuse opportunities could provide significant cost savings and environmental benefits (PennDOT 2020). To aid in the identification alternative applications, PennDOT (2020) provided a table with the typical physical and mechanical properties of RAP as shown in **Table 2.4**.

Table 2.4. Physical and mechanical properties of RAP (PennDOT 2020).

Type of Property	RAP Property	Typical Range of Values
Physical Properties	Unit Weight	1940 - 2300 kg/m³ (120 - 140 lb/ft³
	Moisture Content	Normal: up to 5% Maximum Range: 7 - 8%
	Asphalt Content	Normal: 4.5 - 6% Maximum Range: 3 - 7%
	Asphalt Penetration	Normal: 10 - 80 at 25°C (77°F)
	Absolute Viscosity or Recovered Asphalt Cement	Normal: 4,000 - 25,000 poises at 60°C (140°F)
Mechanical Properties	Compacted Unit Weight	1600 - 2000 kg/m³ (100 - 125 lb/ft³
	California Bearing Ratio (CBR)	100% RAP: 20 - 25% 40% RAP and 60% Natural Aggregate: 150% or higher

2.2.4 District 6 RAP Usage

Many sources have found that RAP use can vary state to state. It is important to determine if RAP use can vary district by district in the state of Pennsylvania. Pennsylvania is divided into 12 Districts, with the focus of this report being on District 6. District 6 is located on the southeast section of the state and contains Montgomery, Bucks, Philadelphia, and Delaware Counties. **Figure 2.6** provides a map of Pennsylvania's 12 districts.

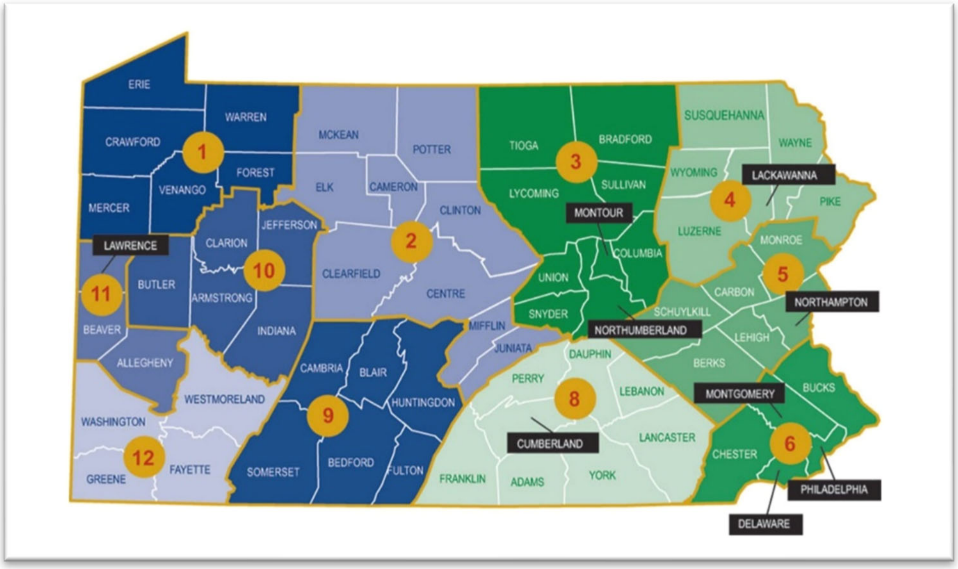


Figure 2.6. PennDOT district map (O'Brien DeTrano 2017).

A study by Goodhart and Koser (2017) compiled PennDOT survey data on the reuse of RAP in Pennsylvania's 12 districts. The survey found that in 2016, 1,956,593 tons of RAP was milled from pavements, with 77% of the generated RAP being given to contractors and 23% of the RAP being retained by the Districts (Goodhart and Koser 2017). **Figure 2.7** shows that in District 6, nearly all of the RAP that is generated is given to contractors. Additionally, the survey found that significantly more RAP was milled in District 6 than in the other Districts. As shown in **Figure 2.8**, in 2016, District 6 milled nearly 500,000 tons of RAP whereas the next highest District, District 12, milled only 300,000 tons of RAP. District 6 produces nearly one fourth of all the RAP in Pennsylvania, leading to a surplus in RAP that is being stockpiled in the District. This solidifies the need for maximizing the amount that is being reused, which leads to investigations in to the reuse of RAP in non-pavement applications.

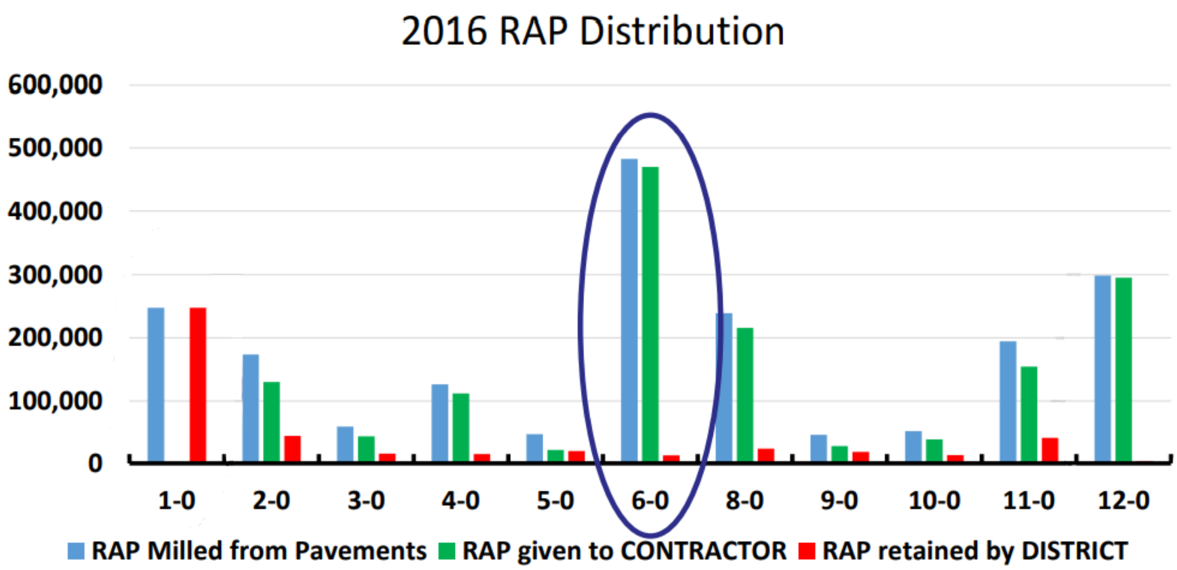


Figure 2.7 The distribution of RAP by District in Pennsylvania, with District 6 highlighted (Goodhart and Koser 2017).

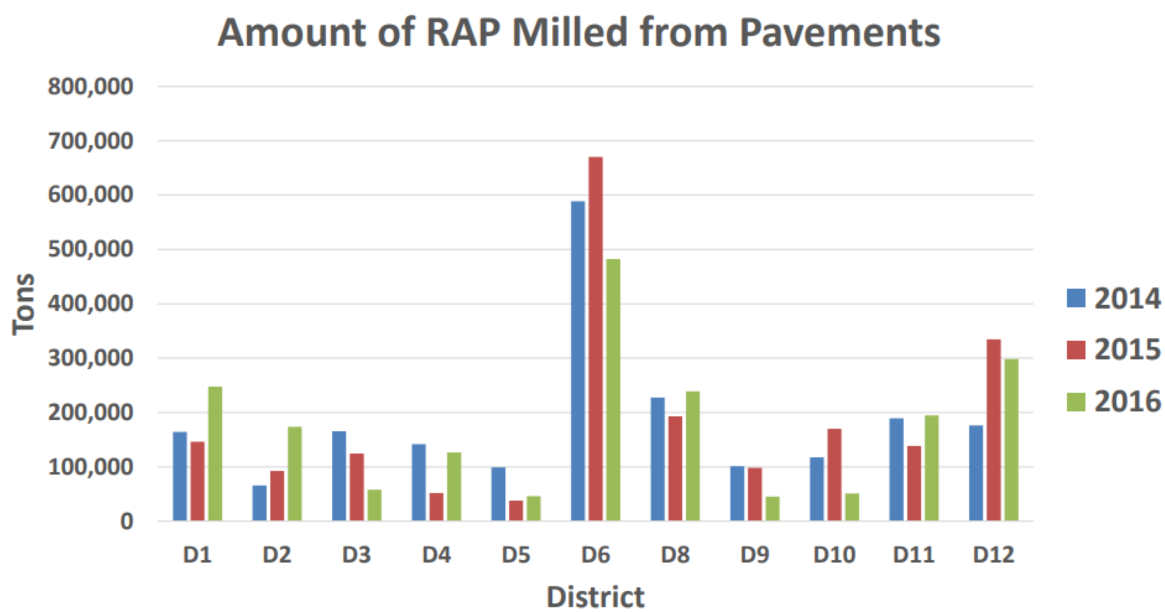


Figure. 2.8 The amount of RAP generated by District in Pennsylvania (Goodhart and Koser 2017).

While RAP has been commonly used in certain applications by PennDOT, there is still a need for further study on the performance of RAP in geotechnical applications. There is also a need for correlating laboratory and field measurement techniques (PennDOT 2020). PennDOT (2020) lists unresolved issues on RAP usage that require further evaluation. The unresolved issues that the Villanova University research team are specifically interested in evaluating are shown in bold:

- **Variability of RAP, especially from blended stockpiles**
- Validation of Superpave mixture design procedures with mixtures containing RAP
- A consensus regarding mixture design and testing procedures for plant recycled cold mixtures and cold in-place recycling of asphalt mixtures
- The suitability of cold in-place recycling for use with surface treatments and/or rubberized paving materials
- A more accurate determination of the structural layer coefficient for plant recycled cold mix asphalt mixtures
- An environmental evaluation of any potentially harmful impacts from cold mixture plant recycling and/or cold in-place recycling
- **Establish standard specifications for the incorporation of RAP into granular base and standard methods for determining in-place compacted density**
- **Evaluation of environmental concerns regarding leachability characteristics for RAP, as well as various RAP-aggregate blends, to develop procedures for the stockpiling and placing of base or subbase materials containing RAP in situations where there may be groundwater contact.**

2.3 Geotechnical Properties

Geotechnical properties encompass the index properties and the engineering properties of a soil. The index properties are used to classify a material (i.e., gradation, specific gravity) and the engineering properties are used to evaluate how a material will behave in certain engineering/design applications. The geotechnical properties evaluated for this literature review include gradation, specific gravity, maximum dry density/optimum moisture content, hydraulic conductivity, leaching, shear strength and creep.

2.3.1 Gradation

The gradation of RAP is used to identify key characteristics such as percentage of fines, various grain size diameters (D_{60}, D_{30}, D_{10}), the coefficient of curvature (C_c), and the coefficient of uniformity (C_u). These properties provide an indication of expected material performance in engineering applications and the properties help to identify trends between different sources of materials. The gradation of RAP is highly dependent upon how the RAP was processed. RAP is milled to different particle sizes based on its desired uses. Due to the frequent use of RAP in asphalt mixtures, the most common gradation of RAP follows the requirement set forth by the specific mixture design. Generally, the maximum allowable aggregate size is 2 inches, with most RAP gradations being 1 inch or less in particle size (FHWA 2016).

Based on the review of the literature, the gradation curves of the RAP investigated fell within a similar gradation band and had similar classifications. The particle size distribution curves from the studies evaluated are shown in **Figure 2.9** (Abedalqader et al. 2021; Arulrajah et al. 2013; Bejarano 2001; Bennert and Maher 2005; Cooley 2005; Cleary 2005; Cosentino et al. 2003; Hajj et al. 2012; Kalpacki et al. 2018; Locander 2009; Ma et al. 2015; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Solaimanian et al. 2011; Thakur et al. 2013; Titi et al. 2019; Yin et al. 2017; Yousefi et al. 2021). From the literature studies that evaluated the gradation of RAP, eight of the most comprehensive studies were compiled in **Table 2.5** to identify the common properties of RAP. These eights studies found RAP to be a non-plastic material that had a very small percentage of fines ranging from 0% to 6% for the dry sieve method. As shown in **Table 2.5**, RAP typically classifies as either well-graded sand with gravel (SW) or well-graded gravel with sand (GW), based on the Unified Soil Classification System (USCS) and A-1-a material using the AASHTO system (Arulrajah et al. 2013; Bennert and Maher 2005; Cooley 2005; Cosentino et al. 2003; Mijic et al. 2020; Mousa et al. 2021; Rathje et al. 2002; Titi et al. 2019).

It was found that there was no consistent maximum particle size from each study (Abedalqader et al. 2021; Arulrajah et al. 2013; Bejarano 2001; Bennert and Maher 2005; Cooley 2005; Cleary 2005; Cosentino et al. 2003; Gao et al. 2021; Hajj et al. 2012; Kalpacki et al. 2018; Locander 2009; Ma et al. 2015; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Solaimanian et al. 2011; Thakur et al. 2013; Titi et al. 2019; Yin et al. 2017; Yousefi et al. 2021; Zhou et al. 2010).This indicates that RAP gradation varies within the U.S and throughout the world, and that the variation is most likely due to the different milling processes. Although the studies had different maximum particle sizes, the general shape of the gradation curves were similar. Studies showed a relatively well-graded gradation curve with very little fines present (Abedalqader et al. 2021; Arulrajah et al. 2013; Bejarano 2001; Bennert and Maher 2005; Cooley 2005; Cleary 2005; Cosentino et al. 2003; Hajj et al. 2012; Kalpacki et al. 2018; Locander 2009; Ma et al. 2015; Mijic et al. 2020; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Solaimanian et al. 2011; Thakur et al. 2013; Titi et al. 2019; Yin et al. 2017; Yousefi et al. 2021). The RAP used in Abedalqadar et al. (2021) was unprocessed, therefore its gradation curve was uniformly graded and it varied from the other studies. Rahardjo et al. (2013) used processed RAP, however, the processing procedure created two types of RAP; one being uniformly fine-grained (R1) and the other being uniformly coarse-grained (R2). This resulted in the uniformly coarse-grained RAP having a gradation curve that varied from the other studies.

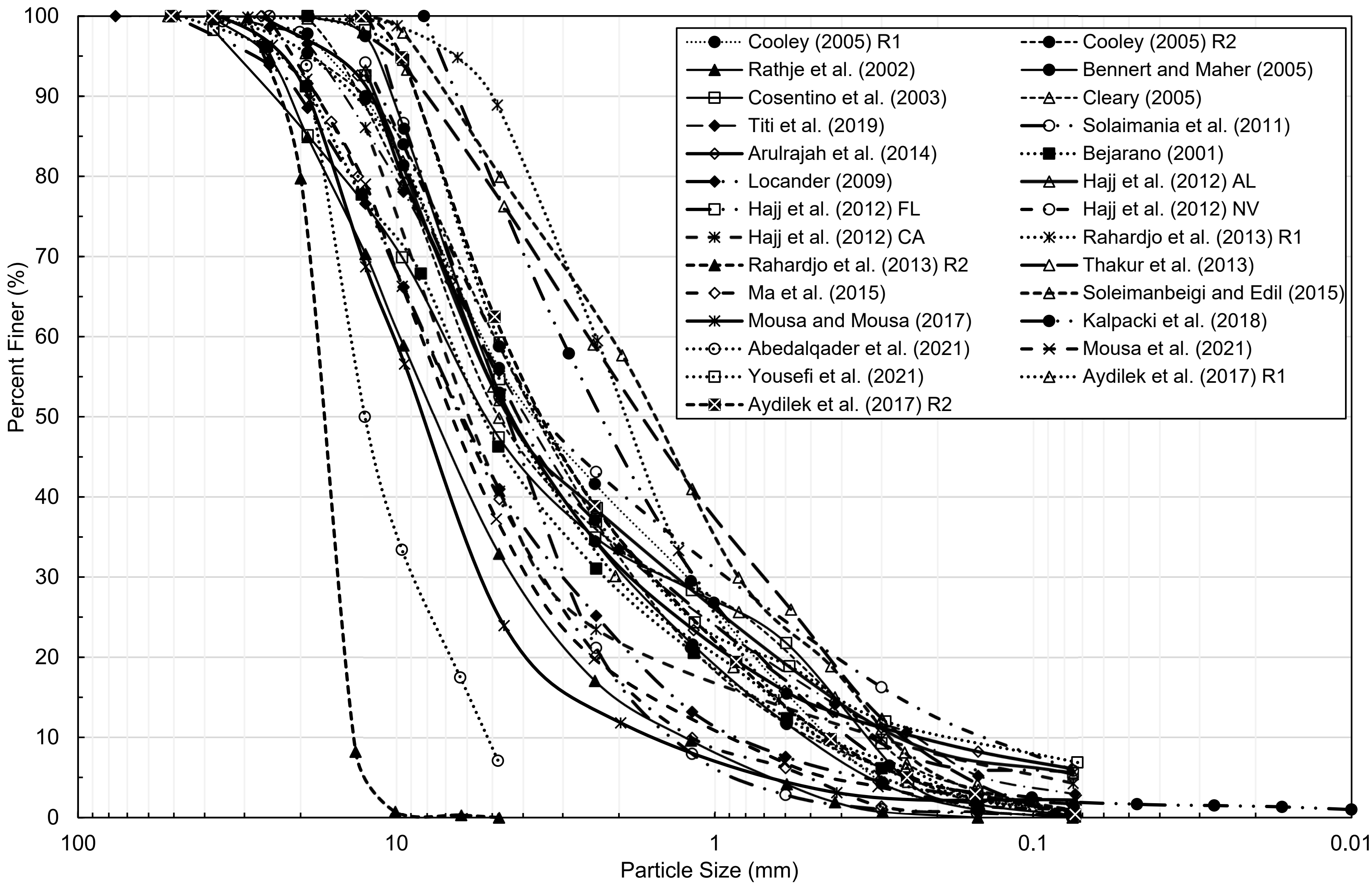


Figure 2.9 Gradation curves for RAP reported in the literature.

Table 2.5. Summary of geotechnical properties of RAP reported in eight experimental studies.

Parameter	Cooley 2005 R1	Cooley 2005 R2	Rathje et al. 2002	Bennert and Maher 2005	Cosentino et al. 2003	Mousa et al. 2021	Titi et al. 2019	Mijic et al. 2020	Arulrajah et al. 2013
Max Size (mm)	19	19	37.5	12.5	37.5	25.4	25	n/a	n/a
Percent Fines (Dry Sieve)	0	0	0	0.1	0	1.0	3	0.13 to 1.83	6.0
Percent Fines (Soil Wash)	7.9	0.5	n/a	n/a	n/a	n/a	0.99 to 17.1	n/a	n/a
D_{60} (mm)[a]	5.4	5	9.6	5.7	7	8	5.4	n/a	5.9
D_{30} (mm)[b]	1.21	1.8	4.2	1.9	1.5	3.5	1.6	n/a	1.9
D_{10} (mm)[c]	0.43	0.5	1.2	0.51	0.33	0.85	0.23	n/a	0.24
C_c [d]	0.63	1.3	1.53	1.22	0.97	1.80	2.06	1.03 to 1.79	2.5
C_u [e]	12.6	10.0	8.0	10.9	21.2	9.4	23.5	5.6 to 14.0	25.6
Liquid Limit	NP	NP	NP	NP	NP	NP	NP	NP	NP
Plastic Limit	NP	NP	NP	NP	NP	NP	NP	NP	NP
USCS Classification	SW	SW	GW	SW	GW	GW	SW	SW	GW
AASHTO Classification	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a
Specific Gravity	2.47	2.47	2.33	n/a	2.19	2.24	2.28 to 2.77	2.35	n/a
Maximum Dry Density (pcf)	129.7	115.3	117.0	n/a	117.9	124.1	n/a	109.5 to 124.7	127.2
Optimum Moisture Content (%)	5.6	5.8	3.0	n/a	8.0	6.0	n/a	5.7 to 8.2	8.0
Saturated Hydraulic Conductivity (cm/s)	n/a	n/a	0.5×10^{-3} to 4.0×10^{-3}	6.0×10^{-3}	2.0×10^{-4}	3.3×10^{-2}	n/a	6.3×10^{-3} to 1.6×10^{-2}	3.5×10^{-4}

a. 60% of soil particles are finer than this size

b. 30% of soil particles are finer than this size

c. 10% of soil particles are finer than this size

d. Coefficient of curvature; $C_c = \frac{(D_{30})^2}{(D_{60})(D_{10})}$

e. Uniformity coefficient; $C_u = \frac{D_{60}}{D_{10}}$

PennDOT Publication 408 sets standards for the gradation envelopes of coarse aggregate materials that are used in various applications non-pavement applications such as embankments or fill, pipe bedding, shoulder backfill, and MSE wall backfill. Because RAP would be replacing coarse aggregate material in these applications, the gradation of RAP must be comparable to the gradation of the coarse aggregates typically selected. The gradations of RAP found in literature were compared to PennDOT's coarse aggregate requirements provided by Publication 408, and the range of particle-size distributions set forth by PennDOT are highlighted in red (**Figures 2.10 – 2.15**).

According to Publication 408, typical coarse aggregates used in embankment or fill applications are as follows: AASHTO No. 8, AASHTO No. 57, PennDOT 2A, PennDOT open-graded subbase (OGS), and PennDOT select granular material (2RC). The gradation of typical coarse aggregate materials used in embankment or fill applications is shown in **Table 2.6**. **Figures 2.10** – **2.14** provide the particle-size distribution curves for coarse-aggregates allowable in embankment or fill applications.

Table 2.6. Required gradation for coarse aggregate material in embankment or fill (PennDOT 2022).

Requirements	2RC (% Passing)	2A (% Passing)	OGS (% Passing)	No.8 (% Passing)	No.57 (% Passing)
50 mm (2")	100	100	100		
37.5 mm (1 1/2")					100
25 mm (1")					90-100
19 mm (3/4")		52-100	52-100		
12.5 mm (1/2")				100	25-60
9.5 mm (3/8")		36-70	36-65	85-100	
4.75 mm (No. 4)	15-60	24-50	8-40	10-30	0-10
2.36 mm (No. 8)		16-38		0-10	0-5
1.18 mm (No. 16)		10-30	0-12	0-5	
150 µm (No. 100)	0-30				
0.75 µm (No. 200)		0-2	0-2	0-2	

The type of coarse aggregate used for pipe bedding applications in Pennsylvania is dependent upon the type of pipe being utilized. For concrete pipes, AASHTO No. 8 aggregate is used. For metal and thermoplastic pipes, PennDOT 2A is used. The gradation of the typical coarse aggregates used in pipe bedding applications is shown in **Table 2.7**. The particle-size distributions of RAP found in literature were compared to coarse aggregates used in pipe bedding requirements in **Figure 2.11** and **Figure 2.12**.

Table 2.7. Required gradation for coarse aggregate material in pipe bedding (PennDOT 2022).

Requirement	2A (% Passing)	No. 8 (% Passing)
50 mm (2")	100	
19 mm (3/4")	52-100	
12.5 mm (1/2")		100
9.5 mm (3/8")	36-70	85-100
4.75 mm (No. 4)	24-50	10-30
2.36 mm (No. 8)	16-38	0-10
1.18 mm (No. 16)	10-30	0-5
0.75 µm (No. 200)	0-2	0-2

According to PennDOT Publication 23 – Chapter 5, RAP is an approved material for shoulder backfill applications. For the reuse of RAP in this application, the gradation of RAP must be like typical coarse aggregate material used for shoulder backfill, which includes AASHTO's No. 2A or AASHTO's open-graded subbase (OGS). The required gradation for No. 2A and OGS is shown in **Table 2.8**. The particle-size distribution curves of RAP found in literature were compared to No. 2A material in **Figure 3.4** and No. OGS material in **Figure 3.5** for shoulder backfill applications.

Table 2.8. Required gradation for coarse aggregate material in shoulder backfill (PennDOT 2022).

Requirement	2A (% Passing)	OGS (% Passing)
50 mm (2")	100	100
19 mm (3/4")	52-100	52-100
9.5 mm (3/8")	36-70	36-65
4.75 mm (No. 4)	24-50	8 to 40
2.36 mm (No. 8)	16-38	
1.18 mm (No. 16)	10 to 30	0-12
.75 µm (No. 200)	0-2	0-2

Typical reinforced fill used in MSE wall applications in Pennsylvania are dependent upon the type of geogrid utilized. For Class 1 geogrids, No. 8 aggregate is used in areas that require free drainage or in areas that are below the 100-year flood elevation. For other areas, a structural fill mixture is created. For Class 2 and 3 geogrids, AASHTO No. 8, AASHTO No. 57, and PennDOT 2A aggregates are typically used. The required gradation for structural fill, No. 8, No. 2A and No. 57 is shown in **Table 2.9**. The particle-size distribution curves of RAP found in literature were compared to the typical coarse aggregates used MSE walls in **Figures 2.11 - 2.12** and **Figures 2.14 – 2.15.**

Table 2.9 Required gradation for coarse aggregate material in an MSE wall (PennDOT 2022).

Requirement	Structural Fill (% Passing)	2A (% Passing)	No.8 (% Passing)	No.57 (% Passing)
50 mm (2")		100		
37.5 mm (1 1/2")				100
25 mm (1")				90-100
19 mm (3/4")		52-100		
12.5 mm (1/2")	100		100	25-60
9.5 mm (3/8")		36-70	85-100	
4.75 mm (No. 4)		24-50	10-30	0-10
2.36 mm (No. 8)		16-38	0-10	0-5
1.18 mm (No. 16)		10-30	0-5	
450 µm (No. 40)	0-60			
0.75 µm (No. 200)	0-10	0-2	0-2	

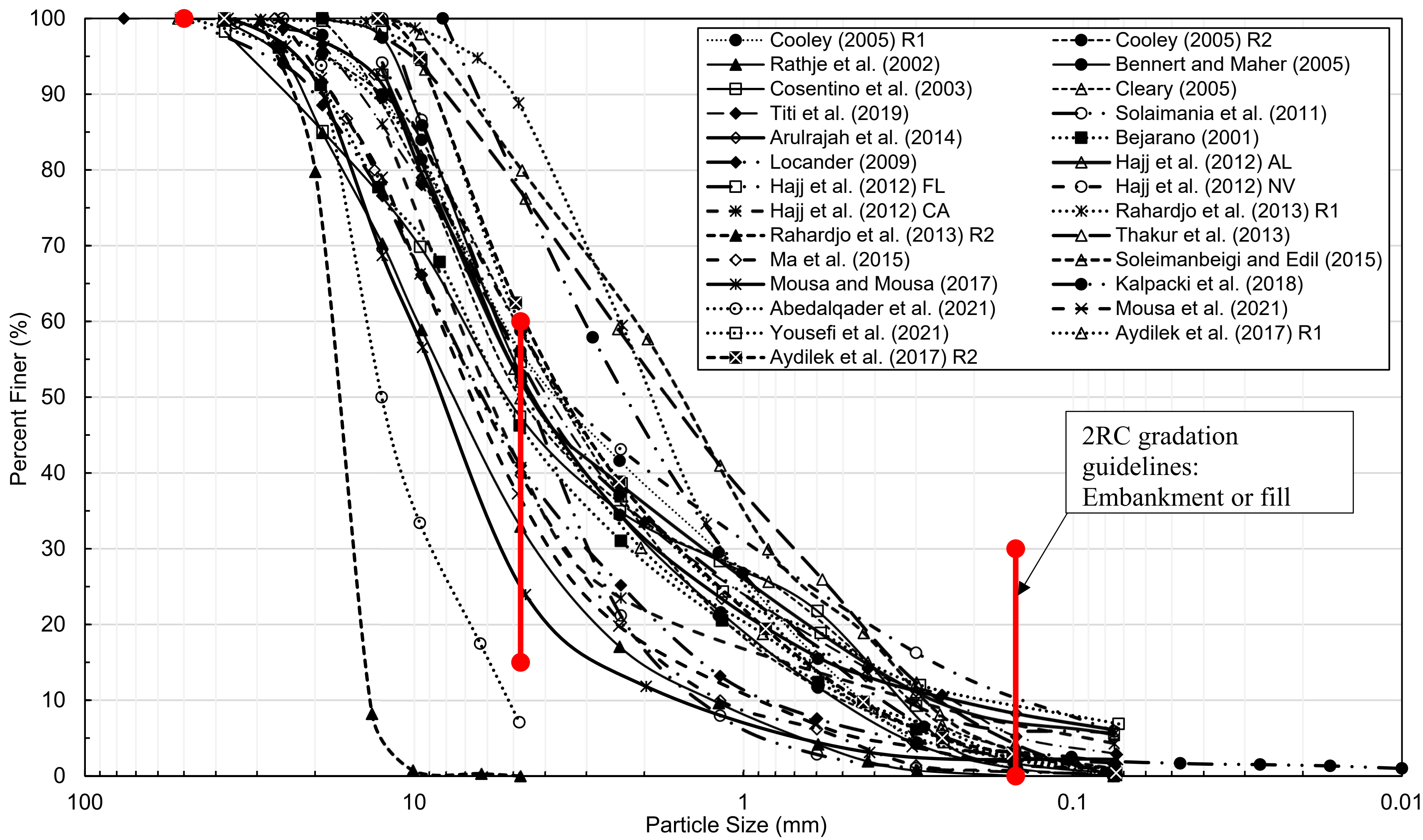


Figure 2.10 Gradation envelope for select granular material 2RC compared to literature studies (PennDOT 2022).

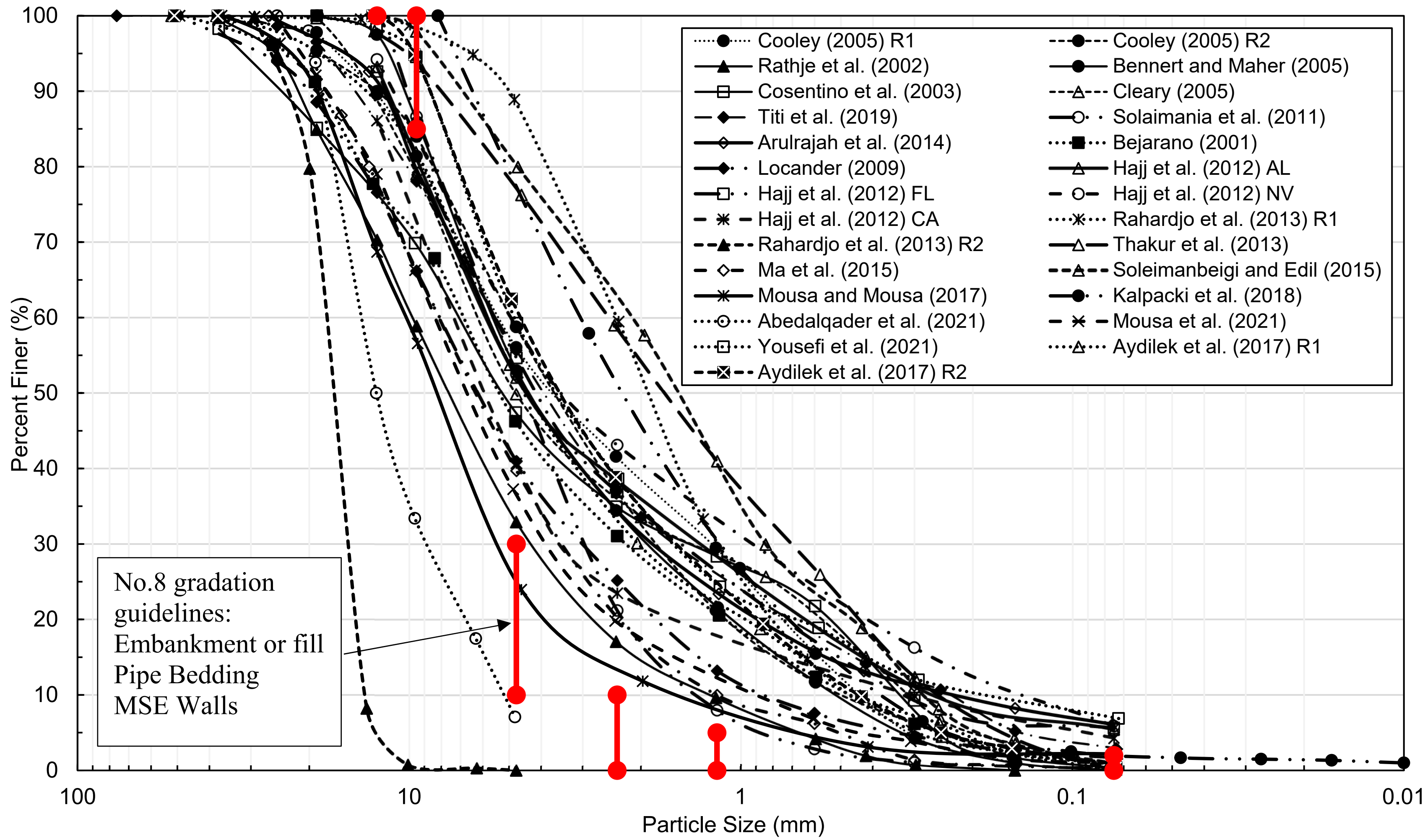


Figure 2.11 Gradation envelope for No. 8 stone compared to literature studies (PennDOT 2022).

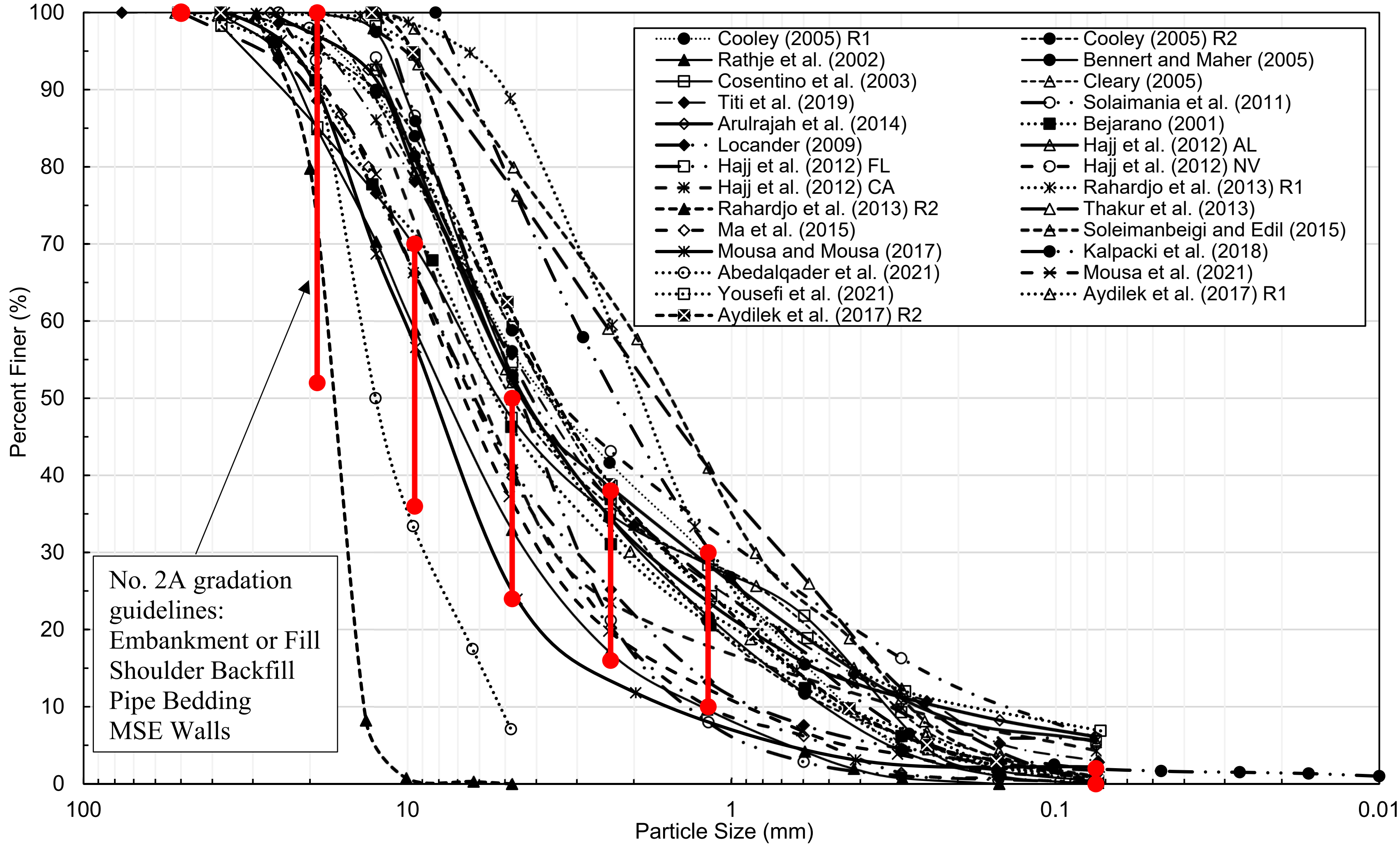


Figure 2.12 Gradation envelope for No. 2A material compared to literature studies (PennDOT 2022).

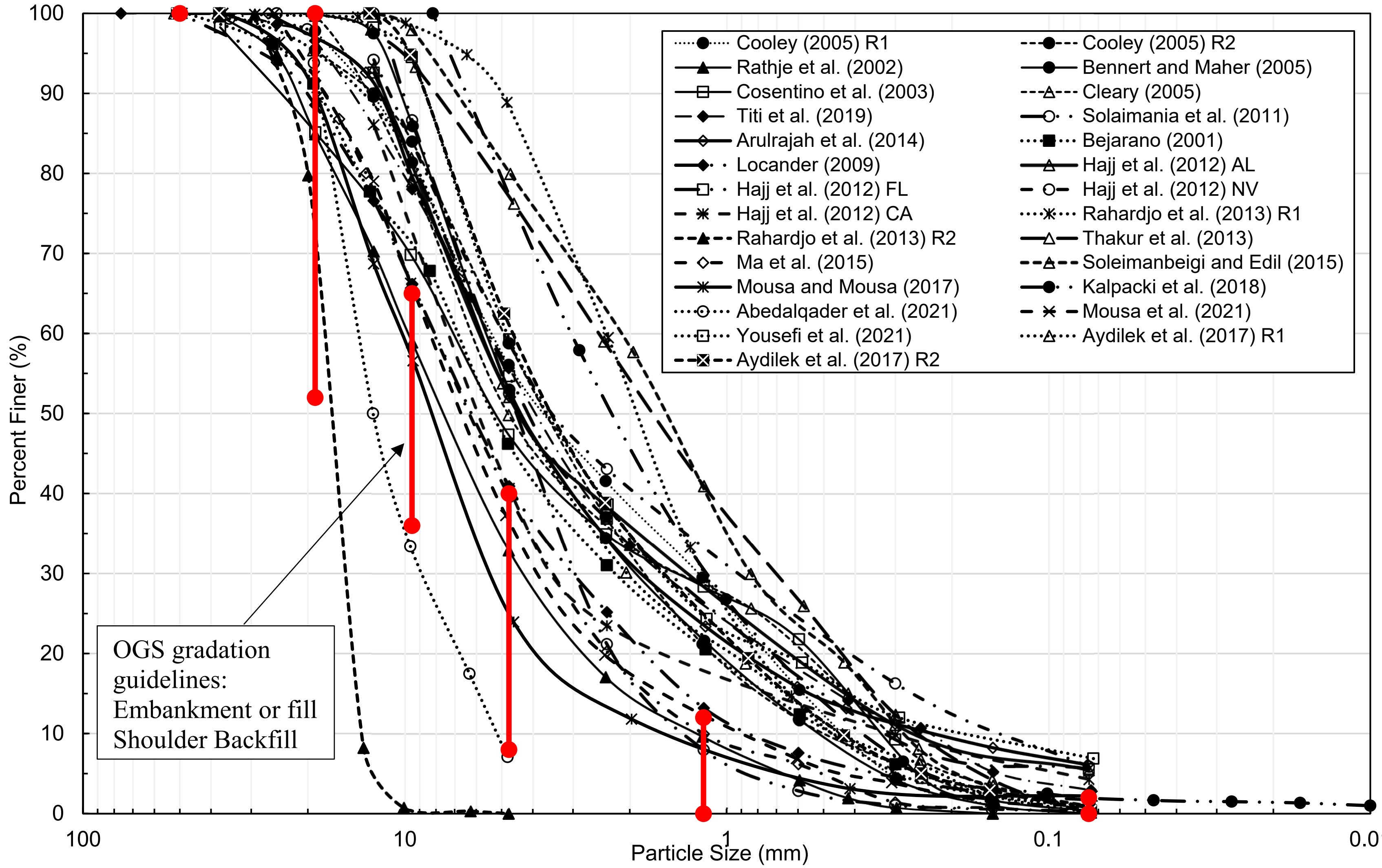


Figure 2.13 Gradation envelope for open-graded subbase compared to literature studies (PennDOT 2022).

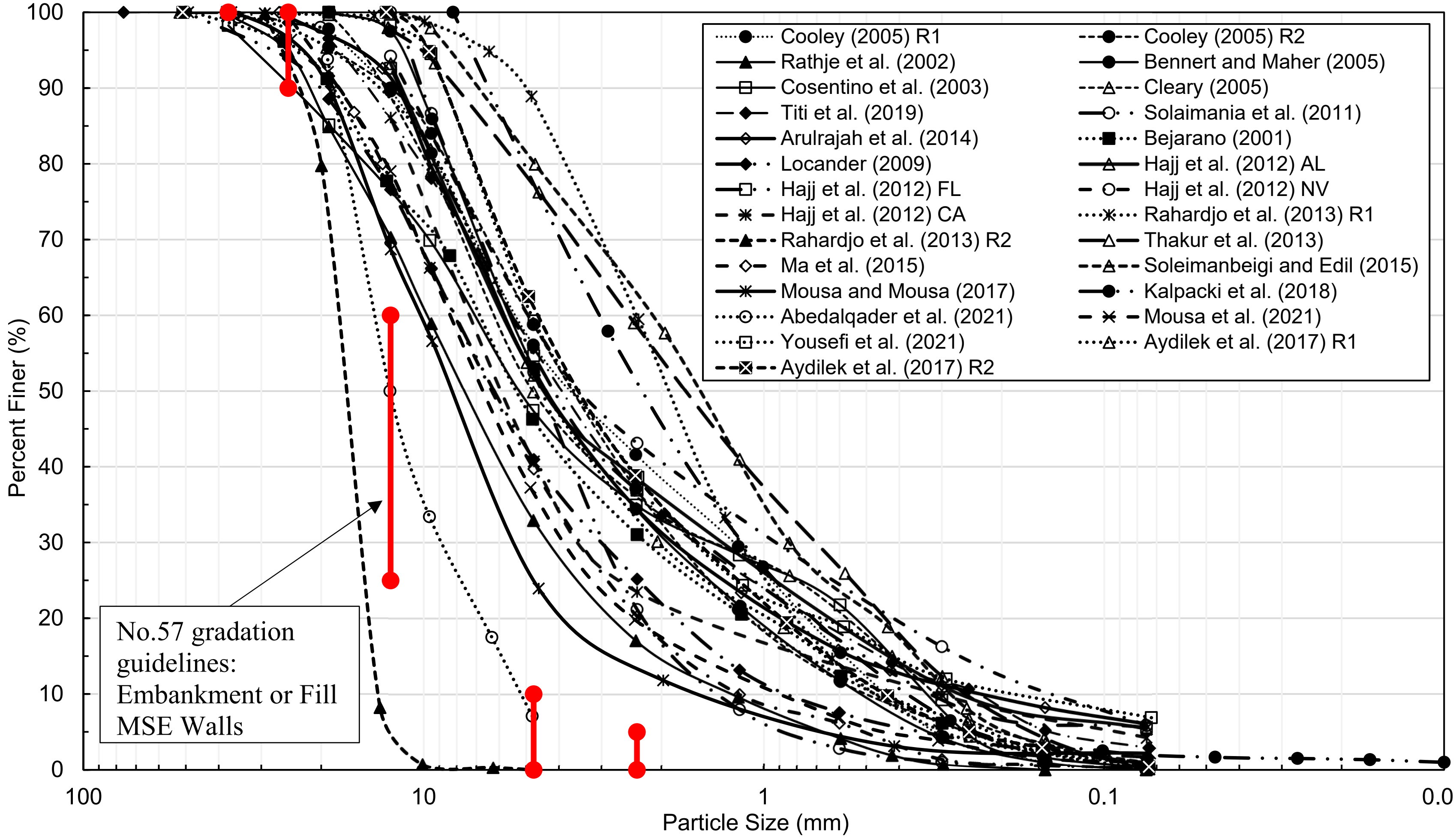


Figure 2.14 Gradation envelope for No. 57 stone material compared to literature studies (PennDOT 2022).

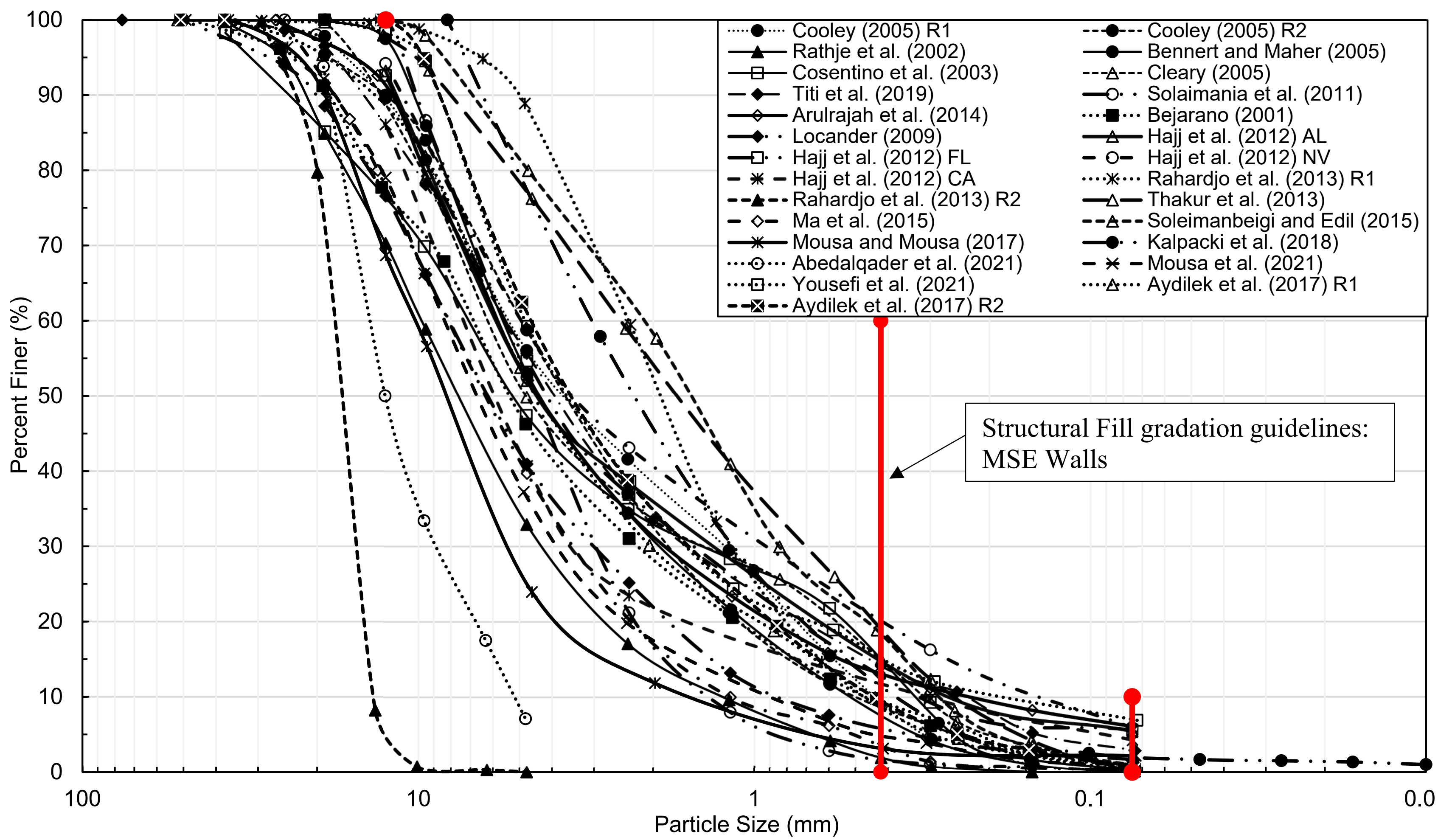


Figure 2.15 Gradation envelope for structural fill material compared to literature studies (PennDOT 2022).

For material 2RC as shown in **Figure 2.10**, the majority of the gradations found in literature fit into the 2RC requirements from Publication 408. Both Abedalqader et al. (2021) and Rahardjo et al. (2013) R2 had gradations larger than the 2RC requirements. Some sources (Kalpacki et al. 2018; Rahardjo et al. 2013 R1; Soleimanbeigi and Edil 2015; Thakur et al. 2013) had gradations finer than the 2RC requirements, but this could be combated by mixing the RAP with other coarse aggregate materials. Because very few literature studies fell outside of the 2RC requirements, in general, RAP would be suitable for applications that require 2RC material without much material adjustment.

For AASHTO No.8 as shown in **Figure 2.11**, the majority of the literature does not fall into the acceptable range. In general, the RAP found in literature is well-graded whereas the requirement for pipe bedding is much more uniformly-graded. The coarse-grained material for RAP was larger in particle size than the requirement, while the finer-grained material for RAP was smaller in particle size than the requirement. However, if the RAP from literature was scalped to less than ½ inch and fine-grained material was removed, RAP could meet the requirements for use in pipe bedding applications.

For material 2A, shown in **Figure 2.12**, the RAP from literature generally fell within the allowable envelope, but in the coarser-grained range, RAP's particle sizes were smaller than the requirement. This could be easily adjusted by adding some coarser-grained material to the RAP mix in order to allow it to meet the material 2A gradation requirement.

For material OGS and AASHTO No. 57, shown in **Figure 2.13** and **2.14**, a few literature studies fell within the allowable envelope, but the majority of the RAP from literature had material that was finer than the requirement. If coarser-grained material was added to RAP, the gradation curve would be shifted left, and the gradation would meet the requirement for material OGS and AASHTO No. 57.

For structural fill as shown in **Figure 2.15**, RAP from literature generally falls outside the allowable envelope and this is because many of the studies had material larger than ½ inch. If RAP from literature was scalped to less than ½ inch, the curve would be shifted to the right and RAP would meet the requirement for structural fill.

Overall, RAP from literature either fell within the required gradations, or with gradation adjustment could meet the requirements set forth by PennDOT's Publication 408. It is important to note that the most of the RAP from literature was considered processed RAP. Processed RAP has been more thoroughly reviewed by literature therefore it has been compared to the required gradation for construction applications. Further studies would need to be conducted to compare unprocessed RAP gradation to Publication 408 requirements.

2.3.2 Specific Gravity

Like gradation, the specific gravity of RAP shows variability across different studies which is most likely due to different milling processes. The most common laboratory specific gravity test from literature was ASTM C127-15 (ASTM 2015). It was found that RAP has a lower specific gravity than typical coarse-grained aggregate materials, and values from seven studies are provided in **Table 2.5**.

Overall, the range of specific gravity values of RAP from the literature evaluated was 2.25 to 2.77, with an average value of 2.43 (Abedalqader et al. 2021; Cooley 2005; Cosentino et al. 2003; Hajj et al. 2012; Locander 2009;; Mijic et al. 2020; Mousa et al. 2021; Yousefi et al. 2021; Rahardio et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012; Thakur et al. 2013; Titi et al. 2019). This value is lower than the typical assumed values of 2.60 - 2.70 for soils and aggregates. The lower value for RAP suggests that the bitumen coating around the aggregate creates a larger impermeable volume of solids, resulting in a smaller calculated specific gravity (Rathje et al. 2002). While RAP does have a lower specific gravity than common coarse aggregate materials, it is likely that specific gravity will not be the determining factor for the ability to reuse RAP in new highway transportation applications.

2.3.3 Maximum Dry Density/Optimum Moisture Content

To determine the maximum dry density (MDD) and optimum moisture content (OMC) of RAP, the most common laboratory compaction test from literature was the modified proctor test (ASTM D1557-12), with very few studies utilizing the standard proctor or other compaction methods (ASTM 2021). Additionally, it is also common to test compaction in the field using a nuclear gauge test. Due to the hydrogen content in the asphalt binder, nuclear gauge tests are not accurate, and they result in higher maximum dry density values than the values obtained in laboratory testing (McGarrah 2007; Rathje et al. 2002; Wen et al. 2022).

PennDOT Publication 408 does not provide standard laboratory compaction values for MDD and OMC, however it does give compaction guidance for the placement of embankments and backfill materials in the field. Depending on the gradation and the material type, granular materials must be compacted in the field to either 97% MDD or to a condition of non-movement (PennDOT 2022). As defined by Publication 408, a condition of non-movement is stable condition where there is no rutting, displacement, or shear wave during construction compaction (PennDOT 2022).

The MDD's from literature ranged from 108 pcf to 131 pcf, with the average being 122 pcf. The OMC ranged from 3% to 8% (Arulrajah et al. 2013; Bejarano 2001; Cooley 2005; Cosentino et al. 2003; Kalpacki et al. 2018; Locander 2009; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardio et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012; Soleimanbeigi an Edil 2015; Thakur et al. 2013). A maximum dry density range provided by the PennDOT (2020) for compacted unit weight was 100 pcf to 125 pcf and the range for moisture content 5% to 8%. In general, the MDD and OMC for RAP is slightly lower than typical coarse aggregate materials, however the MDD range from literature is consistent with the typical range provided by PennDOT (2020). This indicates that RAP has good compaction characteristics and would be suitable in embankment and fill applications.

MDD results from seven studies are summarized in **Table 2.5**. **Figure 2.16** provides the compaction curves from five studies. The compaction results indicate that RAP has a relatively flat compaction curve. This is common for coarse-aggregates due to free drainage characteristics (Mijic et al. 2020). Typically, the required maximum dry density of coarse aggregates can be obtained regardless of the water content due to the compaction curves being flat, with no clear peak value (Rathje et al. 2002).

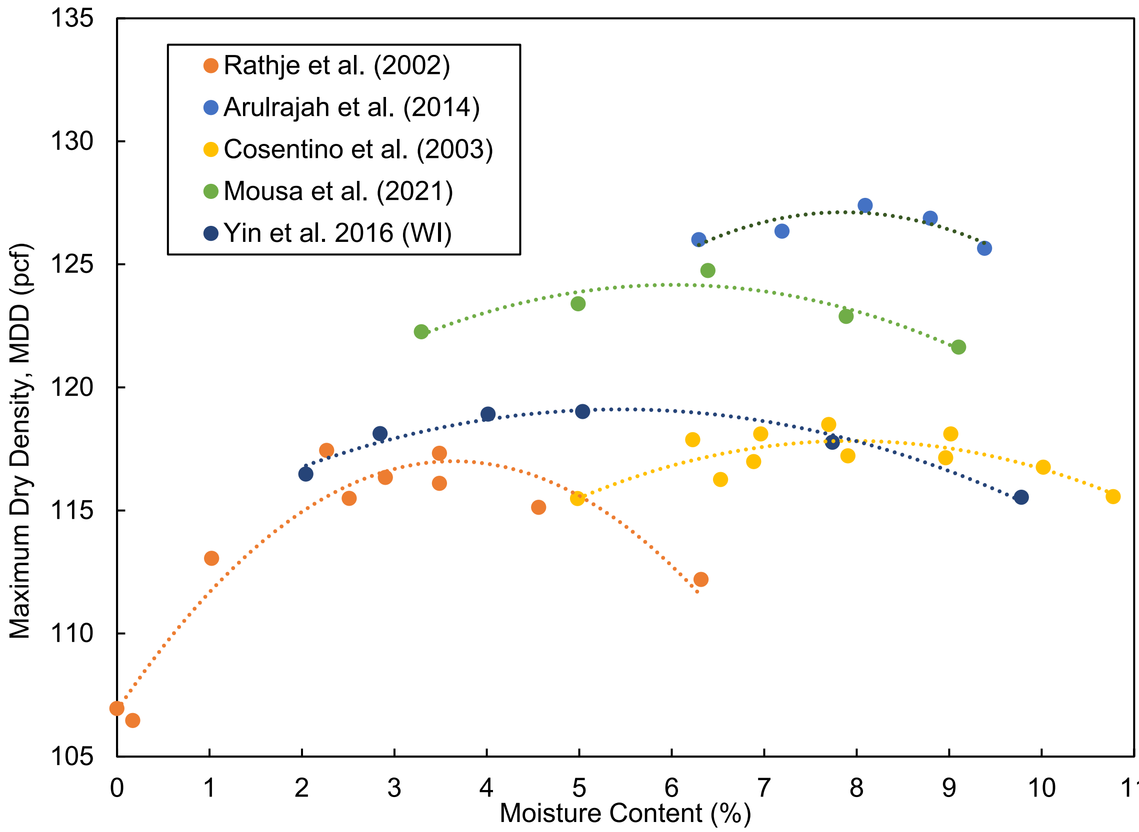


Figure 2.16 Compaction curves from different studies.

Additionally, the generation of fines after compaction is an important characteristic to evaluate. Low particle breakage characteristics is critical in embankment and fill applications because both applications require high drainage to prevent the build-up of particles that can cause long term stability issues. If significant amounts of fines are generated after the compaction of RAP, this would indicate that the material may not be suitable for embankment and fill construction. Results from literature indicate that there was no significant particle breakage after compaction. In Rathje et al. (2002), the increase in fines content was only 0.6%, which was less than the increase in fines content of 3.6% for other common coarse aggregate materials used in non-pavement applications.

2.3.4 Hydraulic Conductivity

The milling process and storage methods for RAP impacts the fines content, and correspondingly the saturated hydraulic conductivity (k_{sat}). Most of the literature for RAP utilized the constant head test (ASTM D2434) as it is most suitable for coarse-grained materials (ASTM 2022). Values of k_{sat} reported in the literature for RAP range from 2.0 x 10^{-4} cm/s to 1.5 x 10^{-1} cm/s (Arulrajah et al. 2013; Cosentino et al. 2003; Locander 2009; Mijic et al. 2020; Mousa et al. 2021; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012). This wide range of values can be attributed to both differences in laboratory testing methods and variability in the RAP particle sizes. All RAP from the literature was classified as free draining based on the Casagrande and Fadum (1940) requirement of a k_{sat} value greater than or equal to 1.0 x 10^{-4} cm/s. The results from six literature studies are provided in **Table 2.5**.

As previously mentioned, the use of free draining materials is important for embankment and fill applications to avoid long-term stability issues. In applications where backfill is being reinforced, such as in an MSE wall, if the backfill is not free draining there is corrosion potential for the metallic reinforcements (Rathje et al. 2002). Based on hydraulic conductivity information, RAP could be considered a viable option for use in embankment and backfill applications.

2.3.5 Leaching

There are environmental concerns regarding the leaching of contaminants from RAP. Contaminants within the leachate are highly variable, which can be attributed to many factors. Variability of RAP leachate arises due to the manufacturing of the original asphalt, the application of RAP, the exposure during its lifespan as a roadway material, and the RAP storage length (Herrara 2019).

Herrara (2019) collected data from eight sources throughout the world that conducted leaching tests on RAP. The report found that some of the studies detected concentrations that were above allowable limits set forth by the Washington State Groundwater Quality Standards (Herrera 2019). Batch tests from four of the eight studies found metals above Washington's allowable limits, with some concentrations slightly above the limit and other concentrations well above the limit (Morse et al. 2001; Kang et al. 2011; Seybou-Insa et al. 2021; Mehta et al. 2017). These metals consisted of arsenic, manganese, iron, and selenium. While the studies did find metal concentrations exceeding Washington's allowable limits, the exceedances occurred within the first flush of water through the RAP. The study concluded that the impact to the environment would be insignificant if RAP leachate was diluted and if soil assimilation occurred (Herrera 2019).

All metals that were tested in the Herrara (2019) study as well as additional literature studies were evaluated to determine which pollutants were most frequently tested during leaching investigations. A total of 10 studies were reviewed, with RAP being tested from multiple different sources. **Table 2.10** displays the totals from the literature ranked in order of most to least frequent tested, with bolded metals having exceeded state/federal MCL standards in at least one study.

Table 2.10 Chemical properties reported in the experimental RAP literature, and the number of studies that reported each property. Bolded parameters exceeded allowable limits in some studies (Cosentino et al. 2003; Herrera 2019; Kang et al. 2011; Morse et al. 2001; Shedivy et al. 2012).

Property or Species	Number of Sources
Cadmium (Cd)	8
Chromium (Cr)	8
Lead (Pb)	8
Electric Conductivity (EC)	8
pH	8
Copper (Cu)	**7**
Nickel (Ni)	7
Zinc (Zn)	**7**
Barium (Ba)	6
Aluminium (Al)	5
Arsenic (As)	**5**
Manganese (Mn)	**5**
Molybdenum (Mo)	5
Silver (Ag)	5
Iron (Fe)	4
Beryllium (Be)	3
Selenium (Se)	**3**
Magnesium (Mg)	3
Mercury (Mg)	2
Antimony (Sb)	2
Thallium (Tl)	2
Potassium (K)	1
Silicon (Si)	1

Based on the literature reviewed, it was found that leaching of metals does occur, however, it does not generally occur in levels significantly higher than applicable MCL standards (Birgisdottir et al. 2007; Brantley and Townsend 1999; Cosentino et al. 2003; Herrera 2019; Kang et al. 2011; Legret et al. 2005; Mehta et al. 2017; Mijic et al. 2020; Morse et al. 2001; Norin and Stromvall 2004; Seybou-Insa et al. 2021; Shedivy et al. 2012; Yang et al. 2020). If MCLs were exceeded, after a few pore volumes of flow were flushed through the RAP, the concentration levels dropped below the MCL standards (Mijic et al. 2020). In both Mijic et al. (2020) and Yang et al. (2020), when RAP leachates were permeated through natural soils, attenuation occurred and the contaminant concentrations dropped below EPA MCL standards. Additionally, it was found that the chemicals that leached out of RAP varied study-by-study. This would indicate that chemical composition of RAP is highly dependent on its source, use, and exposure over time. Yang et al. (2020) concluded that the reuse of RAP as an unbounded material was allowable in non-acidic environments. Literature suggests that RAP does not pose a major leaching threat, and it could be used in non-pavement applications if it is not placed in locations near sources of water. If RAP is to be placed near sources of water, natural soils should be utilized along the flow path to allow for the chemical attenuation of the leachate (Mijic et al. 2020; Yang et al. 2020).

Currently, the state of Pennsylvania has environmental restrictions on the use of RAP. The Pennsylvania Department of Environmental Protection (DEP) provides restrictions on the use of RAP in its Special Conditions General Permit WMGR101. The permit considers RAP a waste product, and sets limits on the quantity, storage, and uses of RAP. Due to leaching concerns, RAP is currently unable to be placed in contact with surface water or groundwater. It cannot be placed near a wetland or near private/public water sources. Additionally, runoff cannot cause surface water pollution or groundwater degradation (DEP 2020).

Guidelines for leachate testing of RAP are provided in the Pennsylvania DEP's Special Conditions General Permit WMGM022 (DEP 2022). The permit provides a list of chemicals and the maximum concentrations associated with them for RAP material being used in construction activities. **Table 2.11** provides the list of chemicals and the RAP leachate maximum concentrations.

Table 2.11 Maximum leachate concentrations per WMGM022 (DEP 2022).

List of Chemicals	Maximum Leachate Concentrations (mg/L)
Arsenic	1.25
Barium	50.0
Cadmium	0.125
Chromium	2.5
Copper	32.5
Lead	1.25
Mercury	0.05
Molybdenum	-
Zinc	125
Nickel	2.5
Selenium	1.0
Silver	2.5
Benzene	0.005
Ethylbenzene	0.7
Xylenes	10
Toluene	1.0

2.3.6 Shear Strength

Shear strength is typically evaluated in the laboratory using the direct shear and triaxial tests. Conventional direct shear devices are typically better suited to materials with smaller particle sizes, and due to the coarse-grained nature of RAP, triaxial testing has been more commonly used to evaluate shear strength in literature.

The results from literature indicate that RAP has a high friction angle which correlates to high shear strength, and most of the literature performed Consolidated Drained (CD) triaxial tests in accordance with ASTM D7181-20 (ASTM 2020). In general, the friction angles ranged from 42 - 45 degrees, with some outliers that were higher and lower (Arulrajah et al. 2013; Bennert and Maher 2005; Bejarano 2001; Cosentino et al. 2003; Ma et al. 2015; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002). The lowest friction angle that was evaluated was 37 degrees which was reported in Rathje et al. (2002) and Rahardjo et al. (2013); however, a friction angle of 37 degrees is still generally considered high strength.

The values of cohesion had more scatter, with most results showing some cohesion (Arulrajah et al. 2013; Bennert and Maher 2005; Cosentino et al. 2003; Ma et al. 2015; Mousa et al. 2021; Rathje et al. 2002) and Rahardjo et al. (2013) and Bejarano (2001) showing no cohesion. The variability in cohesion values is likely attributed to the asphalt binder content of the RAP, however, the values of cohesion from all of the literature studies were considered low (Cosentino et al. 2003; Rathje et al. 2002). Most tests did not display a distinct failure plane but instead it was observed that the specimens bulged radially during strain (Rathje et al. 2002). Shear strength and cohesion results from literature are shown in **Table 2.12** and a compilation of ranges of deviator stresses versus axial strain plots are plotted in **Figure 2.17**. At lower deviator stresses ranging from 0 to 1500 psf, the peak deviator stress was attained below 6% axial strain, and when the peak deviator stress was reached, the stress continually decreased. At higher deviator stresses ranging from 1500 to 7200 psf, the peak deviator stress was attained at 9% axial strain or higher, and the deviator stress leveled off and did not decrease significantly (Arulrajah et al. 2013; Cosentino et al. 2003; Rathje et al. 2002).

Table 2.12 Shear strength and cohesion values for RAP from literature.

Source	Test	Friction Angle (deg.)	Cohesion (psf)
Arulrajah et al. (2013)	Consolidated Drained	37	1107
Rathje et al. (2002)	Consolidated Drained	37	1153
Rahardjo et al. (2013)	Consolidated Drained	42	0
Cosentino et al. (2003)	Consolidated Drained	44	706
Bennert and Maher (2005)	Not Reported	44.5	359
Mousa et al. (2021)	Unconsolidated Undrained	39	2045
Ma et al. (2015)	Not Reported	49	2632
Bejanaro et al. (2001)	Consolidated Drained	52	0

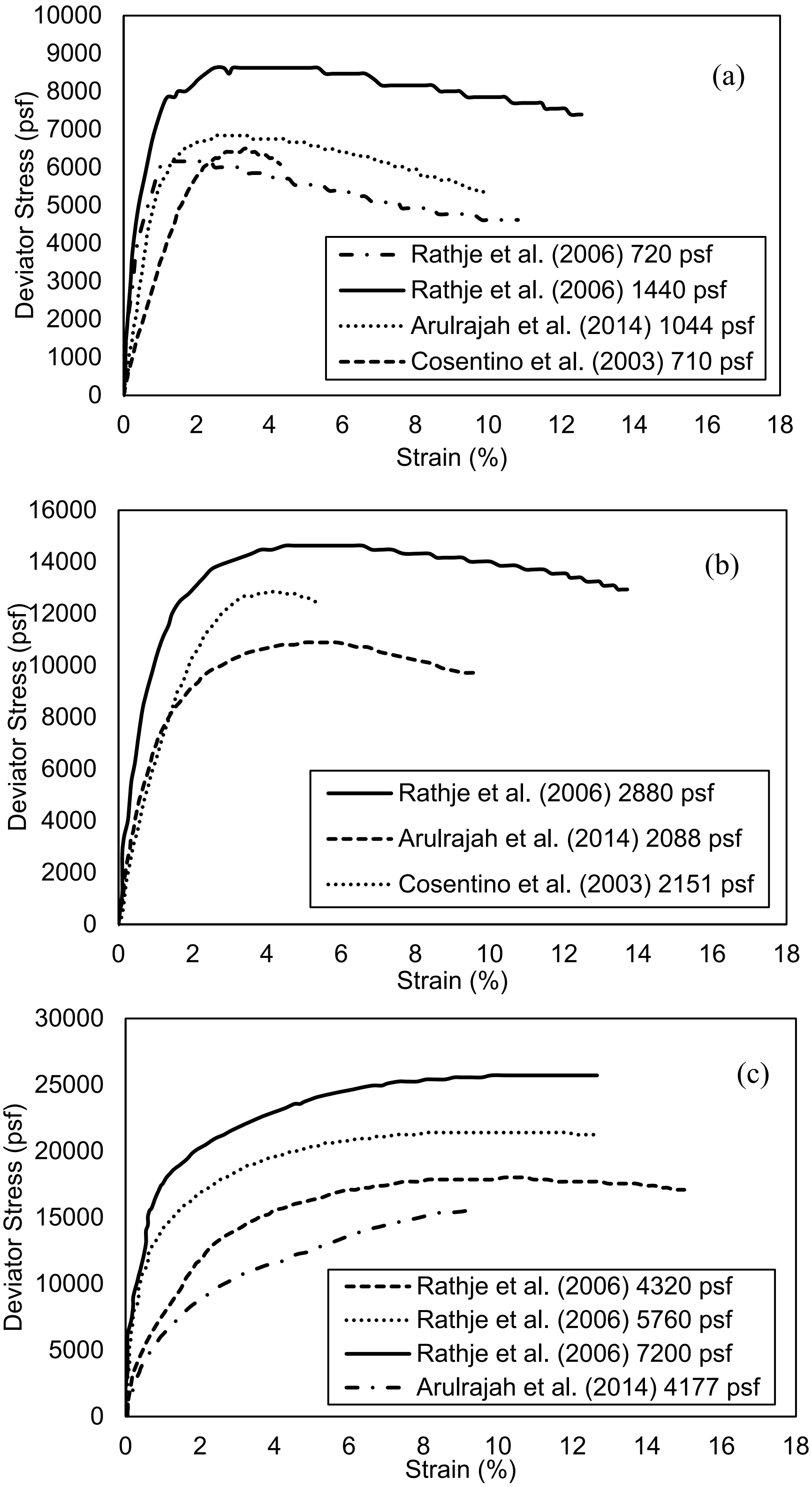


Figure 2.17 Deviator stress versus axial strain for RAP from the literature for (a) confining stress of 0 – 1500 psf, (b) confining stress of 1500 – 2900 psf, and (c) confining stress of 290 – 7200 psf.

It is generally accepted that coarse-grained materials have high strength characteristics and PennDOT Publication 408 states that coarse-aggregate material does not need to be tested for an angle of internal friction (PennDOT 2022). Based on the USCS classifications of RAP, all of the studies found that RAP is a coarse-grained material. This, paired with the high friction angles found from triaxial tests in literature, indicates that RAP has high strength characteristics. Based on literature, it can be concluded that RAP has adequate strength characteristics for use in non-pavement applications.

2.3.7 Creep

RAP has been found in several studies to creep at an excessive rate. In general, coarse aggregates typically do not display significant creep deformations leading to creep rupture (Cosentino et al. 2003). This, paired with having high shear strength characteristics make coarse aggregate materials ideal for fill applications. Although RAP is often found to have a relatively high shear strength and it is categorized as a coarse aggregate material, the presence of asphalt binder on the aggregate increases the materials compressibility, leading to significant creep deformations over time (Yin et al. 2017). This severely impairs RAP's potential to be used in non-pavement applications and all the studies evaluated found that the creep of RAP poses a significant problem (Bleakley and Cosentino 2012; Cleary 2005; Cosentino et al. 2003; Cosentino et al. 2008; Dikova 2006; Rathje et al. 2006; Thakur et al. 2013; Viyanant 2006; Viyanant et al. 2007; Yin et al. 2017; Yousefi et al. 2021).

When a material experiences creep, there are three distinct stages: Primary, secondary, and tertiary creep. Primary creep occurs immediately after stress is applied, where large amounts of strain are observed initially, however over time, the strain rate decreases (Viyanant 2006). Secondary creep is when the strain rate is at a minimum, and it remains constant (Viyanant 2006). Eventually, the strain rate will sharply increase, representing tertiary creep. The acceleration of the strain rate during tertiary creep indicates that creep rupture has occurred (Viyanant 2006). **Figure 2.18** shows the three stages of creep.

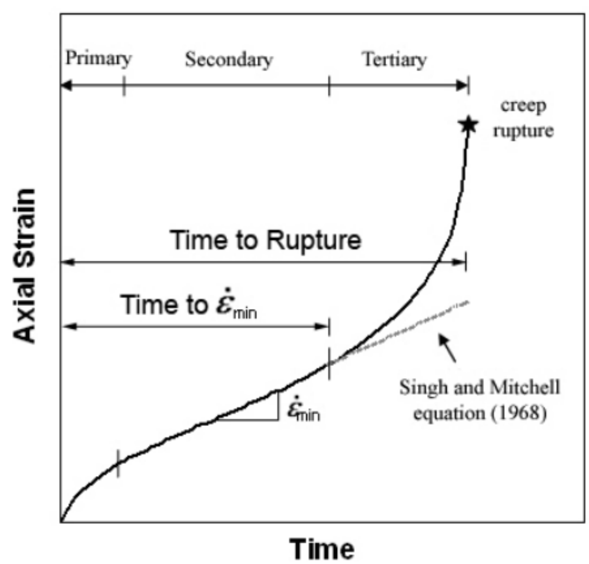


Figure 2.18 Three stages of creep (Viyanant 2006).

Singh and Mitchell (1968) developed an equation to model creep. The model evaluates only primary and secondary creep and it uses various deviator stresses to predict the strain rate of a soil. The Singh and Mitchell (1968) equation is provided below in **Equation 2.1**:

$$\dot{\varepsilon} = Ae^{\bar{\alpha}\bar{D}}\left(\frac{t_1}{t}\right)^m \qquad \textbf{(Equation 2.1)}$$

Where:

$\dot{\varepsilon}$ = strain rate
t_1 = reference time
t = time
$\bar{D}$ = deviator stress level
A = strain rate at time t_1 and $\bar{D} = 0$
m =absolute value of slope of a log (strain rate) versus log (time)
$\bar{\alpha}$ = slope of linear portion of plots between log (strain rate) versus deviator stress level, all points corresponding to the same time

For creep in RAP, the most significant variable from the Singh and Mitchell (1968) equation is the *m* value. The *m* value represents the slope of axial strain versus time data, and it provides a strong indication of creep potential. A *m* value larger than 1 indicates that RAP will reach an asymptotic strain value whereas a *m* value less than 1 will not achieve an asymptotic strain value and will experience a creep rupture (Viyanant 2006). Viyanant (2006) conducted CD triaxial tests at various percentages of the maximum deviator stress to achieve an *m* value The tests found *m* values ranging from 0.3 to 0.9, with an average *m* value of 0.7. The *m* value identified was less than 1, indicating that RAP has high creep susceptibility, and will eventually experience rupture. Additionally, Viyanant et al. (2007) observed that 3% axial strain was the limiting percentage of strain before creep rupture was observed

Thakur et al. (2013) investigated creep using plate loading tests. The researchers found that as the applied vertical stress on RAP was increased from 231 kPa to 462 kPa, the percent of axial creep strain was increased, indicating applications that experience high stresses may not be advisable for RAP. Cosentino et al. (2008) conducted 100% RAP tests at 6 psi, 12 psi, and 18 psi and found that the axial strains at 12 psi and 18 psi stresses exceeded the strain limitation of 3% identified by Viyanant et al. (2007). This indicates that at higher stresses, creep rupture is expected in RAP.

Because RAP is known to creep, different studies have assessed ways to improve upon RAP's creep effects. It has been predicted that RAP is temperature dependent due to its asphalt binder content, with high creep deformations likely at higher temperatures (Rathje et al. 2006). Yin et al. (2017) concluded that if RAP is compacted and consolidated at higher temperatures, creep deformations are reduced. It was recommended that if RAP is being used in structural fill applications, the construction activities should be done in the summer to reduce the amount of creep (Yin et al. 2017).

Another way to improve upon RAP's creep is to confine the material or incorporate geosynthetics into the design. Thakur et al. (2013) concluded that RAP crept more at lower degrees of confinement and incorporating geocell confinement into the design improved upon the RAP's creep tendencies. A few studies assessed blending RAP with other aggregate materials to improve upon its creep behavior. Cosentino et al. (2008) found that blending materials improved upon RAP's 50-year settlement values, with decreasing amounts of RAP corresponding to decreasing settlement. Additionally, Cosentino et al. (2008) estimated 50-year settlement values for a typical 20-foot high MSE wall and found that the total creep movement for a 20-foot high MSE wall constructed with 100% RAP was 27.8 inches. The total creep movement for the same wall constructed with 80% RAP was reduced to 13 inches.

Based on the literature reviewed, 100% RAP is not recommended for critical applications experiencing heavy loads. However, if certain steps are taken such as elevated compaction temperatures, adding confinement/geosynthetic reinforcement, and mixing RAP with other aggregates, the creep susceptibility can be reduced, and RAP could potentially be used in non-pavement applications.

2.4 Recent Developments and Challenges on RAP Reuse

Recently, researchers have evaluated the effects of elevated temperatures and aggregate mixing on the properties of RAP. Most notably, the effect that temperature and mixing have on creep susceptibility has been identified by various studies. Future directions for RAP research should evaluate the challenges associated with RAP variability, and the differences between geotechnical properties of unprocessed RAP and processed RAP.

2.4.1 Temperature Effects

Several studies have investigated the effect of temperature on the properties of RAP (Abedalqader et al. 2021; Soleimanbeigi and Edil 2015; Wen et al. 2022; Yin et al. 2017). RAP is susceptible to temperature changes due the bituminous binder coating the coarse aggregate (Wen et al. 2022; Yin et al. 2017). A study by Yin et al. (2017) evaluated the effect of thermal conditioning (i.e., elevated temperatures during construction) on embankment fill and backfill construction. The study found that when RAP was compacted and consolidated at elevated temperatures, void space was reduced after construction, which corresponded to a decrease in strain rate and creep susceptibility. It was concluded that when using RAP as embankment fill or backfill, the construction activities should take place in the summer to reduce compressibility, increase strength, and reduce creep (Yin et al. 2017).

A study by Wen et al. (2022) conduct compaction and consolidation tests at varying temperatures. The study found that as temperature was increased from 72°F (room temperature) to 100°F during compaction, the MDD values increased. It was concluded that this was due to asphalt binder being softer and more easily deformed as it was heated (Wen et al. 2022). One-dimensional consolidation tests were conducted on RAP that was compacted at room temperature, but consolidated at elevated temperatures. The RAP that was consolidated at higher temperatures exhibited higher settlements due to softer and more deformable binder (Wen et al. 2022). This would indicate that compacting RAP at higher temperatures improves upon compaction characteristics, but applying stresses to the RAP at higher temperatures has the opposite effect.

The testing in Yin et al. (2017) and Wen et al. (2022) was conducted at 35°C and 37.7°C which corresponds to 95°F and 100°F. As this relates to Pennsylvania District 6, in the summer months these temperatures are possible. This would indicate that the improved properties of RAP found at elevated temperatures in these studies can relate to field conditions in the state of Pennsylvania in the summer.

2.4.2 Mixtures

Many studies have investigated combining RAP with other aggregates to improve upon its properties (Cosentino et al. 2003; Cosentino et al. 2008; Cleary 2005; Dikova 2006; Kalpacki et al. 2018; Mousa and Mousa 2017; Wen et al. 2022). The most common material that RAP is blended with is sand. Reports found that mixing RAP with other aggregates altered characteristics such as gradation, compaction, hydraulic conductivity, strength, and creep. Cosentino et al. (2003) found that the addition of sand improved upon density, bearing strength, and stiffness, while permeability was decreased as the fines content was increased. It was found that an 80% RAP – 20% soil mixture provided the best strength properties, maintained an acceptable hydraulic conductivity, and reduced creep significantly (Cosentino et al. 2003). Studies by Kalpacki et al. (2018) and Mousa and Mousa (2017) found that a 50% RAP-50% sand blend provided the highest MDD and was the ideal RAP-soil mixture for improving upon compaction. The differences in the ideal mixture percentages from these studies is likely attributed to variability of RAP.

For use in the state of Pennsylvania, RAP-soil mixtures would be beneficial in allowing RAP to meet the gradation requirements for certain applications set forth by Publication 408. As discussed in **Section 2.2.1**, many of the applications of interest require an adjustment of the RAP gradation in order to be within the required gradation envelope. By selecting an aggregate material of a grain-size appropriate to the application, mixing the aggregate with RAP can allow for the blend to meet gradation requirements without drastically altering other properties such as compaction and strength.

Further, creating RAP-soil mixtures improves upon creep characteristics. Of all the geotechnical properties evaluated, creep is the most limiting factor for RAP’s use non-pavement applications. Cosentino et al. (2003) found that creating a RAP-soil mixture did reduce creep significantly. Creating a mixture could be a potential solution to RAP’s susceptibility to creep, and this could allow for a wider range of RAP uses.

When selecting an aggregate material to blend with RAP, it is important to note that if a finer gradation is created, this can negatively affect the hydraulic conductivity of mixture (Cosentino et al. 2003). In fill applications, it is important that the material remains free draining to prevent the buildup of pressures that can cause failure. When finer material is added, this reduces the hydraulic conductivity and this can ultimately cause a reduction in the beneficial drainage properties associated with coarse-grained backfill. This should be kept in mind when moving forward with RAP-soil blends.

2.4.3 Challenges

The review of literature identified challenges associated with the reuse of RAP in non-pavement applications. Those challenges include variability and the differences between processed and unprocessed RAP.

2.4.3.1 Variability

In the future, certain challenges regarding the use of RAP must be addressed. Studies by Gao et al. (2021) and Zhou et al. (2010) concluded that RAP varies significantly by source. Limiting the variability of RAP is critical because it provides confidence in engineering design. Understanding material behavior helps to ensure safety and longevity in design. The variability of RAP poses a challenge moving forward as new applications of RAP reuse are explored. Developing guidelines and standards for the stockpiling, processing, and geotechnical properties would be beneficial in the future to limit the inconsistency of RAP.

2.4.3.2 Unprocessed RAP

An additional challenge associated with the reuse of RAP is the lack of literature on unprocessed RAP. The overwhelming majority of studies in literature have evaluated processed RAP due to its commonality in recycled asphalt mixtures. The processing procedure most likely alters some of the properties of RAP, therefore it is likely that unprocessed RAP may behave differently than processed RAP. Additionally, the larger particle-sizes of unprocessed RAP are difficult to evaluate in the laboratory. In applications where unprocessed RAP may be suitable, it is critical that further research is conducted on how unprocessed RAP’s properties vary from processed RAP.

While research has not focused on unprocessed RAP, the takeaways from the literature studies on processed RAP can be used to hypothesize the performance of unprocessed RAP in the applications of interest. Based on the studies, processed RAP displays high shear strength, high compaction ability, and high drainage capabilities all of which are desirable in embankment and fill applications. It is unlikely that the properties of unprocessed RAP would vary significantly from processed RAP because most coarse-grained materials generally display these characteristics. Similarly, processed RAP and unprocessed RAP are the same material with the same chemical composition, with the only difference being the particle size, therefore leaching characteristics are likely unchanged. For processed RAP, creep is the property that is of most concern, and a high creep susceptibility is associated with the compressibility of asphalt binder. The asphalt binder in unprocessed RAP is likely to be a concern, therefore it is expected that excessive creep would also pose problems in unprocessed RAP. Additional research is needed to corroborate these hypotheses, and to develop a better understanding of the differences between processed and unprocessed RAP.

2.5 Literature Summary and Conclusions

Several conclusions can be made from the literature that was reviewed. These conclusions are important because they helped to identify the properties of RAP that may be limiting the use of RAP in non-pavement applications, and they provided a roadmap for the District 6 experimental testing program conducted by the Villanova research team. The conclusions from the literature reviewed are listed below:

Gradation - RAP from literature either fell within the required coarse aggregate gradations set forth by PennDOT Publication 408 or with gradation adjustment would meet the required standards. Scalping RAP or combining RAP with other aggregate materials would be a simple and cost-effective solution to adjust RAP gradations to be within the allowable limits for use in non-pavement applications (Abedalqader et al. 2021; Arulrajah et al. 2013; Bejarano 2001; Bennert and Maher 2005; Cooley 2005; Cleary 2005; Cosentino et al. 2003; Gao et al. 2021; Hajj et al. 2012; Kalpacki et al. 2018; Locander 2009; Ma et al. 2015; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Solaimanian et al. 2011; Thakur et al. 2013; Titi et al. 2019; Yin et al. 2017; Yousefi et al. 2021; Zhou et al. 2010).

Specific Gravity - RAP has a lower specific gravity than typical aggregate materials. The range of specific gravity values of RAP from the literature examined was 2.25 to 2.77, with an average value of 2.43. These values are lower than the typical assumed values of 2.60 - 2.70 for soils and aggregates. The lower specific gravity value for RAP is most likely due to the bitumen coating around the aggregate, however, lower specific gravity values do not seem to significantly impact the use of RAP in non-pavement applications (Abedalqader et al. 2021; Cooley 2005; Cosentino et al. 2003; Hajj et al. 2012; Locander 2009;; Mijic et al. 2020; Mousa et al. 2021; Yousefi et al. 2021; Rahardio et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012; Thakur et al. 2013; Titi et al. 2019).

Maximum Dry Density/Optimum Moisture Content – RAP has a relatively flat compaction curve which is common for coarse-grained materials. The MDD's from literature ranged from 109 pcf to 131 pcf, with an average of 122 pcf. The OMC ranged from 3% to 8%. Both the MDD and OMC values fall within the typical RAP property range provided by the FHWA (2016). It was also found that no significant particle breakage was observed after compaction. This allows for free drainage to be maintained within the compacted RAP, making it suitable for embankment and fill applications (Arulrajah et al. 2013; Bejarano 2001; Cooley 2005; Cosentino et al. 2003; Kalpacki et al. 2018; Locander 2009; Mijic et al. 2020; Mousa and Mousa 2017; Mousa et al. 2021; Rahardio et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012; Soleimanbeigi an Edil 2015; Thakur et al. 2013).

Hydraulic Conductivity – RAP has high k_{sat} values ranging from 2.0 x 10^{-4} cm/s to 1.5 x 10^{-1} cm/s, which corresponds to high drainage capabilities. Embankment fill and backfill applications require free drainage to prevent the buildup of pressure. The high hydraulic conductivity of RAP makes it a good candidate for use in these applications (Arulrajah et al. 2013; Cosentino et al. 2003; Locander 2009; Mijic et al. 2020; Mousa et al. 2021; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012).

Leaching – Literature suggests that RAP does not pose a major leaching threat, however, a few studies found that RAP leached metals over the required MCL's set by the EPA. When this occurred, the metal concentrations quickly dropped below the MCL's after a few pore volumes of flow or after the leachate was run through soil. Because of this, it is possible that RAP could be used as embankment material or fill material if it is not placed in locations near sources of water. If RAP is to be placed near sources of water, natural soils should be utilized along the flow path to allow for the chemical attenuation of the leachate (Birgisdottir et al. 2007; Brantley and Townsend 1999; Cosentino et al. 2003; Herrera 2019; Kang et al. 2011; Legret et al. 2005; Mehta et al. 2017; Mijic et al. 2020; Morse et al. 2001; Norin and Stromvall 2004; Seybou-Insa et al. 2021; Shedivy et al. 2012; Yang et al. 2020).

Shear Strength – The results from literature indicate that RAP has a high friction angle which corresponds to high shear strength. High shear strength is common for coarse-grained materials. Most of the literature performed CD triaxial tests, and the friction angles ranged from 42-45 degrees with a few outliers. The high shear strength properties of RAP indicate that it could be used in non-pavement applications (Arulrajah et al. 2013; Bennert and Maher 2005; Bejarano 2001; Cosentino et al. 2003; Ma et al. 2015; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002).

Creep – RAP is likely to pose problems associated with creep. The low *m* values of RAP found in literature suggest that RAP is highly susceptible to creep. Without modification, RAP is not suggested to be used in structural fill applications. Adjustments to RAP such as mixing with soil, adding geosynthetic reinforcement, and increasing temperatures during construction are possible mitigation measures to reduce creep in RAP. Further research is needed on reducing the creep susceptibility of RAP (Bleakley and Cosentino 2012; Cleary 2005; Cosentino et al. 2003; Cosentino et al. 2008; Dikova 2006; Rathje et al. 2006; Thakur et al. 2013; Viyanant 2006; Viyanant et al. 2007; Yin et al. 2017; Yousefi et al. 2021).

Temperature Effects – Elevating the temperature of RAP during compaction and consolidation can increase the stiffness and strength of RAP. Additionally, if higher temperatures are introduced to RAP during the construction phase, strain rates and creep susceptibility are reduced. If RAP is being used in structural fill applications, it is suggested that construction activities take place during the summer months (Abedalqader et al. 2021; Soleimanbeigi and Edil 2015; Wen et al. 2022; Yin et al. 2017).

Mixtures – Utilizing RAP-aggregate mixtures would be beneficial in allowing RAP to meet the gradation requirements for embankment or fill applications. Mixtures also have been found to improve upon the creep characteristics of RAP and tend to increase the MDD (Cosentino et al. 2003; Cosentino et al. 2008; Cleary 2005; Dikova 2006; Kalpacki et al. 2018; Mousa and Mousa 2017; Wen et al. 2022).

It is important to note that most of the RAP studied in literature was processed (i.e., crushed down to a smaller particle size). Literature is sparse for performance and the properties of unprocessed RAP. This is primarily because of the commonality of RAP being used for HMA/WMA mixtures which requires the particle sizes of RAP to be smaller. Further study on unprocessed RAP would be beneficial due to the cost-savings associated with eliminating the processing procedure.

Additionally, further study on the variability of RAP is recommended. Many literature studies found that RAP was highly variable, and this was most likely attributed to the processing, exposure, and stockpiling of the material. In PennDOT (2020), PennDOT specifically lists the variability of RAP as an unresolved issue. Further study on the variability of RAP would be beneficial to gain a better understanding of how the properties of RAP change state-by-state and source-by-source.

3. LABORATORY TESTING FOR DISTRICT 6 RAP

3.1 Introduction

This chapter provides a comprehensive laboratory investigation for the geotechnical properties of RAP. The laboratory testing program included the evaluation of hydraulic conductivity, shear strength, compaction, leaching, and most importantly creep behavior of the RAP and RAP mixtures with aggregate (No. 57 Stone and Bar Sand). The effects of temperature were evaluated on RAP that was compacted to a temperature of 35°C (95°C), and these results are also included in the testing program. In addition, standard geotechnical classification testing was performed to thoroughly characterize RAP and RAP mixtures (e.g., particle-size distribution and specific gravity). Both the RAP and the RAP mixtures were compared with typical materials used for retaining walls and other transportation infrastructure.

3.2. Test Materials

Six sources of RAP from throughout Pennsylvania's District 6 were obtained for this study. The sources of RAP were named based on the company that supplied the RAP or the location that the RAP was sampled from. The RAP used for this study included: Malvern, Erie, Highway Materials, Delaware Valley Asphalt, Glasgow, and Glen Mills.

3.2.1 Sources of Test Materials

Ten bags of the Malvern RAP were obtained on July 8, 2021 from Allan Myers Material Headquarters in Malvern, Pennsylvania. Eight buckets of the Erie Ave RAP were sampled on June 15, 2021 from a bridge embankment construction project on Erie Avenue in Philadelphia, Pennsylvania. An additional 2 buckets and 5 bags were sampled on October 22, 2021. Six bags of the Highway Materials RAP were obtained on October 29, 2021 from the Highway Materials Asphalt Plant in Plymouth Meeting, Pennsylvania. Six bags of the Delaware Valley Asphalt RAP were obtained on October 29, 2021 from the Delaware Valley Asphalt Plant in Philadelphia, Pennsylvania. And finally, six bags of the Glasgow RAP were obtained on October 29, 2021 from the Bridgeport Asphalt Plant at the McCoy Quarry in King of Prussia, Pennsylvania.

Previously, the Villanova team had conducted research on Glen Mills RAP, and results from that testing series are included in this report. Five bags of RAP were obtained in September 2017 from Hanson Aggregates in Glen Mills, Pennsylvania. An additional eight bags were collected in April 2018 along with another two bags collected that June. In 2020, ten more bags of Glen Mills RAP were collected. Individual photos of the six sources of District 6 RAP are shown in **Figure 3.1** and the locations of the sources of RAP within Pennsylvania's District 6 are shown in **Figure 3.2**.

Figure 3.1 Photos of the five sources of District 6 RAP provided by PennDOT.

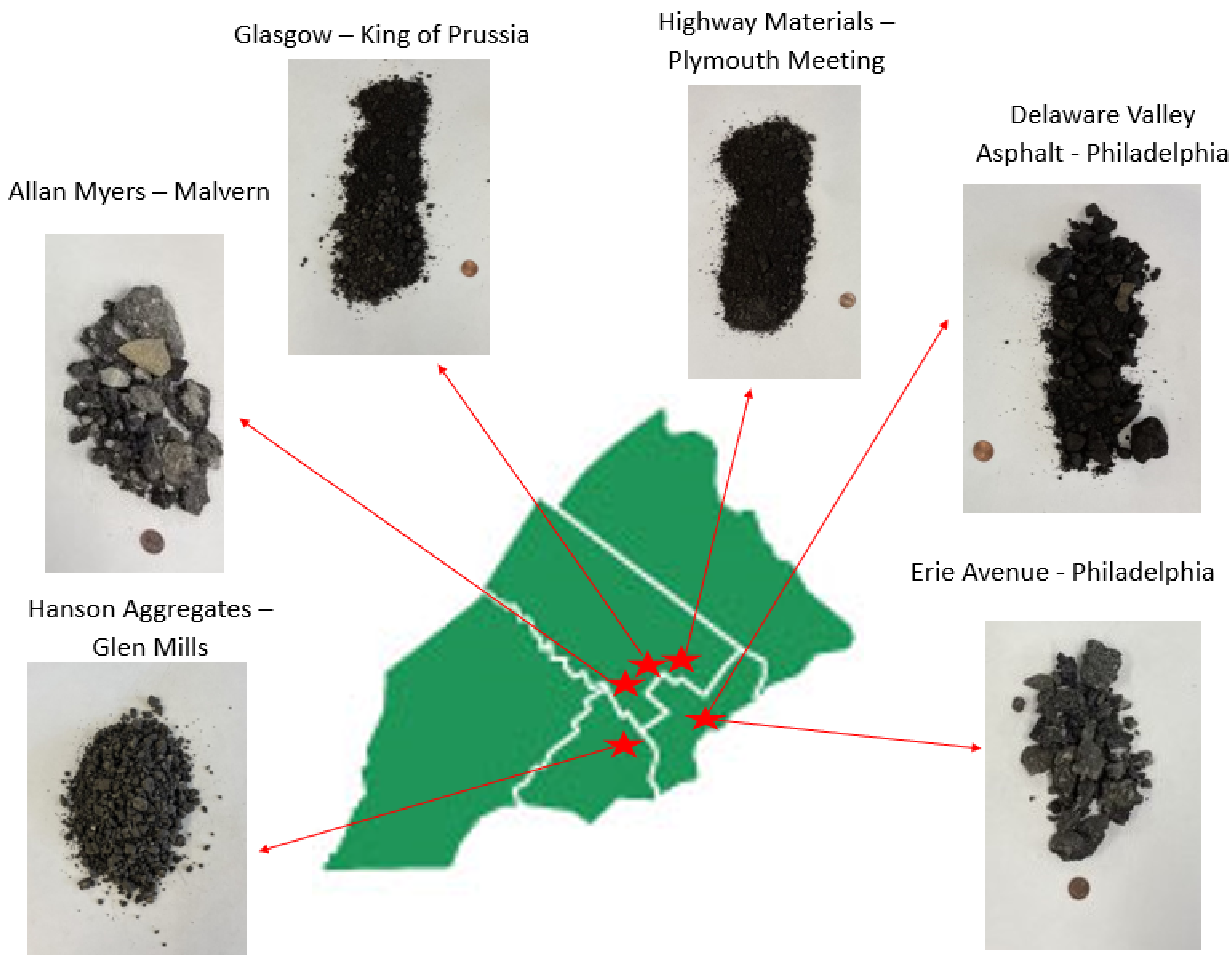


Figure 3.2 Photos and the locations of the six sources of District 6 RAP.

3.2.2 Unprocessed and Processed RAP

Based on the literature review that was conducted, it was determined that two types of RAP are generated: unprocessed and processed. The initial roadway milling creates RAP of variable size, with some RAP particles exceeding 2 inches in size. The RAP in this initial state is considered unprocessed. Once roadway milling is complete and unprocessed RAP is created, RAP can be further processed (i.e., screened, crushed, and ground down) to the desired particle size. This RAP is considered processed, and it is more frequently generated due to its commonality in recycled asphalt mixtures.

The six sources of RAP were categorized as either unprocessed or processed, as shown in **Table 3.1**. Malvern, Erie, and Delaware Valley Asphalt are unprocessed, with maximum particle sizes of larger than 1 inch. Highway Materials, Glasgow and Glen Mills RAP are processed, with maximum particle sizes less than 1/2 inch. Laboratory testing was conducted on all sources of RAP, however, in some instances, the unprocessed RAP sources were scalped. This was done to avoid violating experimental particle-size criteria for certain laboratory tests. If scalping was conducted, it was identified in the appropriate sections of this report.

Table 3.1 Sources of RAP categorized as unprocessed or processed.

Source	Category	Maximum Particle Size (in)
Malvern	Unprocessed	$\geq$2
Erie	Unprocessed	$\geq$2
Highway Materials	Processed	1/2
Delaware Valley Asphalt	Unprocessed	$\geq$2
Glasgow	Processed	1/2
Glen Mills	Processed	1/2

3.3 Index Properties

The index properties of RAP are used for the identification and classification of the material. These properties provide an indication of the general engineering characteristics of a material. For this study, the index properties investigated were gradation and specific gravity.

3.3.1 Gradation

The gradation of RAP is used to identify key characteristics such as percentage of fines, the grain size diameters corresponding to a specific percentage passing (D_{60}, D_{30}, D_{10}), the coefficient of curvature (C_c), and the coefficient of uniformity (C_u). These properties provide an indication of material performance in engineering applications and help to identify trends between different sources of materials. The gradation of RAP is highly dependent upon how the RAP was processed, and the processing size is based upon the desired application of RAP.

3.3.1.1 Methods

The gradation of RAP was determined by conducting a sieve analysis in accordance with ASTM C136 (ASTM 2019). RAP was taken out of storage bags and placed in trays overnight for air drying prior to running the sieve analysis. After air drying, the required sample size was determined to be 2000 grams based on the nominal maximum size of ½ inches. It is important to note that some sources of RAP had a nominal maximum size of larger than ½ inches, however, only a small percentage of that RAP was larger than ½ inch, therefore a 2000-gram sample was deemed sufficient for all sources of RAP. The RAP was placed onto a stack of sieves of the following sizes: 2-inch, 1 1/2-inch, 1 inch, 1/2-inch, 3/8-inch, 5/16-inch, 1/4-inch, #4, #10, #20, #40, #100, and the #200. For the sieve seizes ranging from 2 inches to ¼ inches, the analysis was conducted by hand shaking, whereas a mechanical sieve shaker was used for the sieve sizes ranging from #4 to #200. **Figure 3.3** shows the equipment used for the gradation analysis. Following the sieve testing, particle-size distribution curves were developed to understand the gradation properties of each material

Figure 3.3 Equipment used for gradation analysis: (a) sieve shaker (b) sieve stacks (Morro 2021).

3.3.1.2 Results

For the Malvern RAP, 29 sieve analyses were conducted, and the results from those analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.1** shows the average percent of material retained on each sieve from the 29 sieve analyses, and **Figure 3.4** shows the particle-size distribution curve of the Malvern RAP.

Table 3.1 Gradation of Malvern RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	99%
1-1/2"	37.5	99%
1"	25	96%
3/4"	19	88%
1/2"	12.5	68%
3/8"	9.5	52%
5/16"	8	44%
1/4"	6.3	33%
4	4.75	24%
10	2	9%
20	0.85	4%
40	0.425	2%
100	0.15	1%
200	0.075	0.6%
Pan	-	0%

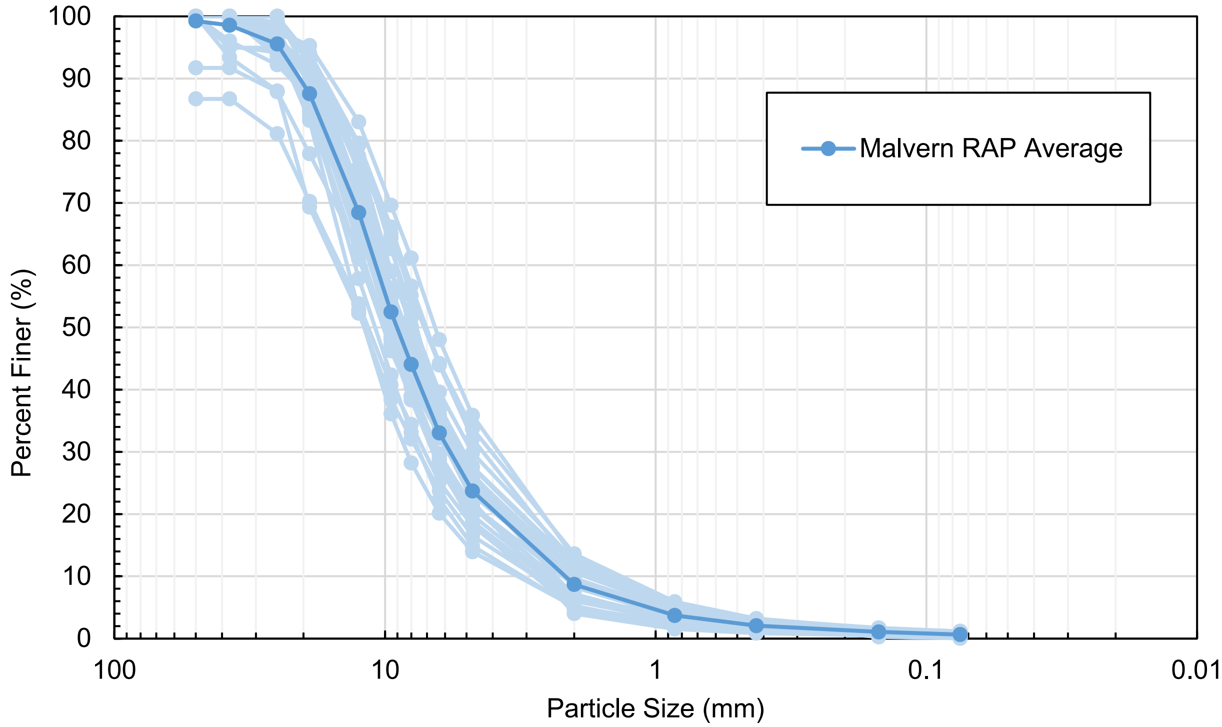


Figure 3.4 Particle-size distribution curves for Malvern RAP.

For the Erie RAP, a total of 24 sieve analyses were conducted, with 15 analyses coming from the first site visit, and 9 analyses coming from the second site visit. The results from all the analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.2** shows the average percent of material retained on each sieve from the 24 sieve analyses, and **Figure 3.5** shows the particle-size distribution curve of the Erie RAP.

Table 3.2 Gradation of Erie RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	98%
1-1/2"	37.5	95%
1"	25	86%
3/4"	19	73%
1/2"	12.5	56%
3/8"	9.5	44%
5/16"	8	39%
1/4"	6.3	31%
4	4.75	25%
10	2	12%
20	0.85	5%
40	0.425	2%
100	0.15	1%
200	0.075	0.3%
Pan	-	0%

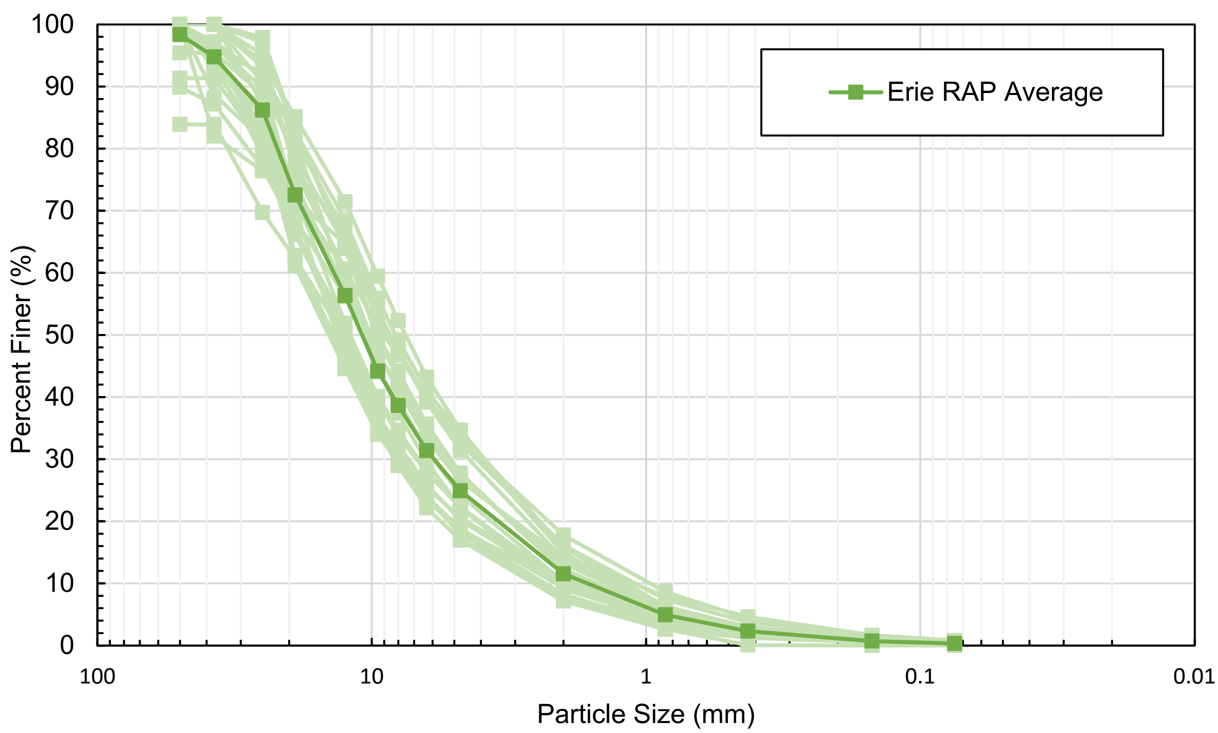


Figure 3.5 Particle-size distribution curves for Erie RAP.

For the Highway Materials RAP, a total of 9 sieve analyses were conducted, and the results from all the analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.3** shows the average percent of material retained on each sieve from the 9 sieve analyses, and **Figure 3.6** shows the particle-size distribution curve of the Highway Materials RAP.

Table 3.3 Gradation of Highway Materials RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	100%
1-1/2"	37.5	100%
1"	25	100%
3/4"	19	100%
1/2"	12.5	100%
3/8"	9.5	94%
5/16"	8	87%
1/4"	6.3	75%
4	4.75	65%
10	2	36%
20	0.85	18%
40	0.425	9%
100	0.15	2%
200	0.075	0.2%
Pan	-	0%

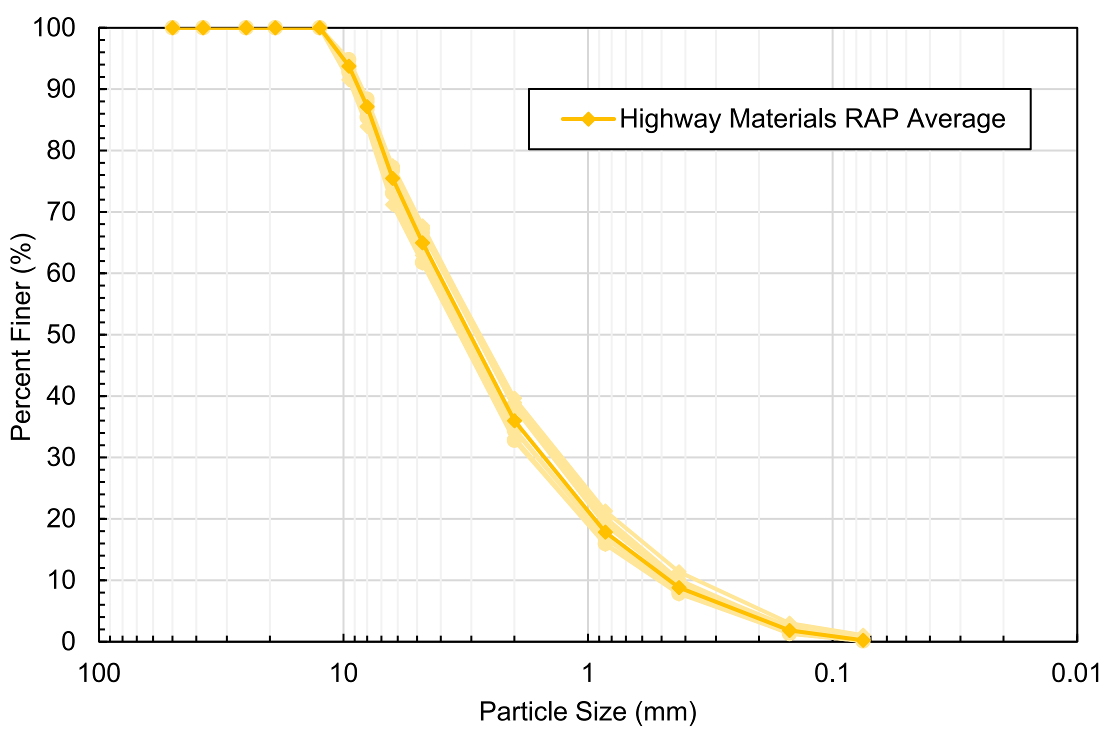


Figure 3.6 Particle-size distribution curves for Highway Materials RAP.

For the Delaware Valley Asphalt RAP, a total of 9 sieve analyses were conducted, and the results from all the analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.4** shows the average percent of material retained on each sieve from the 9 sieve analyses, and **Figure 3.7** shows the particle-size distribution curve of the Delaware Valley Asphalt RAP.

Table 3.4 Gradation of Delaware Valley Asphalt RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	96%
1-1/2"	37.5	91%
1"	25	86%
3/4"	19	79%
1/2"	12.5	68%
3/8"	9.5	57%
5/16"	8	51%
1/4"	6.3	43%
4	4.75	36%
10	2	19%
20	0.85	10%
40	0.425	5%
100	0.15	1%
200	0.075	0.2%
Pan	-	0%

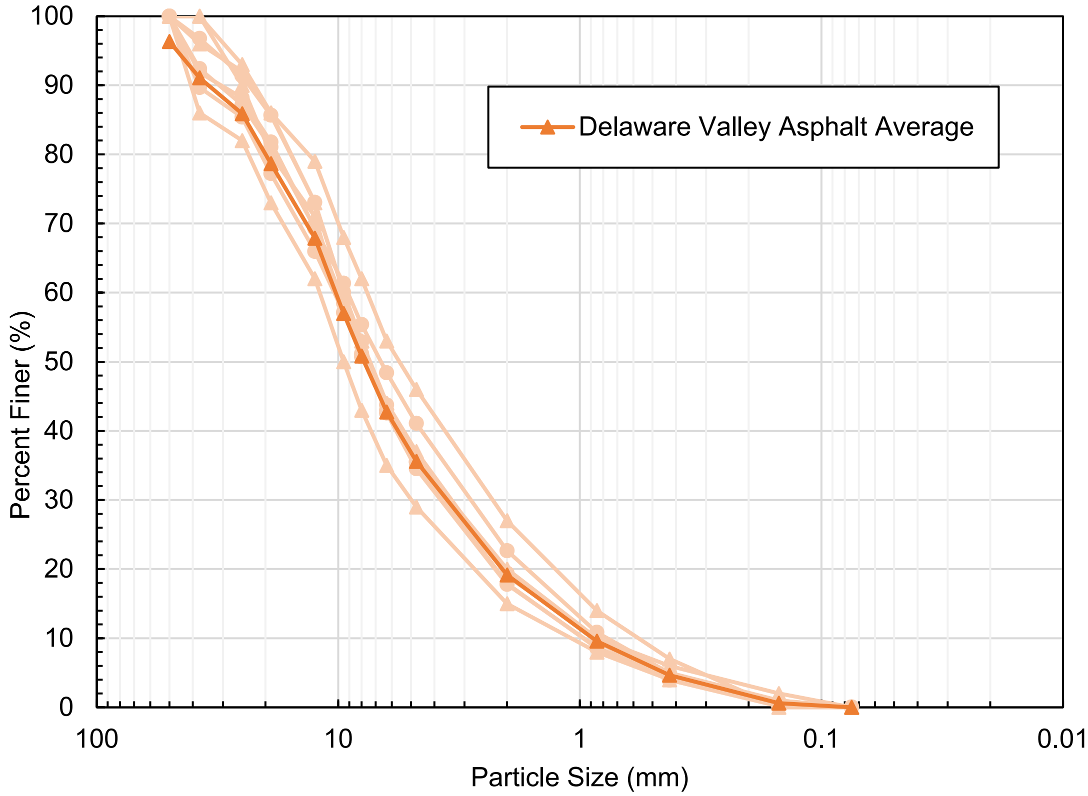


Figure 3.7 Particle-size distribution curves for Delaware Valley Asphalt RAP.

For the Glasgow RAP, a total of 10 sieve analyses were conducted, and the results from all the analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.5** shows the average percent of material retained on each sieve from the 10 sieve analyses, and **Figure 3.8** shows the particle-size distribution curve of the Glasgow RAP.

Table 3.5 Gradation of Glasgow RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	100%
1-1/2"	37.5	100%
1"	25	100%
3/4"	19	100%
1/2"	12.5	100%
3/8"	9.5	94%
5/16"	8	85%
1/4"	6.3	71%
4	4.75	60%
10	2	33%
20	0.85	17%
40	0.425	9%
100	0.15	3%
200	0.075	0.7%
Pan	-	0%

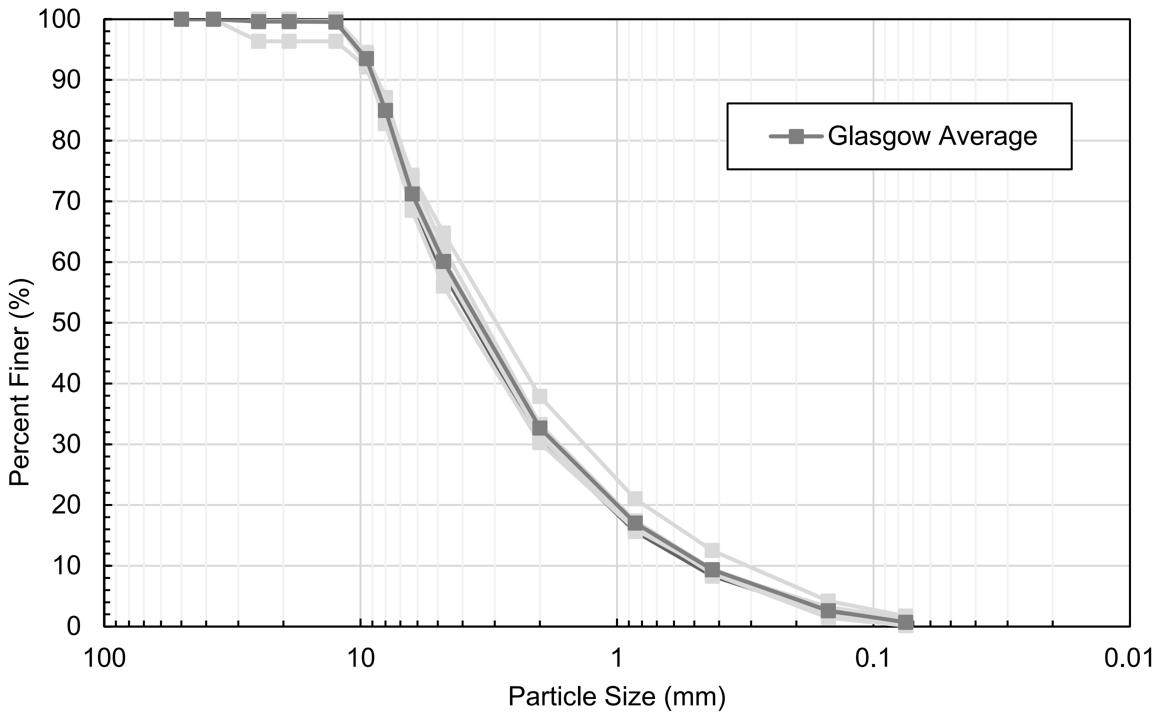


Figure 3.8 Particle-size distribution curves for Glasgow RAP.

For the Glen Mills RAP, a total of 30 sieve analyses were conducted, and the results from all the analyses were averaged together to develop the particle-size distribution curve of the material. **Table 3.6** shows the average percent of material retained on each sieve from the 30 sieve analyses, and **Figure 3.9** shows the particle-size distribution curve of the Glen Mills RAP.

Table 3.6 Gradation of Glen Mills RAP.

Sieve	Sieve opening size (mm)	Percent Passing
2"	50	100%
1-1/2"	37.5	100%
1"	25	100%
3/4"	19	100%
1/2"	12.5	100%
3/8"	9.5	91%
5/16"	8	82%
1/4"	6.3	70%
4	4.75	58%
10	2	31%
20	0.85	16%
40	0.425	8%
100	0.15	2%
200	0.075	0.7%
Pan	-	0%

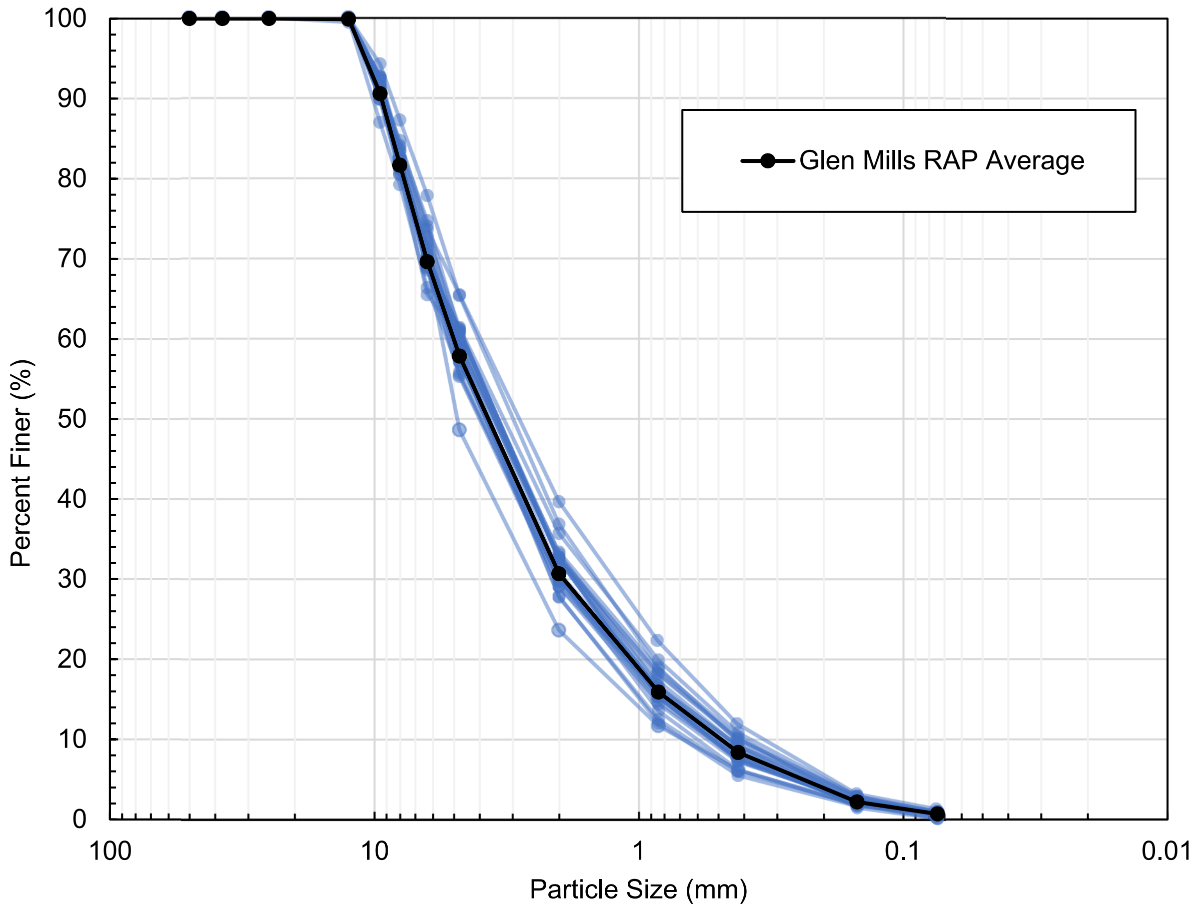


Figure 3.9 Particle-size distribution curves for Glen Mills RAP.

Based on the particle-size distribution curves, typical gradation properties were identified. The nominal maximum particle size is critical in evaluating the processing procedure of the RAP, and its potential uses moving forward. The percentage of fines provides an indication of how the RAP will behave in applications where free drainage is important. The values of D_{60}, D_{30}, and D_{10} are used to calculate C_c and C_u, which gives an indication of how well-graded the RAP is. The gradation properties of all the sources of RAP are summarized in **Table 3.7**.

Table 3.7 Average gradation properties of all the sources of RAP.

RAP Source	Malvern	Erie	Highway Materials	Delaware Valley Asphalt	Glasgow	Glen Mills
Nominal Max. Particle Size	2 in	2 in	1/2 in	2 in	1/2 in	1/2 in
Percent Fines	0.6%	0.3%	0.2%	0.2%	0.7%	0.7%
D_{60}	10.1 mm	15 mm	4.0 mm	10.0 mm	5.1 mm	4.8 mm
D_{30}	5.9 mm	6.3 mm	1.5 mm	3.5 mm	1.8 mm	1.9 mm
D_{10}	2.2 mm	1.6 mm	0.46 mm	0.85 mm	0.45 mm	0.52 mm
C_c	1.6	1.7	1.2	1.4	1.5	1.4
C_u	4.6	9.4	8.7	11.8	10.6	9.8

The particle-size distribution curves from all the sources of RAP were compiled to evaluate the different RAP sources. Variable gradations of the RAP from multiple sources can be explained by different milling processes, different desired applications, and different storage practices. The comparison of the particle-size distribution curves for all RAP sources is shown in **Figure 3.10**.

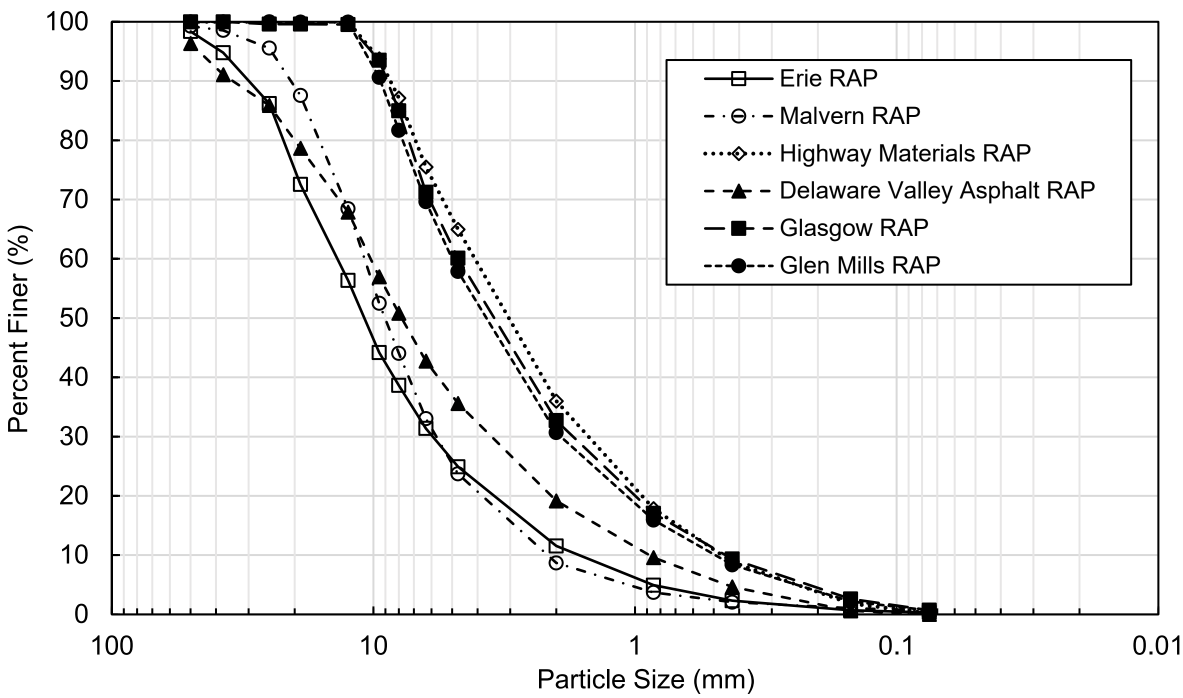


Figure 3.10 Gradation comparison for all sources of RAP.

As shown in **Figure 3.10**, while all sources have a similar curvature and are generally well-graded, there is a distinct difference in the particle sizes. The Malvern, Erie, and Delaware Valley Asphalt RAP are shifted left, indicating that overall the particle sizes are larger. These sources had a nominal maximum particle size of 2 inches whereas Highway Materials, Glasgow, and Glen Mills

RAP had a nominal maximum particle size of 1/2 inches. These differences can be attributed to the different milling proceses occuring for each source.

As previously mentioned, for certain applications, scalping of unprocessed RAP to a particle size of ½ inch was necessary. **Figures 3.11 - 3.13** show the particle size distributions of the scalped Malvern, Erie, and Delaware Valley Asphalt RAP. Table 3.8 provides the gradation properties of the scalped RAP.

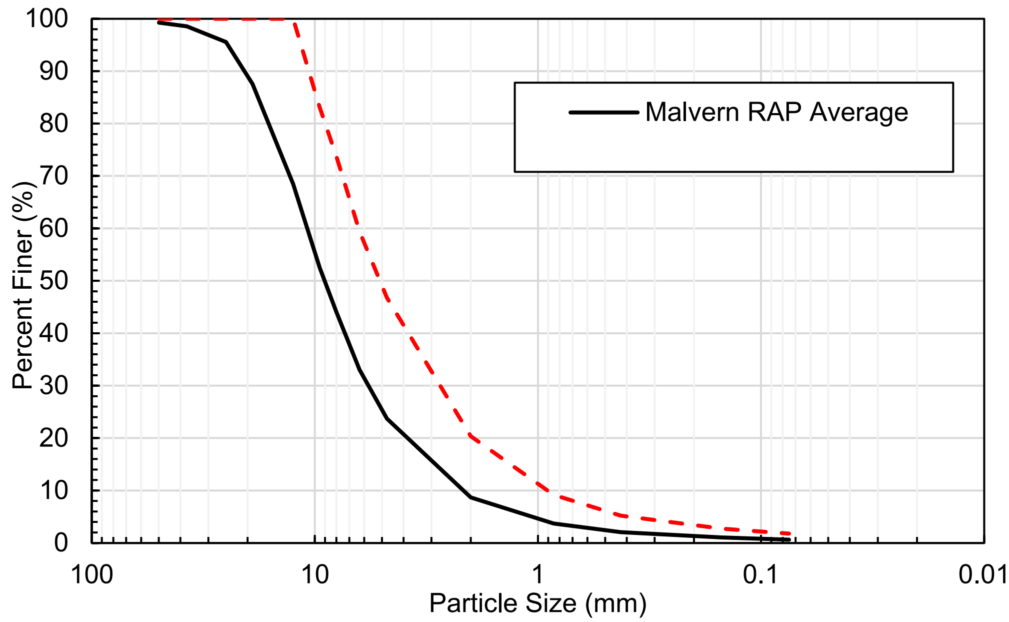


Figure 3.11 Scalping comparison for Malvern RAP.

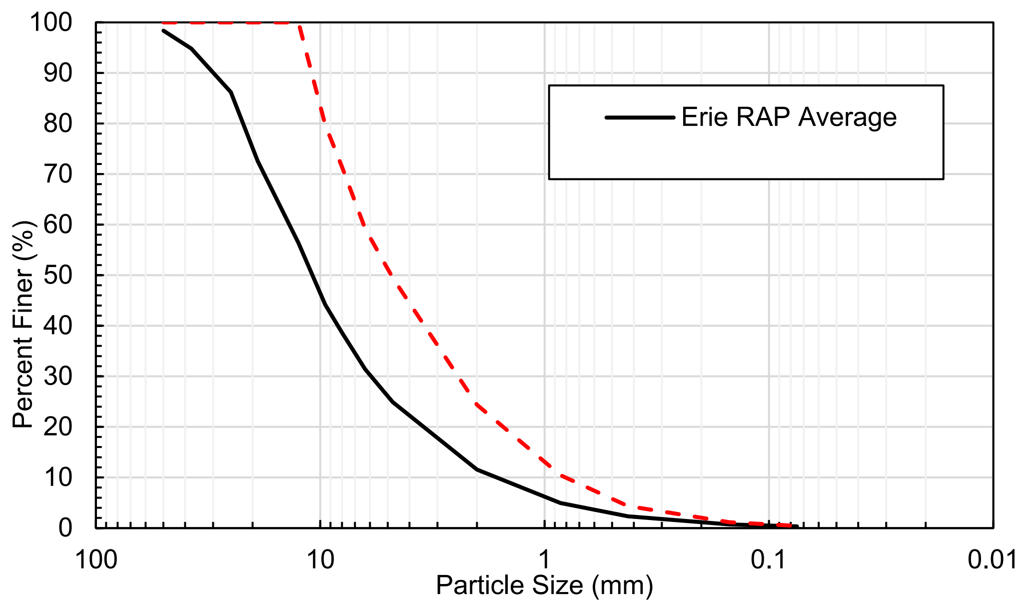


Figure 3.12 Scalping comparison for Erie RAP.

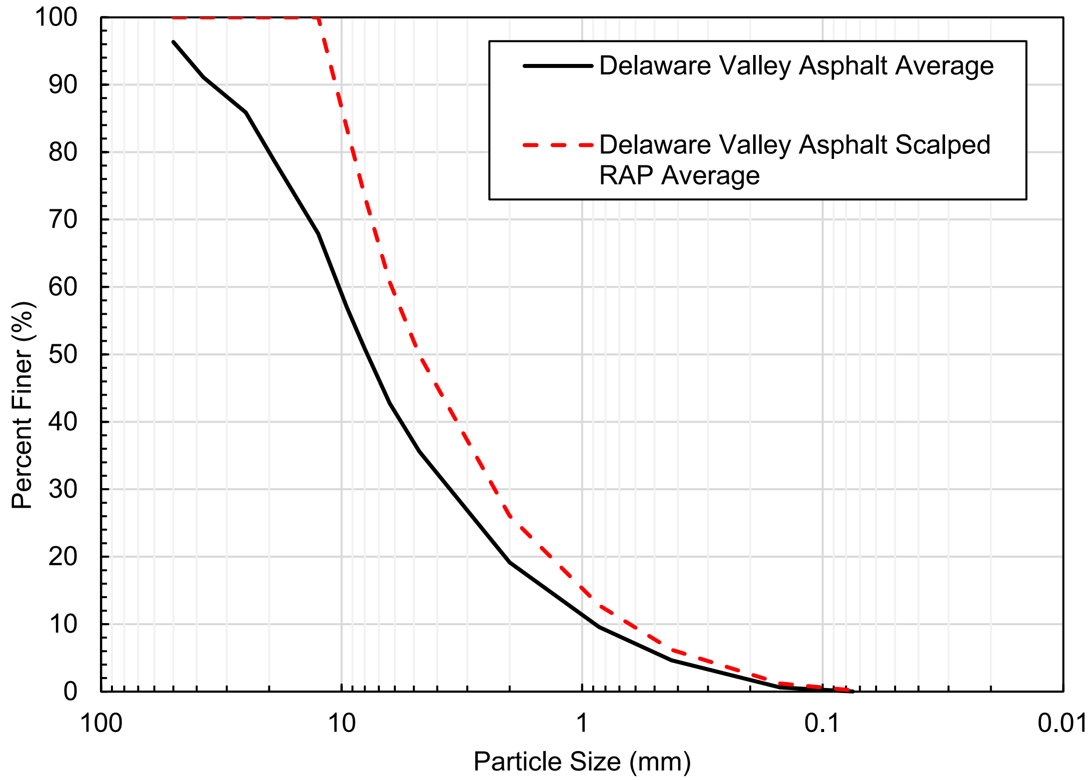


Figure 3.13 Scalping comparison for Delaware Valley Aspahlt RAP.

Table 3.8 Gradation properties of scalped sources of RAP.

RAP Source	Malvern	Erie	Delaware Valley Asphalt
Nominal Max. Particle Size	1/2 in	1/2 in	1/2 in
Percent Fines	1.8%	0.4%	0.0.2%
D_{60}	6.3 mm	6.4 in	6.2 in
D_{30}	2.8 in	2.5 in	2.4 in
D_{10}	0.90 in	0.85 in	0.65 in
C_c	1.4	1.1	1.4
C_u	7.0	7.5	9.5

3.3.1.3 Discussion

As previously discussed in **Section 2.2.1**, PennDOT Publication 408 provides gradation requirements for coarse aggregate materials commonly used in non-pavement applications, such as embankments, pipe bedding, shoulder backfill, and MSE wall backfill. The gradations of all the sources of District 6 RAP were compared to PennDOT's coarse aggregate requirements provided by Publication 408, with the gradation range provided by PennDOT highlighted in red (**Figures 3.12 – 3.16).**

For material 2RC, the gradations of the RAP sources generally fell within the requirements as shown in **Figure 3.14**. The gradations of the unprocessed RAP (Malvern, Erie, and Delaware Valley Asphalt) are better suited for replacement of 2RC due to their larger particle sizes. Processed RAP was slightly finer than the requirement, however, if free drainage is maintained, finer RAP would be allowable. Mixing the processed RAP with aggregate material would allow for it to meet the gradation requirements for 2RC.

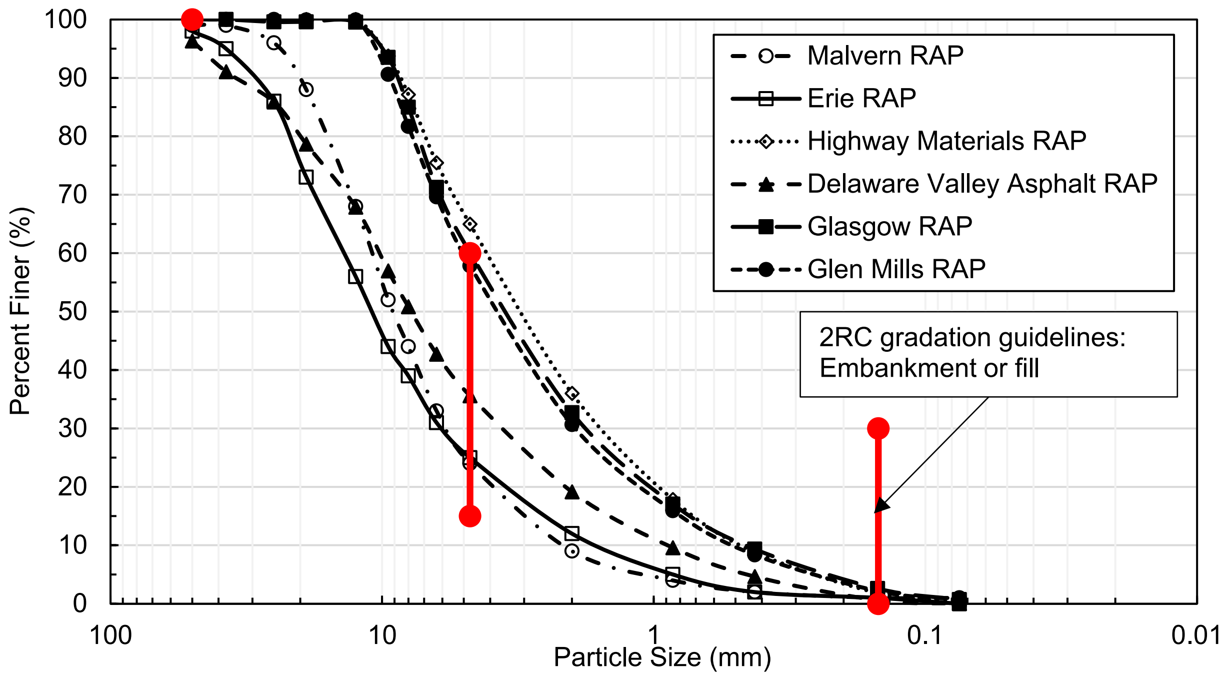


Figure 3.14 RAP sources compared to 2RC specifications from Publication 408.

For AASHTO No. 8, the gradations of the RAP sources did not fit within the requirements as shown in **Figure 3.15**. The requirements indicate that this application requires a uniformly graded material. The RAP sources were all generally well-graded, so additional measures would be needed to use RAP as a replacement for No.8 material. Scalping and aggregate mixtures could allow RAP to be used in this application.

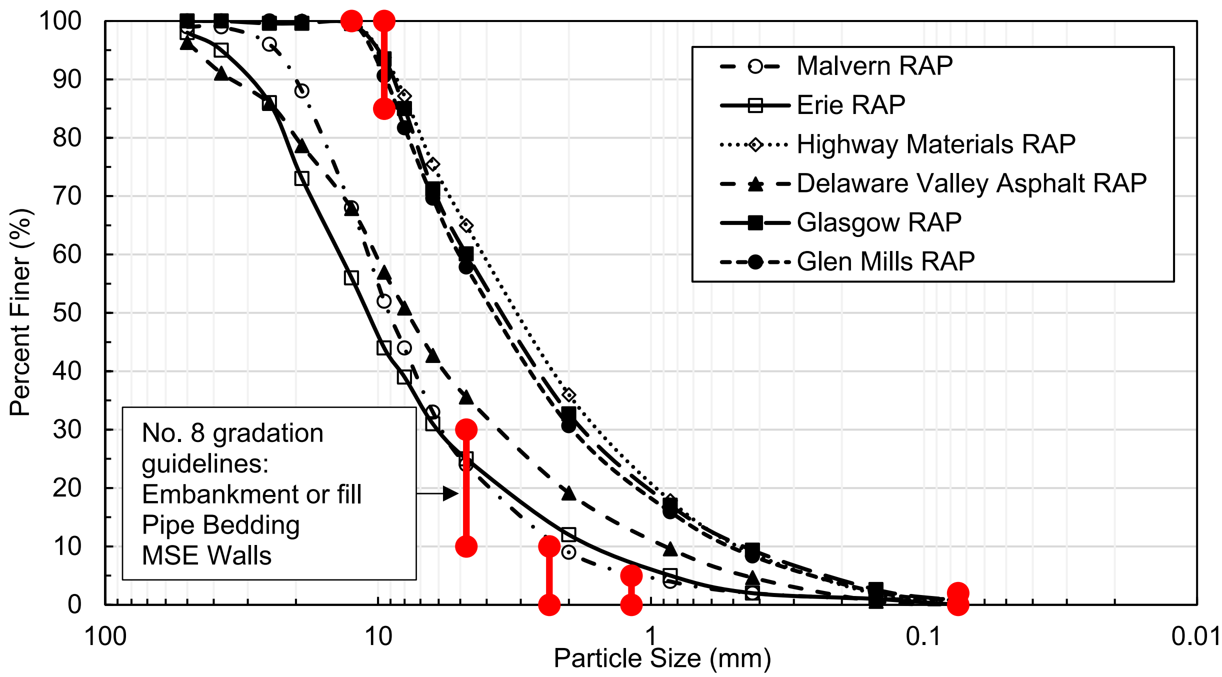


Figure 3.15 RAP sources compared to No. 8 specifications from Publication 408.

For the OGS material, the unprocessed RAP sources fit within the requirements as shown in **Figure 3.16.** This would indicate that this application requires coarser-grained materials, therefore it would be recommended that if processed RAP is used, it should be mixed with aggregate material to better suit the requirements.

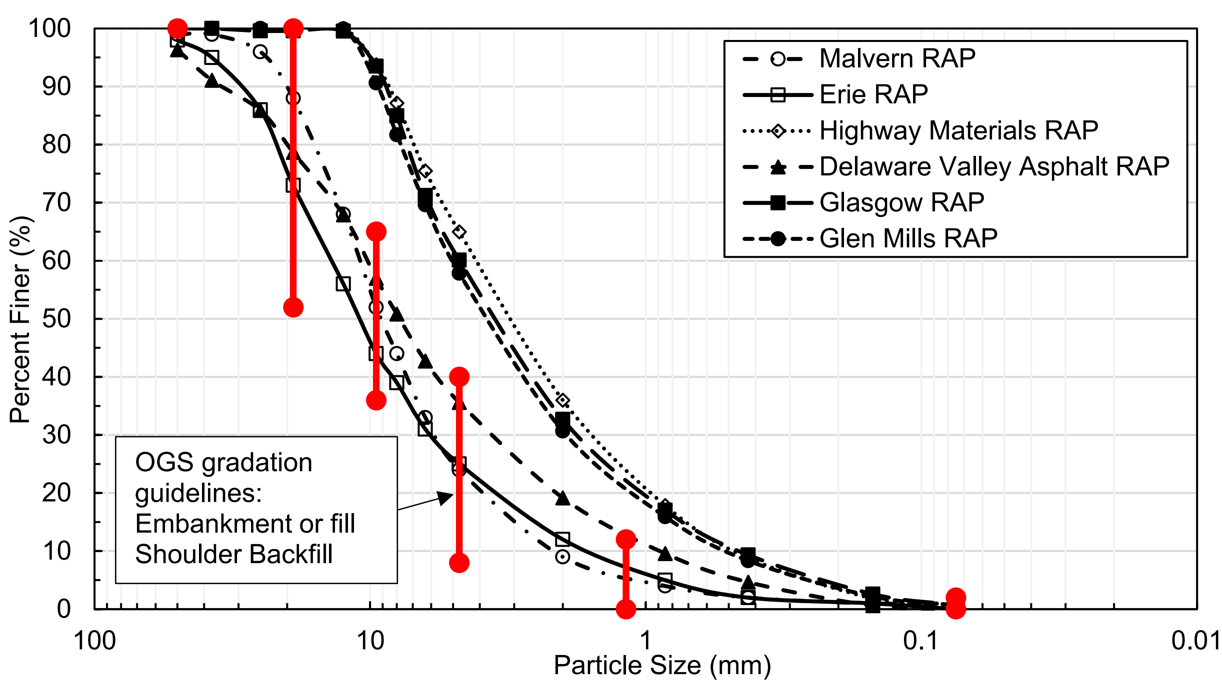


Figure 3.16 RAP sources compared to OGS specifications from Publication 408.

No. 2A requirements are similar to OGS, however, it requires more well-graded material. As shown in **Figure 3.17**, unprocessed RAP is better suited for this application. Processed RAP is only slightly outside of the requirements so if free draining is maintained, it would be allowable. Aggregate mixing is an alternative option to allow for processed RAP to be used.

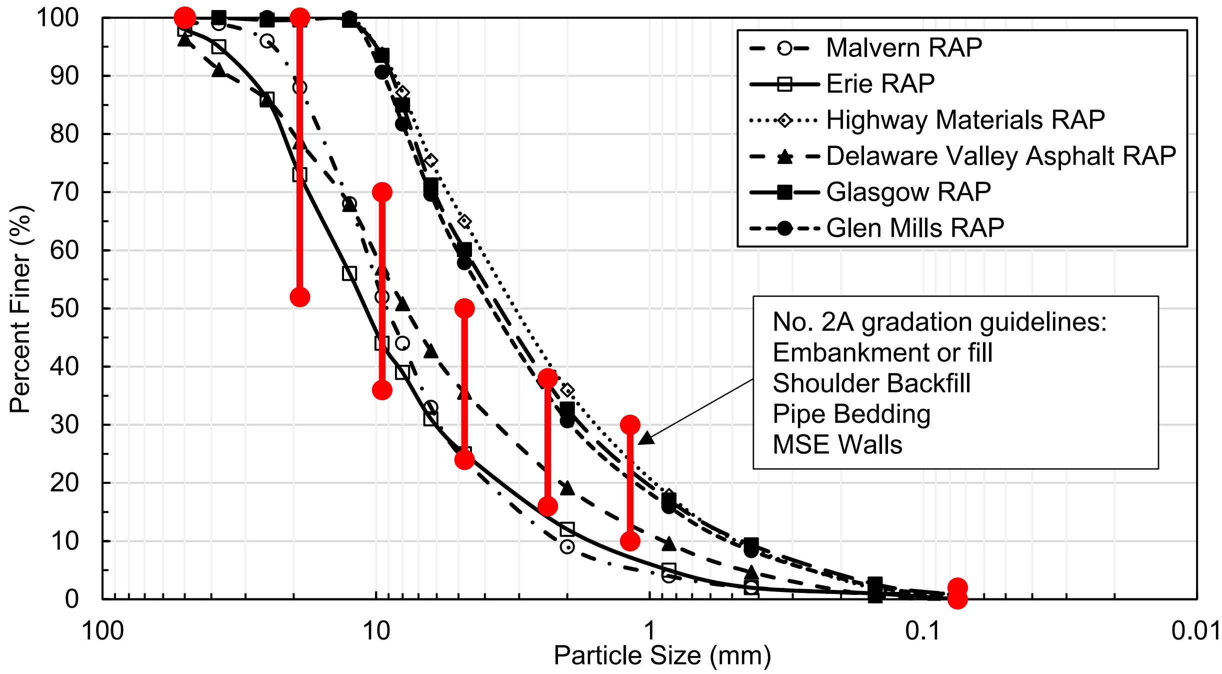


Figure 3.17 RAP sources compared to No. 2A specifications from Publication 408.

Structural fill material requires a finer gradation when compared to the other coarse aggregates of interest. As show in **Figure 3.18**, processed RAP fits within the requirements. If unprocessed RAP were to be used, scalping would be necessary to fit within the MSE wall backfill gradation requirements.

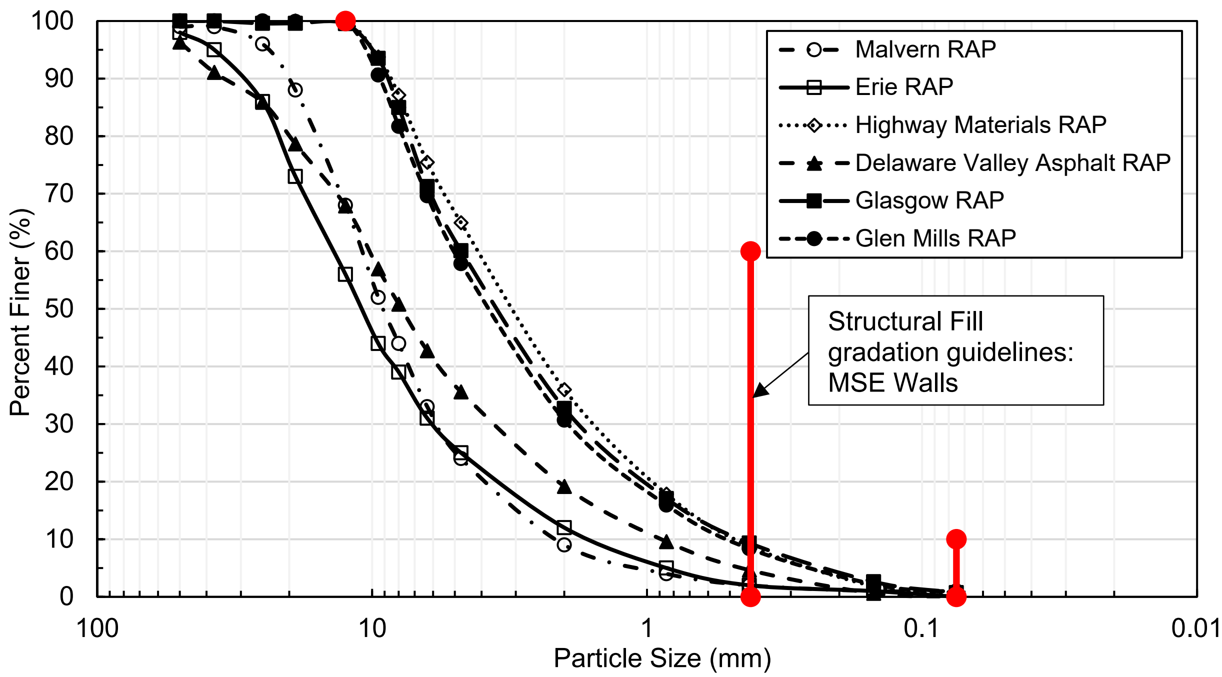


Figure 3.18 RAP sources compared to structural fill specifications from Publication 408.

3.3.2 Specific Gravity

Specific gravity represents the ratio of the density of aggregate (RAP) to the density of water. It provides an indication on how porous the material is and how many voids it may contain. This is a useful parameter for the classification of RAP as a construction material.

3.3.2.1 Methods

The specific gravity of RAP was determined in accordance with ASTM C127 for coarse aggregates and ASTM C128 for fine aggregates (ASTM 2015; ASTM 2015). The tests were conducted on Erie, Highway Materials, Delaware Valley Asphalt, Glasgow, and Glen Mills RAP. Both the coarse-grained specific gravity, and the fine-grained specific gravity were tested, and a weighted average was calculated to determine the overall specific gravity.

While ASTM C127 and ASTM C128 were commonly conducted in literature, PennDOT conducts specific gravity tests following ASTM D2041-19 because RAP is treated as bituminous material (ASTM 2019). The asphalt binder in RAP prevents water from being absorbed into the aggregate pores, so treating RAP as an aggregate material result in a smaller calculated specific gravity. The Villanova research team did not have the capabilities to test RAP as a bituminous material, therefore ASTM C127 and ASTM C128 were conducted to be consistent with literature. PennDOT provided the Villanova research team with results from specific gravity testing for Highway Materials, Glasgow, and Glen Mills RAP that were in accordance with ASTM D2041-19. These results are provided in a subsequent section.

To calculate specific gravity in accordance with ASTM C127 and ASTM C128, first the sample size was determined based on the nominal maximum particle size of the sources of RAP. For Erie

RAP, the nominal maximum particle size was 2 inches, therefore 8 kg of coarse RAP and 1 kg of fine RAP had to be tested. For Glen Mills RAP, the nominal maximum particle size was 3/8 inch, therefore 2 kg of coarse RAP and 1 kg of fine RAP was tested. Samples were sieved through the No. 4 sieve until the required amount of coarse-grained RAP was obtained. The material passing through the No. 4 sieve was used for the fine-grained analysis.

For coarse-grained specific gravity testing, 1000 g samples were placed in bread pans and allowed to soak overnight in water. The RAP was then removed from the water and rolled in an absorbent cloth until the RAP was at saturated surface dry conditions (SSD). Once at SSD, the samples were weighed, and the mass at SSD was recorded. The samples were then placed in a basket and completely submerged in a water tank. The submerged mass of the RAP was measured and recorded. Once this testing was complete, the samples were placed in an oven for 24 hours, and the dry mass of the RAP was measured and recorded. Using this data, the oven dry specific gravity, the SSD specific gravity, the apparent specific gravity, and the absorption were calculated for the coarse-grained samples.

For fine-grained specific gravity testing, 500 g samples were placed in pans and soaked overnight. Once completely saturated, water was decanted from the pans and the saturated RAP was placed onto a heat resistant plastic sheet. A heat gun was used to evaporate the free water to allow RAP to reach SSD conditions. To test if RAP was at SSD, RAP was placed in a cylindrical mold and tamped 25 times. The mold was removed, and if half of the sample had slumped, the RAP was at SSD. If the sample held its shape, the RAP was placed back onto the plastic sheet and continually heated until it reached SSD. This process is shown in **Figure 3.19**. When the RAP had reached SSD, a pycnometer was filled with 500 mL of distilled water (DI) and the mass was measured and recorded. The water was then emptied from the pycnometer and a funnel was used to put the SSD RAP into the pycnometer. The pycnometer with RAP was filled with water until the RAP was completely submerged. To removed air bubbles, the pycnometer was spun and tipped. Once air was removed, the pycnometer was filled with 500 mL of water, and the submerged weight of the RAP was measured and recorded. This process is shown in **Figure 3.20**. The submerged RAP was placed in oven for 24 hours and the oven dry weight was measured and recorded. Using this data, the oven dry specific gravity, the SSD specific gravity, the apparent specific gravity, and the absorption were calculated for the fine-grained samples.

After determining the coarse-grained specific gravity and the fine-grained specific gravity, the values were averaged together to determine the overall specific gravity of RAP.

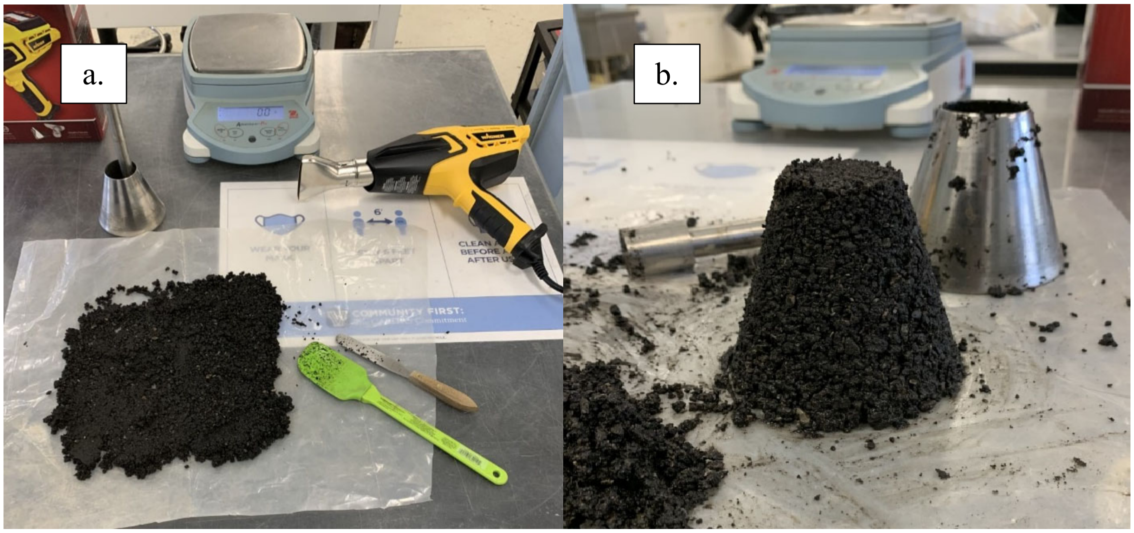


Figure 3.19 Specific Gravity Testing: (a) Wet RAP after soaking overnight (b) Cone test to determine if SSD conditions were reached (Morro 2021).

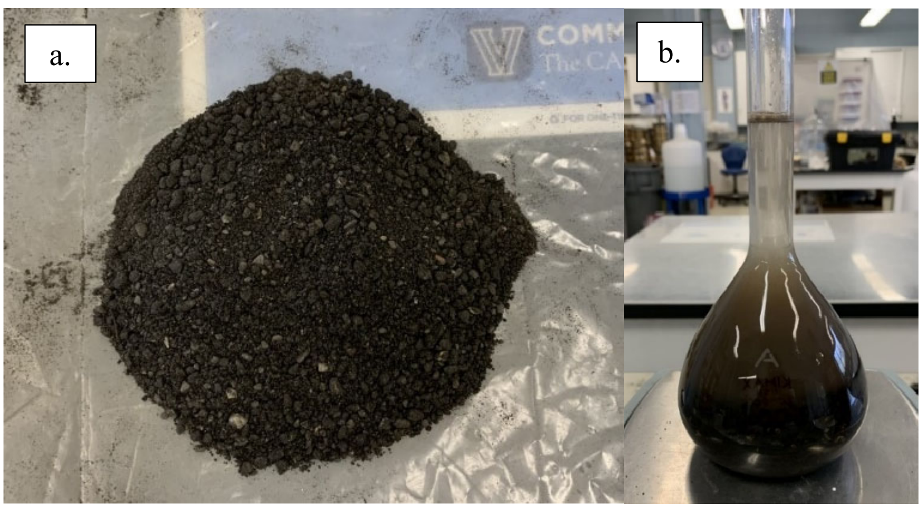


Figure 3.20 (a) Glen Mills RAP in SSD Condition. (b) Pycnometer filled with RAP and water (Morro 2021).

3.3.2.2 Results

For Erie RAP, the 9 kg of coarse RAP 2 kg of fine RAP was tested. The apparent specific gravity for the coarse material was 2.60 and the apparent specific gravity for the fine material was 2.49. Using the percent passing the No. 4 sieve from Erie's particle size distribution curve, the weighted average apparent specific gravity was calculated to be 2.58 as shown in **Table 3.9**.

Table 3.9 Erie specific gravity.

Gradation	Sample	Pan ID	SG (OD)	SG (SSD)	Apparent SG	Absorption (%)
Coarse	1	1	2.53	2.56	2.61	1.23
		2	2.52	2.56	2.61	1.31
		3	2.51	2.54	2.58	1.16
		4	2.54	2.57	2.60	0.91
		5	2.54	2.57	2.62	1.16
		6	2.52	2.56	2.61	1.38
		7	2.54	2.56	2.61	1.13
		8	2.50	2.53	2.58	1.32
		9	2.51	2.54	2.59	1.20
	Average		2.52	2.55	2.60	1.20
Fine	1	1	2.38	2.43	2.50	2.08
		2	2.34	2.41	2.50	2.66
	2	3	2.31	2.39	2.49	3.10
		4	2.31	2.38	2.50	3.32
	3	5	2.29	2.38	2.51	3.71
		6	2.29	2.37	2.47	3.19
	4	7	2.28	2.37	2.49	3.61
	Average		2.32	2.39	2.49	3.10
Average Total Specific Gravity						**2.58**

For Highway Materials RAP, the 4 kg of coarse RAP was tested and 2 kg of fine RAP was tested. The apparent specific gravity for the coarse material was 2.65 and the apparent specific gravity for the fine material was 2.41. Using the percent passing the No. 4 sieve from Highway Material's particle size distribution curve, the weighted average apparent specific gravity was calculated to be 2.59 as shown in **Table 3.10**.

Table 3.10 Highway Materials specific gravity.

Gradation	Sample	Pan ID	SG (OD)	SG (SSD)	Apparent SG	Absorption (%)
Coarse	1	1	2.56	2.59	2.63	1.03
		2	2.57	2.60	2.64	1.00
	2	3	2.61	2.63	2.68	1.07
		4	2.57	2.60	2.65	1.19
	Average		2.58	2.60	2.65	1.07
Fine	1	1	2.26	2.29	2.33	1.50
	2	2	2.38	2.38	2.38	0.06
	3	3	2.38	2.41	2.44	0.88
	4	4	2.30	2.37	2.48	3.18
	Average		2.33	2.36	2.41	1.41
Average Total Specific Gravity						**2.59**

For Delaware Valley Asphalt RAP, the 4 kg of coarse RAP was tested and 2 kg of fine RAP was tested. The apparent specific gravity for the coarse material was 2.61 and the apparent specific gravity for the fine material was 2.58. Using the percent passing the No. 4 sieve from Delaware Valley Asphalt RAP particle size distribution curve, the weighted average apparent specific gravity was calculated to be 2.60 as shown in **Table 3.11**.

Table 3.11 Delaware Valley Asphalt specific gravity.

Gradation	Sample	Pan ID	SG (OD)	SG (SSD)	Apparent SG	Absorption (%)
Coarse	1	1	2.53	2.55	2.59	1.03
		2	2.53	2.56	2.62	1.37
	2	3	2.58	2.60	2.65	1.02
		4	2.45	2.47	2.50	0.91
	3	5	2.60	2.63	2.68	1.18
		6	2.46	2.51	2.59	2.11
	4	7	2.53	2.57	2.63	1.58
		8	2.46	2.53	2.64	2.70
	Average		2.52	2.55	2.61	1.49
Fine	1	1	2.33	2.38	2.44	1.83
		2	2.36	2.39	2.43	1.19
	Average		2.49	2.52	2.58	1.49
Average Total Specific Gravity						**2.60**

For Glasgow RAP, the 4 kg of coarse RAP was tested and 2 kg of fine RAP was tested. The apparent specific gravity for the coarse material was 2.70 and the apparent specific gravity for the fine material was 2.47. Using the percent passing the No. 4 sieve from Delaware Valley Asphalt RAP particle size distribution curve, the weighted average apparent specific gravity was calculated to be 2.56 as shown in **Table 3.12**.

Table 3.12 Glasgow specific gravity.

Gradation	Sample	Pan ID	SG (OD)	SG (SSD)	Apparen t SG	Absorption (%)
Coarse	1	1	2.59	2.63	2.68	1.29
		2	2.60	2.63	2.67	1.03
	2	3	2.63	2.67	2.74	1.56
		4	2.59	2.63	2.70	1.62
	Average		2.60	2.64	2.70	1.37
Fine	1	1	2.44	2.45	2.48	0.73
	2	2	2.38	2.42	2.49	1.98
	3	3	2.25	2.33	2.45	3.61
	4	4	1.74	2.04	2.47	17.07
	Average		2.20	2.31	2.47	5.85
Average Total Specific Gravity						**2.56**

For Glen Mills RAP, the 4 kg of coarse RAP was tested and 2 kg of fine RAP was tested. The apparent specific gravity for the coarse material was 2.71 and the apparent specific gravity for the fine material was 2.55. Using the percent passing the No. 4 sieve from Delaware Valley Asphalt RAP particle size distribution curve, the weighted average apparent specific gravity was calculated to be 2.62 as shown in **Table 3.13**.

Table 3.13 Glen Mills specific gravity.

Gradation	Sample	Pan ID	SG (OD)	SG (SSD)	Apparent SG	Absorption (%)
Coarse	1	1	2.63	2.66	2.71	1.05
		2	2.63	2.66	2.71	1.07
	2	3	2.64	2.67	2.71	0.99
		4	2.64	2.67	2.72	1.03
	Average		2.64	2.67	2.71	1.03
Fine	1	1	2.35	2.43	2.55	3.25
	2	2	2.25	2.36	2.53	4.88
	3	3	2.33	2.42	2.57	4.01
	4	4	2.22	2.35	2.54	5.64
	Average		2.29	2.39	2.55	4.45
Average Total Specific Gravity						**2.62**

The apparent specific gravity for the sources of District 6 RAP tested by Villanova is compared in **Table 3.14**. There is little variability in the results, and the specific gravity values range from 2.56 to 2.62. Glasgow RAP had the smallest specific gravity value and Glen Mills had the largest specific gravity value. The average value for all the District 6 RAP sources tested by Villanova was 2.59.

Table 3.14 District 6 RAP specific gravity results on tests conducted by Villanova.

Source	Apparent Specific Gravity
Erie	2.58
Highway Materials	2.59
Delaware Valley Asphalt	2.60
Glasgow	2.56
Glen Mills	2.62

The specific gravity results that were provided by PennDOT are compared in **Table 3.15**. The results from the three sources show little variability, with all sources having similar specific gravities. As expected, the results from PennDOT have significantly higher specific gravities than the Villanova results. This difference can be attributed to the asphalt binder preventing the water from absorbing into the aggregate pores during the Villanova tests.

Table 3.15 District 6 RAP specific gravity results provided by PennDOT.

Source	Apparent Specific Gravity
Highway Materials	2.82
Glasgow	2.80
Glen Mills	2.81

3.3.2.3 Discussion

The apparent specific gravity values for District 6 RAP were very similar, and little variation was observed. It is likely that the differences in specific gravity values can be attributed to the type of coarse aggregate used in the RAP, and the bitumen binder content coating the aggregate. These slight differences highlight the variability of RAP; however, they are unlikely to have a significant impact on the ability for RAP to be used in non-pavement applications.

When compared to literature, the District 6 RAP tested by Villanova had a much narrower range of specific gravity values than other studies. The range for District 6 RAP was 2.56 to 2.62, with an average of 2.59 whereas literature had a range of 2.25 to 2.77, with an average of 2.43 (Abedalqader et al. 2021; Cooley 2005; Cosentino et al. 2003; Hajj et al. 2012; Locander 2009; Mijic et al. 2020; Mousa et al. 2021; Yousefi et al. 2021; Rahardio et al. 2013; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012; Thakur et al. 2013; Titi et al. 2019). This proves that RAP is highly variable, and different sources of RAP can provide different results. The results from the District 6 RAP testing conducted by Villanova had a specific gravity range that fell within what was observed in literature, so the results are consistent with other findings.

As discussed previously, it is important to note that the Villanova research team treated RAP as an aggregate material for specific gravity testing and this was consistent with other studies from literature. PennDOT recommends treating RAP as a bituminous material for specific gravity testing, so the Villanova specific gravity values were much smaller than the values calculated by PennDOT for the same sources of RAP. While the testing methods were different, specific gravity is unlikely to limit the reuse of RAP in non-pavement applications, therefore the different testing methods do not impact the overall conclusions from this study.

3.4 Engineering Properties

Understanding the engineering properties of soil aids in the design of geotechnical infrastructure under various loading conditions. For this study, the engineering properties evaluated were maximum dry density/optimum moisture content, saturated hydraulic conductivity, and shear strength.

3.4.1 Maximum Dry Density/Optimum Moisture Content

The maximum dry density (MDD) and the optimum moisture content (OMC) provide information on the compaction characteristics of a material. During construction activities, most applications require compaction to a percentage (typically 95%) of the MDD and OMC. Understanding the MDD and OMC of a material is critical during the design and construction stages of a geotechnical infrastructure projects.

3.4.1.1 Methods

The MDD and the OMC was determined using the modified proctor method in accordance with ASTM D1557 Method C (ASTM 2021) and tests were performed each District 6 RAP source. RAP samples were mixed with varying percentages of water and placed into a 6-inch diameter cylindrical compaction mold with an extension collar. RAP was placed in 5 equal lifts, and a compaction effort of 56,000 ft-lbf/ft^3 was applied by dropping a 10 lbf rammer from a height of 18 inches, as shown in **Figure 3.21**. A minimum of 5 compaction tests at varying moisture contents were conducted for each RAP material to develop a compaction curve. A trendline was fit to the data and the MDD and OMC was determined from the trendline equation.

It is important to note that the Malvern, Erie, and Delaware Valley Asphalt RAP were scalped down to size of ½ inch. Based on trial and error, it was found that it was extremely difficult to develop a compaction curve with particle sizes larger than ½ inch. Water freely drained through the material and was not retained in the mold when large particles were present. Therefore, for laboratory testing, scalping was conducted on the materials with a nominal maximum particle size of 2 inches.

Figure 3.21 RAP compacted wet of optimum (Morro 2021).

3.4.1.2 Results

Compaction tests were performed on each RAP material and compaction curves were developed. Six compaction tests were completed for Erie and Glasgow RAP, 11 were completed for Glen Mills RAP, and 5 were completed for Malvern, Erie, and Delaware Valley RAP. The compaction curves for each RAP source are illustrated in **Figures 3.22 – 3.27**. **Figure 3.28** shows a comparison of all of the compaction curves and **Table 3.15** provides the MDD and OMC for each material.

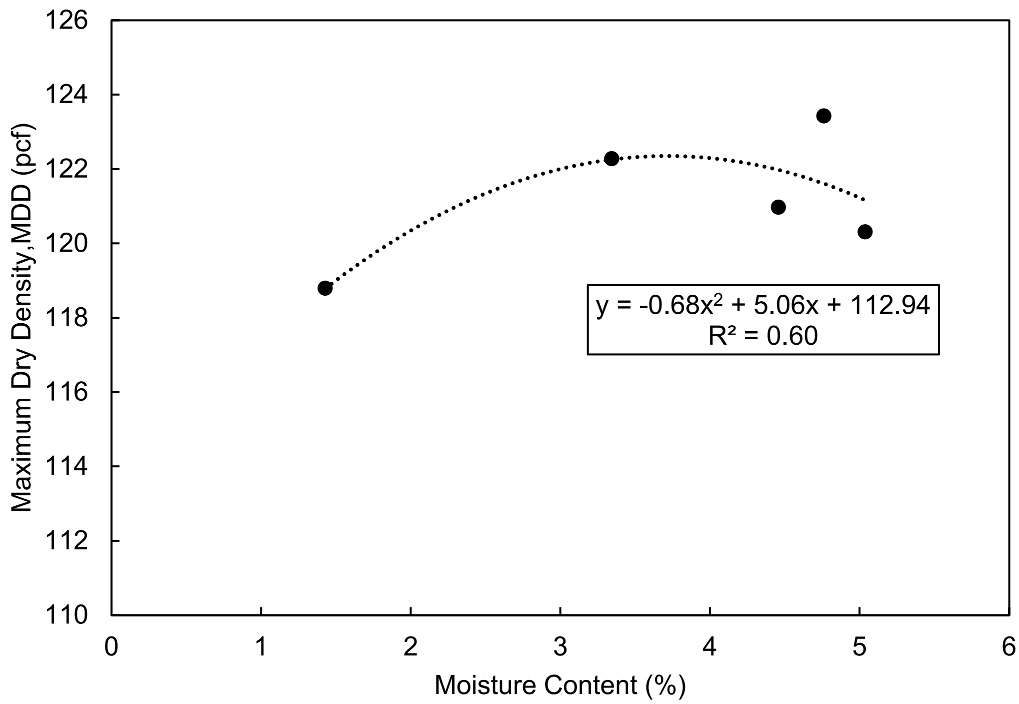


Figure 3.22 Compaction curve for Malvern RAP.

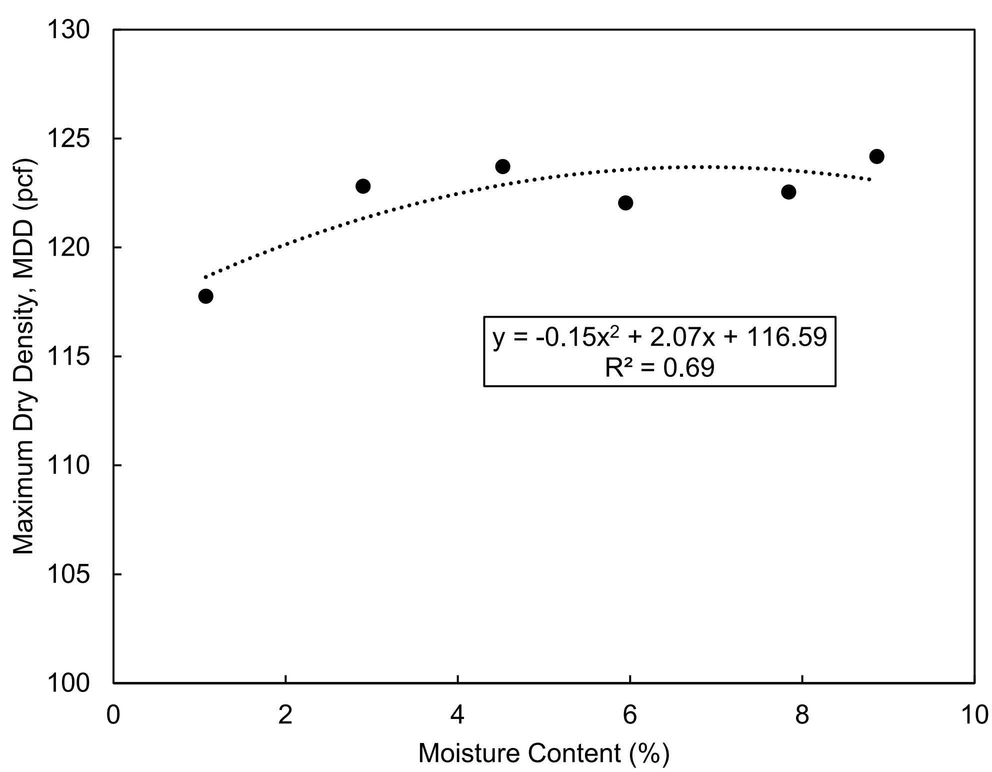


Figure 3.23 Compaction curve for Erie RAP.

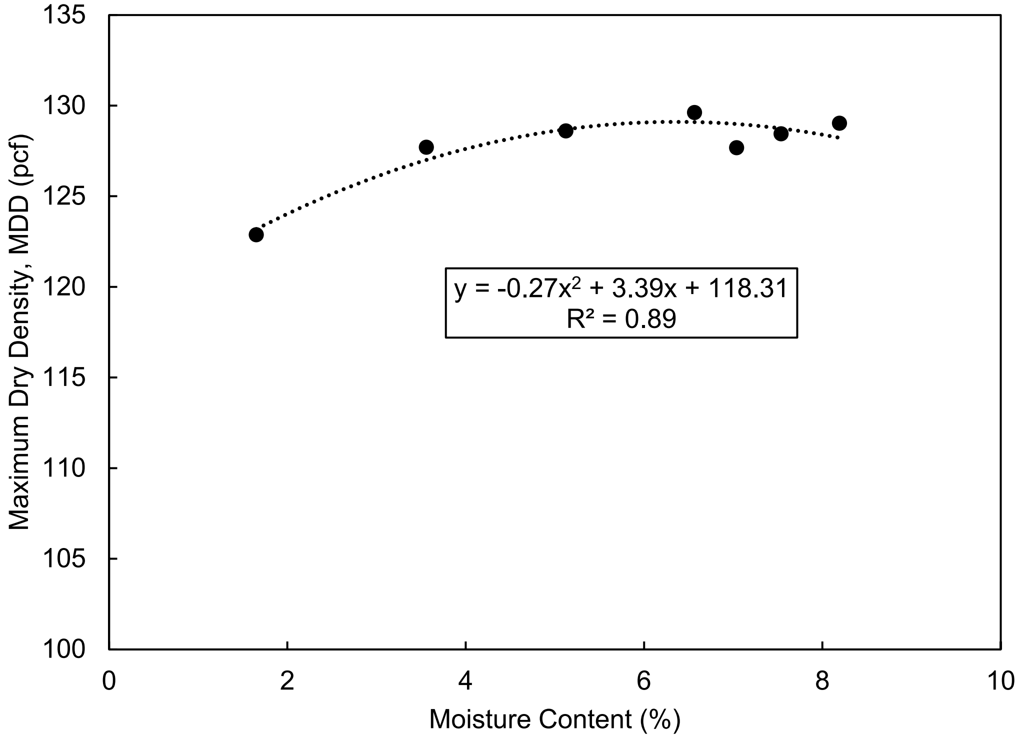


Figure 3.24 Compaction curve for Highway Materials RAP.

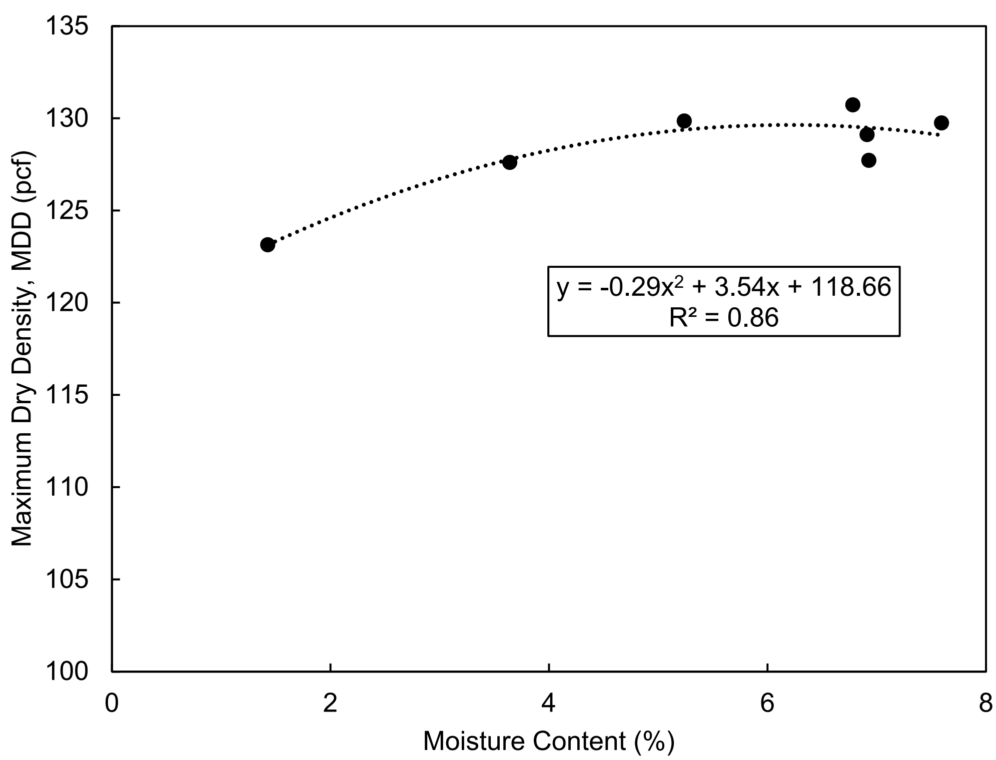


Figure 3.25 Compaction curve for Delaware Valley Asphalt RAP.

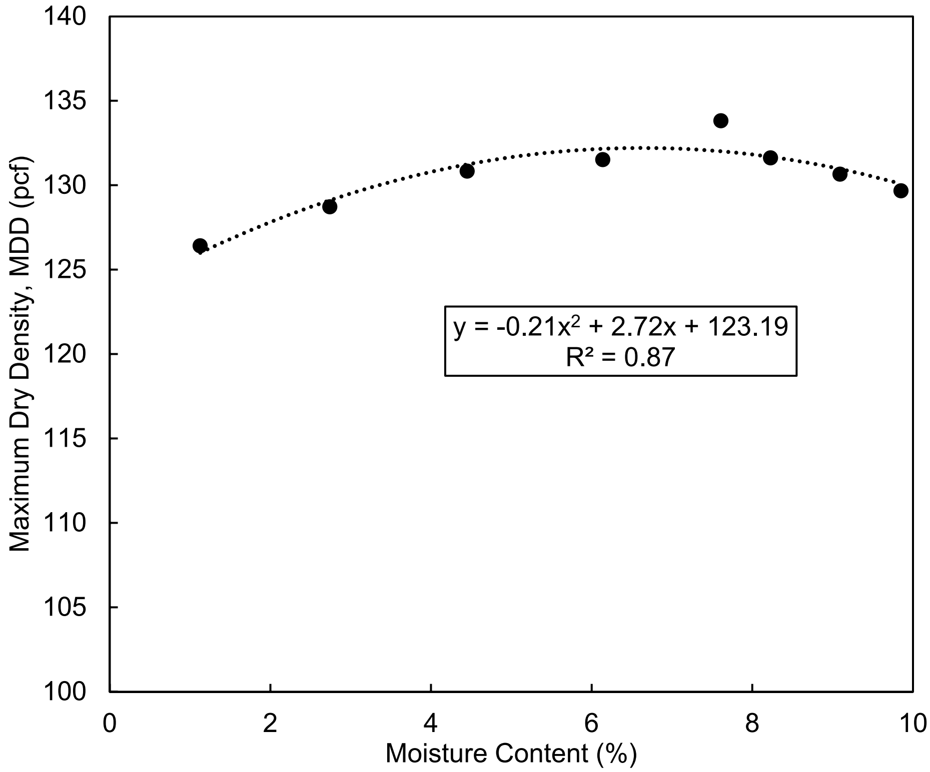


Figure 3.26 Compaction curve for Glasgow RAP.

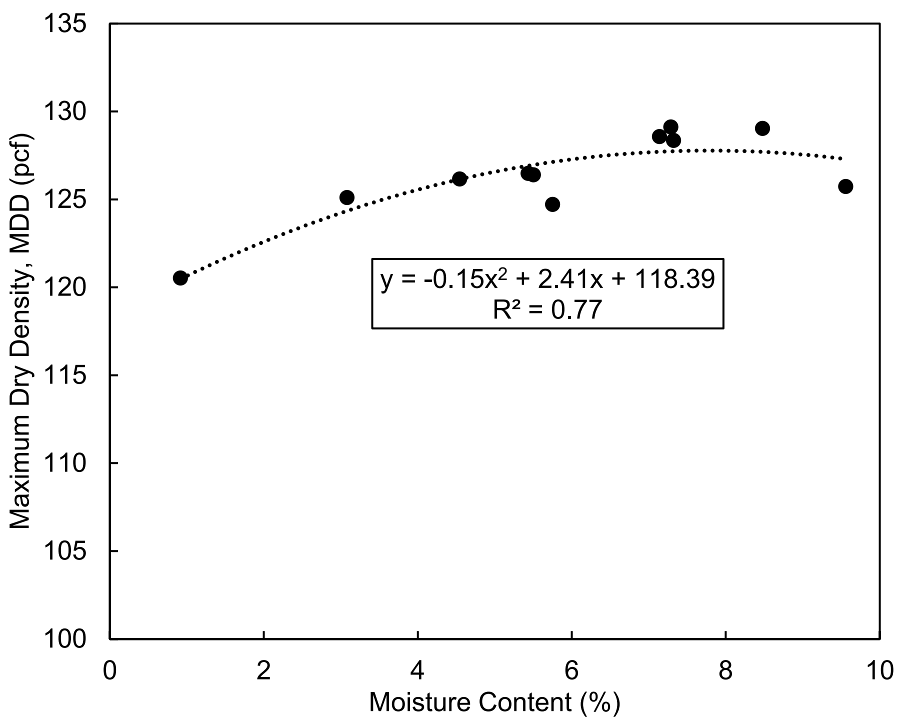


Figure 3.27 Compaction curve for Glasgow RAP.

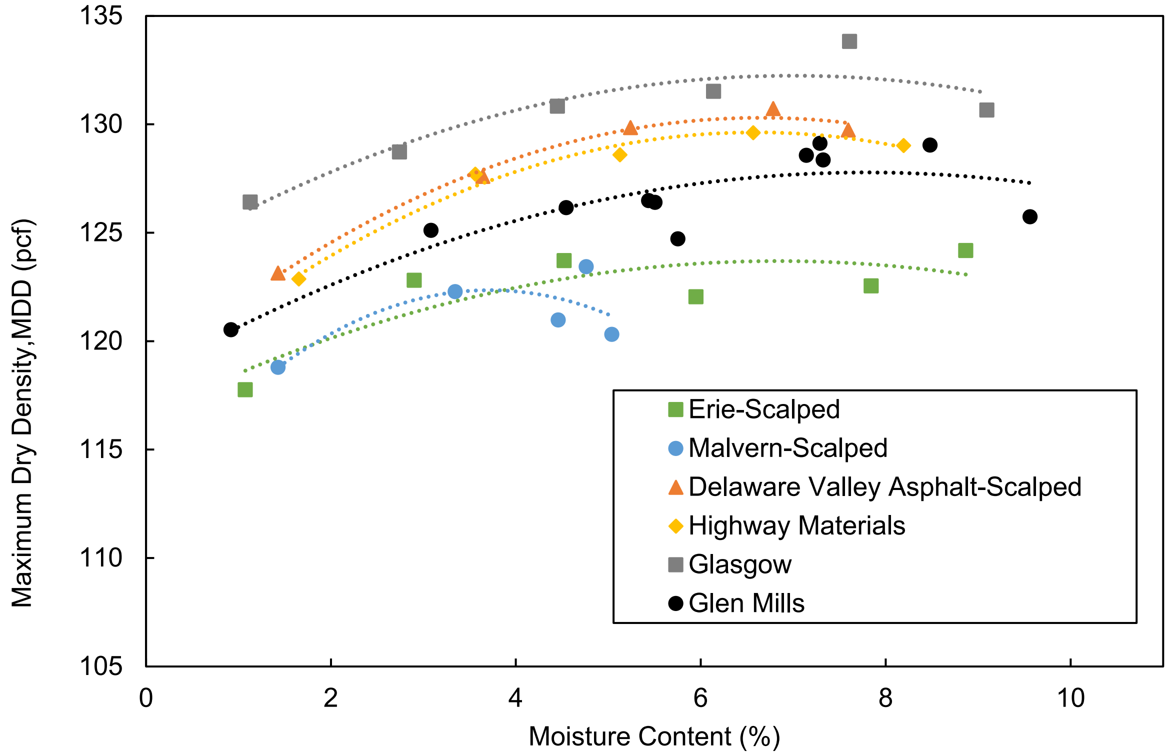


Figure 3.28 Compaction curves for all sources of RAP.

Table 3.15 MDD and OMC results.

RAP Source	MDD (pcf)	OMC (%)
Malvern	122.3	3.7%
Erie	123.3	6.8%
Highway Materials	129.3	6.6%
Delaware Valley Asphalt	129.9	6.6%
Glasgow	132.3	7.0%
Glen Mills	127.8	7.8%

In general, the compaction curves were relatively flat, showing no distinct peak. This indicates that moisture content is not extremely critical when compacting RAP, and a range of moisture contents can be used to be within 95% of MDD. The MDD's had two distinct groupings, with Malvern and Erie RAP having lower MDD's than the other 4 materials. The OMC generally fell around 6.6 - 7.0%, with a lower outlier of 3.7% for Malvern RAP, and higher outlier of 7.8% for Glen Mills RAP.

Additionally, post-compaction particle breakage was evaluated by running a sieve analysis before and after compaction. This was done to evaluate if the percentage of fines would increase significantly after compaction, which would influence the drainage of the material. Particle-size distribution curves for each material were created that compared the gradation of the material before and after compaction, and those curves are shown in **Figures 3.29 – 3.34**. The percentage of fines for each material were compared in **Table 3.16**.

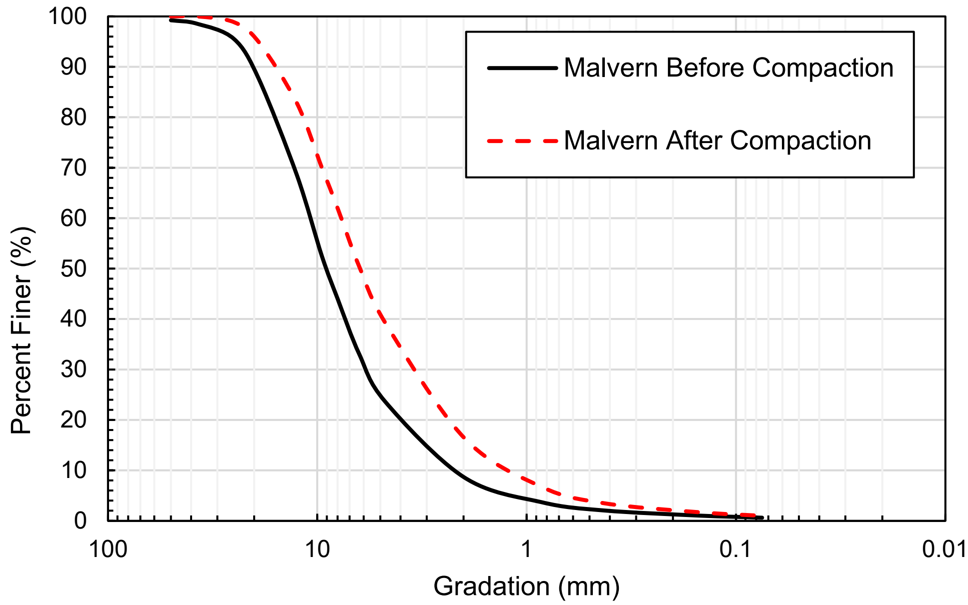


Figure 3.29 Gradation comparison of Malvern RAP before and after compaction.

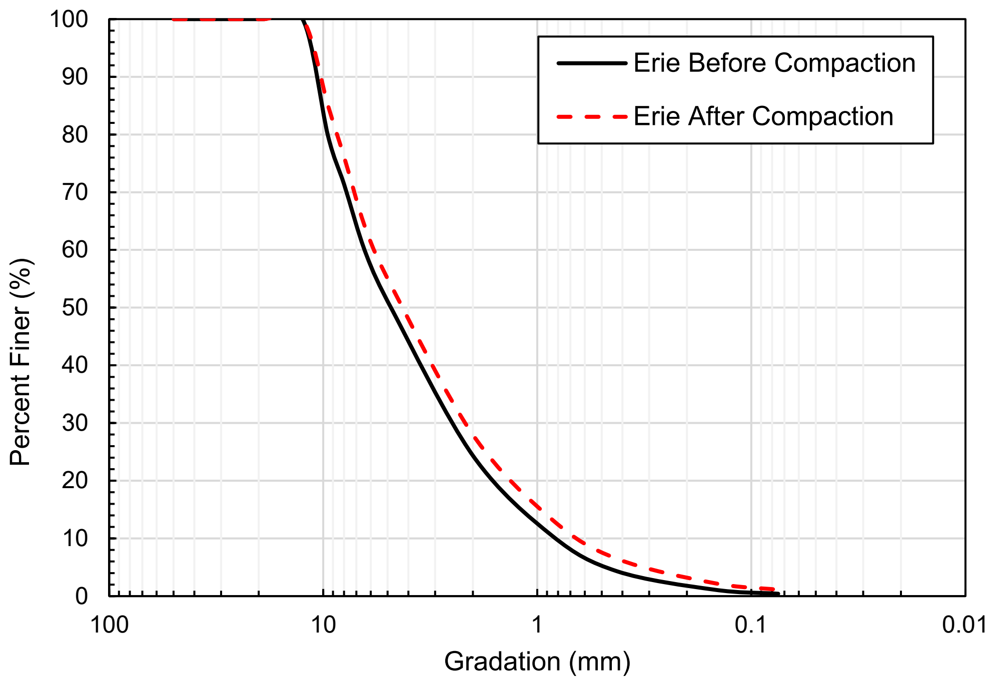


Figure 3.30 Gradation comparison of Erie RAP before and after compaction.

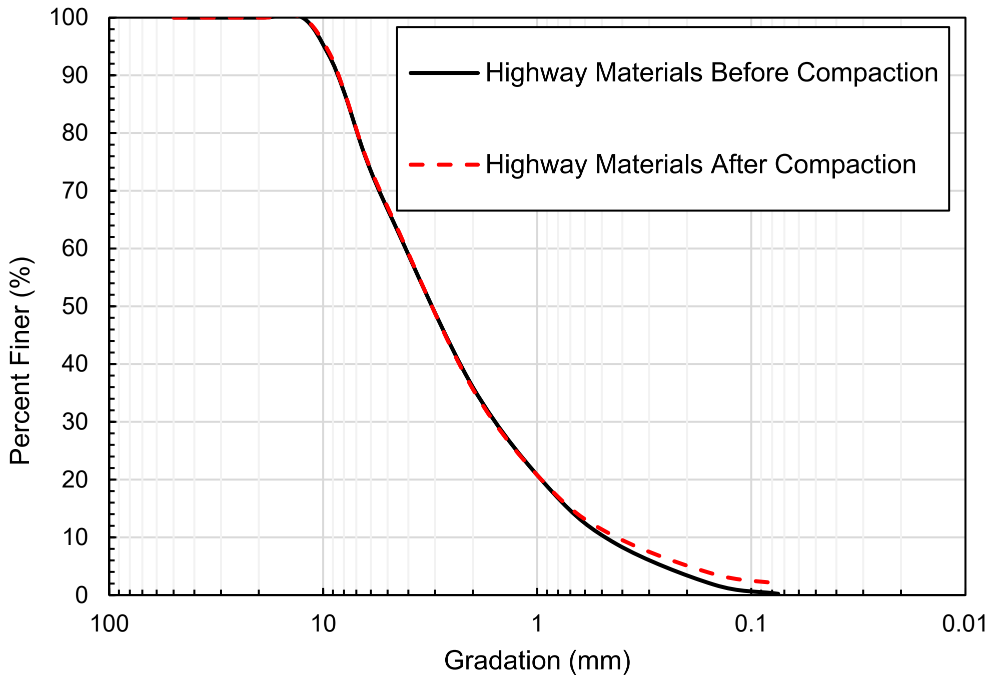


Figure 3.31 Gradation comparison of Highway Materials RAP before and after compaction.

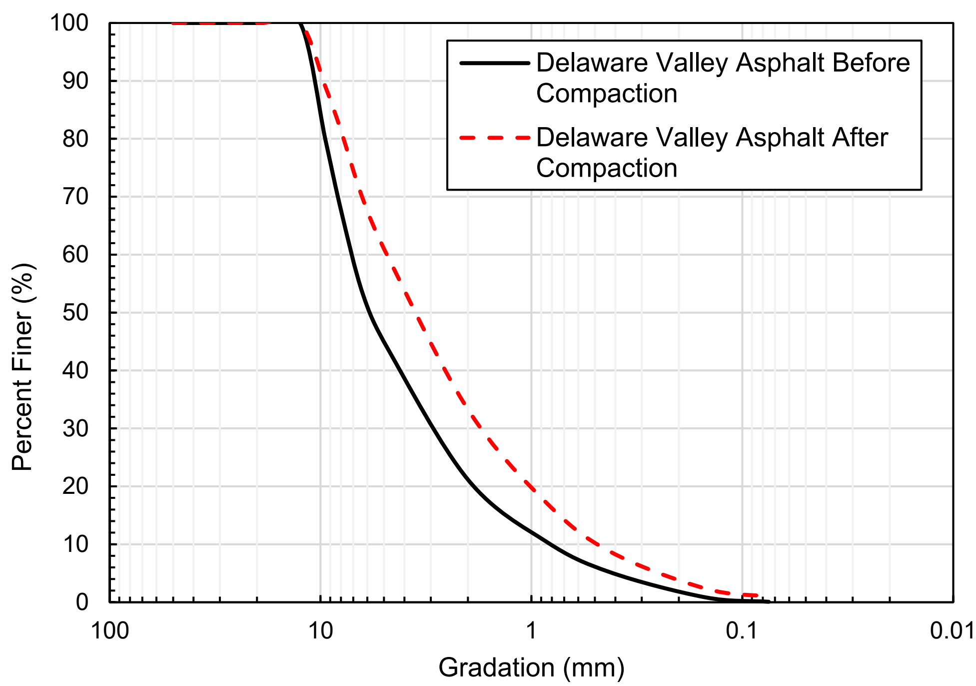


Figure 3.32 Gradation comparison of Delaware Valley Asphalt RAP before and after compaction.

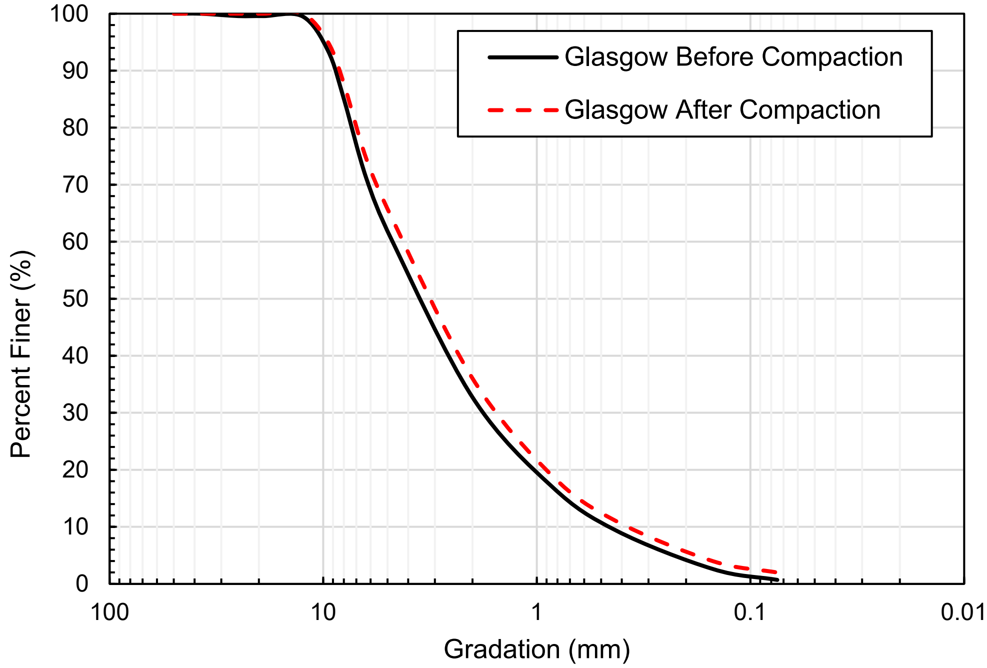


Figure 3.33 Gradation comparison of Glasgow RAP before and after compaction.

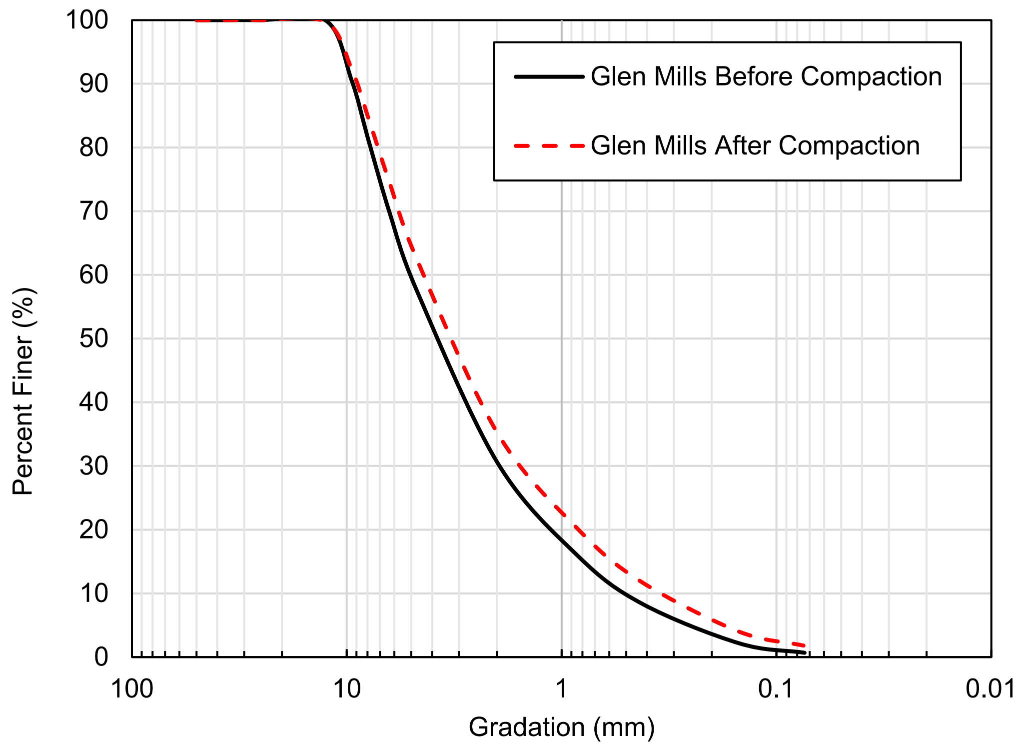


Figure 3.34 Gradation comparison of Glen Mills RAP before and after compaction.

Table 3.16 Comparison of percent of fines before and after compaction.

RAP Source	Percent Fines Before Compaction	Percent Fines After Compaction
Malvern	0.6%	1.0%
Erie	0.3%	1.1%
Highway Materials	0.2%	2.0%
Delaware Valley Asphalt	0.2%	1.0%
Glasgow	0.7%	2.0%
Glen Mills	0.7%	1.8%

The particle-size distribution curves indicate that compaction causes the gradation to shift to the right, meaning that the overall gradation becomes more fine-grained. However, for all the materials, the shift is not very large, and the general shape of the curves remain the same. Additionally, the percent of fines, which is the material that passes through the No. 200 sieve, does not increase significantly after compaction. The largest increase in percent of fines occurred in the Highway Materials RAP where the fines increased from 0.2% to 2.0%. While this is an increase in fines content, 2.0% fines post-compaction is still small and should not negatively impact the drainage of the material.

3.4.1.3 Discussion

Overall, RAP exhibited high MDD values with the range of values being from 122 pcf to 132 pcf. Coarse aggregate, which is commonly used in embankment or fill applications generally exhibits higher MDD values, with a range of 125 pcf to 150 pcf. Although RAP has slightly lower MDD values than coarse aggregate, the range of values found from laboratory testing are considered acceptable for non-pavement applications. Also, because the generation of fines after compaction is small, RAP would be a suitable material for applications that require free drainage. Based on the laboratory results, RAP would display similar compaction characteristics to typical material used during construction activities.

3.4.1.3.1 Maximum Dry Density Compared to Literature

The compaction results found during laboratory testing for District 6 RAP were compared to literature results (Rathje et al. 2002; Cosentino et al. 2003; Yin et al. 2016; Arulrajah et al. 2014; Mousa et al. 2021). This comparison was completed to identify the variability of RAP from different sources. The comparison is shown in **Figure 3.35**, with District 6 laboratory results shown with solid markers and solid polylines, and literature results shown as open markers with dashed polylines.

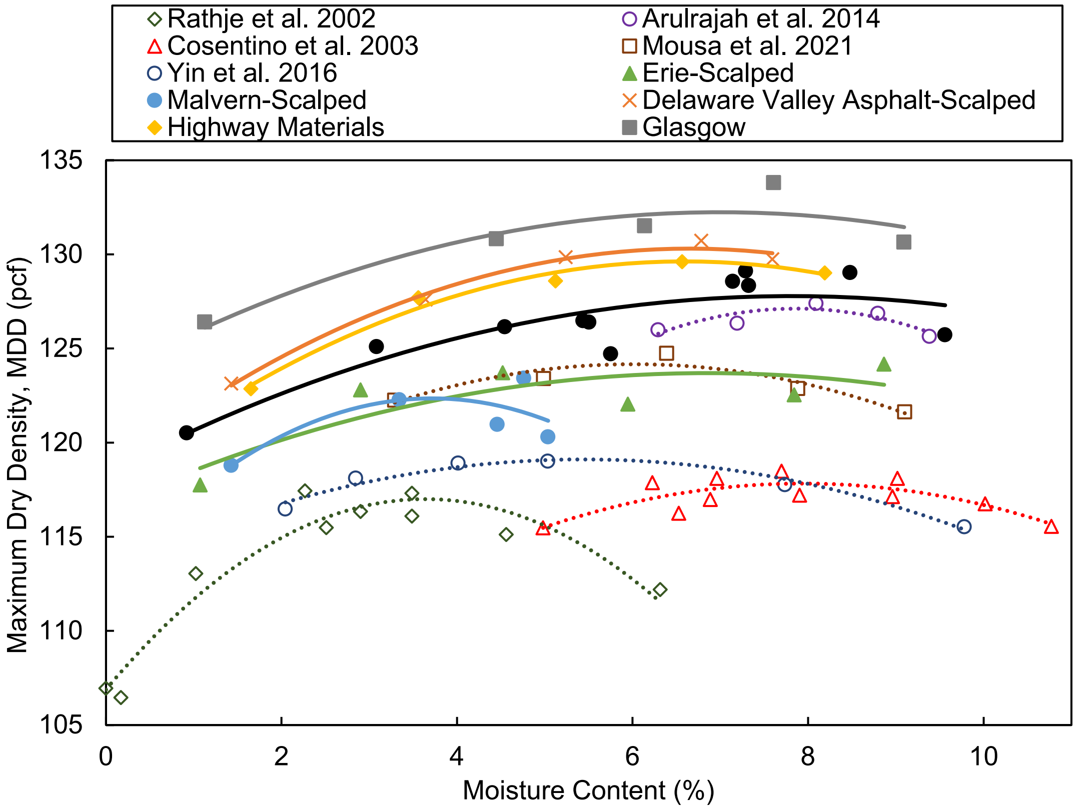


Figure 3.35 Comparison of District 6 MDD results with literature MDD results.

The comparison indicates that in general, District 6 RAP displayed higher MDD values than literature. This can be attributed to a variety of factors such as the generation of fines from the milling process, the asphalt binder content of the RAP, or the gradation of the RAP. Higher amounts of fines and a more well-graded gradation contribute to higher MDD values. Also, differences in laboratory compaction methods could contribute to different in MDD values. In general, most literature studies utilized the modified proctor method, however, different molds, different hammer sizes, and different hammer-dropping techniques could cause differences in MDD values. Although District 6 RAP displayed higher MDD values than literature, this is not a concern because coarse aggregate materials that are commonly used in embankment and fill applications typically display high MDD values. The differences between the District 6 MDD values and the literature MDD values highlight the variability of RAP obtained from different sources.

3.4.1.3.2 Maximum Dry Density and Coefficient of Uniformity Correlation

The compaction results show differences in MDD from each source. Common gradation properties such as grain size diameters (D_{10}, D_{30}, D_{60}), the nominal maximum particle size, the coefficient of curvature (C_c), and the coefficient of uniformity (C_u) were compared against the MDD for each material to determine if there was a correlation. It was determined that the coefficient of uniformity provided a strong linear correlation with MDD. **Figure 3.36** and **Table 3.17** compare C_u to MDD.

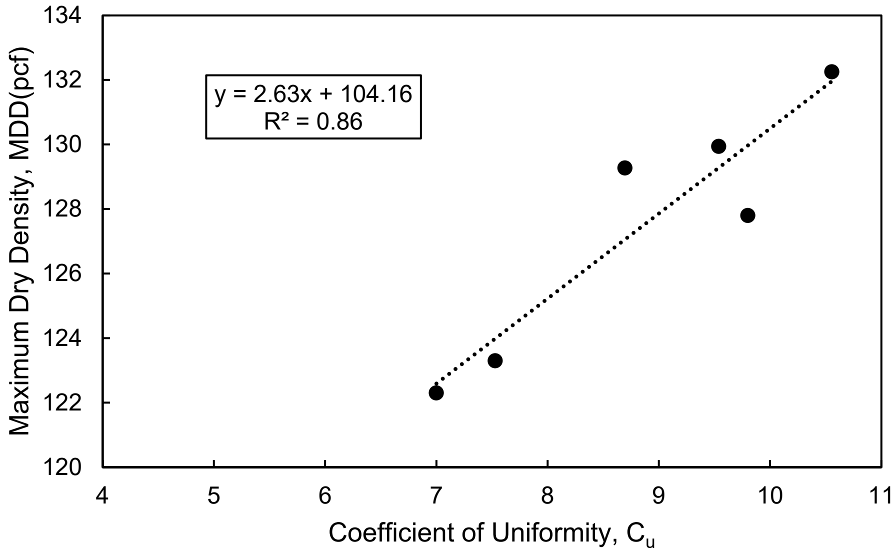


Figure 3.36 Comparison of District 6 C_u values to MDD.

Table 3.17 Comparison of C_u to MDD.

RAP Source	C_u	MDD (pcf)
Malvern	7.0	122.3
Erie	7.5	123.3
Highway Materials	8.7	129.3
Delaware Valley Asphalt	9.5	129.9
Glasgow	10.6	132.3
Glen Mills	9.8	127.8

The coefficient of uniformity provides an indication of how well-graded a material is, with a high C_u value indicating a well-graded material, and a low C_u value indicating a poorly-graded material. The results from this comparison show that as RAP becomes more well-graded, the MDD increases. The correlation is very strong, with an R^2 value equal to 0.86. When a material is well graded (high C_u value), there is a larger distribution in particle sizes throughout its gradation. As the material is compacted, the large range of particle sizes can fill void space which allows for the material to become denser during compaction. This results in higher overall MDD values. Coefficient of uniformity comparisons were evaluated in additional sections of this report to determine if other engineering properties provide strong correlations. This information would be valuable when providing material recommendations for non-pavement RAP applications.

It is important to note that the range of the coefficients of uniformity for RAP were from 7.0 - 10.6, which represents only a small portion of the possible C_u values. To better understand how C_u relates to MDD, sources of RAP from literature were also analyzed to develop a correlation (Rathje et al. 2002; Cosentino et al. 2003; Arulrajah et al. 2014; Mousa et al. 2021; Cooley et al. 2005; Mijic et al. 2020; Rahardjo et al. 2013). The results are shown in **Figure 3.37**.

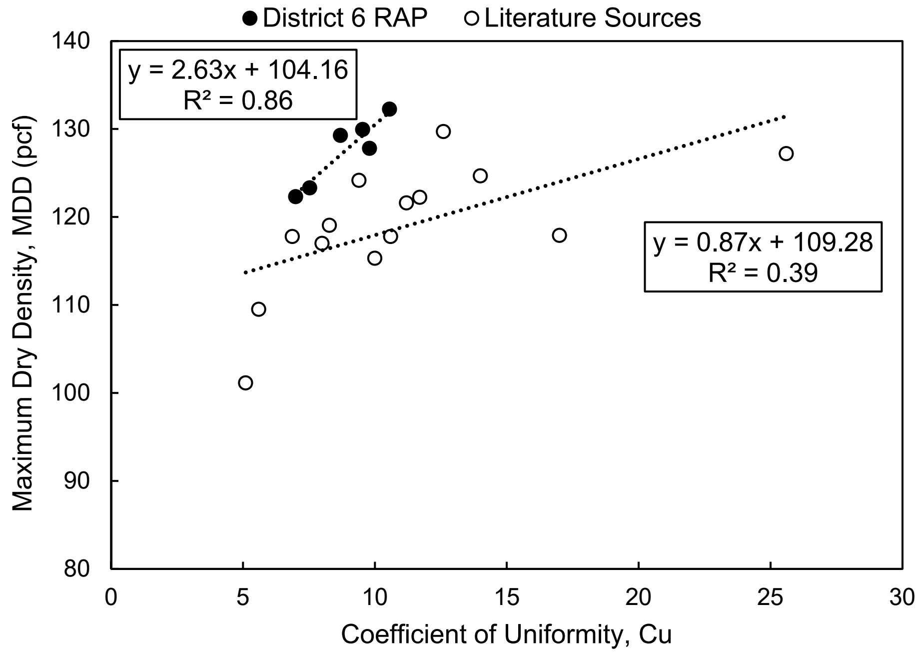


Figure 3.37 Correlation of C_u and MDD for District 6 sources and literature sources.

At a larger range of C_u values, including both District 6 sources and literature sources, the correlation between C_u and MDD followed a linear trend. It was observed that as C_u increased, the MDD increased until around a C_u value of 12. At that point, the MDD values began flattening out, showing no additional improvement in MDD as the RAP became very well-graded.

3.4.2 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (k_{sat}) is a measure of the rate in which water moves through saturated soil. The k_{sat} value can vary significantly due to the milling process and the storage of RAP. Both the milling and the storage of RAP can have a direct impact on the fines content, and thus the ability of the RAP to conduct liquid.

3.4.2.1 Methods

The saturated hydraulic conductivity (k_{sat}) was determined using constant-head hydraulic conductivity tests in general accordance with ASTM D2434 (ASTM 2019). Prior to hydraulic conductivity testing, samples of RAP were compacted to 95% MDD in a 6-inch compaction mold utilizing the modified proctor compaction method. After compaction, filter paper and porous stones were placed on the top and bottom of the specimen, and the specimen was attached to the constant-head testing apparatus. The length of the specimen along the path of flow was measured to be 11.9 cm. The specimen was placed at an elevation such that the hydraulic head difference was 30.5 cm. This resulted in a hydraulic gradient (i) of 2.6. Tubing was attached to the permeameter so water flowed from the bottom of the specimen to the top. The constant-head test set-up is shown in **Figure 3.38**.

The water level in the graduated cylinder was measured at either 2-minute intervals or 5-minute intervals until four readings in a row were within 25% of the average of the previous four readings, there was no observable upward or downward trend in the calculated k_{sat} values, and more than one pore volume of flow (PVF) had been completed.

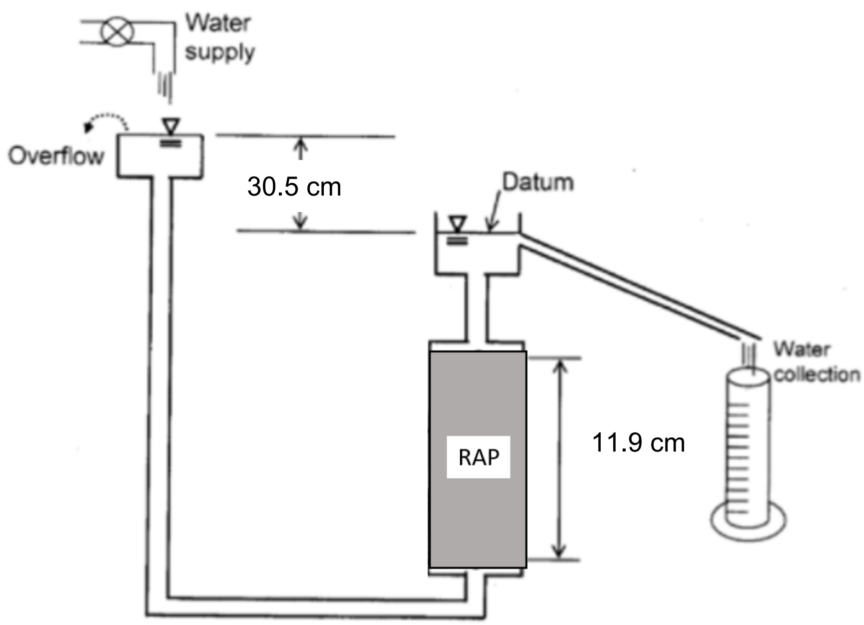


Figure 3.38 Constant-head test set-up.

3.4.2.2 Results

A minimum of two k_{sat} tests were performed on each RAP material. The average k_{sat} value for each material was compared to the Casagrande and Fadum (1940) standard for free draining material. Casagrande and Fadum (1940) stated that a material could be considered free draining if it had a k_{sat} value larger than 1 x 10^{-4} cm/s. This was used as the standard for evaluating the k_{sat} values of RAP. **Table 3.18** compares the k_{sat} values of each RAP material to the Casagrande and Fadum (1940) standard.

Table 3.18 Comparison of k_{sat} values to Casagrande and Fadum (1940) standard.

RAP Source	k_{sat} (cm/s)	Casagrande and Fadum (1940) Drainage Classification
Malvern	6.9 x 10^{-3}	Free Draining
Erie	7.6 x 10^{-3}	Free Draining
Highway Materials	5.8 x 10^{-4}	Free Draining
Delaware Valley Asphalt	8.9 x 10^{-4}	Free Draining
Glasgow	2.2 x 10^{-4}	Free Draining
Glen Mills	1.7 x 10^{-3}	Free Draining

All the k_{sat} values are categorized as free draining. It is important to note that the Malvern, Erie, and Delaware Valley Asphalt RAP were scalped down to size of ½ inch. As previously mentioned, it was difficult to compact specimens with particle sizes larger than ½ inch. Water freely drained through the material and was not retained in the mold when large particles were present. Therefore, for k_{sat} testing, scalping was conducted on the materials with a nominal maximum particle size of 2 inches. It is expected that k_{sat} values for the full gradation of these materials would be higher due to additional void space provided by the larger particles. Evaluating the drainage characteristics of the scalped gradation was deemed allowable because it is more conservative than what the conditions would be in the field.

3.4.2.3 Discussion

The free draining nature of District 6 RAP is ideal for embankment and fill applications. Free drainage must be maintained to prevent the buildup of pore water pressure in embankments and retaining walls. Because all sources of RAP were found to be free draining, pore water pressure buildup is unlikely to be issue. Free drainage is common in coarse-grained materials, and based on the laboratory results, RAP is considered free draining making it a suitable candidate for embankment and fill applications.

3.4.2.3.1 Saturated Hydraulic Conductivity Compared to Literature

The results from hydraulic conductivity testing are consistent with values found in literature. Like District 6 RAP, all literature sources were free draining, with k_{sat} values larger than 1.0 x 10^{-4} cm/s (Arulrajah et al. 2013; Cosentino et al. 2003; Locander 2009; Mijic et al. 2020; Mousa et al. 2021; Rathje et al. 2002; Seybou-Insa et al. 2021; Shedivy et al. 2012). The range of k_{sat} values from literature are from 10^{-4} to 10^{-1} cm/s, and the District 6 RAP falls within this range as shown in **Table 3.19**.

Table 3.19 Comparison between RAP from literature and District 6 for k_{sat}.

RAP Source		k_{sat} (cm/s)
Literature	Bennert and Maher (2005)	6.0 x 10^{-3}
	Cosentino et al. (2003)	2.0 x 10^{-4}
	Shedivy et al. (2012)	3.8 x 10^{-3}
		8.3 x 10^{-3}
		2.2 x 10^{-3}
		3.7 x 10^{-2}
	Mijic et al. (2020)	9.8 x 10^{-3}
		5.7 x 10^{-2}
		1.1 x 10^{-1}
		2.5 x 10^{-2}
		6.9 x 10^{-3}
		2.0 x 10^{-2}
		5.3 x 10^{-2}
	Mousa et al. (2021)	3.3 x 10^{-2}
District 6	Malvern	6.9 x 10^{-3}
	Erie	7.6 x 10^{-3}
	Highway Materials	5.7 x 10^{-4}
	Delaware Valley Asphalt	8.9 x 10^{-4}
	Glasgow	2.2 x 10^{-4}
	Glen Mills	1.7 x 10^{-3}

3.4.2.3.2 Saturated Hydraulic Conductivity and Coefficient of Uniformity Correlation

Like compaction, there is a strong correlation between k_{sat} values and C_u values. As the C_u values increased, meaning the RAP became more well-graded, the k_{sat} values decreased. This was as expected because there is less void space for water to flow through in a well-graded material. Similarly, the higher MDD of the RAP, the lower the k_{sat} value. MDD also has a correlation with C_u, therefore when the coefficient of uniformity, the compaction characteristics, or the saturated hydraulic conductivity of a source of RAP is known, it can be used to predict the other characteristics of the material. All three characteristics are correlated to of each other. The comparison of k_{sat} and C_u is shown in **Figure 3.39** and the comparison of k_{sat} and MDD is shown in **Figure 3.40**. **Table 3.20** summarizes the values for each source of RAP.

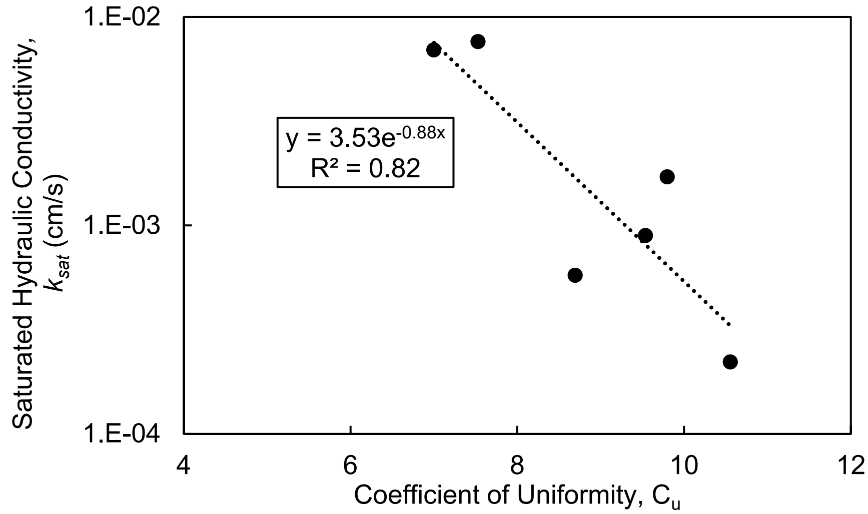


Figure 3.39 Comparison of k_{sat} value and C_u values from all sources of RAP.

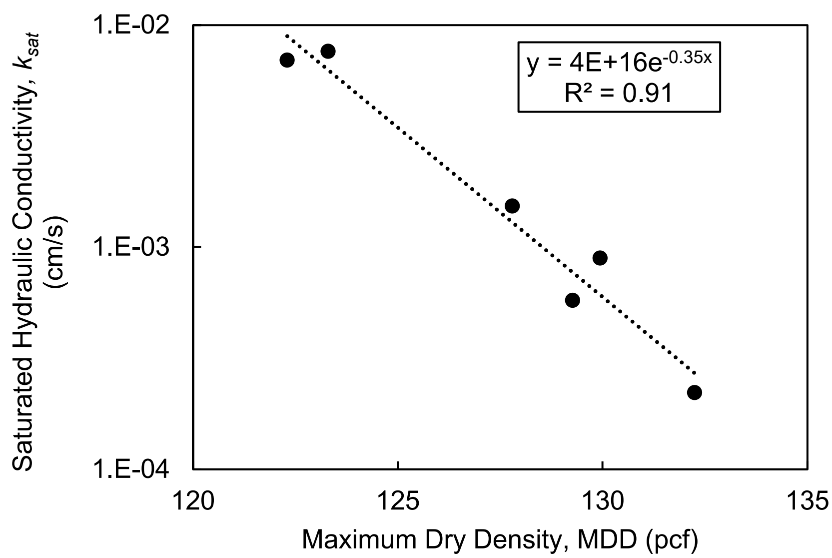


Figure 3.40 Comparison of k_{sat} value and MDD values from all sources of RAP.

Table 3.20 Summary of k_{sat}, C_u, and MDD values from all sources of RAP.

RAP Source	C_u	k_{sat} (cm/s)	MDD (pcf)
Malvern	7.0	6.9 x 10^{-3}	122.3
Erie	7.5	7.6 x 10^{-3}	123.3
Highway Materials	8.7	5.8 x 10^{-4}	129.3
Delaware Valley Asphalt	9.5	8.9 x 10^{-4}	129.9
Glasgow	10.6	2.2 x 10^{-4}	132.3
Glen Mills	9.8	1.7 x 10^{-3}	127.8

Like the C_u comparison with MDD, it is important to note that the range of coefficients of uniformity for RAP were from 7.0 - 10.6, which represents only a small portion of the possible C_u values. To better understand how C_u relates to k_{sat}, sources of RAP from literature were also analyzed to develop a correlation (Arulrajah et al. 2013; Bennert and Maher 2005; Cosentino et al. 2003; Mijic et al. 2020; Mousa et al. 2021. The results are shown in **Figure 3.41**.

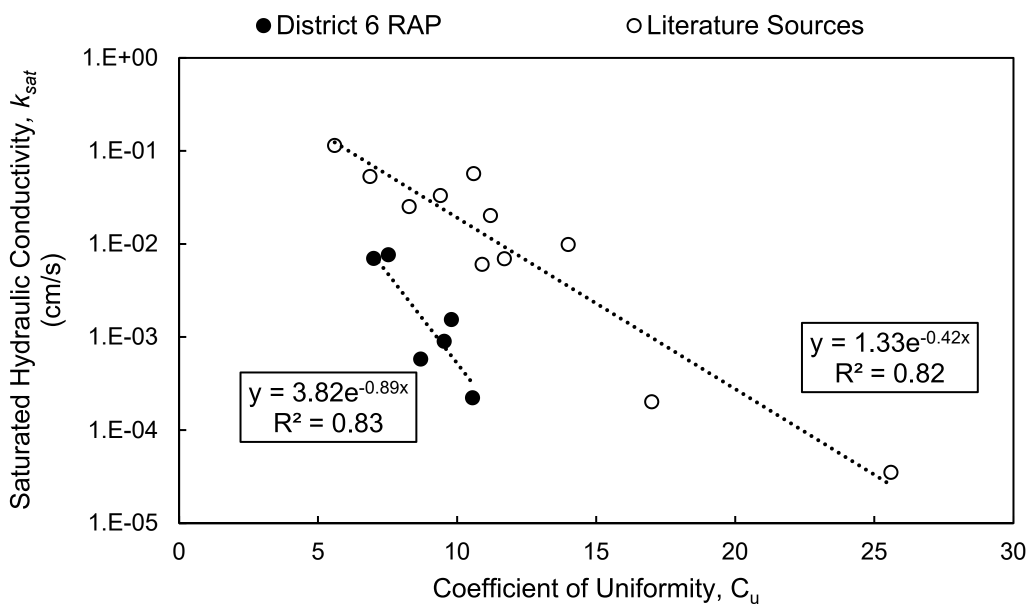


Figure 3.41 Correlation of C_u and k_{sat} for District 6 sources and literature sources.

At a larger range of C_u values, including both District 6 sources and literature sources, the correlation between C_u and k_{sat} followed a power trend. It was observed that as C_u increased, the k_{sat} decreased. This was as expected because when RAP is well-graded, more void spaces are being filled, making it harder for liquid to flow through. Although this trend was observed, RAP is typically free draining at higher C_u values, making it a suitable candidate for embankment/fill material.

3.4.3 Triaxial Shear Testing

Triaxial shear testing was conducted to determine the strength properties of RAP. High shear strength is necessary in non-pavement applications to provide stability. Oftentimes, loads are applied to these structures, therefore it is critical that the fill material has high strength characteristics to be able to withstand these loads.

3.4.3.1 Methods

Consolidated Drained (CD) triaxial tests were conducted on Malvern, Erie, Delaware Valley Asphalt, and Glasgow RAP in general accordance with ASTM D7181 (ASTM 2020). CD triaxial tests were selected due to the commonality in literature, as well as the tendency of RAP to be in the drained condition in the field. When running CD triaxial tests, the specimen must be fully saturated, and the two testing stages are consolidation and shearing.

3.4.3.1.1 Specimen Preparation

To prepare the RAP samples for testing, RAP was compacted in 3-inch diameter, 6-inch-tall cylindrical compaction mold using the standard proctor hammer to at least 95% of the MDD. This was achieved by soaking the RAP overnight in water to achieve the OMC, and then compacting the sample with 15 drops of the hammer, in approximately 7 equal lifts. After compaction, the specimen was extracted into a latex membrane using a hydraulic jack. The specimen was weighed, and four diameter and height measurements were taken at different locations along the specimen. Filter paper and porous stones were placed on the bottom and top of the specimen, and the specimen was placed on the bottom pedestal of the triaxial chamber. The top pedestal with holes for the drainage lines was placed on top of the specimen, and three O-rings were rolled over the membrane on the top and bottom to keep a tight seal between the membrane and the pedestals. The initial specimen set up is shown in **Figure 3.42**. Drainage lines were attached to the top pedestal and the triaxial chamber was filled with distilled water. The top cap was then placed over the chamber and the entire set-up was attached to a water panel. Pore pressure and cell pressure transducers were attached to the triaxial chamber.

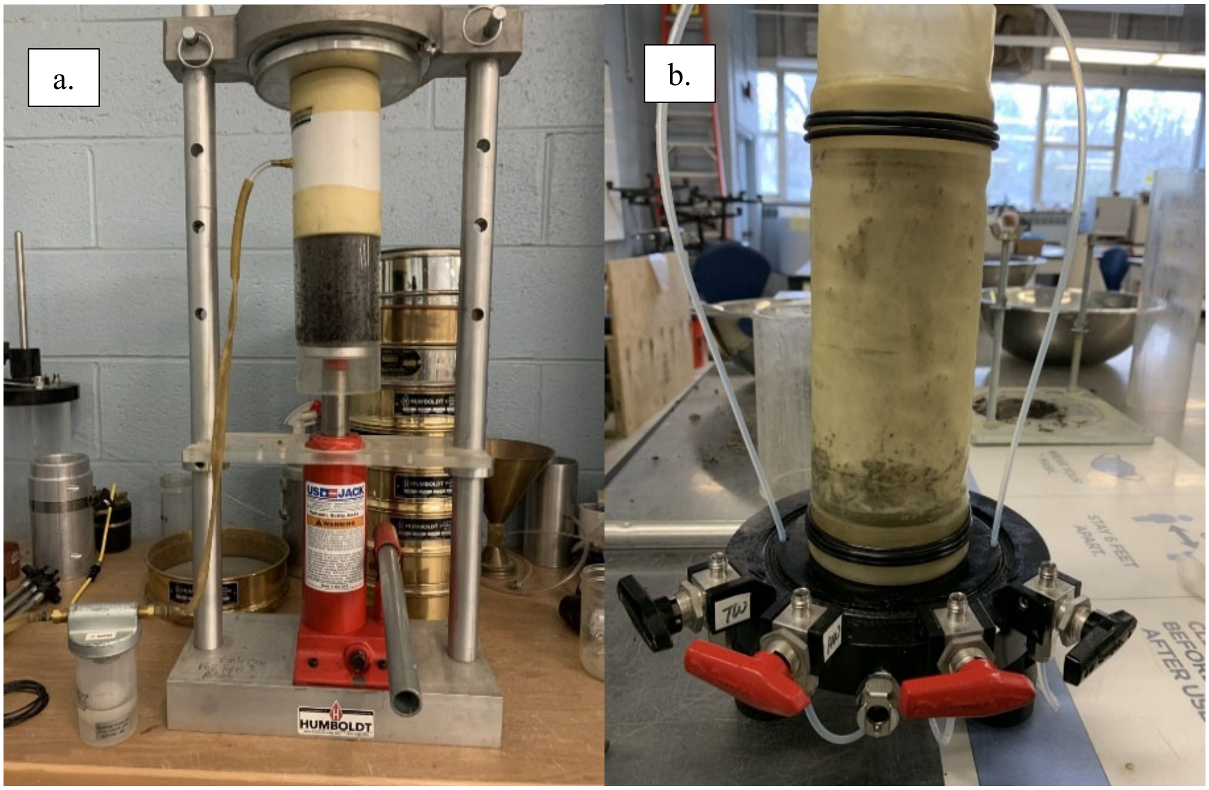


Figure 3.42 (a) Sample extruder pressing RAP sample of out mold and into a membrane stretcher. (b) Sample inside membrane and placed on triaxial pedestal (Morro 2021).

3.4.3.1.2 Saturation

Before consolidation and shearing tests were performed, the specimen had to be fully saturated. Saturation is required to ensure that all void spaces are filled with water and that the drainage lines are deaired. To achieve this, back pressure saturation was utilized. This involved increasing the cell and back pressures while maintaining the same effective stress. For this procedure, the effective stress was maintained at 3.4 kPa (71 psf). The effective stress was kept at a low value to ensure that over-consolidation did not occur within the specimen. Initially, the cell pressure started at 34.5 kPa (721 psf) and the back pressure started at 31 kPa (647 psf). The specimen was allowed to sit at these pressures for some time, and the degree of saturation was checked using Skempton's B-value.

The B-value provides an indication of saturation, and a B-value of 0.95 is generally accepted as fully saturated. In practice, achieving B-value of 0.95 is difficult, therefore achieving a B-value of 0.90 was considered acceptable in the laboratory (Rees 2013). To check the B-value, the drainage lines were closed, and the cell pressure was raised by 69 kPa (1441 psf). The Geojac triaxial device's B-check test was utilized, and this measured the change in pore pressure versus the change in cell pressure. Ideally, the change in pore pressure should be equal to the change in cell pressure, and this would provide a B-value equal to 1. If the B-check resulted in a B-value less than 0.90, back pressure saturation had to continue at higher pressures. To do this the drainage lines are reopened, and the back pressure was raised by 69 kPa (1441 psf) to maintain the 3.4 kPa (71 psf) effective stress with the cell pressure. Again, the specimen was allowed to sit at these pressures for some time, and the B-value was checked again. The process of raising the cell and back pressure by 69 kPa (1441 psf) and checking the B-value continued until a B-value of 0.90 is achieved. For RAP, it was found that typically the saturation process takes around 2 hours, and the final cell and back pressure generally ended at 370 kPa (7732 psf) and 376 kPa (7849 psf).

3.4.3.1.3 Consolidation

Once saturation was complete, the consolidation phase of triaxial testing began. Three different consolidation stresses were used for the CD triaxial testing: 50 kPa (1044 psf), 100 kPa (2088 psf), and 200 kPa (4177 psf). To consolidate at these pressures, the back pressure remained at the same pressure it ended at during saturation, and the cell pressure was raised to apply an effective stress equal to the desired consolidation stress. Once the effective stress was set at its desired level, the backpressure valves on the triaxial chamber were opened and the water panel was turned on. Consolidation was terminated when it was visually observed that the pore pressure transducer readings and the cell pressure transducer readings had a difference equal to the effective stress that was applied to the specimen. This indicated that all the excess pore pressure had dissipated from the water by transferring to the soil specimen. For RAP, it was observed that consolidation occurred within 30 seconds after the consolidation pressure was applied. This was likely due to the high drainage capabilities of the material. A RAP specimen during the consolidation is shown in **Figure 3.43**.

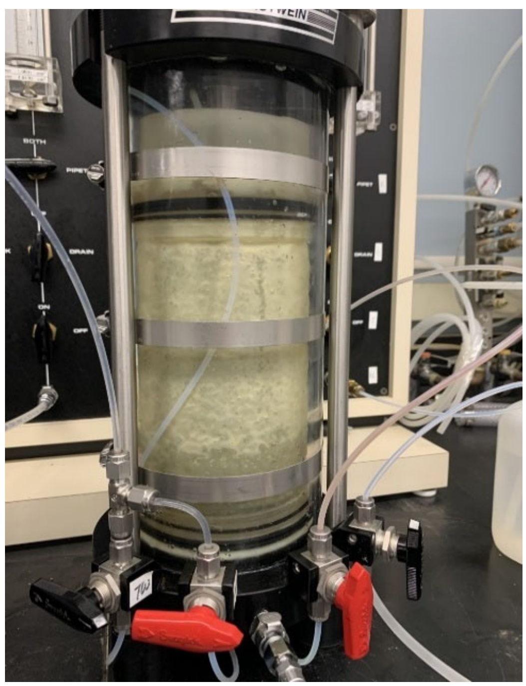


Figure 3.43 RAP triaxial specimen during consolidation (Morro 2021).

3.4.3.1.4 Shear Testing

After consolidation, the shearing phase of triaxial testing could begin. The rate at which shearing occurred was based on the time it took for consolidation. The strain rate was calculated using the following equation:

$$\mathcal{E} = \frac{4\%}{10t_{90}}$$

Where:

$\mathcal{E}$ = strain rate (%/min)

t_{90} = time to 90% consolidation

For RAP, 100% consolidation generally occurred in 30 seconds. Based on the equation, this would calculate the strain rate to be 53.3%/hr. To be conservative, the strain rate of 30%/hr was used to prevent the buildup of pore pressure. Once the strain rate was determined, the triaxial chamber was placed underneath the GeoJac shear system and the system was lowered until it was 2 mm above the piston that was attached to the triaxial top cap. The strain rate, the specimen diameter, the specimen height, and the maximum axial strain at failure (20%) were inputted into the GeoJac computer system and the piston was released. The valves on the triaxial chamber remained open and the water panel was turned on. At this point shearing began.

During shearing, the pore pressure was continually monitored to ensure that no excess pore pressure was generated. The shear test continued until the maximum axial strain of 20% was attained. Based on the shear rate, the shear tests typically lasted 40 minutes. For Malvern, Erie, Delaware Valley Asphalt, and Glasgow RAP, three shear tests were run at different consolidation stresses (50 kPa, 100 kPa, 200 kPa) to develop a Mohr's circle. The Mohr's circle was used to determine the material's friction angle and cohesion.

3.4.3.2 Results

CD triaxial tests at three different consolidation stresses (50 kPa, 100 kPa, 200 kPa) were used to develop Mohr's circles for Malvern, Erie, Delaware Valley Asphalt, and Glasgow RAP. AutoCAD was used to draw the Mohr's circles to scale, and the equation of a line running tangent to the three circles provided the friction angle and cohesion of each RAP source. **Figures 3.44** – **3.47** show the Mohr's circles from the four sources of RAP that were tested. **Table 3.21** summarizes the friction angles and cohesion values from each RAP source.

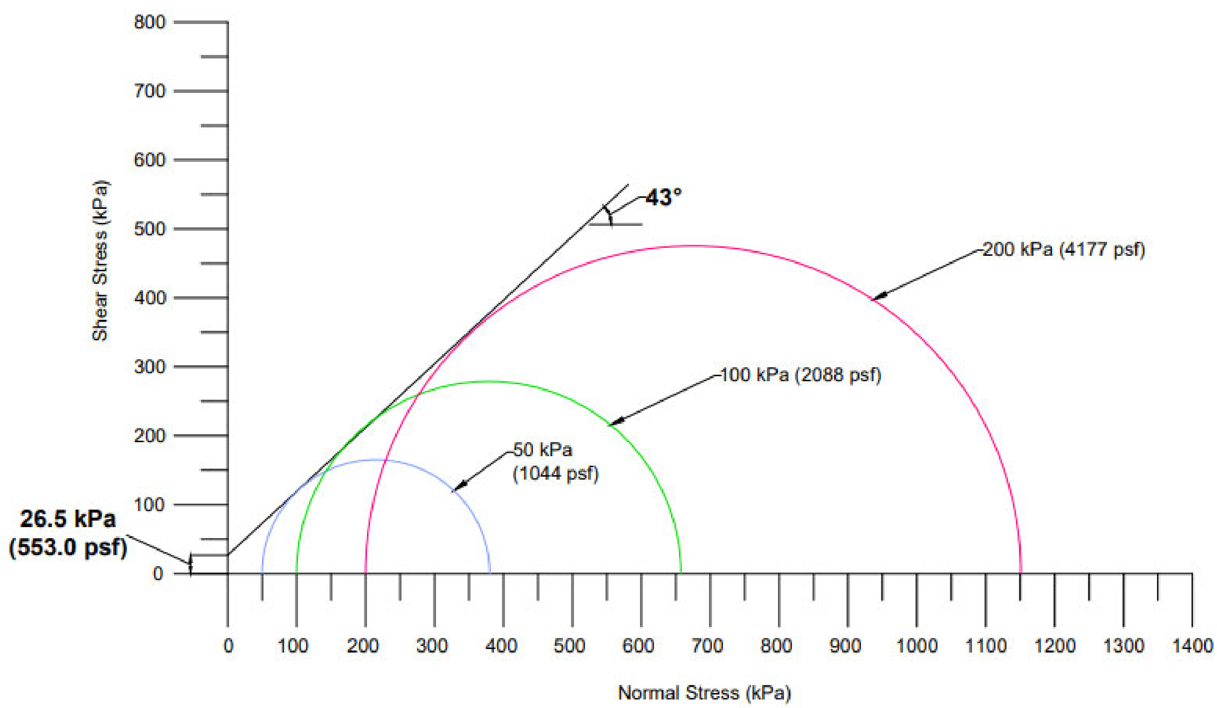


Figure 3.44 Malvern RAP Mohr's circles.

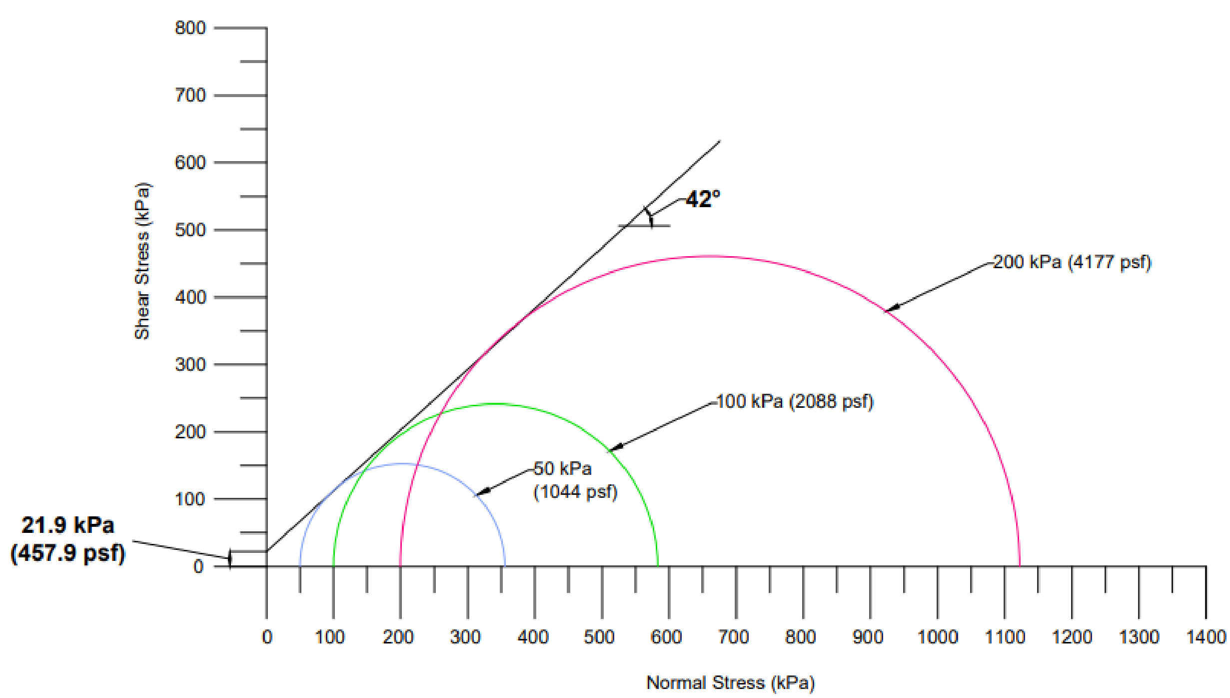


Figure 3.45 Erie RAP Mohr's circles.

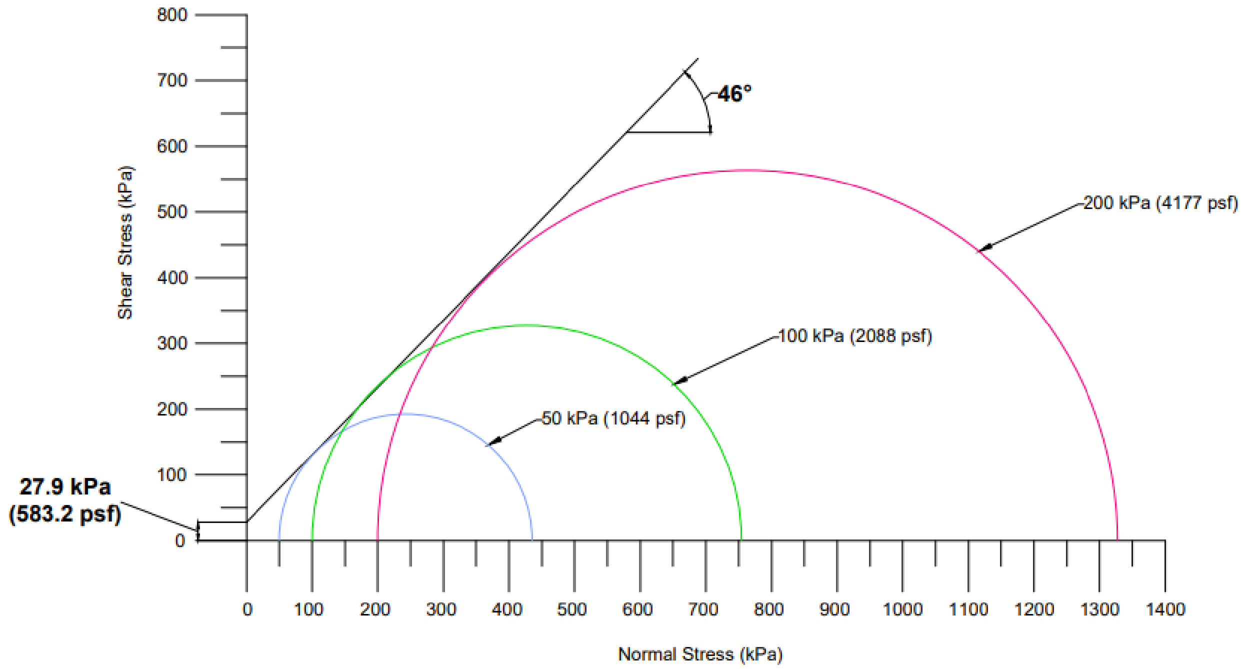


Figure 3.46 Delaware Valley Asphalt RAP Mohr's circles.

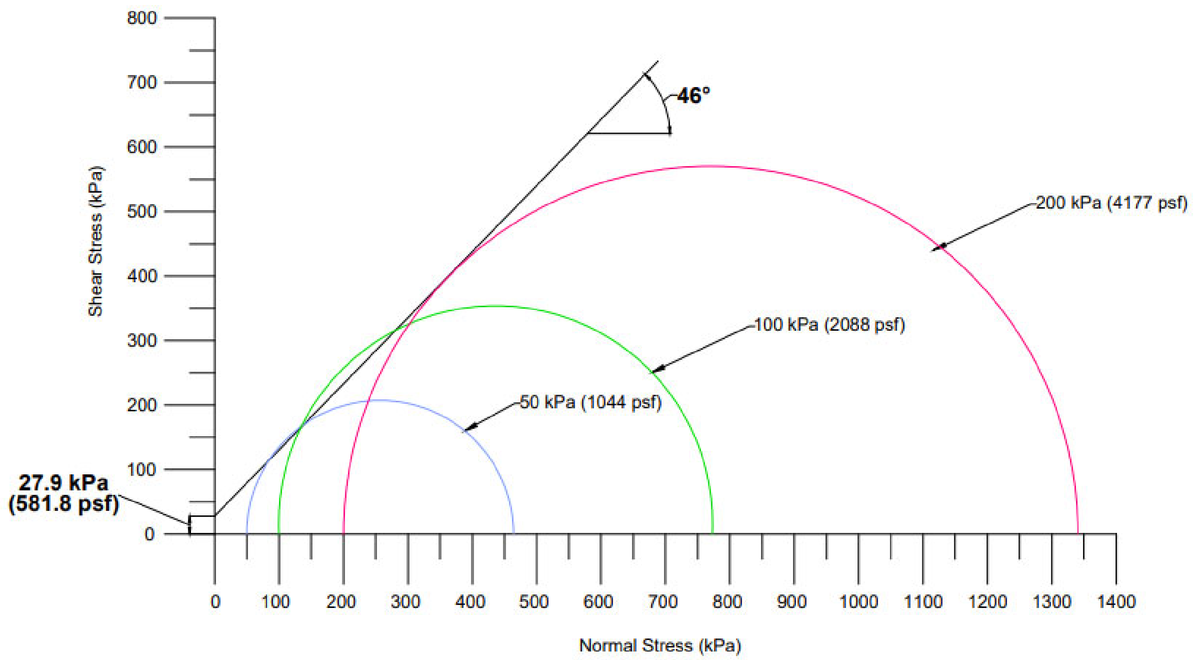


Figure 3.47 Glasgow RAP Mohr's circles.

Table 3.21 Friction angle and cohesion from the RAP sources.

RAP Source	Friction Angle (deg.)	Cohesion (psf)
Malvern	43	553
Erie	42	458
Delaware Valley Asphalt	46	583
Glasgow	46	582

3.4.3.3 Discussion

The friction angles identified during triaxial shear testing ranged from 42 - 46 degrees. The friction angles are large, indicating that RAP has high shear strength properties. High shear strength is necessary in embankment and fill applications to withstand heavy traffic or structural loads. Typically, coarse aggregate material displays high shear strength characteristics, and because RAP displays similar behavior, this makes RAP suitable for use in embankment and fill applications. The values of cohesion for RAP ranged from 457 to 583 psf. Overall, the values of cohesion are considered low, and this can be attributed to the asphalt binder content of RAP.

3.4.3.3.1 Friction Angle Compared to Literature

The results from District 6 RAP were similar to results from literature. Literature results from CD triaxial tests found friction angles ranging from 37 – 52 degrees, with an average value of 42 degrees (Arulrajah et el. 2013; Bejarano et al. 2001; Cosentino et al 2003; Rahardjo et al. 2013; Rathje et al. 2002). The values of cohesion from literature were much more variable than District 6 RAP, with values ranging from 0 psf – 1153 psf. The cohesion values from District 6 RAP fell within the range from literature. The large range for cohesion is likely due to the interpretation of laboratory data. Friction angles are determined by Mohr's Circles, and commonly, Mohr's circles for RAP can be drawn by both considering cohesion and not considering cohesion. This likely attributed to the variability of results. The literature comparison is provided in **Table 3.22**.

Table 3.22 Comparison of literature and District 6 RAP friction angle and cohesion values from CD triaxial tests.

Source		Test	Friction Angle (deg.)	Cohesion (psf)
Literature	Arulrajah et al. 2013	Consolidated Drained	37	1107
	Rathje et al. 2002	Consolidated Drained	37	1153
	Rahardjo et al. 2013	Consolidated Drained	42	0
	Cosentino et al. 2003	Consolidated Drained	44	708
	Bejanaro et al. 2001	Consolidated Drained	52	0
District 6 RAP	Malvern	Consolidated Drained	43	553
	Erie	Consolidated Drained	42	458
	Delaware Valley Asphalt	Consolidated Drained	46	583
	Glasgow	Consolidated Drained	46	582

3.4.3.3.2 Friction Angle and Coefficient of Uniformity Correlation

For friction angle, as observed in **Figure 3.48**, literature studies did not provide a clear correlation within the data, therefore a trendline was not applied. In general, the data showed a positive trend until a C_u value of around 12, where the trend becomes negative (Arulrajah et el. 2013; Bejarano et al. 2001; Bennert and Maher 2005; Cosentino et al 2003; Ma et al. 2015; Mousa et al. 2021; Rahardjo et al. 2013; Rathje et al. 2002). This would indicate that well-graded materials provide an increase in strength characteristics until a point where the well-graded nature of the material begins to reduce the strength of the material. More data is needed to strengthen this correlation. Only two studies reported C_u values larger than 12. If results from those studies were removed, there is a strong positive trend within literature, where increasing C_u values correlate to increasing friction angle values. When evaluating the District 6 RAP data, the strong positive trend is also observed. Additional studies on well-graded RAP with high C_u values are necessary to definitively identify potential trends with friction angle.

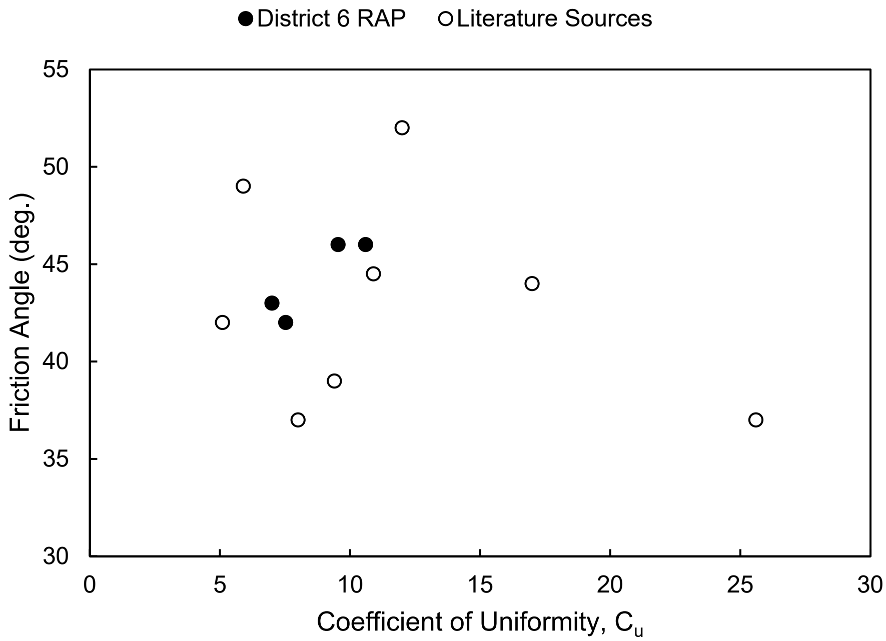


Figure 3.48 Correlation of C_u and friction angle for District 6 sources and literature sources.

3.5 Creep

Many literature studies have found that RAP creeps at an excessive rate (Rathje et al. 2006; Cosentino et al. 2003; Yin et al. 2016). Creep testing was conducted to determine the extent of RAP's creep, and to evaluate the different methods for reducing RAP's creep. Creep tests were conducted using two methods. The first method utilized a CD triaxial set-up. The second method utilized a 6-inch compaction mold and free weights. The two different testing methods were conducted to evaluate how different conditions affected rate of creep of RAP.

3.5.1 CD Triaxial Creep Tests

CD triaxial creep tests were the most common testing method conducted in literature (Rathje et al. 2006; Soleimanbeigi and Edil 2015). To evaluate the variability of RAP, creep tests on District 6 RAP was run in a similar way as literature. Two methods were used to determine the shear stress selected for each creep test. The first method tested creep at 35-85% of each sources own maximum deviator stress found from triaxial shear tests. The second method ran the creep tests at a 50 kPa (1044 psf) shear stress for each material.

3.5.1.1 Percentage of Maximum Deviator Stress Testing Series

Testing RAP at various percentages of its maximum deviator stress is valuable because it gives an indication of the load limitations for RAP when creep is a concern. Evaluating the amount of deformation at different stresses can lead to conclusions about which applications/scenarios could be suitable for the reuse of RAP.

3.5.1.1.2 Methods

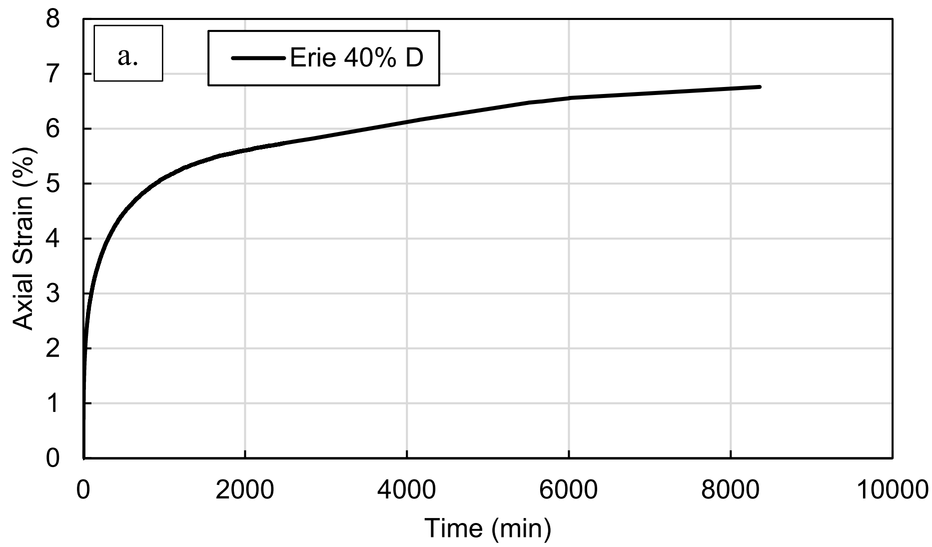
For the CD triaxial creep tests, the general set up, the saturation, and the consolidation phase were conducted in the same manner as the shear testing described in **Section 3.4.4.1**. After consolidation, creep was tested following the methodology described in Rathje et al. (2006).

Rathje et al. (2006) conducted creep tests by loading the specimen to stress levels ranging from 40% to 88% of the maximum deviator stress that was determined during shear testing. The rate at which the specimen was loaded was the same as the strain rate that was used during the shear testing to maintain consistency between procedures. Once the desired stress level was reached, the axial load was held constant. The axial load was held constant until creep rupture had occurred. If creep rupture was not observed after 7 days, the test was terminated. The axial strain rate was plotted against the log of time for each stress level and the slope of the steepest portion of each plot was used to determine the *m* value. The average *m* value from all the creep tests was found, and that value was used to determine the creep potential of RAP. Values larger than 1 indicate that a creep will approach an asymptotic value over time. Values less than one indicate that RAP will experience increasing strains over time and will eventually experience creep rupture.

Triaxial creep tests were conducted on Erie, Delaware Valley Asphalt, and Glasgow RAP. A minimum of two tests for each material were run at 30-85% of the maximum deviator stress. The tests were loaded at a strain rate of 30%/hour until the intended stress level was met. It was found that each specimen typically reached its stress level within 5 minutes of starting the creep test. The creep tests were run for 7-13 days, or until 20% axial strain had occurred.

3.5.1.1.3 Results

For Erie RAP, triaxial creep tests were run at 40% and 80% of the material's maximum deviator stress as shown in **Figure 3.49**. For 40% of the maximum deviator stress, Erie RAP reached 6.8% axial strain after 8,357 minutes (5.8 days), with deformations appearing to slow down. While deformations did slow, creep continued to occur over time. For 80% of the maximum deviator stress, Erie RAP reached 20% axial strain after around 655 minutes (10.8 hours), with deformations not appearing to slow down. Axial strain of 20% is very high, indicating that creep is a concern at high stresses. It can be concluded that at lower stresses, Erie RAP exhibited less axial strain, however 40% of the material's maximum deviator stress still exhibited creep concerns.



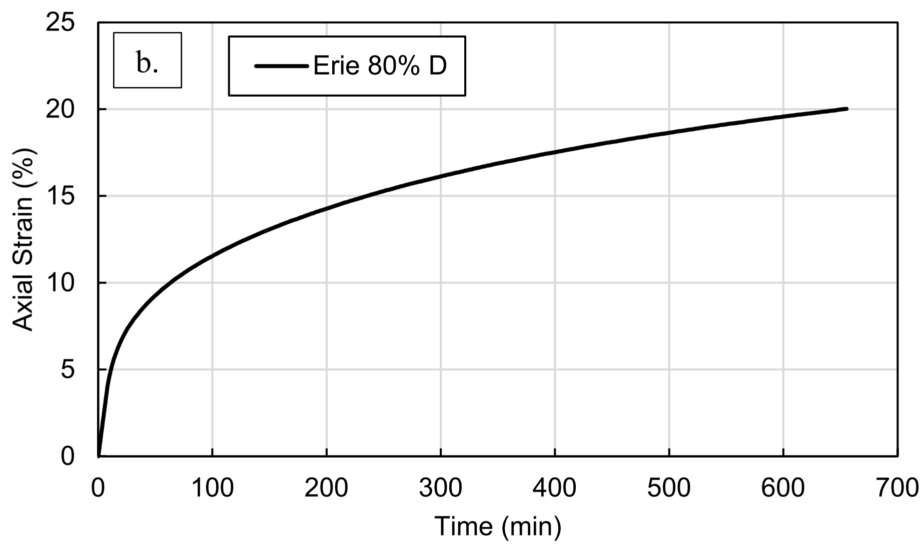


Figure 3.49 (a) Axial strain of Erie RAP at 40% of the material's maximum deviator stress and (b) axial strain of Erie RAP at 80% of the material's maximum deviator stress.

As per Rathje et al. (2006), creep tests were run at different percentages of the material's maximum deviator stress to determine the materials *m* value. For 80% and 40% of Erie's maximum deviator stress, time versus the strain rate was plotted with a power distribution in **Figure 3.50**. The slope of the power trendlines were identified as *m*, and these values are provided in **Table 3.23**.

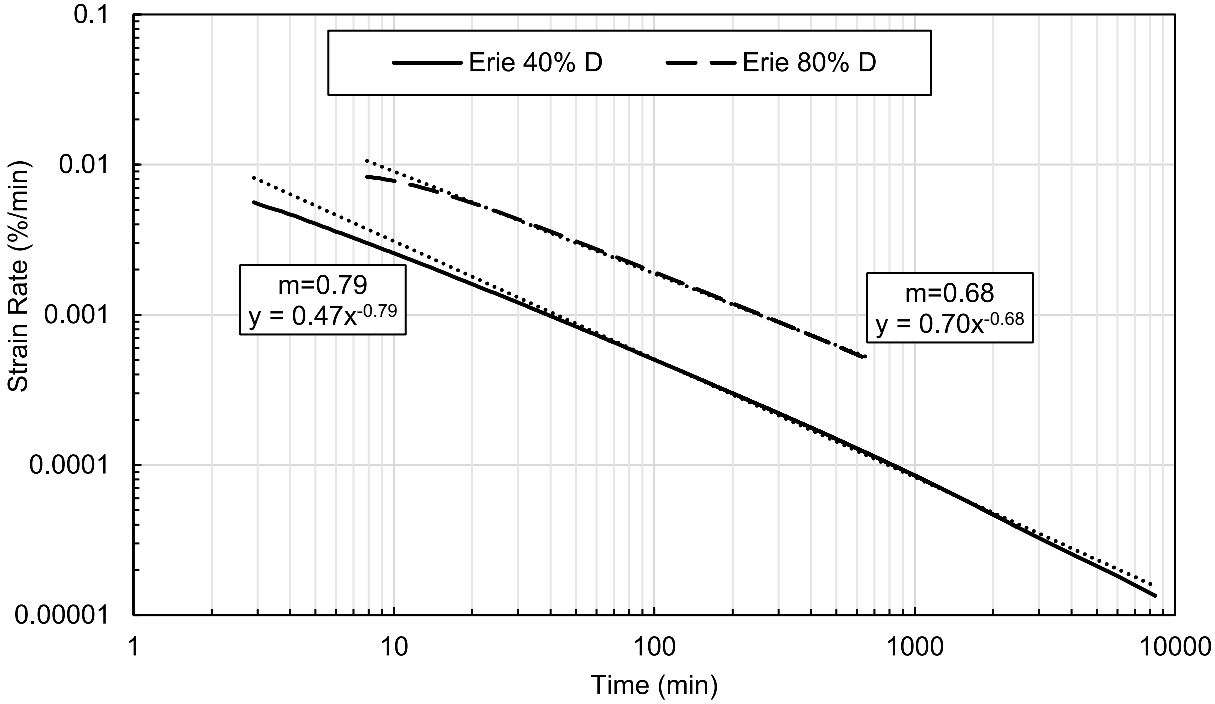


Figure 3.50 Erie RAP *m* value evaluation at 40% and 80% of the maximum deviator stress.

Table 3.23 Erie RAP *m* values.

Test	*m* value
80% D	0.68
40% D	0.79

The *m* values for Erie RAP were below 1.0, which indicates that deformations will continue over time, and eventually creep rupture will occur. The *m* value was improved at a lower percentage of the maximum deviator stress, meaning that Erie RAP crept less at lower stresses. However, it can be concluded that Erie RAP will continue to creep over time.

For Delaware Valley Asphalt RAP, triaxial creep tests were run at 40% and 70% of the material's maximum deviator stress as show in **Figure 3.51**. For 40% of the maximum deviator stress, Delaware Valley Asphalt RAP reached 6.9% axial strain after 9,038 minutes (6.3 days), and deformations did not appear to slow significantly. For 70% of the maximum deviator stress, Delaware Valley Asphalt RAP reached 14.7% axial strain after around 1,239 minutes (20.7 hours), with deformations not appearing to slow down. Axial strain of 14.7% is very high, indicating that creep is a concern at high stresses. It can be concluded that at lower stresses, Delaware Valley Asphalt RAP exhibited less axial strain, however, 40% of the material's maximum deviator stress still exhibited creep concerns.

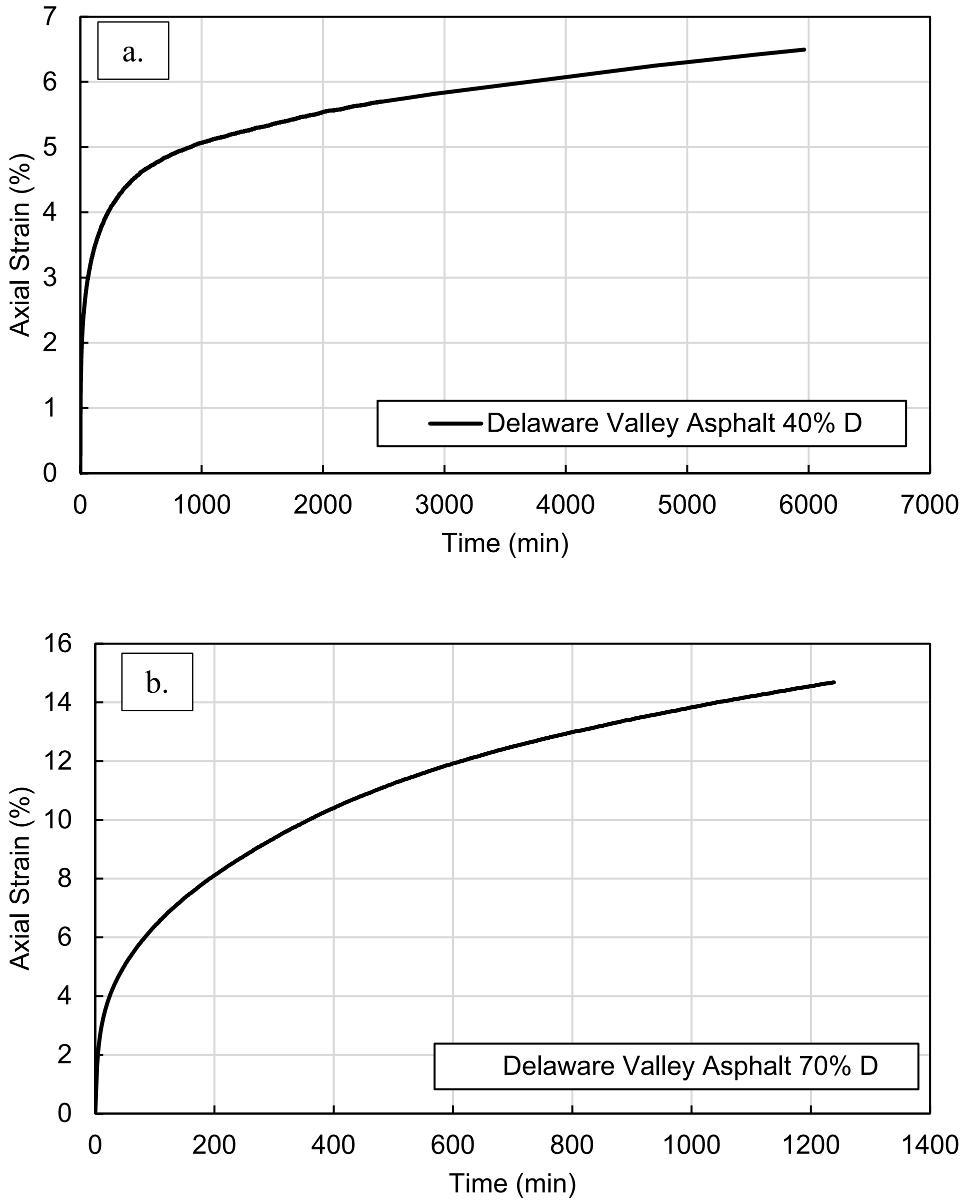


Figure 3.51 (a) Axial strain of Delaware Valley Asphalt RAP at 40% of the material's maximum deviator stress and (b) axial strain of Delaware Valley Asphalt RAP at 70% of the material's maximum deviator stress.

As previously discussed, creep tests were run at different percentages of the material's maximum deviator stress to determine the materials *m* value. For 80% and 40% of Delaware Valley Asphalt's maximum deviator stress, time versus the strain rate was plotted with a power distribution in **Figure 3.52**. The slope of the power trendlines were identified as *m*, and these values are provided in **Table 3.24**.

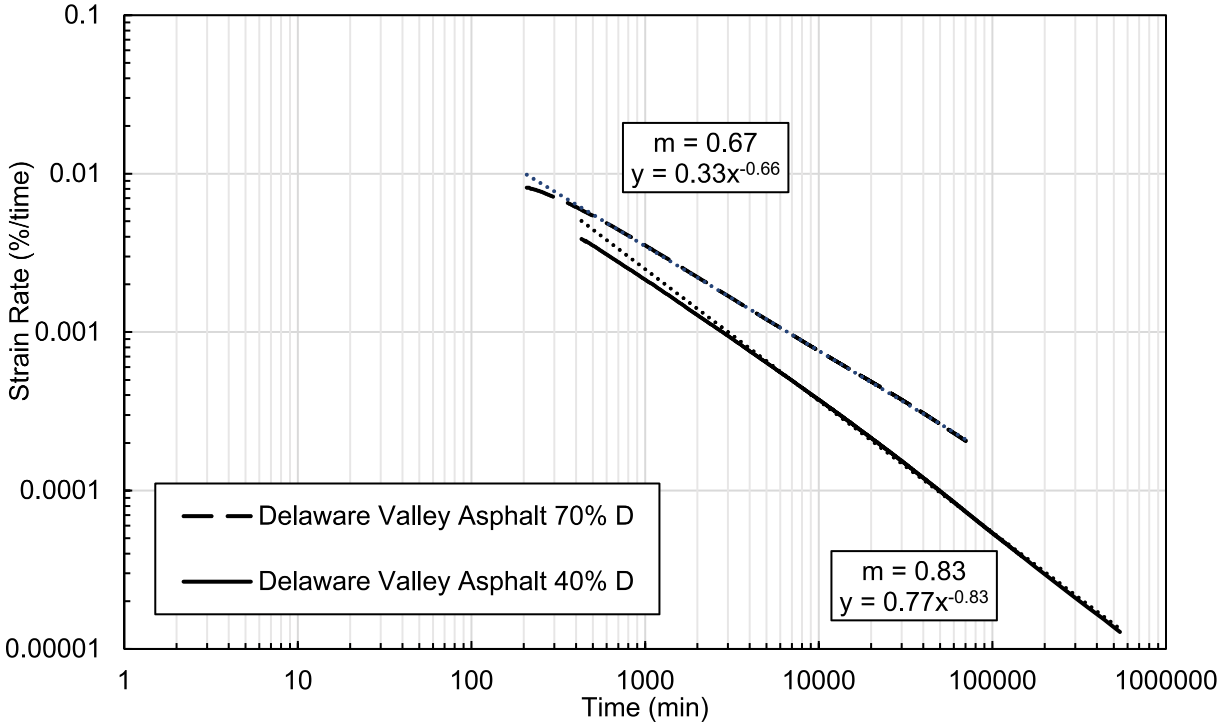


Figure 3.52 Delaware Valley Asphalt RAP *m* value evaluation at 40% and 70% of the maximum deviator stress.

Table 3.24 Delaware Valley Asphalt RAP *m* values.

Test	*m* value
70% D	0.67
40% D	0.83

The *m* values for Delaware Valley Asphalt RAP were found to be less than 1.0. Because the value was less than 1.0, this indicates that deformations will continue over time, and eventually creep rupture will occur. These results were very similar to Erie RAP, and also showed a higher *m* value at lower stresses, indicating that lower stresses reduce creep. Based on these results it can be concluded that Delaware Valley Asphalt RAP will continue to creep over time.

Glasgow RAP provided the most comprehensive data set for triaxial creep testing. Creep tests were run at 30%, 40% 60%, and 85% of the material's maximum deviator stress as show in **Figure 3.53**. At 30% of the maximum deviator stress, Glasgow RAP reached 2.6% axial strain after 12,780 minutes (8.90 days). 40% of the maximum deviator stress reached 7.4% axial strain after 18,641 minutes (12.9 days). 60% of the maximum deviator stress reached 10.1% axial strain after 6,822 minutes (4.7 days). At the highest stress level of 85% of the maximum deviator stress, 17.7% axial strain after 72 minutes (1.2 hours).

As was observed in Erie and Delaware Asphalt RAP, at lower stresses Glasgow RAP had smaller deformations. As the percentage of the maximum deviator stress increased, the amount of axial strain increased. Additionally, lower stresses showed creep slowing over time, whereas at higher stresses, creep continued to occur at a significant rate. It is important to note that even at lower stresses, creep did not stop completely, the rate just slowed down.

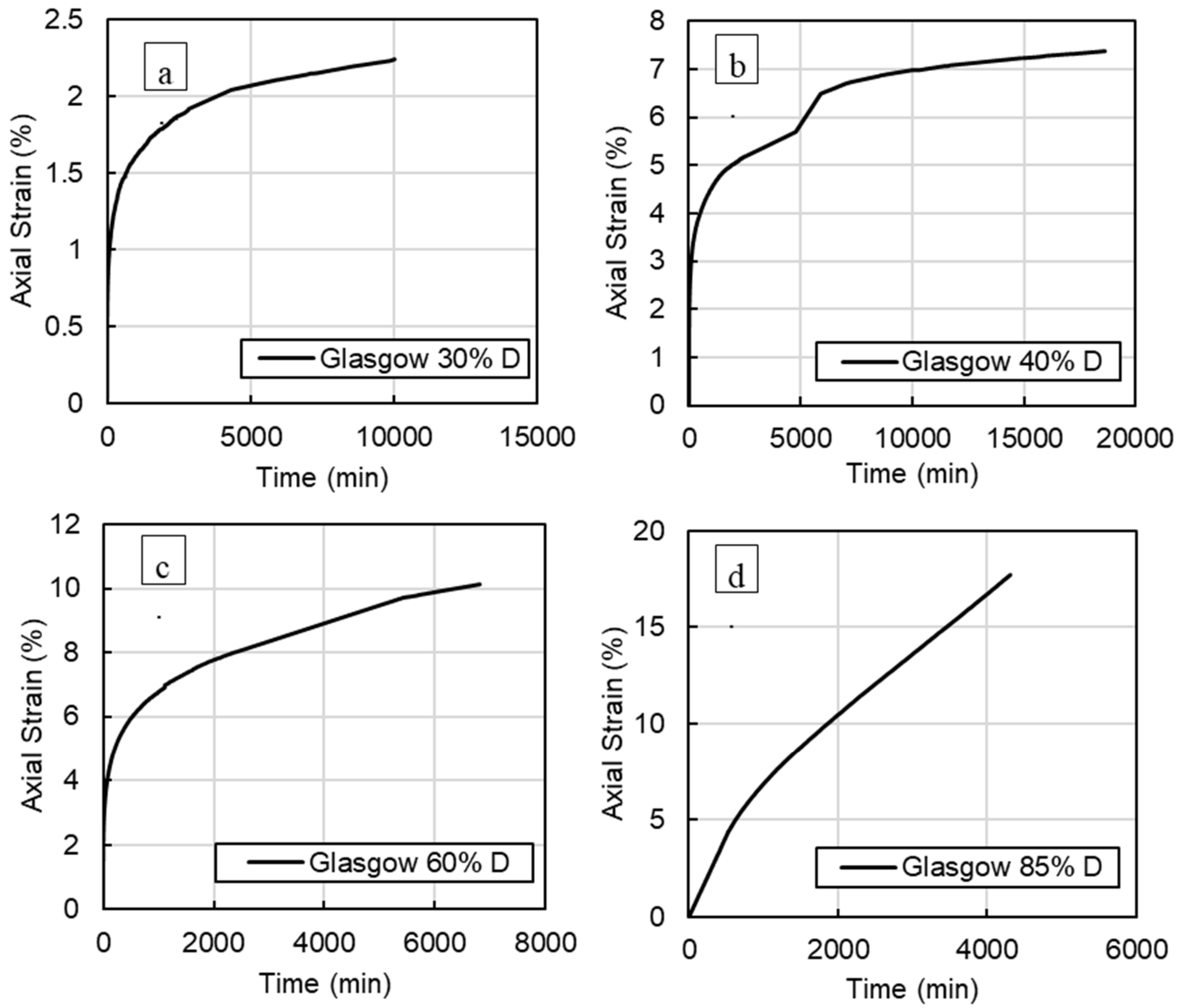


Figure 3.53 Axial strain of Glasgow Asphalt RAP at (a) 30% of the material's maximum deviator stress; (b) 40% of the material's maximum deviator stress; (c) 60% of the material's maximum deviator stress; and (d) 85% of the material's maximum deviator stress.

As previously identified in Erie and Delaware Valley Asphalt RAP, creep tests were run at different percentages of the material's maximum deviator stress to determine the materials *m* value. For 30%, 40%, 60%, and 85% of Glasgow's maximum deviator stress, time versus the strain rate was plotted with a power distribution in **Figure 3.54**. The slope of the power trendlines were identified as *m*, and these values are provided in **Table 3.25**.

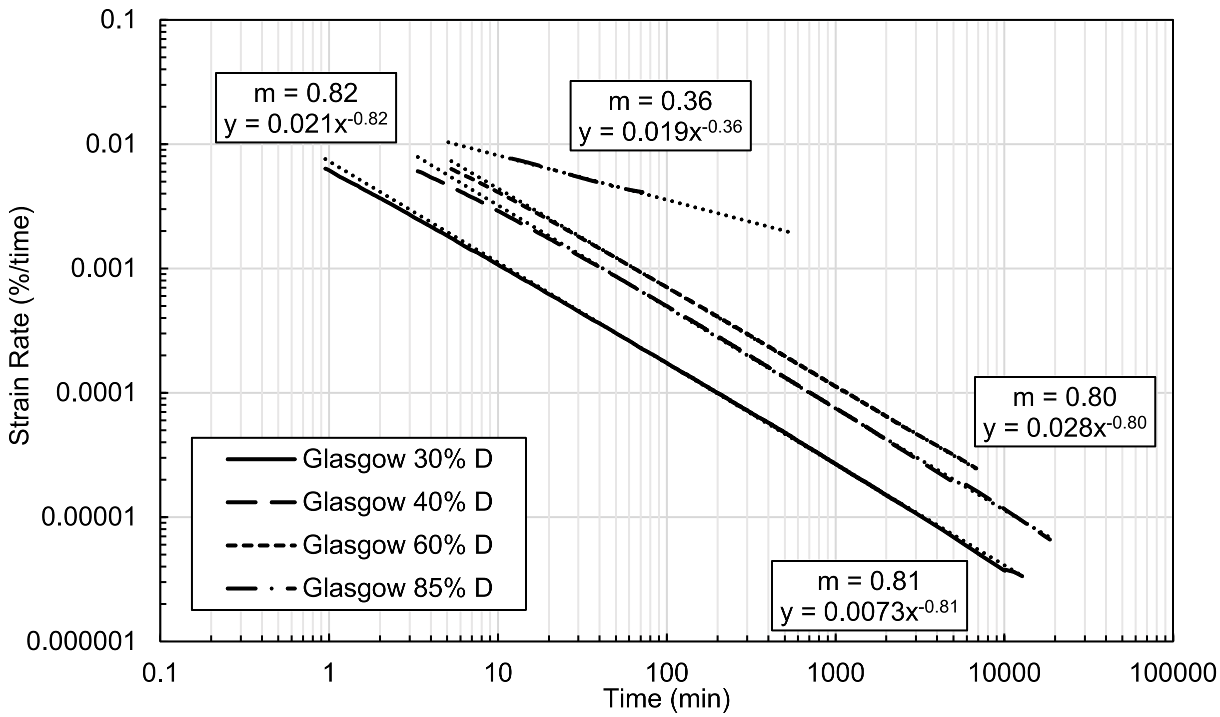


Figure 3.54 Glasgow RAP *m* value evaluation at 30%, 40%, 60%, and 85% of the maximum deviator stress.

Table 3.25 Glasgow RAP *m* values.

Test	*m* value
30% D	0.81
40% D	0.82
60% D	0.80
85% D	0.36

The *m* values for Glasgow RAP were around a value of 0.80 until 85% of the maximum deviator stress, where the *m* value was significantly decreased to 0.36. The decrease in *m* value at 85% of the maximum deviator stress represents creep rupture. This indicates that at very high stresses, Glasgow RAP experiences high deformations and will eventually fail. While creep rupture is expected at high stresses, creep is not expected to stop at lower stresses due to the *m* values being consistently less than 1.0. It can be concluded that creep is a concern in Glasgow RAP.

3.5.1.1.3 Discussion

The results from the triaxial creep tests showed that regardless of the source, RAP is highly susceptible to creep deformations. All three sources of RAP provided *m* values less than 1.0, meaning creep rupture will eventually occur. When RAP experienced lower stresses, creep was improved, but lower stresses did not eliminate the creep concern in RAP. Overall, the results from the triaxial creep testing suggest that creep is problem in RAP, and additional measures such as mixtures and thermal conditioning should be evaluated to limit creep susceptibility.

3.5.1.1.3.1 Creep Compared to Literature

Results from triaxial creep tests for District 6 RAP are similar to reported results in literature. Studies by Viyanant et al. (2007) and Soleimanbeigi and Edil (2015) conducted creep testing using the percentage of maximum deviator stress method, and these studies were directly compared to District 6 RAP. Stress levels were grouped together in the following manner: 30% - 40% D, 58% - 62% D, 70% D, 80% D, and 85% D. Both time and log time were compared to axial strain, and the comparison is shown in **Figures 3.55 – 3.59**.

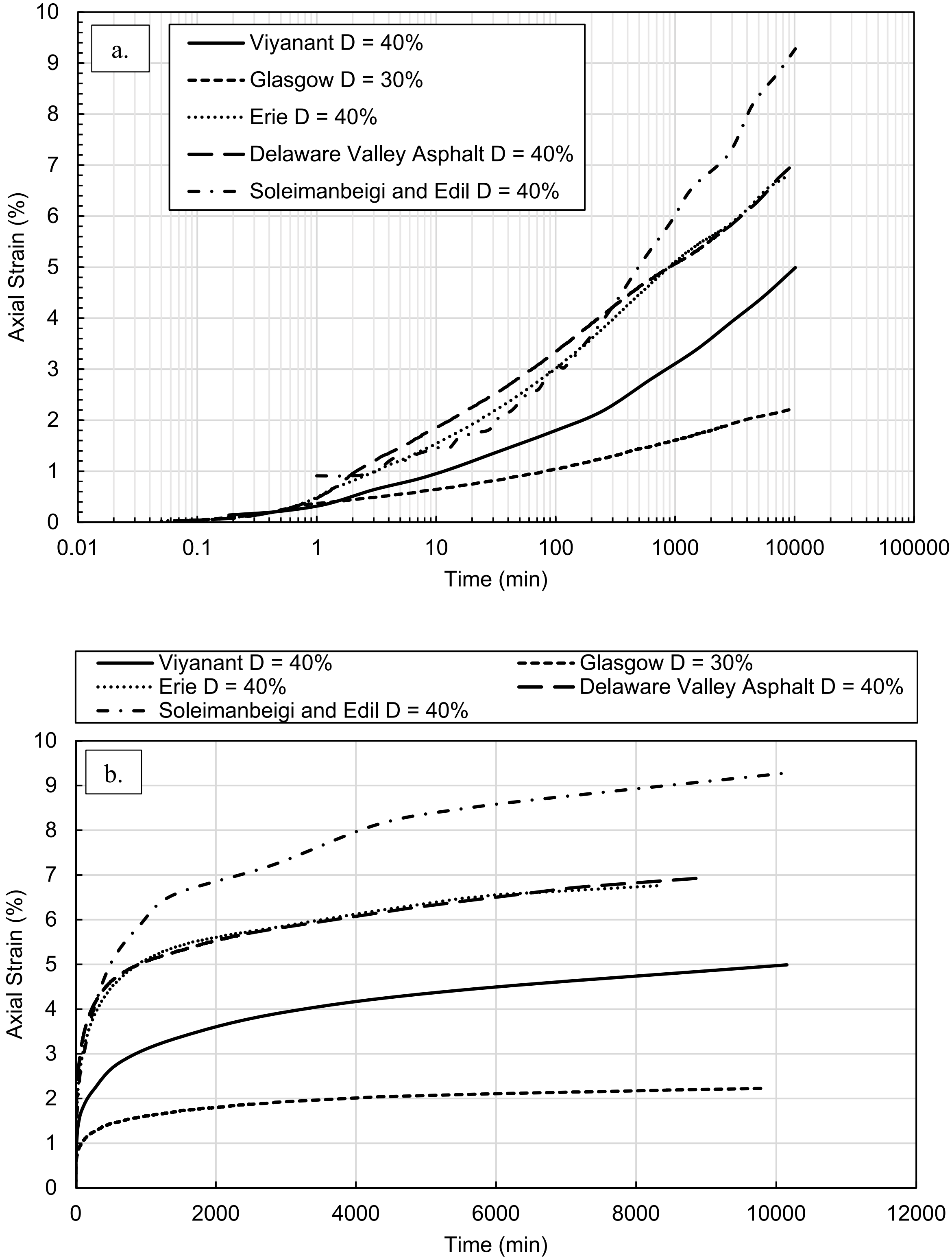


Figure 3.55 District 6 RAP compared to literature at 30 – 40% of the source's respective deviator stresses where (a) is log time vs axial strain and (b) is time vs axial strain.

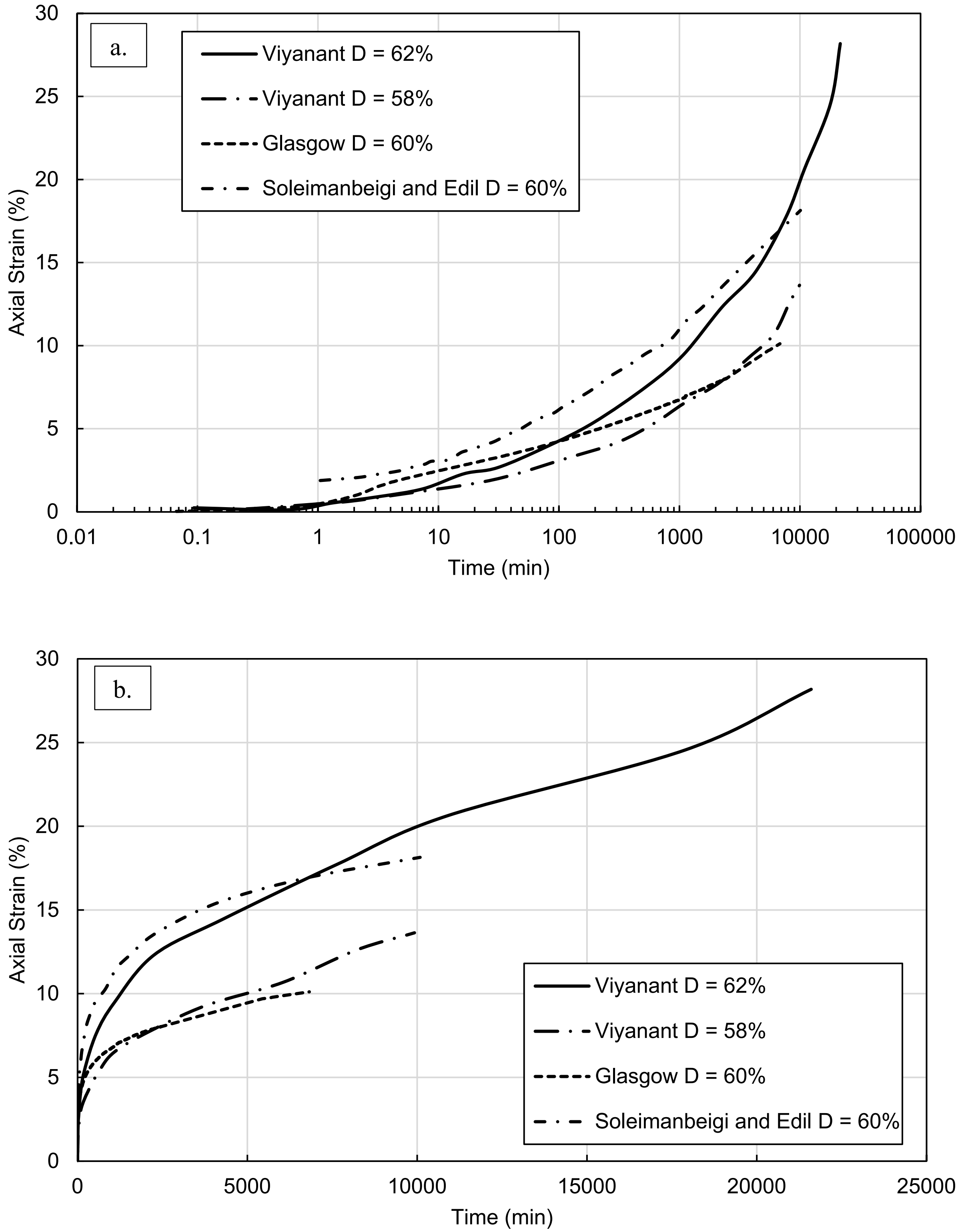


Figure 3.56 District 6 RAP compared to literature at 58 – 62% of the source's respective deviator stresses where (a) is log time vs axial strain and (b) is time vs axial strain.

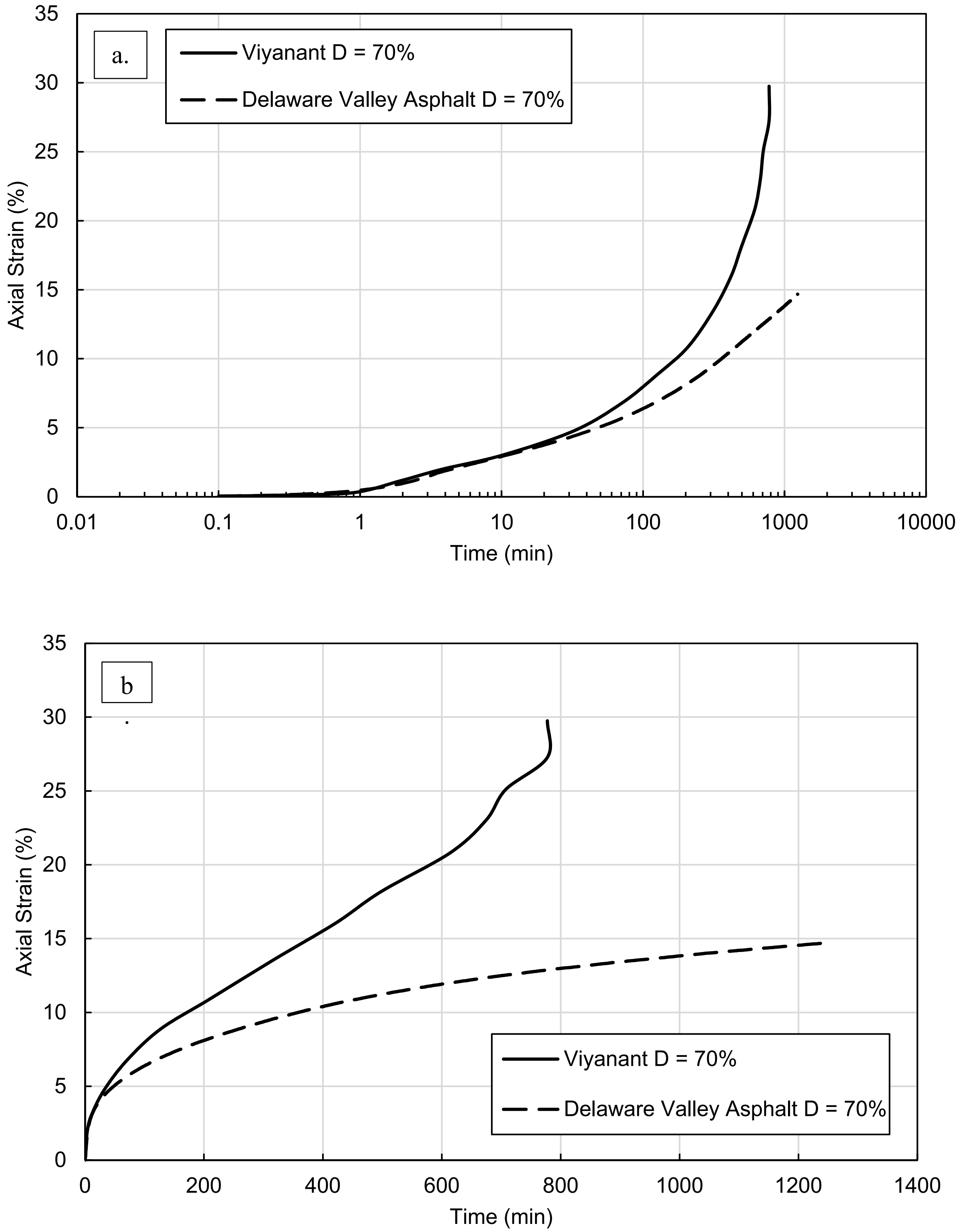


Figure 3.57 District 6 RAP compared to literature at 70% of the source's respective deviator stresses where (a) is log time vs axial strain and (b) is time vs axial strain.

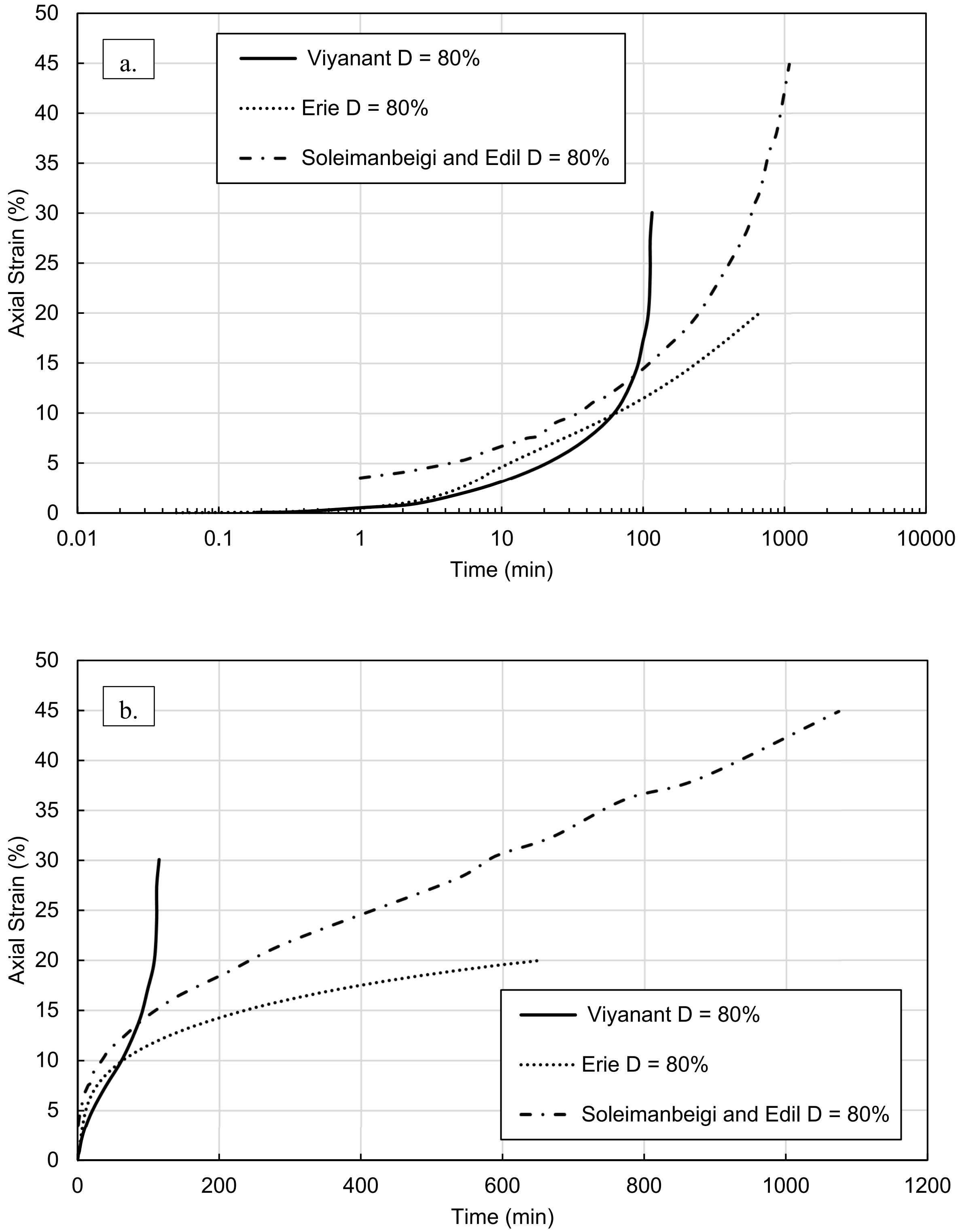


Figure 3.58 District 6 RAP compared to literature at 80% of the source's respective deviator stresses where (a) is log time vs axial strain and (b) is time vs axial strain.

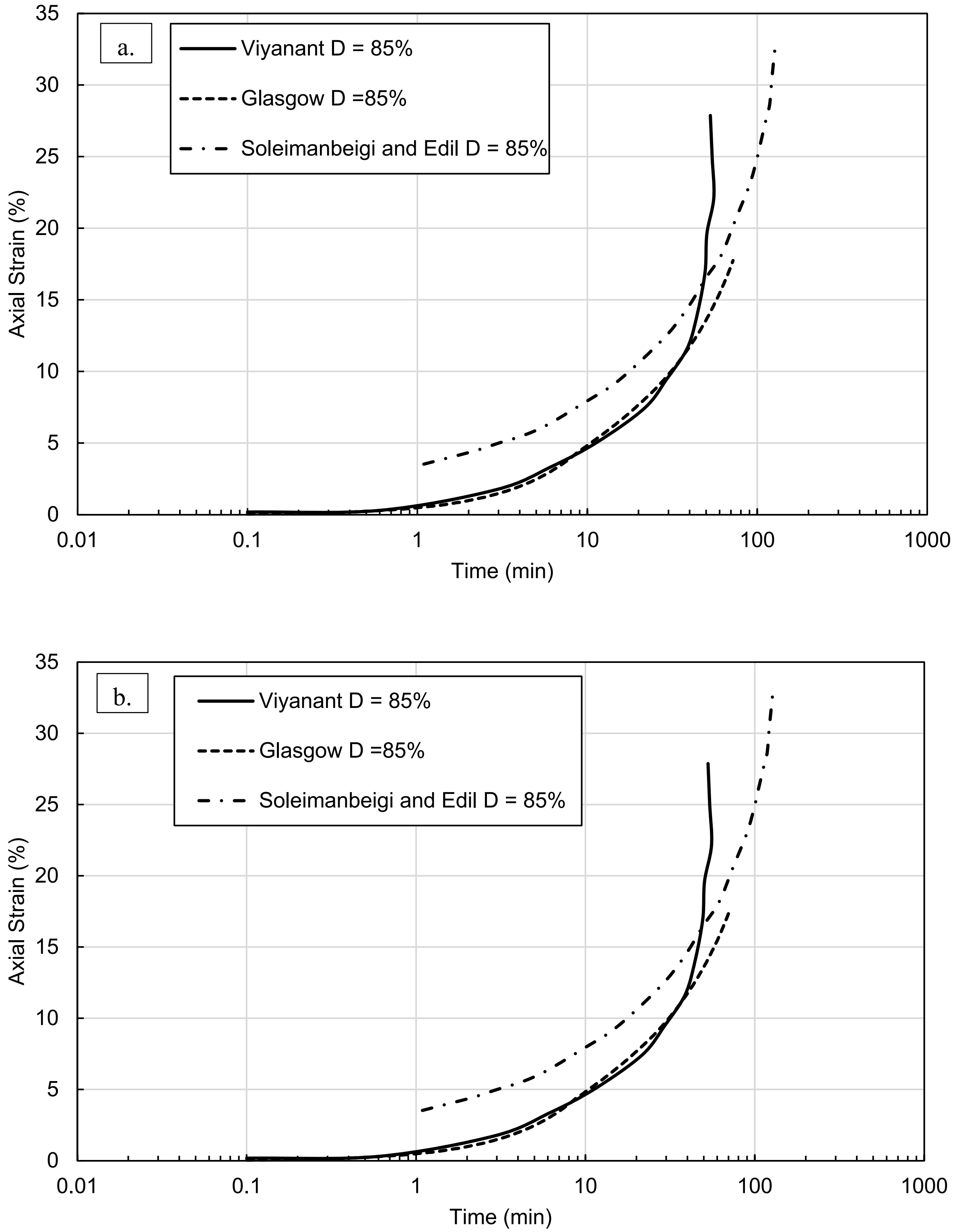


Figure 3.59 District 6 RAP compared to literature at 80% of the source's respective deviator stresses where (a) is log time vs axial strain and (b) is time vs axial strain.

For the log time plots (**Fig. 3.56–3.59(a)**), at every stress level, District 6 RAP behaved similar to literature. At first axial strain gradually increased. Over some time, a sharp increase in the rate of strain was observed. As the percentage of the maximum deviator stress increased, the significant increase in the axial strain rate was observed earlier in the test. This indicates that at higher stresses, creep occurs at a faster rate.

For the time plots, there were some differences between literature and District 6 RAP. At higher stress levels, both Viyanant et al. (2007) and Soleimanbeigi and Edil (2015) observed creep rupture. Creep ruptures are identified as sharp increases in the axial strain value. Viyanant et al. (2007) saw creep rupture occur early in the testing period whereas Soleimanbeigi and Edil (2015) only observed creep rupture after significant time had passed. District 6 RAP did not undergo clear creep rupture in the same time period as Viyanant et al. (2007), however it did follow a similar trend as Soleimanbeigi and Edil (2015). If District 6 RAP had been tested for as long as Soleimanbeigi and Edil (2015), it would be expected that creep rupture would have been observed.

3.5.1.2 50 kPa (1044 psf) Shear Stress Testing Series

After testing the sources of RAP at 30-85% of their deviator stresses, all three sources of RAP were tested at 50 kPa (1044 psf) shear stress to provide a direct comparison of creep susceptibility between the sources of RAP. This testing was conducted to evaluate the variability between the different sources of RAP when tested at the same stress. Additionally, performing the tests at 50 kPa (1044 psf) shear stress was completed to determine if RAP was able to stay below the threshold value of that 3% axial strain which was the lowest strain where failure occurred in specimens with low confining stress as identified by Viyanant et al. (2007).

3.5.1.2.1 Methods

Creep tests performed at a 1044 psf (50 kPa) shear stress were conducted in the same manner as described in **Section 3.5.2.1.2**, with the only difference being the shear stress value. The 50 kPa (1044 psf) value was selected based on typical stress conditions within small embankment applications (Yin et al. 2016). Erie, Delaware Valley Asphalt, and Glasgow RAP were tested at 50 kPa (1044 psf) shear stress regardless of their maximum deviator stress. Tests were run for a duration of 5-7 days, and the axial strain at the end of that time was compared for each source.

3.5.1.2.2 Results

Triaxial creep tests on Delaware Valley Asphalt and Glasgow RAP were run for a duration of 7 days whereas Erie RAP was run for 5 days. The results from these tests are shown in **Figure 3.60**.

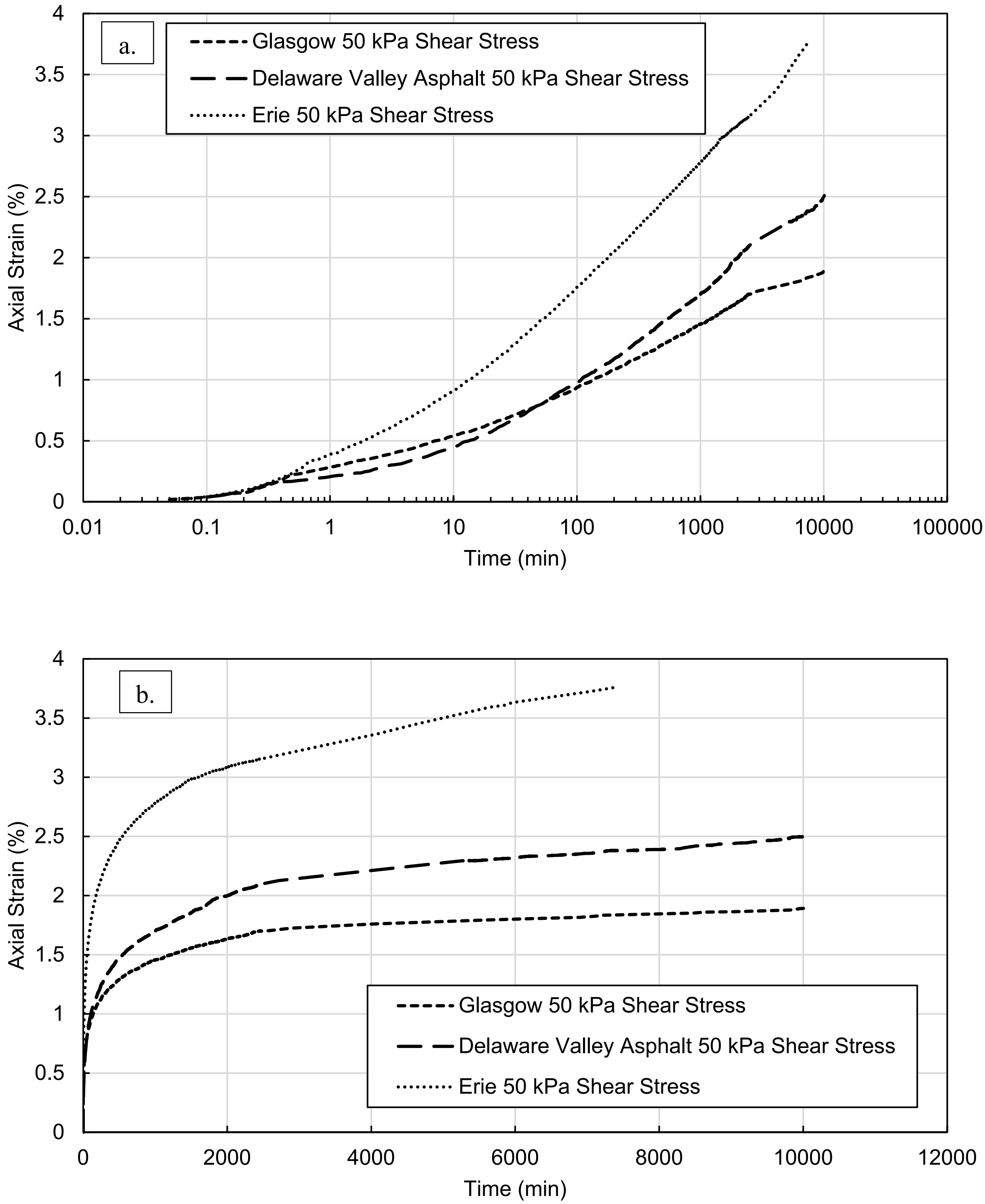


Figure 3.60 Comparison of District 6 creep results at 50 kPa shear stress where (a) is log time vs axial strain and (b) is time vs axial strain.

The results from the 50 kPa (1044 psf)shear stress creep tests were variable between the different sources of District 6 RAP. Glasgow RAP performed the best reaching only 1.9% axial strain after 10,080 minutes (7 days). Delaware Valley Asphalt RAP creeped slightly more, reaching 2.5% axial strain after 10,080 minute (7 days). Erie RAP displayed significantly more creep than the other sources, reaching 3.8% axial strain after 7,360 minutes (5.1 days). Both Glasgow and Delaware Valley Asphalt stayed below the threshold value of 3% axial strain after 7 days, and creep appeared to be slowing, or leveling off, over time. Erie RAP surpassed the threshold value of 3% and creep did not appear to slow over time. The results from this testing show that RAP is highly variable, and some sources of RAP may behave differently than others. Overall, testing creep at lower stresses (50 kPa) limits RAP to lower axial strains, which is promising when determining applications for RAP.

3.5.1.2.2 Discussion

Testing the sources of RAP at the same shear stress highlighted the differences in behavior source-by-source. This can likely be attributed to the differences in roadway exposure, age, and the milling processes. Additionally, creep is likely caused by the asphalt bitumen binder coating the coarse aggregate. While asphalt binder content was not examined for this project, it can be hypothesized that the differences in creep behavior is due to the binder content of the RAP. Future research should be conducted to investigate this factor.

3.5.1.2.2.1 Triaxial Creep and Coefficient of Uniformity Correlation

Another factor that contributes to the variability in creep results at the same stress is the differences in the coefficient of uniformity. As seen with the other geotechnical properties evaluated in this report, trends have been identified with C_u and RAP performance. The comparison between maximum axial strain at the conclusion of testing and C_u is shown in **Figure 3.61**.

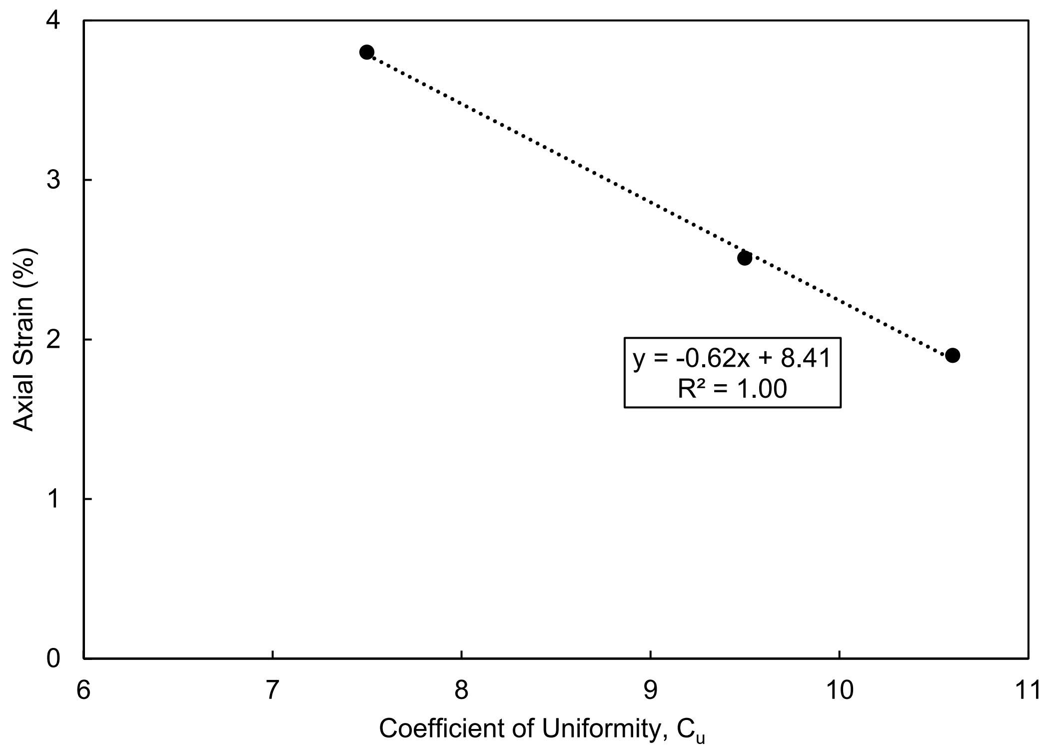


Figure 3.61 Comparison of axial strain and C_u values from the District 6 sources of RAP.

The comparison provided a very strong linear correlation between the maximum axial strain and the C_u value. This trend was expected due to the testing methodology and the results from triaxial shear testing. From triaxial shear testing, Glasgow RAP had the largest maximum deviator stress and Erie RAP had the lowest maximum deviator stress. Because of this, a 50 kPa (1044 psf) shear stress being applied to Glasgow RAP was less significant on the material than it was on Erie RAP. The differences in the maximum deviator stress between the materials is likely explained by the C_u differences, which then corresponds to the differences in the maximum axial strain reached during creep testing. These results indicate that more well-grade RAP will exhibit better creep performance. This trend could be significant when evaluating what types of RAP can be used in various applications.

3.5.2 Free Weight Creep Tests

Free weight creep tests were conducted evaluate creep over longer time periods. Simple setups were used to increase the number and duration of the testing being completed, so that informed decisions for longer term tests could be made for the triaxial setup. These results were compared to the triaxial creep tests to have a complete creep evaluation.

3.5.2.1 Methods

Free weight creep tests were conducted by compacting the RAP samples in a 6-inch compaction mold. The compaction of the sample was prepared in the modified proctor method, as described in **Section 3.4.1.1**. After compaction was complete, a weight with a diameter of 6-inches was placed onto the compacted samples. Weights were continually added over a period of 20 seconds until a weight of 102 – 103 pounds was applied. This weight corresponded to a 25 kPa (522 psf) stress. A dial gauge with a magnetic base was attached to the setup to measure the downward movement of the compacted sample over time. Initially, the dial gauge readings were measured using the following schedule: 15 seconds, 30 seconds, 45 seconds, 1 minute, 2 minutes, 4 minutes, 8 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, and 8 hours. After 8 hours had passed, the dial gauge was measured once daily. In some circumstances, readings were taken every 2 to 3 days.

Free weight creep tests were conducted on Erie, Delaware Valley Asphalt, Highway Materials, and Glasgow RAP. Creep tests on each material were run for a minimum of 7 days, with most running for longer amounts of time. This testing was conducted to evaluate the long – term creep behavior of each source of RAP. Additional creep tests were run on varying mixtures of RAP and No. 57 Stone to evaluate the effects of aggregate mixing, and those tests are discussed in detail in **Section 3.7** of this report. **Figure 3.62** shows the free weight creep testing setup.

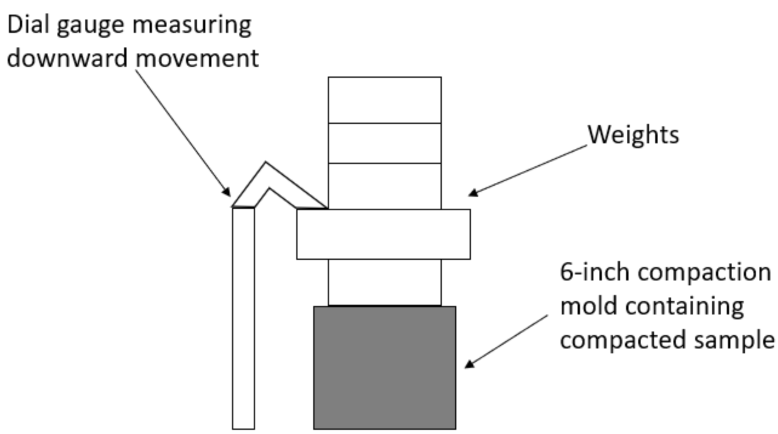


Figure 3.62 Free weight creep test setup.

3.5.2.2 Results

For Erie RAP, the free weight creep test ran for a total of 17 days, reaching a total axial strain of 2.3%. After 8 days, the axial strain had leveled off and the sample stopped creeping. The results from this test are provided in **Figure 3.63**.

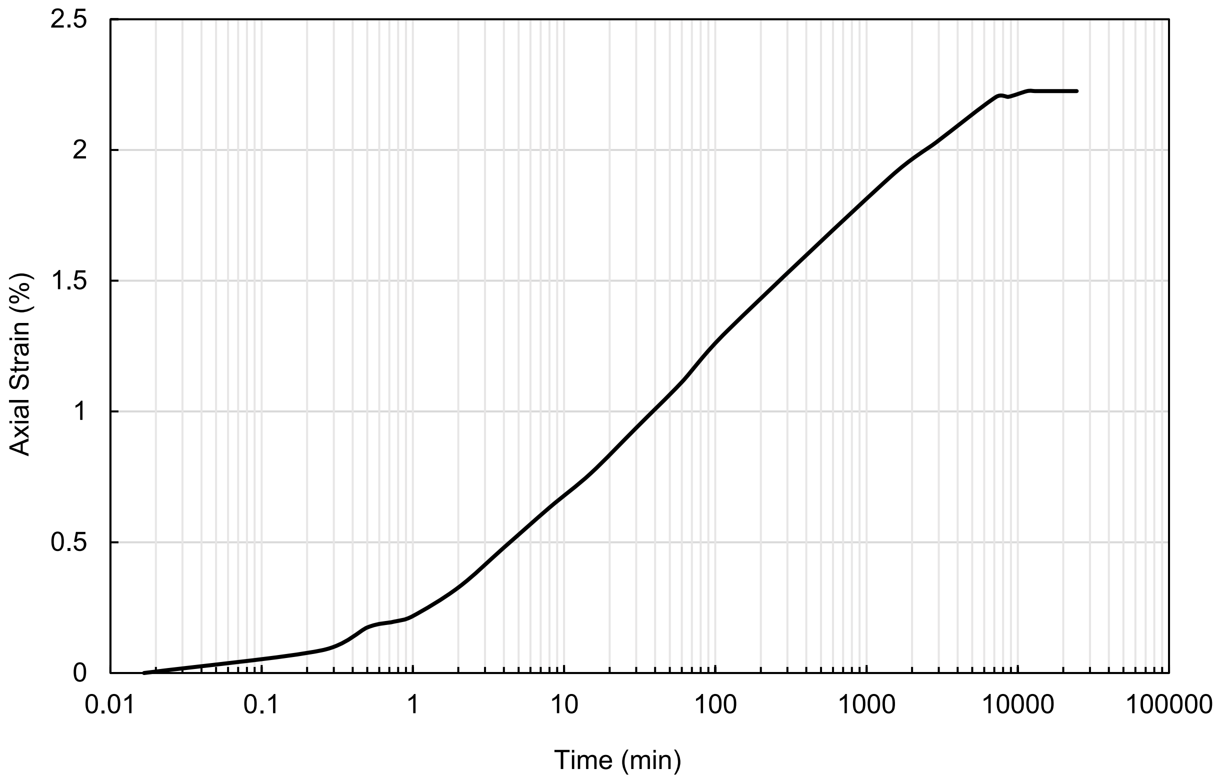


Figure 3.63 Free weight Erie RAP creep tests.

For Highway Materials RAP, one creep test was run for a total of 18 days with axial strain reaching 0.7%. It was observed that deformations had ended after a total of 14 days. The result from this test is provided in **Figure 3.64**.

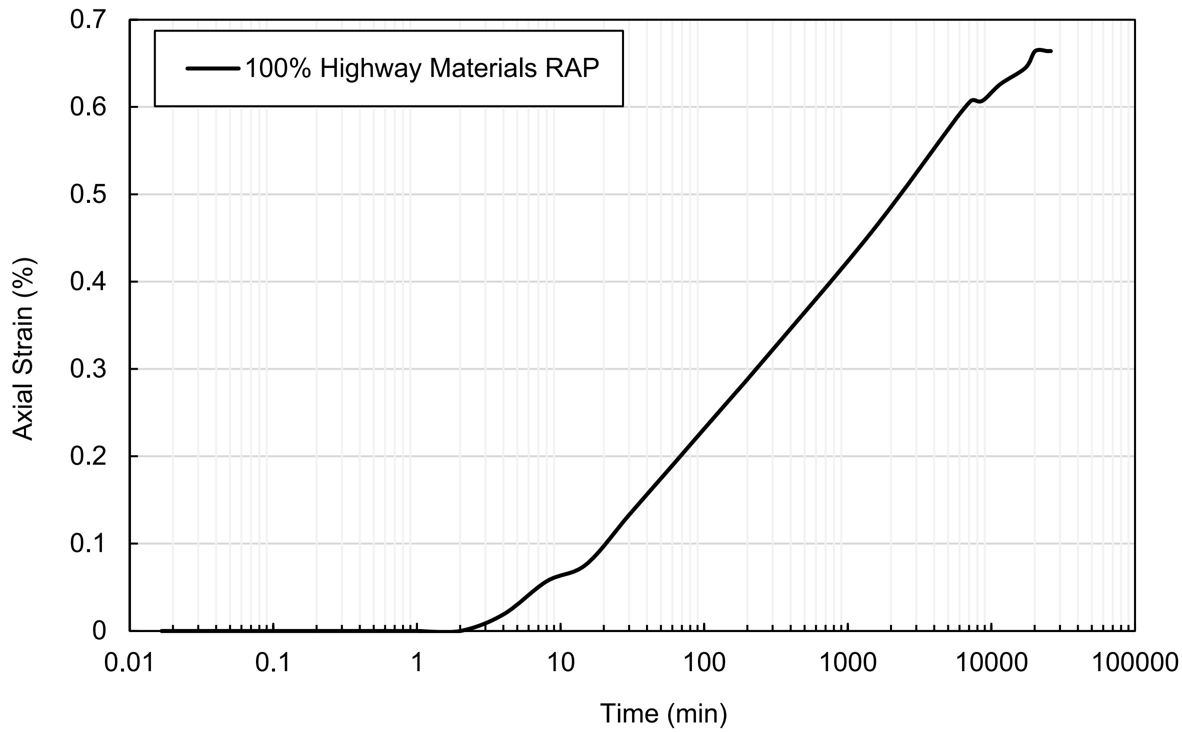


Figure 3.64 Highway Materials RAP free weight creep test.

Two free weight creep tests were conducted on Delaware Valley Asphalt RAP. The first test was run for 37 days and reached an axial strain of 2.7%. It was observed that deformations had stopped after 33 days. A duplicate free weight creep test was conducted to determine if the testing method was consistent. The second test ran for 23 days and reached an axial strain of 1.8%. Deformations had stopped after 17 days. While the two tests did provide different results, due to the simple nature of the testing method, slight inconsistency was expected. The overall trend of creep slowing/stopping over longer durations was observed in both tests. The results from these tests are provided in **Figure 3.65**.

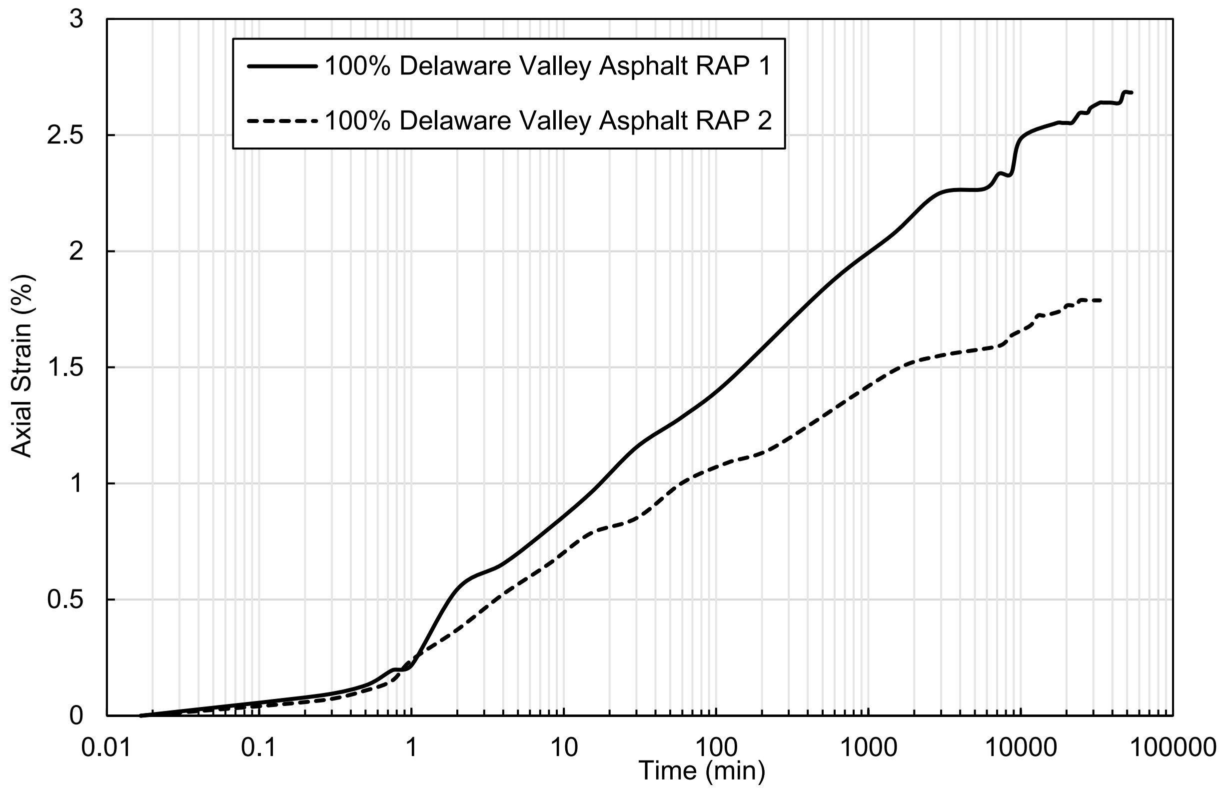


Figure 3.65 Delaware Valley Asphalt RAP free weight creep test.

For Glasgow RAP, two free weight creep tests were conducted. The first test was run for 21 days and reached an axial strain of 0.8%. It was observed that deformations had stopped after 13 days. A duplicate free weight creep test was conducted to determine if the testing method was consistent. The second test ran for 18 days and reached an axial strain of 1.3%. Deformations had stopped after 17 days. The results from these tests are provided in **Figure 3.66**.

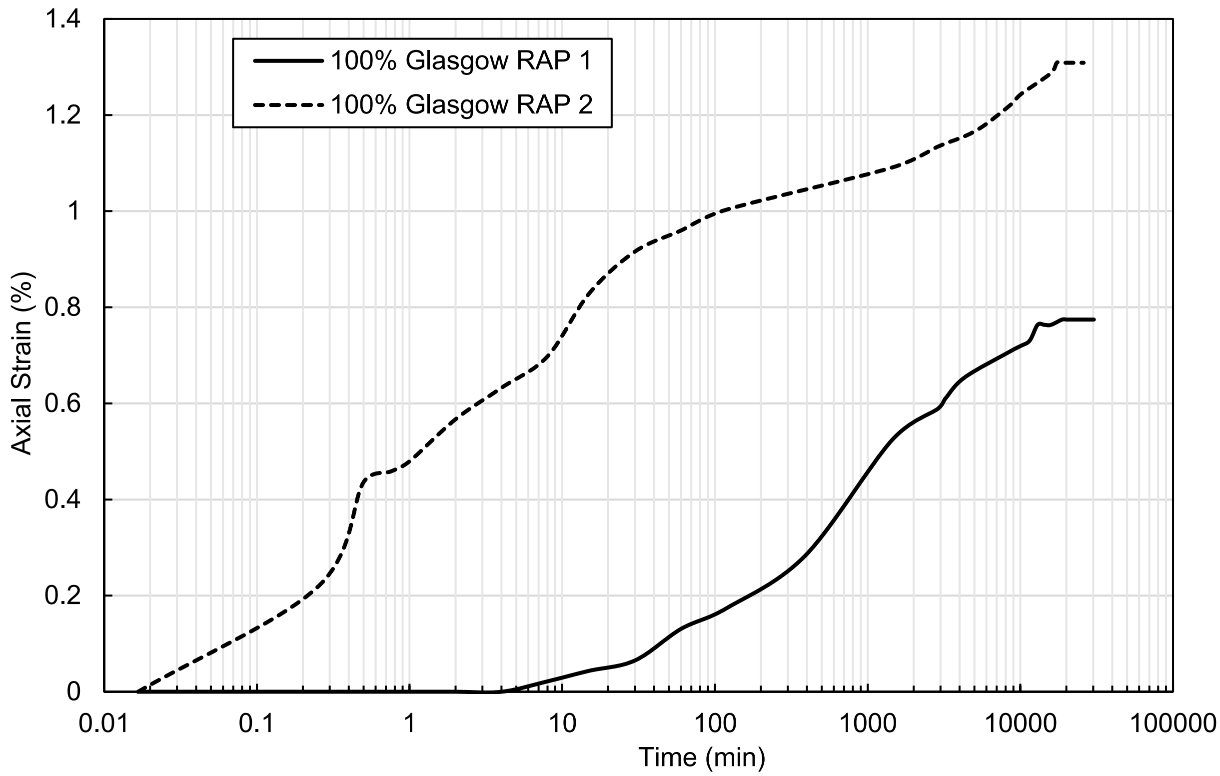


Figure 3.66 Glasgow RAP free weight creep tests.

3.5.2.3 Discussion

All the free weight creep tests at a stress of 25 kPa (522 psf) showed that over a long period of time (14 days or more), creep slows down and eventually stops. Results from all the tests are compared in **Figure 3.67**. While creep did stop for these tests, there were limitations to this testing set up. Because free weights were used, for safety reasons, only 25 kPa (522 psf) was applied. This stress is lower than what has been typically tested in literature. Additionally, due to the use of compaction molds, the tests were confined which could have contributed to the creep stopping over time. Nonetheless, the simple setups provided the opportunity to run several materials at once for long periods of time to understand parameters affecting response. This testing was helpful for determining materials and stresses to apply in long term triaxial tests.

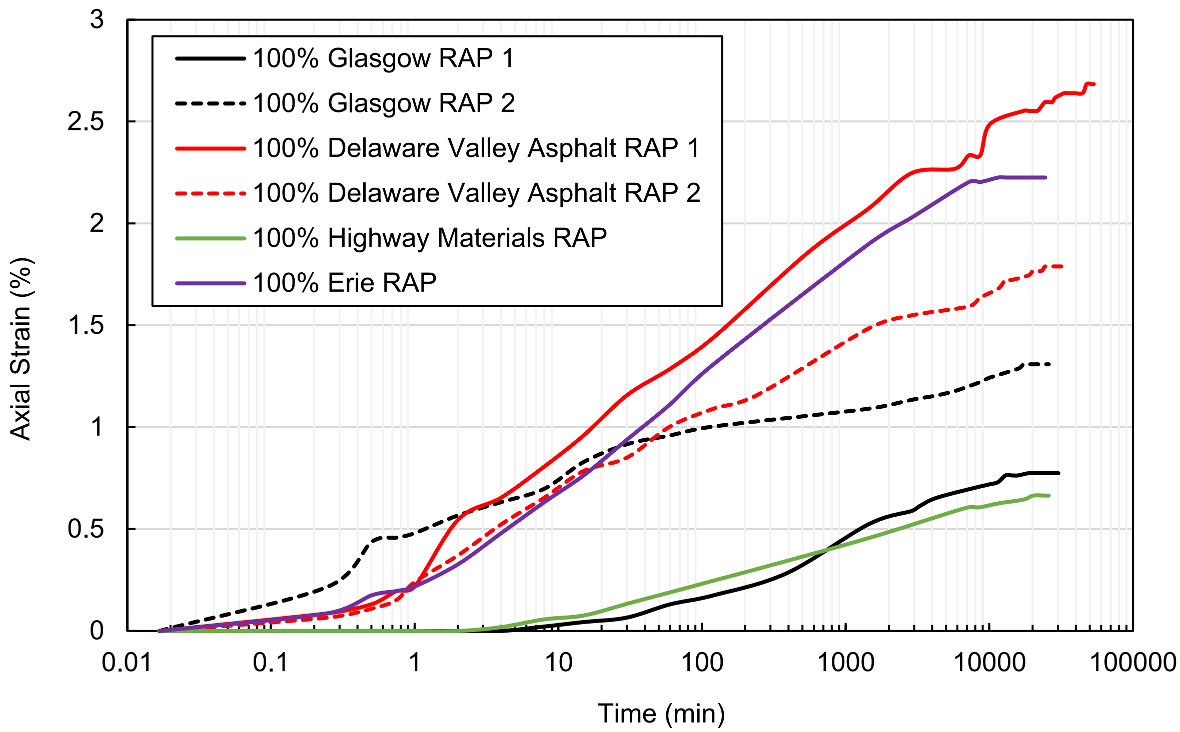


Figure 3.67 Free weight creep test comparison for District 6 RAP sources.

As seen in **Figure 3.67**, there are distinct groupings within the free weight creep data. Erie and Delaware Valley Asphalt RAP, which are unprocessed had larger deformations than Highway Materials and Glasgow RAP, which are processed. It is possible that unprocessed RAP creeps more than processed RAP, however this could also be due to the testing methodology. For this test, unprocessed RAP was not scalped, making it difficult to compact. Because the unprocessed samples did not get as compact as the processed samples, there was more void space within the mold. The higher creep deformations could be attributed to the shifting of the particles as weight was applied to the unprocessed samples. Future research should involve an unconfined, larger scale creep test to investigate this effect.

3.5.2.3.1 Free Weight Creep and D_{50} Comparison

A potential reason that processed and unprocessed RAP showed differences in free weight creep behavior is the differences in each source's D_{50} value. In general, processed RAP has much smaller D_{50} values than unprocessed RAP. The two processed sources, Highway Materials and Glasgow RAP, had D_{50} values of 3.0 and 3.5. The two sources of unprocessed RAP, Erie and Delaware Valley Asphalt RAP, had D_{50} values of 12.0 and 8.0. When the D_{50} values were plotted against the axial strain of each source after 7 days, the logarithmic trendline showed that as D_{50} increased, the axial strain increased. The results from this comparison are provided in **Figure 3.68** and **Table 3.26**.

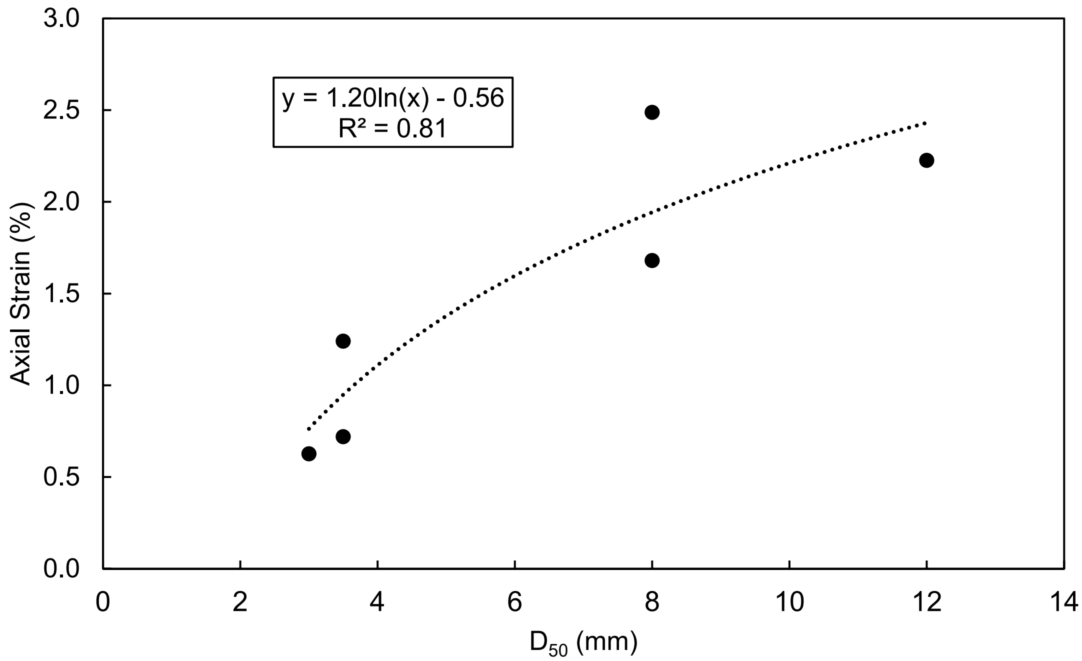


Figure 3.68 D_{50} values compared to axial strain after 7 days.

Table 3.26 D_{50} values for each free weight creep test.

Creep at 7 Days		
Source	Axial Strain (%)	D_{50} (mm)
Glasgow 1	0.72	3.5
Glasgow 2	1.24	3.5
Delaware Valley Asphalt 1	2.49	8.0
Delaware Valley Asphalt 2	1.68	8.0
Highway Materials	0.63	3.0
Erie	2.23	12.0

It is likely that axial strain increased with larger D_{50} values because of increased void space and particle breakage. Larger particles do not compact as well as smaller particles, which leaves larger void spaces. When a load is applied to the compacted samples, more void space causes more particle movement within the sample leading to larger creep deformations.

3.5.2.3.2 Free Weight Creep Compared to Triaxial Creep

The triaxial and free weight setups apply different loading conditions to test specimens. A triaxial creep test using Glasgow RAP was conducted to mimic the conditions of the free weight creep tests. This provided a direct comparison between the different methodologies.

To create a replica test in the triaxial setup, a few assumptions were made. It was assumed that the following equations could be used to provide an accurate lateral earth pressure coefficient (K_o) and confining stress (σ_h) for the compaction mold:

$$K_O = 1 - \sin{(\phi)}$$

$$\sigma_h = (K_O)\sigma_v$$

Where:

K_o = Lateral Earth Pressure Coefficient

Φ = Friction Angle (deg.)

σ_h = Horizontal Stress (kPa or psf)

σ_v = Vertical Stress (kPa or psf)

Using the friction angle of 46 degrees determined from the Glasgow RAP triaxial shear testing, the K_o value was 0.3. The shear stress (vertical stress) was 25 kPa (522 psf), therefore the confining stress (horizontal stress) was 7 kPa (146 psf). For ease of testing, the confining stress was rounded to 10 kPa (209 psf). The same free weight shear stress of 25 kPa (1044 psf) was applied to the specimen, and the triaxial results were compared to the Glasgow free weight test results. The comparison is provided in **Figure 3.69**.

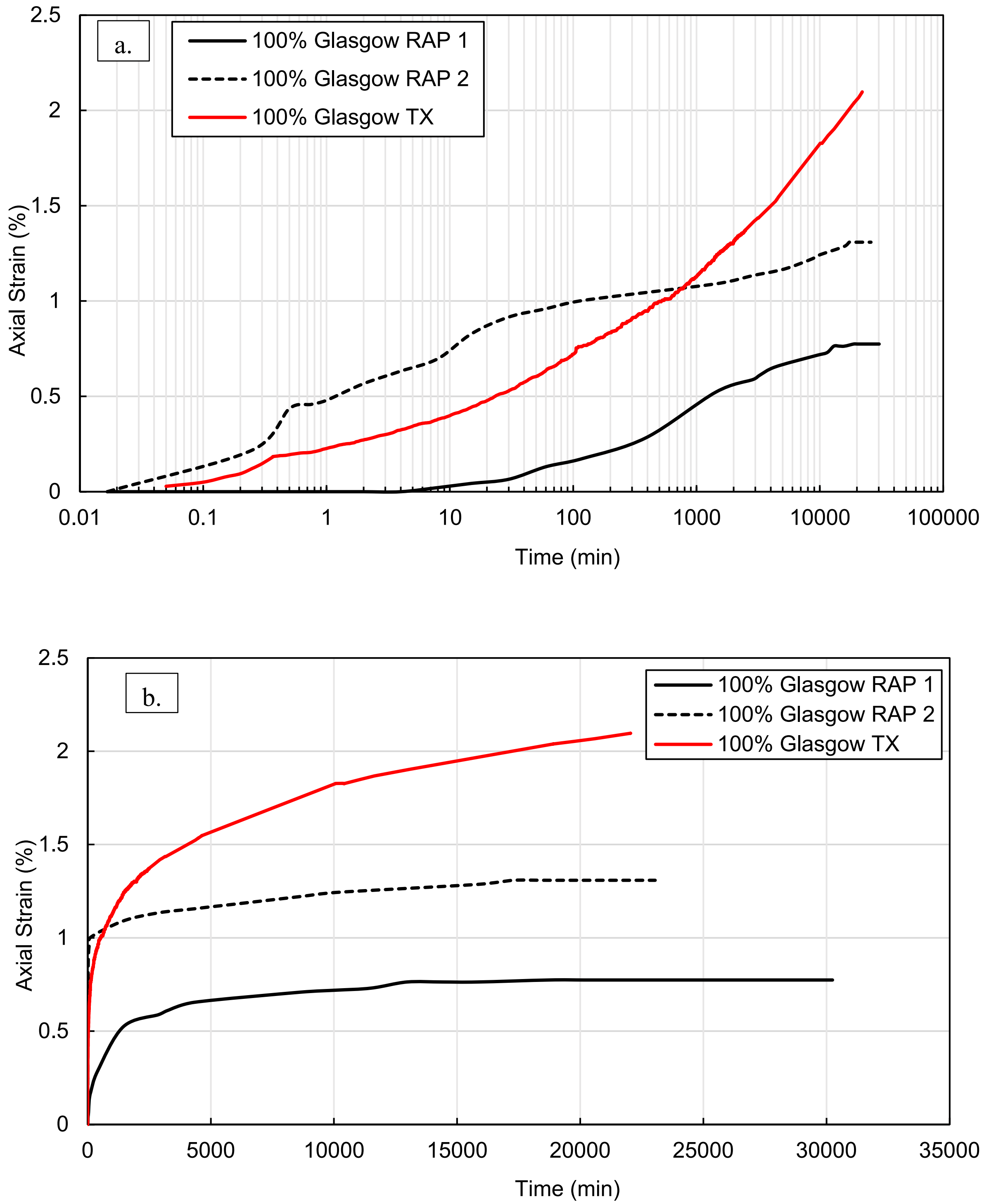


Figure 3.69 Comparison between the triaxial creep test and free weight creep tests for Glasgow RAP where (a) is log time vs axial strain and (b) is time vs axial strain.

The comparison between the testing methodologies shows differences in the results. Overall, the triaxial creep tests showed higher axial strain values. The difference in strain values were expected due to the confining pressure assumptions, and the different testing apparatuses. A difference in axial strain of 0.8% for Glasgow RAP 1, 1.3% for Glasgow RAP 2 and to 2.1% for the Glasgow RAP triaxial test was observed. When time was plotted on a log scale, as shown in **Figure 3.69 (a)**, the triaxial data shows a sharp increase in axial strain, without appearing to level off. The free weight creep data did not display this behavior, and leveling off was observed. It is likely that the different behavior in this plot is due to the drainage conditions. In the triaxial apparatus, drainage is confined to the top of the specimen due to the latex membrane preventing water from infiltrating the specimen. Drainage during the free weight test occurs on the top, the bottom, and the sides of the specimen. Because the drainage conditions were not identical between the two tests, different behavior in the log-time plot was expected.

When time was plotted on a linear scale, as shown in **Figure 3.69 (b)**, over time, the triaxial data showed creep deformations slowing down, which was similar to the free weight data, however creep did not completely stop. The triaxial creep test was run for 15 days, reaching an axial strain of 2.1%. The triaxial creep test did not level off after 15 days whereas the free weight creep tests leveled off after 13 days for Glasgow RAP 1, and 17 days for Glasgow RAP 2. Because the free weight creep tests had a simplistic set up, it is possible that limitations within the apparatus could have shown creep stopping, when in reality it had just slowed significantly. This could explain why creep was not observed to stop in the triaxial test.

Although the strain values and behaviors were not identical between the two testing methodologies, similar conclusions can be made. At low stresses, creep deformations slowed down over time. While RAP does creep excessively, understanding that creep slows over time is useful when identifying which applications are appropriate for the use of RAP. More triaxial testing should be conducted to investigate the behavior of RAP over longer periods of time under a variety of loading conditions.

3.6 Mixtures

RAP is known to creep at an excessive rate. Many studies have investigated combining RAP with aggregates to improve upon creep susceptibility (Cosentino et al. 2003; Kalpacki et al. 2018; Mousa and Mousa 2017). The commonly used aggregates in literature were sand and coarse aggregate material such as No. 57 Stone, and AASHTO 2A. Mixtures with No. 57 Stone and bar sand were investigated in this study to evaluate the effect blending had on creep.

3.6.1 Methods

Mixture testing was performed using the free weight method as described in **Section 3.5.2.1**. Mixtures were prepared by hand mixing the two materials together until fully combined. Once combined, a representative sample of the mixture was used for each compaction lift to ensure an even distribution of material throughout the compacted sample. No. 57 Stone was selected as the primary mixture material due to its commonality in PennDOT construction projects. No. 57 Stone was mixed with RAP at a 50/50 ratio for all the sources of RAP, except for Glen Mills. One additional mixture test was conducted on Glasgow RAP at a ratio of 70/30 RAP to No. 57 Stone. Supplemental mixture tests were conducted using bar sand as the aggregate material, and those tests were performed using the Glen Mills RAP.

3.6.2 RAP – No. 57 Stone Free Weight Creep Tests

Coarse aggregate material is commonly used in embankment and fill applications. For these applications, PennDOT typically selects No. 57 Stone for its construction projects. Due to the familiarity with this material, testing mixtures with No. 57 Stone represents the most relevant material for construction implementation in the field.

3.6.2.1 Results

In order to develop a baseline for creep mixtures, 100% No. 57 Stone was tested to determine its creep susceptibility. The test was run for 10,080 minutes (7 days) and displayed very little creep. In total, the axial strain reached 0.02%, and it was observed that creep had stopped after 1 day. The results indicate the No. 57 Stone is not susceptible to creep, and responded as expected. It is expected that mixing No. 57 Stone with RAP should reduce creep. Results from the No. 57 Stone free weight creep test are provided in **Figure 3.70**.

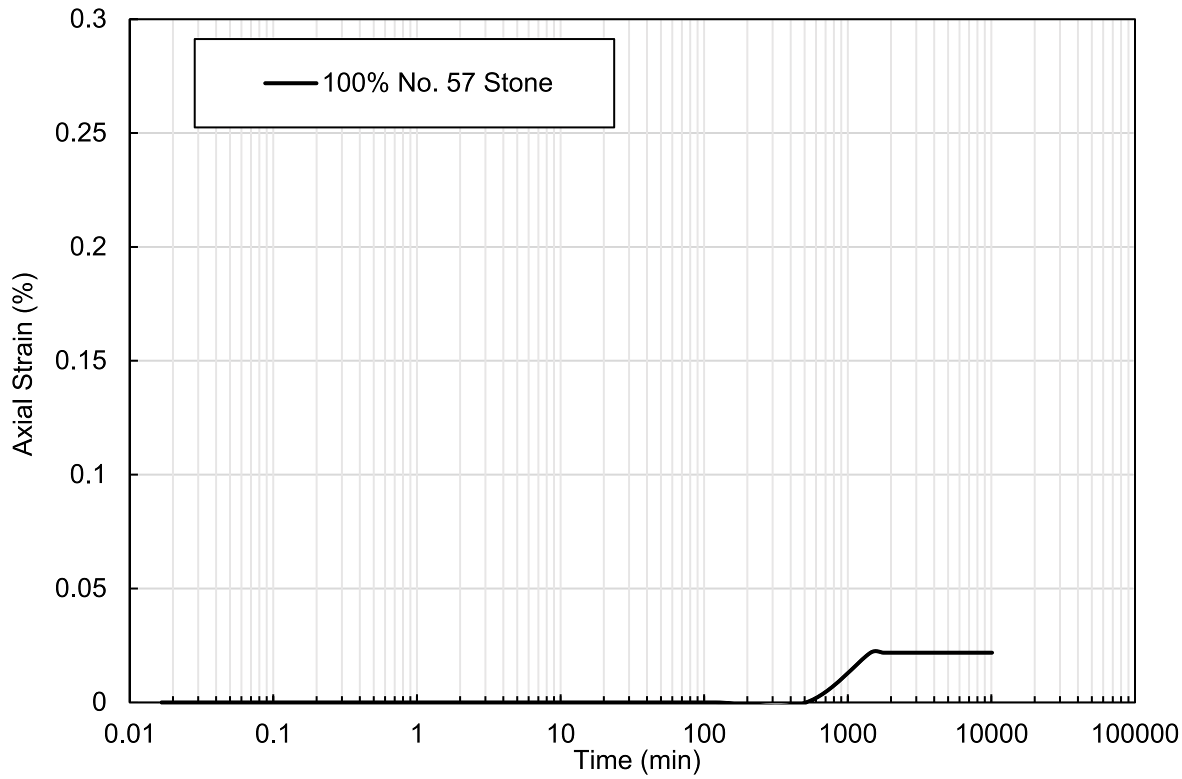


Figure 3.70 No. 57 Stone creep results.

A 50/50 mixture was tested for Erie RAP, and those results were compared to creep results for 100% RAP in **Figure 3.671**. It was observed that mixing Erie RAP with No. 57 Stone significantly improved the creep deformations. The test was run for 23,040 minutes (16 days) and it was observed that creep had stopped after only 15 minutes, reaching an axial strain of 0.1%.

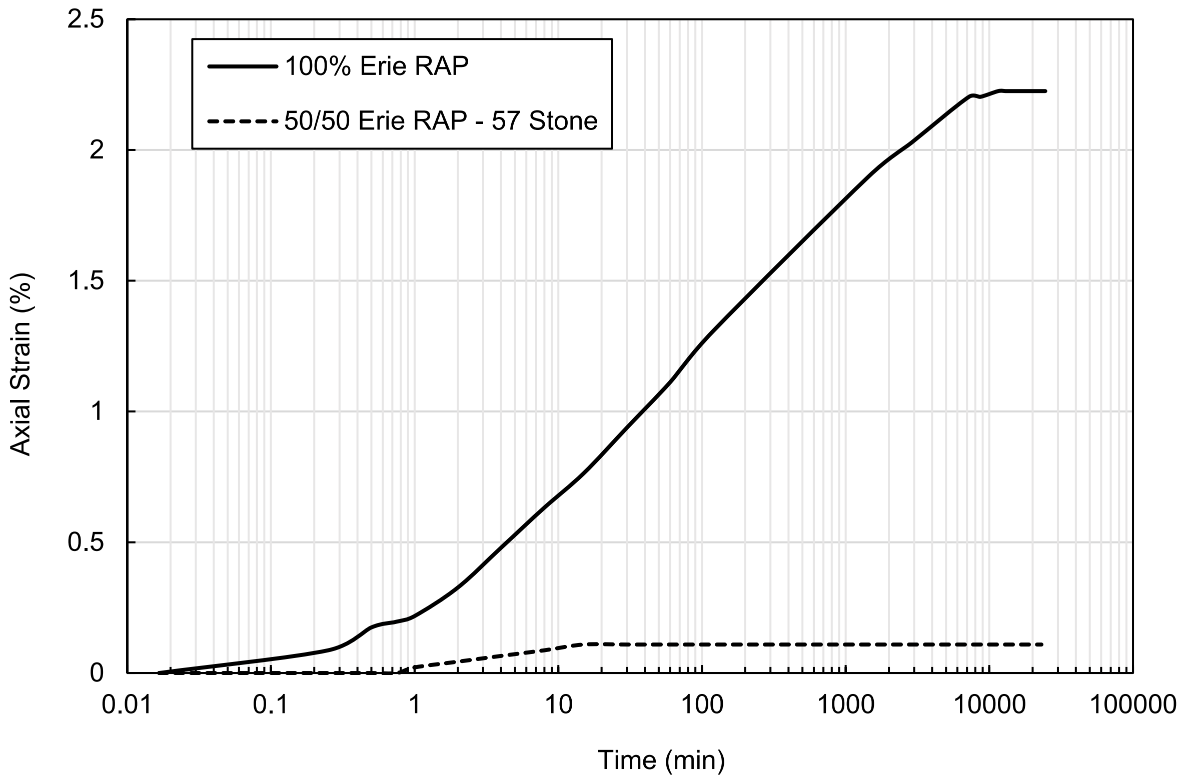


Figure 3.71 Erie RAP and No. 57 Stone mixture comparison.

A 50/50 mixture was tested for Highway Materials RAP, and those results were compared to creep results for 100% RAP in **Figure 3.72**. It was observed that mixing Highway Materials RAP with No. 57 Stone did improve upon creep deformations, however, the difference was not as significant as what was observed for Erie RAP. The test was run for 25,920 minutes (18 days) and it was observed that creep had stopped after 16 days, reaching an axial strain of 0.57%.

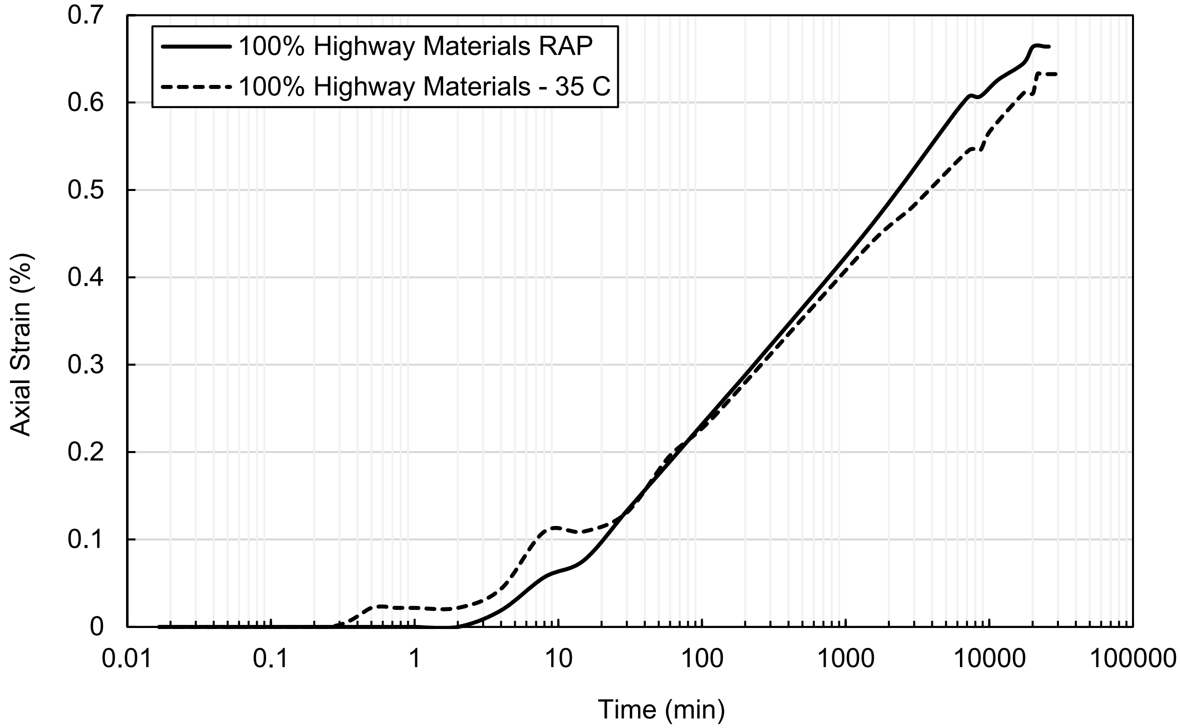


Figure 3.72 Highway Materials RAP and No. 57 Stone mixture comparison.

A 50/50 mixture was tested for Delaware Valley Asphalt RAP, and those results were compared to creep results for 100% RAP in **Figure 3.73**. It was observed that mixing Delaware Valley Asphalt RAP with No. 57 Stone significantly improved the creep deformations. The test was run for 259,200 minutes (25 days) and it was observed that creep had stopped after 20 days, reaching an axial strain of 0.59%.

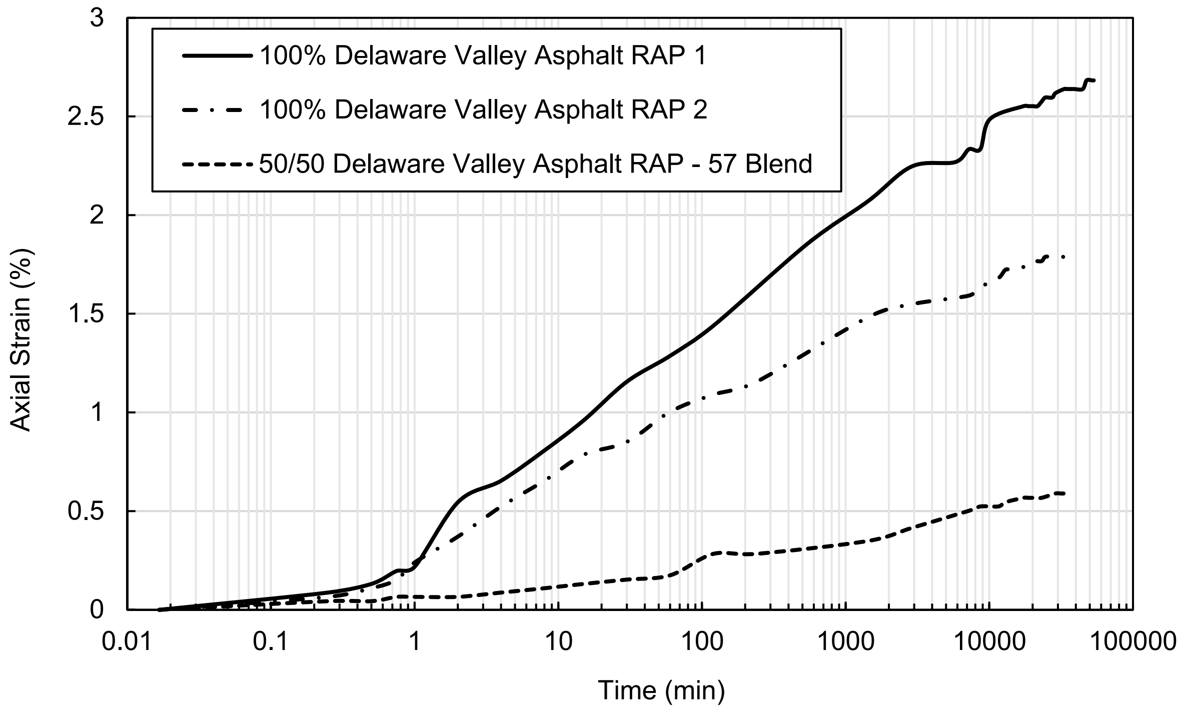


Figure 3.73 Delaware Valley Asphalt and No. 57 Stone mixture comparison.

For Glasgow RAP, both a 50/50 mixture and a 70/30 mixture were tested, and those results were compared to creep results for 100% RAP in **Figure 3.74**. It was observed that mixing Erie RAP with No. 57 Stone significantly improved the creep deformations. The 50/50 test was run for 11520 minutes (8 days) and it was observed that creep had stopped after 1 day, reaching an axial strain of 0.35%. The 70/30 test was run for 17,280 minutes (12 days) and it was observed that creep had stopped after 4 days, reaching an axial strain of 0.43%. The results indicate that at higher percentages of No. 57 Stone, less creep occurs, however, even using only 30% No. 57 Stone significantly improves upon creep deformations.

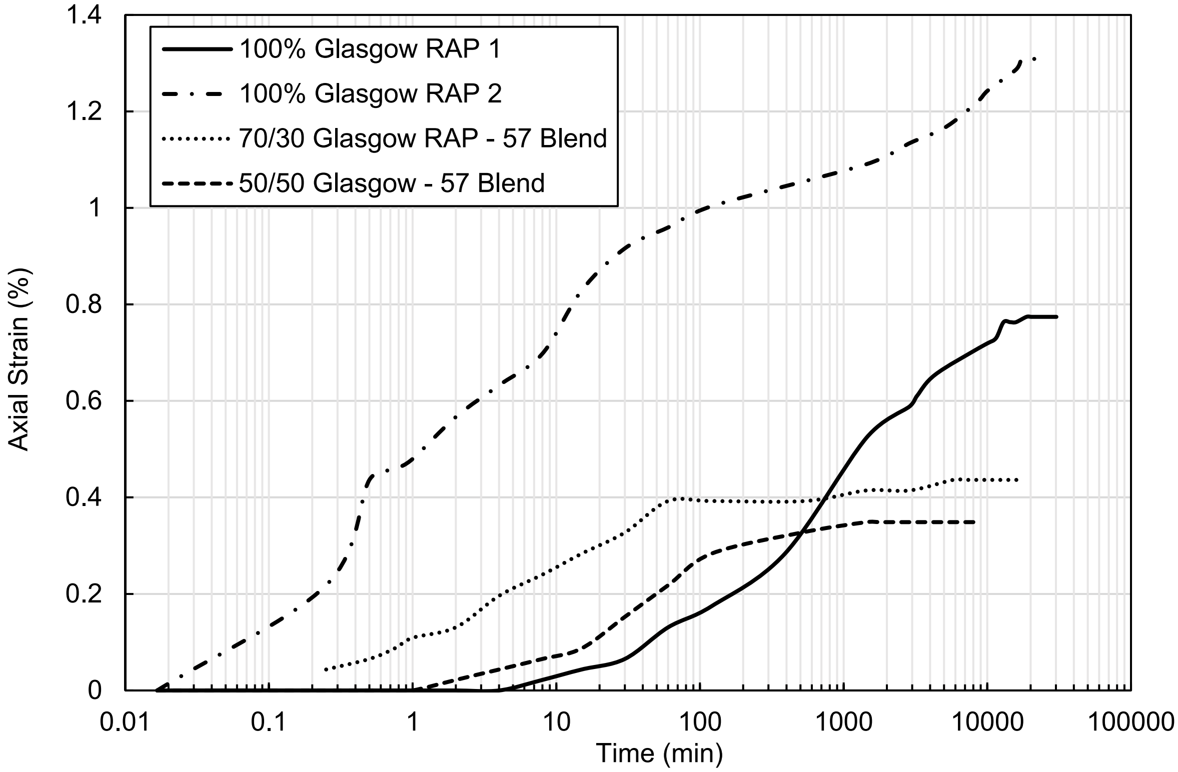


Figure 3.74 Glasgow RAP and No. 57 Stone mixture comparison.

3.6.2.2 Discussion

Mixing RAP with No. 57 Stone is a promising solution for reducing creep. All of the free weight creep tests for mixtures showed significant improvement when No. 57 Stone was introduced at a 50/50 ratio. When the ratio was changed to 70/30, and less No. 57 Stone was used, improvements for creep deformations were still observed. The improvements are likely due to particle locking occurring within the mixture. Additionally, No. 57 does not have bitumen binder therefore, less of the mixture is experiencing the binder effect, resulting in smaller creep deformations. Although RAP is known to creep excessively, mixing it with a commonly used coarse aggregate could allow RAP to be used in more applications, and it would still reduce the amount of RAP being placed into landfills. More research should be conducted to evaluate RAP mixtures.

3.6.3 RAP – Sand Free Weight Creep Tests

The Villanova research team also investigated mixing RAP with bar sand. Sand is a commonly used engineering material, and many literature studies have investigated the effect sand mixtures have on the engineering properties of RAP (Cosentino et al. 2003; Kalpacki et al. 2018; Mousa and Mousa et al. 2017).

3.6.3.1 Results

Following the same procedure as with the No. 57 Stone, a baseline for creep susceptibility was evaluated by conducting two free weight creep tests on 100% Bar Sand. The first test was run for 28,800 minutes (20 days) and displayed little creep. In total, the axial strain reached 0.28%, and it was observed that creep had stopped after 30 seconds. The second test was run for 14,400 minutes (10 days) and displayed slightly less creep. In total, the axial strain reached 0.19%, and it was observed that creep had stopped after 4 days. The results are similar to 100% No. 57, indicating that bar sand is not susceptible to creep. It is expected that mixing bar sand with RAP should reduce creep. Results from the bar sand free weight creep test are provided in **Figure 3.75**.

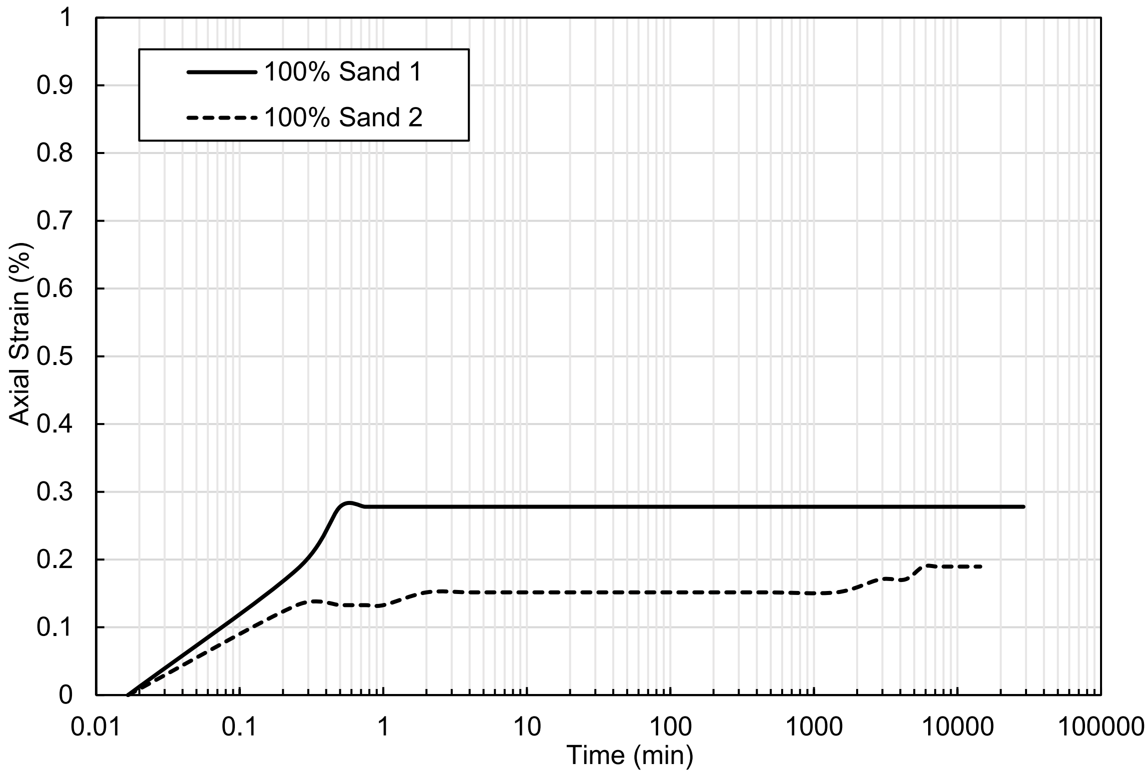


Figure 3.75 Bar Sand creep results.

Glen Mills RAP and bar sand mixtures were conducted at different percentages by weight ranging from 60% RAP to 90% RAP. The results from these tests are shown in **Figure 3.76**. All tests were run for 27,360 minutes (19 days), and as expected, the mixture containing 90% RAP and only 10% RAP experienced the most axial strain of 2.0%. The 80/20 mixture reached an axial strain of 1.2%, the 70/30 mixture reached an axial strain of 0.94%, and the 60/40 mixture reached an axial strain of 1.4%. As the percentage of bar sand increased, the axial strain decreased until the 60/40 mixture, where axial strain began to increase, as shown in **Figure 3.77**.

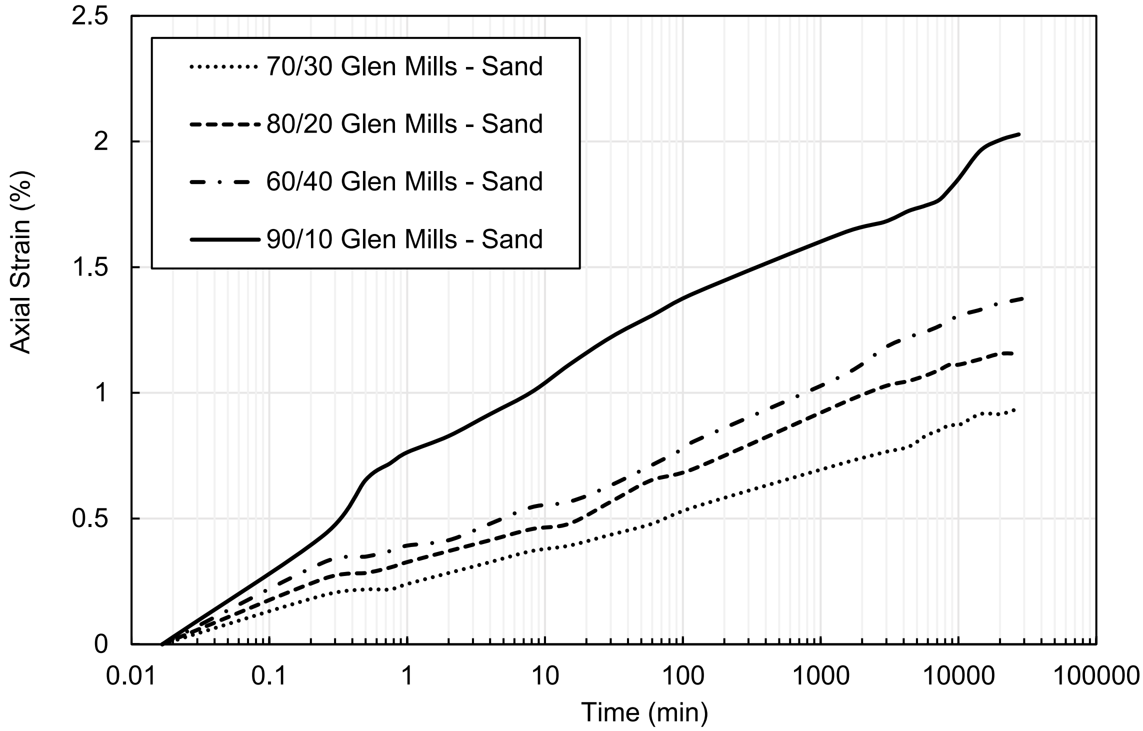


Figure 3.76 Glen Mills RAP and Bar Sand mixture comparison (Morro 2021).

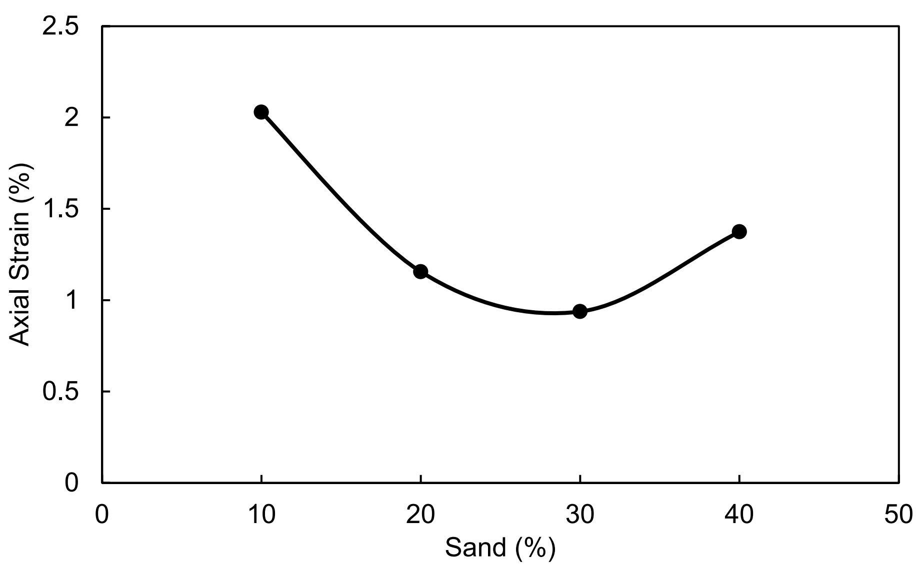


Figure 3.77 Glen Mills RAP and Bar Sand mixture comparison (Morro 2021).

3.6.3.2 Discussion

The results from the Bar Sand mixture analysis provided similar conclusions to the No. 57 Stone mixtures. Mixing RAP with coarse-grained materials that display little to no creep improved upon creep susceptibility. The bar sand mixture tests indicated that a 70/30 mixture provides the best results for creep. More testing would need to be conducted to determine if this mixture provides benefits for the other engineering properties beyond creep. Mixture testing is a promising solution to reducing creep in RAP, and results from this study provided similar conclusions to observations in literature (Cleary 2005; Cosentino et al. 2003; Cosentino et al. 2008; Dikova 2006; Kalpacki et al. 2018; Mousa and Mousa 2017).

3.7 Thermal Conditioning

Recent studies have evaluated the effects of temperature on the geotechnical properties of RAP. Due to the bituminous asphalt binder coating the aggregate, RAP is sensitive to temperature effects. Studies have concluded that compacting and consolidating RAP in the summer (i.e., high temperatures) can improve upon the compaction characteristics, thus reducing the excessive rate of creep (Yin et al. 2016; Soleimanbeigi and Edil).

3.7.1 Maximum Dry Density/Optimum Moisture Content

RAP is known to creep at an excessive rate. Creep can be reduced by decreasing the void ratio through compaction. One method used in previous RAP research to promote increased compaction has been to heat RAP prior to compaction (i.e., thermal conditioning). Studies have shown that this leads to increased maximum dry density and reduces creep (Soleimanbeigi and Edil 2015; Yin et al. 2016).

3.7.1.1 Methods

Thermal conditioning compaction tests were conducted using the modified proctor method as described in **Section 3.4.1.1**. Compaction tests were conducted on Highway Materials RAP to evaluate the effect of temperature on compaction characteristics. RAP was heated to a temperature of 35°C (95°F), with one test utilizing an oven as the heating apparatus, and the other test being heated outside. Samples of RAP were heated outside in the summer months (June and July 2022) to mimic field conditions that would be present on a construction site.

3.7.1.2 Results

Five compactions were conducted on both the oven heated and the outside heated Highway Materials RAP to develop the thermal conditioning compaction curves. Polynomial trendlines were fit to the data to identify the MDD and OMC, and these values were compared to the unheated Highway Materials RAP results for comparison. The compaction curves are provided in **Figure 3.78**, and the MDD and OMC results are provided in **Table 3.27**.

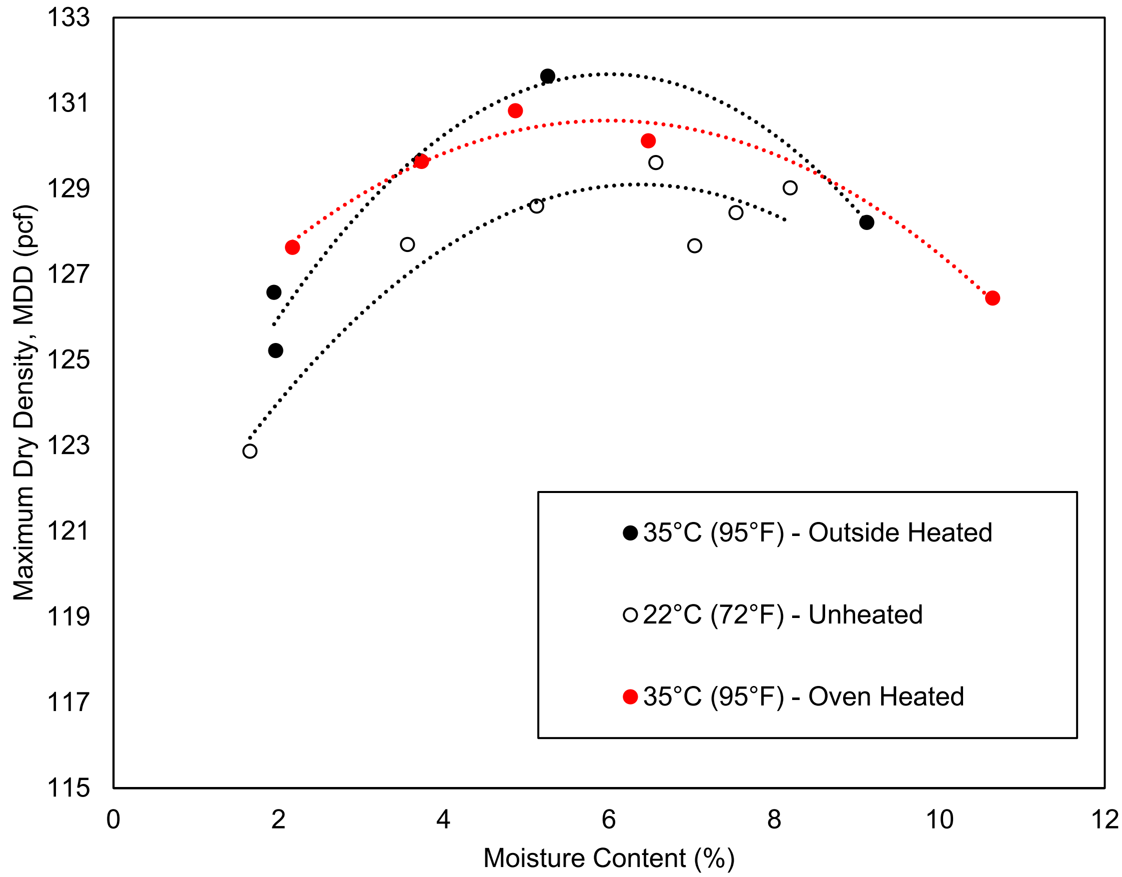


Figure 3.78 Highway Materials thermal conditioning compaction curves compared to the unheated compaction curve.

Table 3.27 Highway Materials thermal conditioning MDD and OMC compared to the unheated MDD and OMC.

Test	MDD (pcf)	OMC (%)
35 C (Outside Heated)	131.6	6.0
35 C (Oven Heated)	130.6	6.0
22 C (Unheated)	129.3	6.6

3.7.1.3 Discussion

Heating RAP to a temperature of 35 C improves upon its compaction characteristics. For both Highway Materials RAP, the MDD values were increased when the RAP was heated. There was no significant difference between heating RAP in the oven versus outside, which indicates that common construction practices of storing RAP outside on a hot summer day would be a sufficient heating method. The results from this analysis were consistent with observations in literature (Soleimanbeigi and Edil 2015; Yin et al. 2016). In general, RAP has slightly lower MDD values than coarse aggregate materials (e.g., No. 57 Stone) so heating RAP to 35 C allows RAP to be more similar to the material it would be replacing as a fill material.

3.7.2 Free Weight Creep Tests

Based on the heated compaction results, it was expected that creep would be reduced at elevated temperatures. Higher MDD values are an indication that less void space was present in the material, therefore less creep is expected to occur.

3.7.2.1 Methods

One free weight creep test was conducted on a heated sample Highway Materials RAP in the method as described in **Section 3.5.3.1**. Highway Materials RAP were compacted at a temperature of 35 degrees Celsius (95 degrees Fahrenheit). The level of creep was compared to RAP that was compacted at room temperature to investigate the effects of thermal conditioning on the creep of RAP.

3.7.2.2 Results

A free weight creep test was run on heated Highway Materials RAP for a duration of 21 days, reaching an axial strain value of 0.63%. After 15 days, it was observed that creep had stopped. These results were very similar to the results for the unheated Highway Materials free weight creep test, as shown in **Figure 3.79**. A difference in total axial strain of 0.63% to 0.66% is not significant.

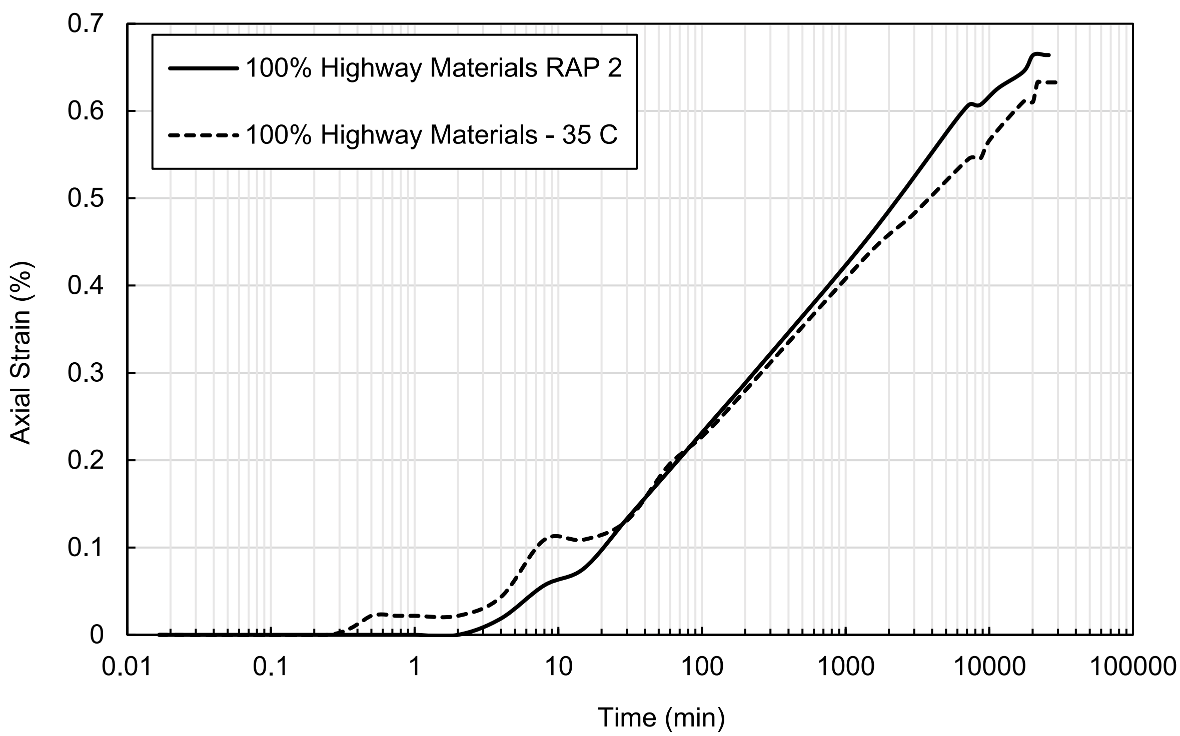


Figure 3.79 Comparison of creep for Highway Materials RAP compacted at 35 C.

3.7.2.3 Discussion

When Highway Materials RAP was compacted at a temperature of 35 C, the creep behavior was very similar to unheated Highway Materials RAP. According to literature, compacting RAP at elevated temperature has been observed to improve upon creep deformations (Soleimanbeigi and Edil 2015; Yin et al. 2016). The results for Highway Materials RAP were inconsistent with what was observed in literature, as no significant change in creep behavior was identified when RAP was heated. This would indicate that heating District 6 RAP during compaction does not improve upon creep deformations, however, because RAP is highly variable, only one test cannot provide conclusive results. Additionally, it is important to note that Highway Materials represents processed RAP, and no thermal conditioning creep testing was conducted on unprocessed RAP. More testing would need to be completed to understand the effect of thermal condition on creep in unprocessed RAP.

While the results from the free weight thermal conditioning creep test did not provide definitive improvements, it did not increase creep. It is still best practice to compact RAP under heated conditions that occur during the summer months. Further research on the effect of thermal conditioning on other engineering properties besides compaction and creep should be conducted.

3.8 Leaching

There are environmental concerns regarding the leaching of RAP. Because RAP is generated from asphalt, contaminants commonly found in roadway materials are of greatest concern. Variability of RAP leachate arises due to the manufacturing of the original asphalt, the application of RAP, the exposure during its lifespan as a roadway material, and the RAP storage length (Cosentino et al. 2003; Shedivy et al. 2012; Yang et al. 2020). For RAP to be allowable for use in non-pavement applications, leachate tests were conducted to determine the concentrations of contaminants found from each source.

3.8.1 Methods

The leaching of metals was evaluated for all the sources of District 6 RAP in general accordance with USEPA Method 1312 (USEPA 1994). To conduct leaching tests, 100 grams of RAP was placed in a 3-liter glass jar. Distilled water was used as the extraction fluid based on previous literature. Because RAP is completely solid, a 20:1 ratio of extraction fluid to RAP was utilized, therefore 2 liters of distilled water was placed in the 3-liter glass jar. The jar was placed on an orbital shaker and agitated at 100 rpm for 18 hours. After agitation had ended, the solution sat in the jar for 15 minutes to allow for the separation of solids from the liquid. After the initial separation occurred, the liquid was filtered through qualitative filter paper to ensure that no solid particles were in the extract solution. The pH of the extract was measured, and the extract was placed in 100 mL tubes. To preserve the samples, nitric acid was added until a pH of 2 was achieved. The samples were stored in a 4-degree Celsius refrigerator until they were sent to the Penn State Agricultural Analytical Laboratory for chemical analysis. Two rounds of testing were conducted on each source of RAP resulting in ten 40 mL tests being analyzed.

As previously discussed in **Section 2.3.5**, guidelines for leachate testing of RAP are provided in the Pennsylvania DEP's Special Conditions General Permit WMGM022 (DEP 2022). The permit provides a list of chemicals and the maximum concentrations associated with them for RAP material being used in construction activities. **Table 3.28** provides the list of chemicals and the RAP leachate maximum concentrations.

Table 3.28 Maximum leachate concentrations per WMGM022.

List of Chemicals	Maximum Leachate Concentrations (mg/L)
Arsenic	1.25
Barium	50.0
Cadmium	0.125
Chromium	2.5
Copper	32.5
Lead	1.25
Mercury	0.05
Molybdenum	-
Zinc	125
Nickel	2.5
Selenium	1.0
Silver	2.5
Benzene	0.005
Ethylbenzene	0.7
Xylenes	10
Toluene	1.0

Due to testing constraints, only some of the chemicals identified in WMGM022 (**Table 3.28**) were analyzed. The chemicals that were unable to be analyzed in this study (greyed out in **Table 3.28**) also were not commonly tested in the RAP literature.

3.8.2 Results

The results from the RAP leachate chemical analysis are provided in **Table 3.29**. The limit of quantitation (LOQ) is the lowest concentration that a chemical can be quantitated in confidence. The method detection limit (MDL) is the minimum concentration that can be reported to distinguish from a blank result. Any concentration below the LOQ and above the MDL was viewed as an approximation.

Table 3.29 Results from RAP leachate analysis.

Sample	As	Ba	Cd	Cr	Cu	Pb	Ni	Se	Zn	Hg
	-----mg/L-----									
PADEP Limits	**1.25**	**50**	**0.125**	**2.5**	**32.5**	**1.25**	**2.5**	**1**	**125**	**0.05**
LOQ	0.006	0.002	0.002	0.01	0.01	0.005	0.01	0.01	0.01	0.001
MDL	0.003	0.001	0.001	0.002	0.003	0.002	0.001	0.003	0.001	0.0001
Erie 1	<0.003	*0.002*	<0.001	<0.002	*0.005*	<0.002	<0.001	<0.003	0.021	*0.0005*
Erie 2	<0.003	*0.002*	<0.001	<0.002	*0.007*	<0.002	<0.001	<0.003	0.053	*0.0003*
Malvern 1	<0.003	0.003	<0.001	<0.002	*0.002*	<0.002	<0.001	<0.003	0.015	*0.0002*
Malvern 2	<0.003	0.002	<0.001	<0.002	<0.003	<0.002	<0.001	<0.003	0.037	*0.0002*
Glasgow 1	<0.003	0.004	<0.001	<0.002	0.011	<0.002	<0.001	<0.003	0.025	*0.0001*
Glasgow 2	<0.003	0.004	<0.001	<0.002	0.050	<0.002	<0.001	<0.003	0.024	*0.0002*
Delaware Valley Asphalt 1	<0.003	0.003	<0.001	<0.002	*0.005*	<0.002	<0.001	<0.003	0.029	*0.0001*
Delaware Valley Asphalt 2	<0.003	0.003	<0.001	<0.002	*0.004*	<0.002	<0.001	<0.003	0.023	*0.0001*
Highway Materials 1	<0.003	0.005	<0.001	<0.002	0.017	*0.003*	<0.001	<0.003	0.028	*0.0004*
Highway Materials 2	<0.003	0.004	<0.001	<0.002	0.204	<0.002	*0.001*	<0.003	0.030	*0.0005*
Note: Values reported below the LOQ but above the MDL should be viewed as an approximation										

3.8.3 Discussion

All results from the District 6 sources of RAP were well below the PADEP requirements for chemical concentrations in leachate. Barium (Ba), Copper (Cu), Zinc (Zn), and Mercury (Hg) provided detectable concentrations, however those concentrations were below the levels of concern for leachate. There was slight variability in the chemical concentrations for each RAP source, but the same metals were detected for all sources, and the differences in concentration were on the scale of the tenths to the ten thousandths decimal place. This indicated miniscule differences source-by-source, and it provided a general understanding of the chemicals of highest concern.

Presently, the PADEP has restrictions in place concerning the placement of RAP near bodies of water due to concerns over contaminant leaching. Based on the chemical analysis results, RAP leachate is not a major environmental concern. However, because RAP is so variable, it is likely that RAP from different sources may present different leaching concerns. The age, exposure, and the varying milling processes can affect the contaminants present within RAP. Further research is needed to definitively categorize the leachate concerns associated with RAP.

3.9 District 6 Experimental Testing Summary

The results from the District 6 RAP experimental testing program are summarized below:

Gradation - There is variability in the gradations of RAP from District 6. While all sources have a similar curvature and are generally well-graded. Unprocessed RAP (Malvern, Erie, and Delaware Valley Asphalt) had maximum particles sizes larger than 2 inches whereas processed RAP (Highway Materials, Glasgow, Glen Mills) had a maximum particle size of ½ inch. In general, District 6 RAP had very small amounts of fines, ranging from 0.2% to 0.7%. Additionally, in some cases, the coefficient of uniformity (C_u) provided trends with certain engineering properties, and for District 6 RAP, the C_u values ranged from 7.0 – 10.6.

Specific Gravity - The range of apparent specific gravity values for District 6 RAP was 2.56 to 2.62, with an average of 2.59. The values for District 6 RAP were within the range identified in literature of 2.25 to 2.77. This indicates that the specific gravity of District 6 RAP is consistent with other findings. The Villanova research team treated RAP as an aggregate material, whereas PennDOT treats RAP as a bituminous material for specific gravity testing. This resulted in smaller calculated specific gravity values for the Villanova tested RAP when compared to PennDOT results for the same material. It is unlikely that the different test methods will impact the ability for RAP to be reused in non-pavement applications.

Maximum Dry Density/Optimum Moisture Content – The maximum dry density (MDD) values for District 6 RAP ranged from 122.3 to 132.3 pcf. The optimum moisture contents (OMC) ranged from 3.7% to 7.8%. Post-compaction gradation analyses found that very little breakage occurred, with the largest increase in fines of 0.2% to 2.0% occurring in Highway Materials RAP. A correlation between MDD and C_u showed that as the C_u value increased, the MDD value increased.

Saturated Hydraulic Conductivity – The saturated hydraulic conductivity (k_{sat}) values for District 6 RAP ranged from 2 x 10^{-4} to 1 x 10^{-2} cm/s. All of the sources were larger than the Casagrande and Fadum (1940) free drainage classification of 1.0 x 10^{-4} cm/s. This indicated that the District 6 RAP was free draining. A trend between k_{sat} and C_u showed that as the C_u value increased, the k_{sat} value decreased. The k_{sat} value also correlated to MDD, showing that as MDD increased, the k_{sat} value decreased. These results indicate that the more well-graded the RAP, the higher density it will achieve, which results in a lower k_{sat} value that is still free draining.

Shear Strength/Cohesion - The friction angles identified during triaxial shear testing ranged from 42 - 46 degrees. The friction angles are large, indicating that RAP has high shear strength properties. The values of cohesion for RAP ranged from 21.9 to 27.9 kPa. Both the friction angle and the cohesion for District 6 RAP were similar to ranges identified in literature.

Creep – District 6 RAP exhibits large amounts of creep which is consistent with literature findings. When varying the deviator stresses for triaxial creep, the *m* values for District 6 RAP were less than 1.0, indicating that creep rupture would occur. When RAP was tested at lower percentages of its maximum deviator stress, creep was reduced, however, creep deformations did still occur. Additional triaxial creep tests were conducted at a shear stress of 50 kPa, and results provided a strong correlation between the total axial strain after 7 days, and the C_u value. As the C_u value increased, the total axial strain decreased. Both Delaware Valley Asphalt and Glasgow RAP had total axial strain values less than 3%, which is the axial strain limit identified by Viyanant et al. (2007). This indicated that at low stresses, creep is limited.

Creep tests using free weights were conducted to evaluate the long-term behavior of RAP. Tests on District 6 RAP were performed for a length of 17-37 days, and it was observed that creep slowed down, and eventually stopped. The results from this testing series were variable, with axial strains varying from 0.7% to 2.8% for District 6 RAP. A trend was observed between D_{50} and C_u, where increasing D_{50} values correlated to larger axial strains. The differences in D_{50} values corresponded to processed and unprocessed RAP, with unprocessed RAP having larger D_{50} values and larger axial strains.

Because the long-term free weight creep tests showed creep stopping after a period of time (around 14 days), a triaxial creep test was performed at the same stress conditions as the free weight creep tests. The triaxial test for Glasgow RAP had a total axial strain value of 2.1% which was larger than the free weight axial strain values of 0.8% and 1.3%. Additionally, the free weight creep tests showed creep stopping over time, whereas creep in the triaxial set-up slowed, but did not stop.

Mixtures – When District 6 RAP was mixed with No. 57 Stone, creep was improved. At a 50/50 blend of RAP and No. 57 Stone, the total axial strains were consistently smaller than what was observed in 100% RAP, and it was observed that creep had stopped after shorter periods of time. When the amount of RAP was increased to a 70/30 blend of RAP and No. 57 Stone, similar improvements were also observed. Supplemental testing was performed on RAP mixed with Bar Sand, and it was concluded that mixing RAP with sand also improved creep performance. All of the findings from the mixture evaluations were consistent with what was observed in literature.

Thermal Conditioning – RAP was compacted at a temperature of 35 C (95 F) to evaluate the effect that thermal conditioning has on creep characteristics. When Highway Materials RAP was heated in an oven and outside, the MDD values increased from 129.3 pcf to 131.6 pcf and 130.6 pcf. This indicated that as RAP is heated, it becomes denser. The creep evaluation showed no improvements as RAP was heated; however, more testing is needed to strengthen this observation.

Leaching – All results from the District 6 sources of RAP were well below the PADEP requirements for chemical concentrations in leachate. This indicates that leaching is not a concern in District 6 RAP.

4. RECOMMENDATIONS FOR RAP REUSE

4.1 Introduction

Based on information provided in various PennDOT/DEP publications (PennDOT 2019; PennDOT 2020; PennDOT 2022; WMGM022; WMGR101), RAP is currently allowable for use in pavement mixture applications, however, there is limited guidance on the reuse of RAP in non-pavement applications. Reuse of RAP as shoulder backfill material is the only non-pavement application that is currently approved by PennDOT in Publication 23 (PennDOT 2019), thus, identifying other reuse opportunities in non-pavement applications is necessary to limit the excess stockpiling of this material. According to FHWA, RAP can be used as an embankment and fill material, and nine states (Connecticut, Indiana, Kansas, Montana, New York, Tennessee, California, Illinois, Louisiana,) have reported use in this manner (FHWA 2016). Wen et al. (2022) identified 11 states that allow RAP to be used as embankment fill and 6 states that allow for the use of RAP as structural backfill. Wen et al. (2022) evaluated embankments that were constructed with RAP and determined that RAP cannot be used in an embankment above a rigid underground structure or bedrock, however, RAP would be allowable as a fill material if it was not placed within the top 5 feet of a rigid pavement embankment or the top 8 feet of a flexible pavement embankment (Wen et al. 2022). With state DOTs throughout the United States beginning to utilize RAP in fill applications, the Villanova research team recommends additional non-pavement applications that require similar engineering properties. The following applications were identified for RAP reuse: (1) embankment or fill, (2) shoulder backfill, (3) pipe bedding, and (4) reinforced fill for MSE walls.

This chapter utilizes information from the literature review and the District 6 experimental testing program to give recommendations on the reuse of RAP in non-pavement applications. The results from **Chapter 2** and **Chapter 3** were summarized in this chapter and the results were correlated into flowcharts that provide guidance on the reuse of RAP. The limitations on RAP reuse are provided, and methods to combat creep were highlighted.

4.2 Summary of Laboratory Results for Reuse of RAP in Non-Pavement Applications

Table 4.1 summarizes the results from laboratory evaluation of District 6 RAP and data reported in literature. These findings were used to evaluate relevant applications for the reuse of RAP.

Table 4.1 Summary of typical engineering properties of RAP.

Property	**Results from District 6 RAP**	**Results from Literature and District 6 RAP**
Gradation	Generally well-graded (C_u range from 4 - 12) Maximum particle size variable – ranging from >2 inches to 1/2 inch	Generally well-graded (C_u values range from 4 – 25) Maximum particle size variable – ranging from >2 inches to 1/2 inch
Maximum Dry Density (MDD)	122 pcf -132 pcf	100 pcf – 135 pcf
Optimum Moisture Content (OMC)	3% – 8%	3% – 8%
Saturated Hydraulic Conductivity (k_{sat})	10^{-3} cm/s – 10^{-2} cm/s	10^{-4} cm/s – 10^{-2} cm/s
Friction Angle (ϕ)	42° – 46°	37° – 46°
Cohesion	40 psf – 460 psf	0 psf – 1150 psf
Leaching	No chemical concentrations exceed requirements provided by PaDEP's WMGM022	Variable - some sources from literature found chemical concentrations exceeding applicable standards
Creep	RAP exhibits significant creep Mixing RAP with other aggregates improved creep	RAP creeps at an excessive rate Elevated temperatures during compaction and mixing RAP with other aggregates improved creep

In general, the findings for each engineering property were similar to typical coarse aggregate material being used in different applications. A comparison of RAP to typical coarse aggregate is necessary because RAP would be replacing aggregate in many of the recommended applications.

For gradation, RAP generally had similar particle size distributions to typical coarse aggregate material. In some circumstances, the particle size of RAP was larger, with maximum particle sizes larger than 2 inches. Scalping or mixing RAP with aggregate would be acceptable to allow RAP to meet the particle size requirements for various applications.

Maximum dry density (MDD) results for RAP were slightly lower than typical coarse aggregate, however, the MDD values were still considered high. If an application requires a higher MDD value, scalping or mixing RAP with other aggregate materials to achieve a higher C_u value would increase the MDD, and would make RAP acceptable for that application. Additionally, RAP is a free draining material, making it suitable for applications that require drainage to prevent the buildup of pore pressures. Also, RAP has high shear strength characteristics, which is similar to other coarse aggregate materials.

While most of the engineering properties for RAP were similar to typical coarse aggregate materials, RAP displays high creep susceptibility whereas coarse aggregates generally do not creep. For many applications, creep is the limiting factor for the reuse of RAP, and these limitations are discussed in a subsequent section.

4.3 Guidelines for RAP Implementation

Flow charts were created to provide recommendations for the applications in which RAP could potentially be reused. Applications include: (1) embankment or fill material, (2) shoulder backfill, (3) pipe bedding, (4) and reinforced fill for MSE walls. The charts are provided in **Appendix 1**.

<u>Embankment or Fill</u> – Typical coarse aggregates used in embankment and fill applications in Pennsylvania include AASHTO No. 8, AASHTO No. 57, PennDOT 2A, PennDOT open-graded subbase (OGS), and PennDOT select granular material (2RC). In general, the requirements for the reuse of RAP in this application are to provide similar engineering properties as typical coarse aggregate material. To meet the requirements for use in embankment or fill applications, the gradation properties of RAP must include a maximum particle size of less than 2 inches, a coefficient of uniformity (C_u) value greater than 4, and a fines content less than 5% (Publication 15M; Publication 408). Additionally, the particle size distribution curve should be comparable to the particle size distribution curves for typical coarse aggregates used in embankment and fill applications. The maximum dry density (MDD) of RAP must have similar densities to typical coarse aggregates, which is generally larger than 100 pcf (FHWA 2016). RAP must be free draining and have a friction angle comparable to other coarse aggregate materials, which is typically larger than 34 degrees (Publication 408; FHWA 2016). Also, chemical concentrations due to leaching cannot surpass the maximum concentrations provided in the Pennsylvania DEP's Special Permit WMGM022.

If the engineering properties of RAP are comparable to typical coarse aggregates used in embankment or fill applications, creep must be evaluated. Coarse aggregate materials generally do not display creep characteristics; however, RAP is known to creep. Allowable amounts of creep deformations are dependent upon the embankment or fill application, thus, engineering judgement must be used to determine how much creep is allowable in the design application. The flowchart for the reuse of RAP as an embankment or fill material is provided in **Appendix 1**.

<u>Shoulder Backfill</u> – RAP is currently an allowable material for gravel shoulder backfill applications in Pennsylvania per PennDOT Publication 23 – Chapter 5. For use in this application, RAP must be considered clean, meaning it is free from subbase, dirt, soil, or other contaminants. If RAP is clean, it can be used as a shoulder backfill material if compaction and a liquid bituminous surface treatment is applied. The flowchart for the reuse of RAP as a shoulder backfill material is provided in **Appendix 1**.

MSE Walls – Typical reinforced fill used in MSE wall applications in Pennsylvania are dependent upon the type of geogrid utilized. For Class 1 geogrids, No. 8 aggregate is used in areas that require free drainage or in areas that are below the 100-year flood elevation. For other areas, a reinforced fill mixture is created. For Class 2 and 3 geogrids, AASHTO No. 8, AASHTO No. 57, and PennDOT 2A aggregates are typically used. Similar to the embankment and fill requirements, RAP must provide comparable engineering properties as typical reinforced fill material used in MSE walls. The gradation properties of RAP must include a maximum particle size of less than 2 inches and a fines content less than 5% (Publication 408; Publication 15M). Additionally, the particle size distribution curve should be comparable to the particle size distribution curves for typical reinforced fill material used in MSE wall applications. The maximum dry density (MDD) of RAP must fall within the range of 90 – 120 pcf (PennDOT 2019). RAP must be free draining and have a friction angle that is larger than 34 degrees for the particle sizes passing through the No. 8 sieve (PennDOT 2019; PennDOT 2022). Also, chemical concentrations due to leaching cannot surpass the maximum concentrations provided in the Pennsylvania DEP's Special Permit WMGM022. Additionally, the pH must be within the range of 5.0 – 9.0 to prevent corrosion (PennDOT 2022). Because RAP is known to creep, the allowable amounts of creep deformations must be evaluated for specific project applications using engineering judgement. The flowchart for the reuse of RAP as reinforced fill for MSE walls is provided in **Appendix 1**.

Pipe Bedding – The type of coarse aggregate used for pipe bedding applications in Pennsylvania is dependent upon the type of pipe being utilized. For concrete pipes, AASHTO No. 8 aggregate is used. For metal and thermoplastic pipes, PennDOT 2A is used. If RAP is used in this application, the maximum particle size must be less than 2 inches and the fines content must be less than 10% (Publication 408). Additionally, the gradation envelope must be comparable to the typical coarse aggregates used in this application. Pipe bedding applications require uncompacted material, therefore maximum dry density is not a concern. RAP must be free draining, and the friction angle must be comparable to typical coarse aggregate materials, which is generally larger than 34 degrees (FHWA 2016; PennDOT 2022). If creep is a concern, further evaluation by the engineer should be completed. Also, chemical concentrations due to leaching cannot surpass the maximum concentrations provided in the Pennsylvania DEP's Special Permit WMGM022. The flowchart for the reuse of RAP as pipe bedding is provided in **Appendix 1**.

4.4 Limitations of RAP Reuse

Literature studies as well as District 6 RAP laboratory testing results showed that RAP may creep at an excessive rate (Cosentino et al. 2003; Cosentino et al. 2008; Rathje et al. 2006; Soleimanbeigi and Edil 2015). While typical coarse aggregate materials do not display creep concerns, the bitumen binder in RAP causes RAP to have high creep deformations. This is a concern in structural applications because the deformations that occur over time can lead to creep rupture.

Because creep is a concern in most applications, it is important to limit the creep deformations. Creating mixtures with RAP and aggregates that do not display creep (No. 57 stone, No. 2A, etc.) limits the creep deformations while still saving costs. Experimental testing on District 6 RAP found that mixing RAP and No. 57 stone at a blend of 50/50 reduced the overall axial strains and limited creep over time. When a mixture with a larger portion of RAP was created at a 70/30 blend, similar characteristics were observed. As more aggregate material was introduced, creep was reduced. Additionally, literature studies investigated RAP – sand mixtures, and found that creep was reduced when sand was introduced (Cosentino et al. 2003; Cosentino et al. 2008; Kalpacki et al. 2018; Mousa and Mousa 2017). Mixtures are a promising solution in applications where creep is a design concern.

Thermal conditioning RAP during compaction is an additional measure to reduce creep. Literature studies found that when RAP was compacted at elevated temperatures, creep was reduced (Abedalqader et al. 2021; Soleimanbeigi and Edil 2015; Yin et al. 2017). These studies recommended that construction with RAP should be conducted in the summer months to lessen the creep deformations.

Creep may limit the use of RAP in structural applications; however, further study of specific RAP materials and loading conditions is needed. The implementation of one or both of the techniques (aggregate mixtures, elevated temperatures) is recommended to allow for a wider range of applications where RAP could be reused.

4.5 Example for Embankment or Fill Flowchart

Below is an example scenario for evaluating RAP for reuse as an embankment material using the flowchart in **Appendix 1**:

Six bags of RAP were collected from the Delaware Valley Asphalt Plant in Philadelphia, Pennsylvania. The RAP was brought to the laboratory and leachate tests were conducted using USEPA Method 1312 (USEPA 1994). The RAP did not exceed the chemical concentrations provided by the Pennsylvania DEPs WMGM022 (DEP 2022).

Once it was determined that leaching was not a concern, laboratory sieve tests were conducted using PTM 616. The gradation analysis identified a maximum particle size of larger than 2 inches, a C_u value of 11.8, and 0.2% fines. The particle size distribution curve showed that the RAP generally fit within the gradation envelope of a PennDOT's 2RC material, which is a typical coarse aggregate used in embankment applications, however its maximum particle size was larger than 2 inches. Because all of the other gradation requirements were met, scalping was conducted to remove the particles larger than 2 inches. When scalping was complete, laboratory sieve tests were conducted on the new gradation, and the scalped material passed all of the requirements.

Next, maximum dry density (MDD) compaction tests were conducted on the scalped RAP using PTM 106 (PTM 2013). The MDD value was identified to be 129.9 pcf, which was comparable to a typical coarse aggregate material. The MDD value for the scalped RAP passed the requirements for embankment material, and additional engineering property tests were conducted using the MDD value.

Saturated hydraulic conductivity (k_{sat}) and triaxial shear tests were conducted concurrently using ASTM D2434 and ASTM D7181 (ASTM 2020; ASTM 2022). The k_{sat} value was identified as 8.8×10^{-4} cm/s and this value indicated that the RAP was free draining. The friction angle was identified as 46 degrees, and this value was comparable to typical coarse aggregate material used in embankment applications. The scalped RAP passed both of the requirements for k_{sat} and friction angle.

Creep tests were conducted using a modification of ASTM 7181, and a design load for a typical embankment was applied during the test (ASTM 2020). At the conclusion of the creep testing, it was found that the scalped RAP exhibited too much creep. To mitigate this, the RAP was mixed with No. 57 Stone, and the creep test was conducted again. Mixing with No. 57 Stone reduced the creep, and engineering judgement was used to determine whether the creep deformations were allowable in the particular embankment application.

5. CONCLUSIONS

A review of literature was conducted on the beneficial reuse and geotechnical properties of RAP. Results from the review found RAP to be highly variable throughout the United States, due in part to differences in how the RAP is processed, stored, and aged, thus, resulting in differences in geotechnical properties. In general, RAP has similar properties to other coarse aggregate materials commonly used in non-pavement highway transportation applications, however, due to its bituminous binder coating, RAP is highly susceptible to creep. Studies identified creep to be the limiting factor in the reuse of RAP, and recent research has investigated techniques such as aggregate mixing and elevated temperatures to reduce the creep susceptibility of RAP.

Experimental testing on District 6 RAP further identified the variability of RAP, with sources throughout the District demonstrating differences in maximum particle size, MDD, k_{sat}, shear strength, and creep. While differences in the geotechnical properties were present, the results were similar to what was found in literature and RAP exhibited similar properties (except for creep) to typical coarse aggregate materials.

Similar to existing studies in the literature, creep was found to be a concern for District 6 RAP. When stress was applied to RAP in triaxial and free weight creep tests, high amounts of deformation was observed. This indicated that RAP was likely to exhibit excessive creep in geotechnical applications without intervention. Techniques such as aggregate mixing with No. 57 Stone and elevated temperatures were investigated to minimize creep. A 50/50 and a 70/30 blend of RAP to No.57 Stone were evaluated and it was observed that reducing the amount of RAP in the mixture reduced the creep deformations. Additionally, one test was conducted on RAP that had been compacted at an elevated temperature (i.e., 95°F), and the results from the test showed that creep was not affected by elevated temperatures. Further testing is needed to investigate creep and factors affecting creep of RAP.

Results from the literature review and the District 6 experimental testing program were used to provide recommendations on RAP reuse opportunities. The reuse applications that were identified included: (1) embankment or fill, (2) shoulder backfill, (3) pipe bedding, and (4) reinforced fill for MSE walls. Flow charts were provided to identify the requirements, the recommended geotechnical properties, and the techniques available to allow for the reuse of RAP in each application.

While RAP reuse opportunities were identified, engineering judgement should be used in regards to creep. Future research should focus on methods to limit creep, and large-scale testing should be conducted to evaluate the long-term behavior of RAP in embankments or as a fill material. Also, methods to limit variability should be evaluated. Standards for the milling process of RAP should be created to provide guidance on the maximum particle size, the C_u value, the asphalt age, and the asphalt content of RAP that is being created. This would ensure that RAP has more uniform properties throughout the state of Pennsylvania.

References

Abedalqader, A., Shatarat, N., Ashteyat, A., Katkhuda, H. (2021). "Influence of Temperature on Mechanical Properties of Recycled Asphalt Pavement Aggregate and Recycled Coarse Aggregate Concrete." *Construction and Building Materials,* 269.

Arulrajah, A., Piratheepan, J. Disfani, M.M., Bo, M.W. (2013). "Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications." *Journal of Materials in Civil Engineering*, 25.

ASTM International. *C136/C136M-19 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. West Conshohocken, PA; ASTM International, 2019. doi: https://doi.org/10.1520/C0136_C0136M-19.

ASTM International. *C127-15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. West Conshohocken, PA; ASTM International, 2015. doi: https://doi.org/10.1520/C0127-15.

ASTM International. *C128-15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. West Conshohocken, PA; ASTM International, 2015. doi: https://doi.org/10.1520/C0128-15.

ASTM International. *D1557-12(2021) Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3))*. West Conshohocken, PA; ASTM International, 2021. doi: https://doi.org/10.1520/D1557-12R21.

ASTM International. *D2041-19 Standard Test Method for Theoretical Maximum Specific Gravity and Density of Asphalt Mixtures*. West Conshohocken, PA; ASTM International, 2019. doi: https://doi.org/10.1520/D2041_D2041M-19.

ASTM International. *D2434(2022) Standard Test Methods for Measurement of Hydraulic Conductivity of Course-Grained Soils*. West Conshohocken, PA; ASTM International, 2022. doi: https://www.astm.org/d2434-22.html.

ASTM International. *D7181-20 Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils*. West Conshohocken, PA; ASTM International, 2020. doi: https://doi.org/10.1520/D7181-20.

Aydilek, A.H., Z. Mijic, and O. Seybou-Insa. 2017. Hydraulic and Environmental Behavior of Recycled Asphalt Pavement in Highway Shoulder Applications. Final Report. University of Maryland, College Park. October.

Bejarano, M. (2001). *Evaluation of Recycled Asphalt Concrete Materials as Aggregate Base.* California Department of Transportation, Sacramento, California.

Bennert, T., Maher, A., (2005). *The Development of a Performance Specification for Granular Base and Subbase Material,* New Jersey Department of Transportation, New Jersey.

Birgisdottir, H., J. Gamst, and T.H. Christensen. (2007). Leaching of PAHs from Hot Mix Asphalt Pavements. Environmental Engineering Science. Volume 24, Number 10.

Bleakley, A.M., Cosentino, P.J. (2012). *Improving the Properties of Reclaimed Asphalt Pavement for Roadway Based Applications through Blending and Chemical Stabilization.* Transportation Research Board, Florida.

Brantley, A.S., and T.G. Townsend. 1999. Leaching of Pollutants from Reclaimed Asphalt Pavement. Environmental Engineering Science Volume 16, Number 2. 105–116.

Casagrande, A., Fadum, R.E. (1940). *Notes on Soil Testing for Engineering Purposes*. Harvard Soil Mechanics, Series No. 8, Cambridge Massachusetts.

Cleary, E.D. (2005). *Long-Term Behavior of RAP-Soil Mixtures for Use as Backfill Behind MSE Walls,* M.S. Thesis, Civil Engineering, Florida Institute of Technology.

Coban, H.S., Cetin, B., Ceylan, H., Likos, W., Edil, T.B. (2021) Effects of Using Recycled Aggregates and Large Stones for Base and Subbase Layers on Modulus Properties of Pavements." *Advances in Transportation Geotechnics IV,* LNCE, 164.

Cooley, D.A. (2005). *Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials*, M.S. Thesis, Civil Engineering, Brigham Young.

Copeland, A. (2011). Recycled Asphalt Pavement and in Asphalt Mixtures: State of Practices, Federal Highway Administration, Mclean, Virginia.

Cosentino, P.J., Kalajian, E.H., Shieh, C.S., Mathurin, W.J.K., Gomez, F.A., Cleary, E.D., Treeratrakoon, A. (2003). *Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill Materials, Phase II, Final Report,* Florida Department of Transportation, Tallahassee, Florida.

Cosentino, P.J., Kalajian, E.H., Dikova, D., Patel, M., Sandin, C. (2008). *Investigating the Statewide Variability and Long-Term Strength Deformation Characteristics of RAP and RAP-Soil Mixtures, Final Report,* Florida Department of Transportation, Tallahassee, Florida.

DEP (Department of Environmental Protection) Bureau of Waste Management. (2020). *Special Conditions General Permit Number WMGR101*, Harrisburg, Pennsylvania.

DEP (Department of Environmental Protection) Bureau of Waste Management. (2021). *Management of Fill Policy*, Harrisburg, Pennsylvania.

DEP (Department of Environmental Protection) Bureau of Waste Management. (2022). *Special Conditions General Permit Number WMGM022*, Harrisburg, Pennsylvania.

Dikova, D. (2006). *Creep Behavior of RAP–Soil Mixtures in Earthwork Applications*. M.S. Thesis. Florida Institute of Technology, Melbourne.

FHWA (Federal Highway Administration) Research and Technology. (2016). *User Guidelines for Waste and Byproduct Materials in Pavement Construction,* Washington, D.C.

FHWA (Federal Highway Administration) Research and Technology. (2020). *Asphalt Pavement Recycling with Reclaimed Asphalt Pavement (RAP),* Washington, D.C.

FHWA (Federal Highway Administration) Research and Technology. (2021). *Resource Responsible Use of Reclaimed Asphalt Pavement in Asphalt Mixtures,* Washington, D.C.

Gao, J., Yang, J., Yu, D., Jiang, Y., Ruan, K., Tao, W., Sun, C., Luo, L. (2021). "Reducing the Variability of Multi-Source Reclaimed Asphalt Pavement Materials: A Practice in China." *Construction and Building Materials,* 278.

Goodhart, C.C., Koser, S.L. (2017). *Reclaimed Asphalt Pavement (RAP) Ownership,* Pennsylvania PAPA Regional Technical Meetings, Pennsylvania Asphalt Pavement Association, Harrisburg, Pennsylvania.

Hajj, E.Y., Sebaaly, P.E., West, R., Morian, N., Luis Loria, L. (2012). "Recommendations for the characterization of RAP aggregate properties using traditional testing and mixture volumetrics." *Road Materials and Pavement Design*. 13, 209-233.

Herrera Environmental Consultants, Inc. (2019). *Contaminant Leaching from Recycled Asphalt Pavement,* Thurston County Community Planning and Economic Development, Olympia, Washington.

Kalpakci, V., Faeq, R., Canakci, H. (2018). "Compaction and CBR Properties of RAP/Sand Blends in Iraq." *Arab J Geosci,* 11, 663.

Kang, D.H., S.C. Gupta, A.Z. Ranaivoson, R. Roberson, and J. Siekmeier. (2011). Recycled Materials as Substitutes for Virgin Aggregates in Road Construction: II. Inorganic Contaminant Leaching. Soil Society of America Journal 75:1276–1284.

Legret, M., L. Odie, D. Demare, and A. Jullien. (2005). Leaching of heavy metals and polycyclic aromatic hydrocarbons from reclaimed asphalt pavement. Water Research 39:3675–4685.

Locander, R. (2009). *Analysis of Using Reclaimed Asphalt Pavement (RAP) as a Base Course Material*. Colorado Department of Transportation-Research, Denver, Colorado.

Ma, T., Wang, H., Zhao, Y., Huang, X. (2015). "Laboratory Investigation on Residual Strength of Reclaimed Asphalt Mixture for Cold Mix Recycling." *International Journal of Pavement Research and Technology*, 8(1):17-22.

McGarrah, E.J. (2007). *Evaluation of Current Practices of Reclaimed Asphalt Pavement/Virgin Aggregate as Base Course Material,* Washington State Department of Transportation, Seattle, Washington.

Mehta, Y.M., A. Ayman, B. Yan, A.E. McElroy, and Y. Huiming. (2017). Environmental Impacts of Reclaimed Asphalt Pavement (RAP). FHWA-NJ-2017-008.

Mijic, Z., Dayioglu, A.Y., Hatipoglu, M., Aydilek, A.H. (2020). "Hydraulic and Environmental Impacts of Using Recycled Asphalt Pavement on Highway Shoulders." *Construction and Building Materials,* 234.

Morro, R.H. (2021). *Characterization of Reclaimed Asphalt Pavement in Pennsylvania and Evaluation of Its Use in Geotechnical Infrastructure Applications*, M.S. Thesis, Department of Civil Engineering, Villanova University.

Morse, A., A.M. Jackson, and R. Davio. 2001. Environmental Characterization of Traditional Construction and Maintenance Materials. In T.T. Eighmy, ed., Proceedings of an International Conference on Beneficial Use of Recycled Materials in Transportation Applications, Arlington, Virginia. November 13–15, 2001. University of New Hampshire, Durham.

Mousa, R.M., Mousa, M.R. (2017). "Viability Assessment Using of Using Reclaimed Asphalt Pavement – Sand Blend in Road Construction: A Case Study in Egypt." *The 96th Transportation Research Board Annual Meeting*, Washington, D.C.

Mousa, E., El-Badawy, S., Azam, A. (2021). "Evaluation of Reclaimed Asphalt Pavement as Base/Subbase Material in Egypt." *Transportation Geotechnics,* 26.

Norin, M., and A-M. Strömvall. 2004. Leaching of Organic Contaminants from Storage of Reclaimed Asphalt Pavement. Environmental Technology, Volume 25, pp. 323–340.

O'Brien DeTrano, J. (2017). "PennDOT Regional Offices" *PennDOT Way.* Accessed October 20, 2021. https://www.penndot.gov/PennDOTWay/pages/Article.aspx?post=40.

PennDOT (Pennsylvania Department of Transportation). (2016). *Publication 19 Field and Laboratory Testing Manual*, Harrisburg, Pennsylvania.

PennDOT (Pennsylvania Department of Transportation). (2019). *Publication 15M/2019 Design Manual, Part 4 (DM-4)*, Harrisburg, Pennsylvania.

PennDOT (Pennsylvania Department of Transportation). (2019). *Publication 23 Maintenance Manual – Chapter 5,* Harrisburg, Pennsylvania.

PennDOT (Pennsylvania Department of Transportation). (2020). *PennDOT Recycling Material Fact Sheet*, Harrisburg, Pennsylvania.

PennDOT (Pennsylvania Department of Transportation). (2022). *Publication 408/2020 Specifications*, Harrisburg, Pennsylvania.

Pennsylvania Test Method. *PTM 106 The Moisture-Density Relations of Soil (Using a 2.5 Kg (5.5lb.) Rammer and a 305 mm (12-inch) Drop*. Harrisburg, Pennsylvania, PA; PennDOT 2013.

Pennsylvania Test Method. *PTM 128 Sample Preparation of Fill Material for Mechanically Stabilized Earth (MSE) Retaining Wall Systems*. Harrisburg, Pennsylvania, PA; PennDOT 2013.

Pennsylvania Test Method. *PTM 616 Sieve Analysis of Coarse and Fine Aggregates*. Harrisburg, Pennsylvania, PA; PennDOT, 2013.

Rahardjo, H., Satyanaga, A., Leong, E., Wang, J. (2013). "Unsaturated Properties of Recycled Concrete Aggregate and Reclaimed Asphalt Pavement." *Engineering Geology*. 161, 44-54.

Rathje, E.M., Rauch, A.F., Trejo, D., Folliard, K.J., Trejo, D., Ogalla, M., Viyanant, C., Esfellar, M., Jain, A. (2002). Recycled Asphalt Pavement and Crushed Concrete Backfill: Results from Initial Durability and Geotechnical Tests, Texas Department of Transportation Research and Technology, Austin, Texas.

Rathje, E.M., Rauch, A.F., Trejo, D., Folliard, K.J., Viyanant, C., Esfellar, M., Jain, A., and Ogalla, M. (2006). *Evaluation of Crushed Concrete and Recycled Asphalt Pavement as Backfill for Mechanically Stabilized Earth Walls,* Texas Department of Transportation Research and Technology, Austin, Texas.

Rees, S. (2013). *Introduction to Triaxial Testing*. GDS Instruments, Hook, Hampshire, United Kingdom.

Seybou-Insa, O., Dayioglu, A.Y., Houlihan, M., Aydilek, A.H. (2021). "pH_{Stat} Testing and Geochemical Modeling of Inorganic Compounds in Recycled Asphalt Pavement Used in Highway Shoulders." *Construction and Building Materials*, 313.

Shedivy, R., Meier, A., Ma, J., Tinjum, J.M., Edil, T.B., Benson, C.H., Chen, J., Bradshaw, S. (2012). *Leaching Characteristics of Recycled Asphalt Pavement Used as Unbound Road Base,* University of Wisconsin System Solid Waste Research Program, Madison, WI.

Singh, A. and Mitchell, J.K. (1968), "General stress-strain-time function for soils," Journal of Soil Mechanics and Foundations Division, Proceedings of the ASCE, Vol. 94, No. SM1, pp. 21-46.

Solaimanian, M., Milander, S., Boz, I., Stoffels, S. (2011). *Development of Guidelines for Usage of High Percent RAP in Warm-Mix Asphalt Pavements,* Pennsylvania Department of Transportation, Harrisburg, Pennsylvania.

Soleimanbeigi, A., Edil, T.B. (2015). “Thermal Conditioning to Improve Geotechnical Properties of Recycled Asphalt Pavements.” *Geotechnical Testing Journal,* 38(4), 1-12.

Soleimanbeigi, A., Ozocak, A., Li, B., Akmaz, E., Dayioglu, A.Y., Tanyu, B.F., Aydilek, A.H., Likos, W.J. (2021) Mechanical and Hydraulic Compatibility of RAP with Geosynthetics Used in MSE Walls.” *Geosynthetics International,* 0, 1-8.

Tarsi, G., Tataranni, P., Sangiorgi, C. (2020). “The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review.” *Materials,* 13(18), 4052.

Thakur, J.K., Han, J., Parsons, R.L. (2013). “Creep Behavior of Geocell-Reinforced Recycled Asphalt Pavement Bases.” *Journal of Materials in Civil Engineering*, 25, 10.

Titi, H.H., Tabatabai, H., Ramirez, J., Sooman, M. (2019). *Evaluation of Recycled Base Aggregates,* Wisconsin Department of Transportation, Madison, Wisconsin.

USEPA. *Method 1312 Sythetic Precipitation Leaching Procedure*. (1994). USEPA. Washington D.C.

Viyanant, C. (2006). *Potential Use of Recycled Asphalt Pavement and Crushed Concrete as Backfill for Mechanically Stabilized Earth Walls*, PhD. Dissertation, University of Texas at Austin.

Viyanant, C., Rathje, E. M., and Rauch, A. F. (2007). “Creep of compacted recycled asphalt pavement.” *Can. Geotech. J.*, 44(6), 687–697.

Williams, B.A., Willis, J.R., Shacat, J. (2020). *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2019.* National Asphalt Pavement Association, Greenbelt, Maryland.

Wen, H., Barzegar, M., Mivehchi, M., Akin, I., Edil, T., Muhunthan, B. (2022). *Utilization and Limitations of Recycled Asphalt Pavement (RAP) as Roadway Embankment Material, Draft Final Report,* Illinois State Toll Highway Authority, Downers Grove, Illinois.

West, R.C. (2010). *Reclaimed Asphalt Pavement Management: Best Practices*, National Center for Asphalt Technology, Auburn University, Auburn, Alabama.

Yang, Q., Yin, H., He, X., Chen, F., Ali, A., Mehta, Y., Yan, B. (2020). “Environmental Impacts of Reclaimed Asphalt Pavement on Leaching of Metals into Groundwater.” *Transportation Research Part D: Transport and Environment,* 85.

Yin, J., Soleimanbeigi, A., Warren, B., Likos, W., and Edil, T. (2016). “Creep Behavior of Recycled Asphalt Pavement at Elevated Temperatures.” ASCE Geotechnical and Structural Engineering Congress 2016, ASCE, Reston, VA, 1426–1434.

Yin, J., Soleimanbeigi, A., Likos, W.J., Edil, T.B. (2017). "Effects of Temperature on Creep Behavior of Compacted Recycled Asphalt Pavement." *Journal of Geotechnical and Geoenvironmental Engineering*, 143 (4).

Yousefi, A., Behnood, A., Nowruzi, A., Haghshenas, H. (2021). "Performance Evaluation of Asphalt Mixtures Containing Warm Mix Asphalt (WMA) Additives and Reclaimed Asphalt Pavement (RAP)." *Construction and Building Materials,* 268.

Zhou, F., Das, G., Scullion, T., Hu, S. (2010). *RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines*, Texas Department of Transportation Research and Technology, Austin, Texas.

Appendix

A.1 RAP Reuse Flowcharts

RAP Reuse as Embankment or Fill Flowchart

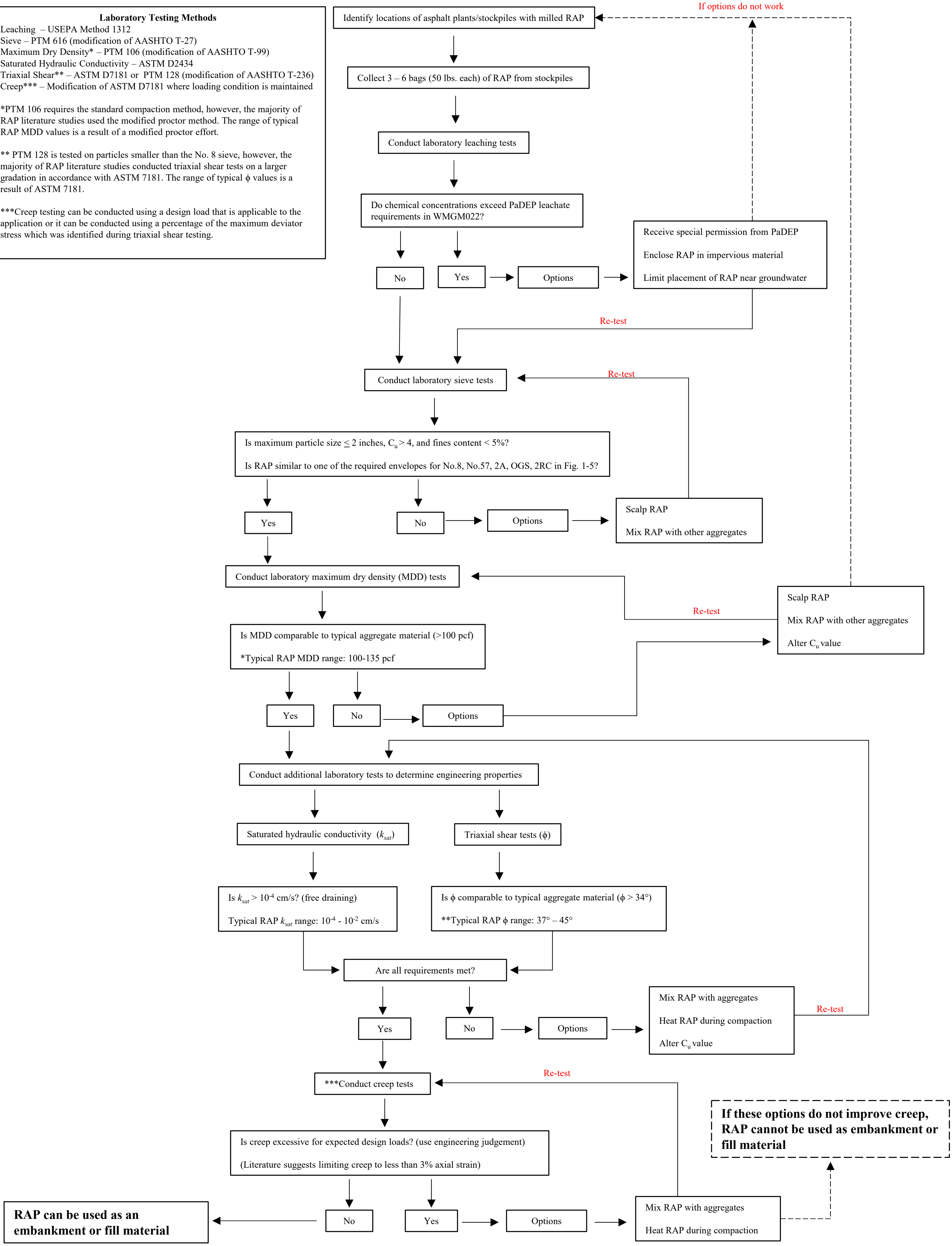
Laboratory Testing Methods

Leaching – USEPA Method 1312
Sieve – PTM 616 (modification of AASHTO T-27)
Maximum Dry Density* – PTM 106 (modification of AASHTO T-99)
Saturated Hydraulic Conductivity – ASTM D2434
Triaxial Shear** – ASTM D7181 or PTM 128 (modification of AASHTO T-236)
Creep*** – Modification of ASTM D7181 where loading condition is maintained

*PTM 106 requires the standard compaction method, however, the majority of RAP literature studies used the modified proctor method. The range of typical RAP MDD values is a result of a modified proctor effort.

** PTM 128 is tested on particles smaller than the No. 8 sieve, however, the majority of RAP literature studies conducted triaxial shear tests on a larger gradation in accordance with ASTM 7181. The range of typical ϕ values is a result of ASTM 7181.

***Creep testing can be conducted using a design load that is applicable to the application or it can be conducted using a percentage of the maximum deviator stress which was identified during triaxial shear testing.



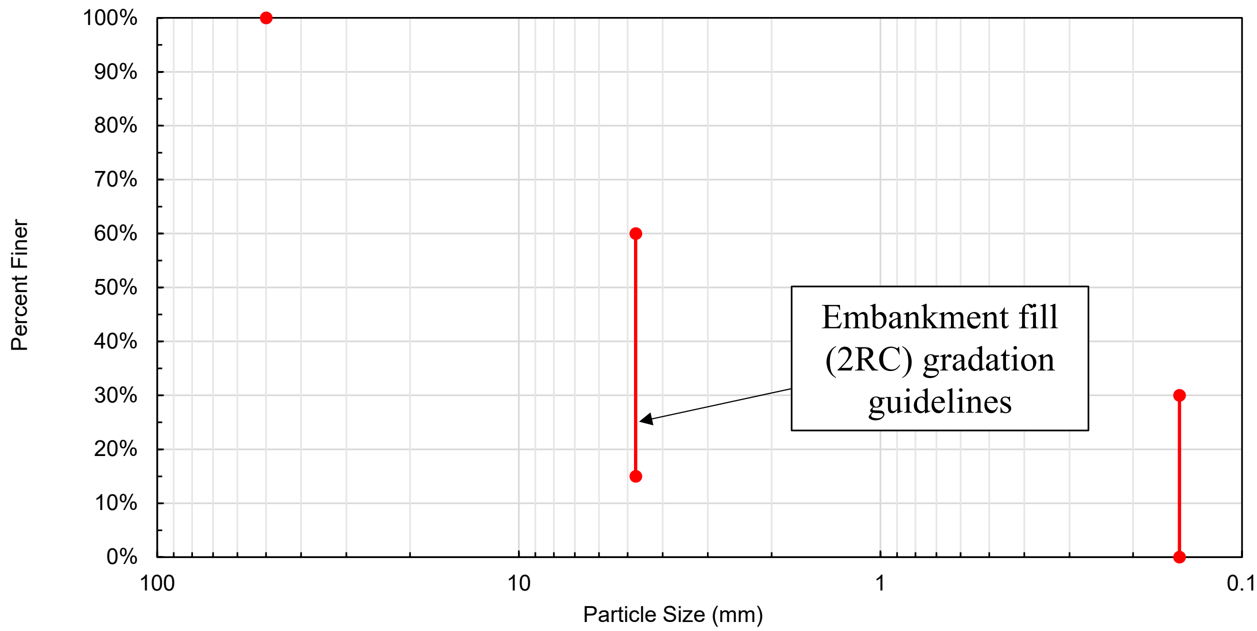


Figure 1. PennDOT Publication 408 embankment fill (2RC) gradation envelope.

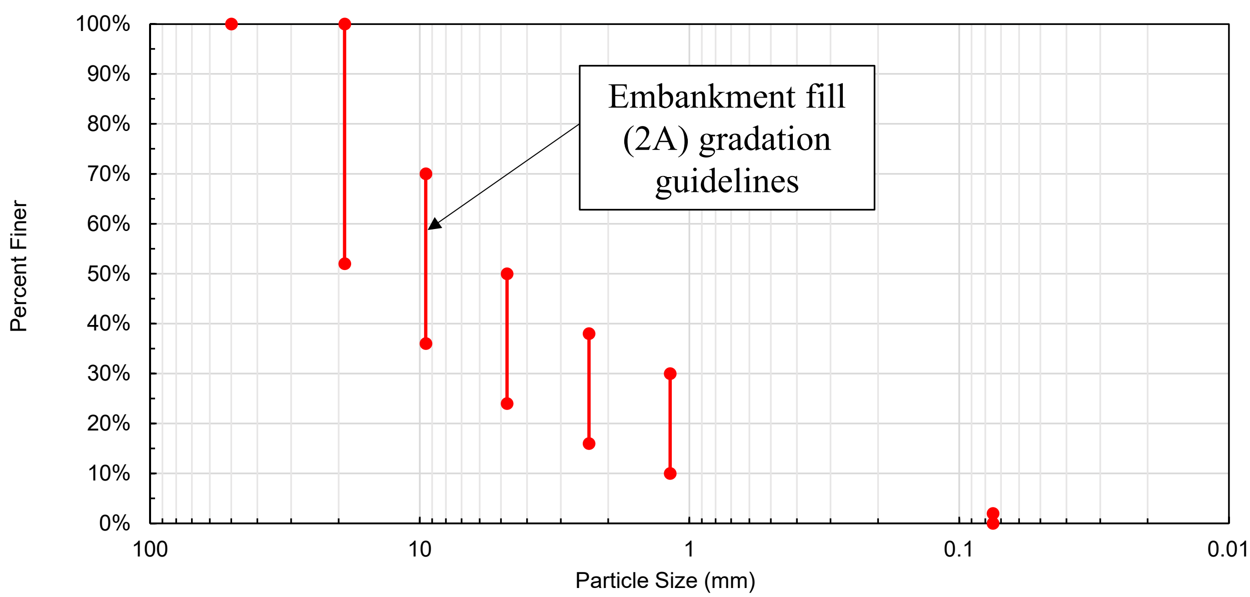


Figure 2. PennDOT Publication 408 embankment fill (2A) gradation envelope.

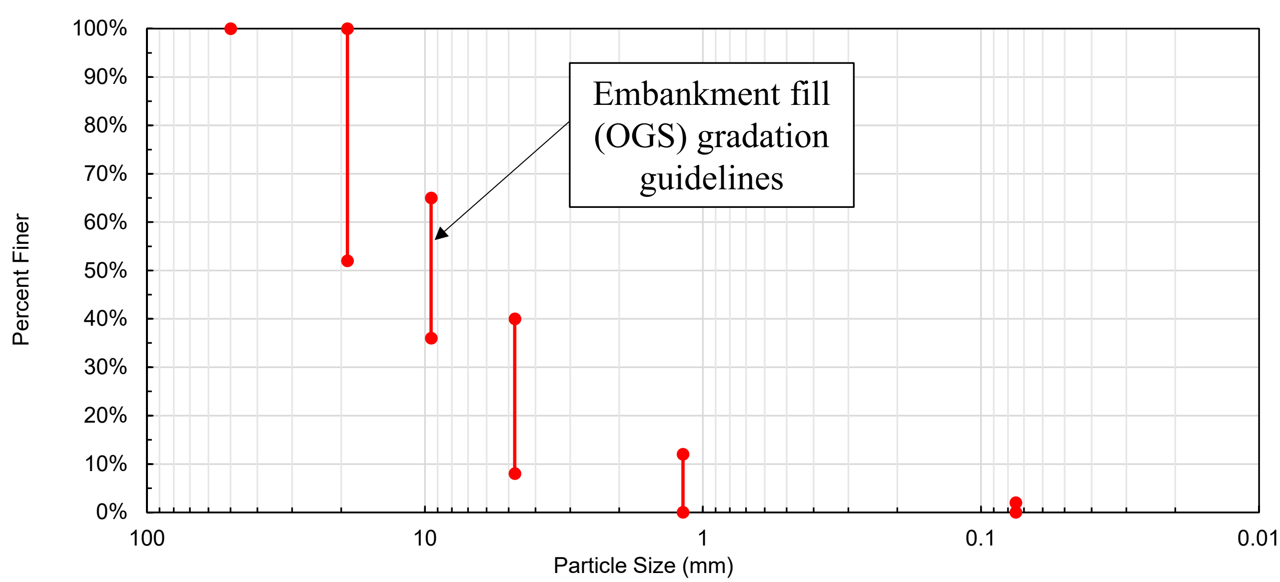


Figure 3. PennDOT Publication 408 embankment fill (OGS) gradation envelope.

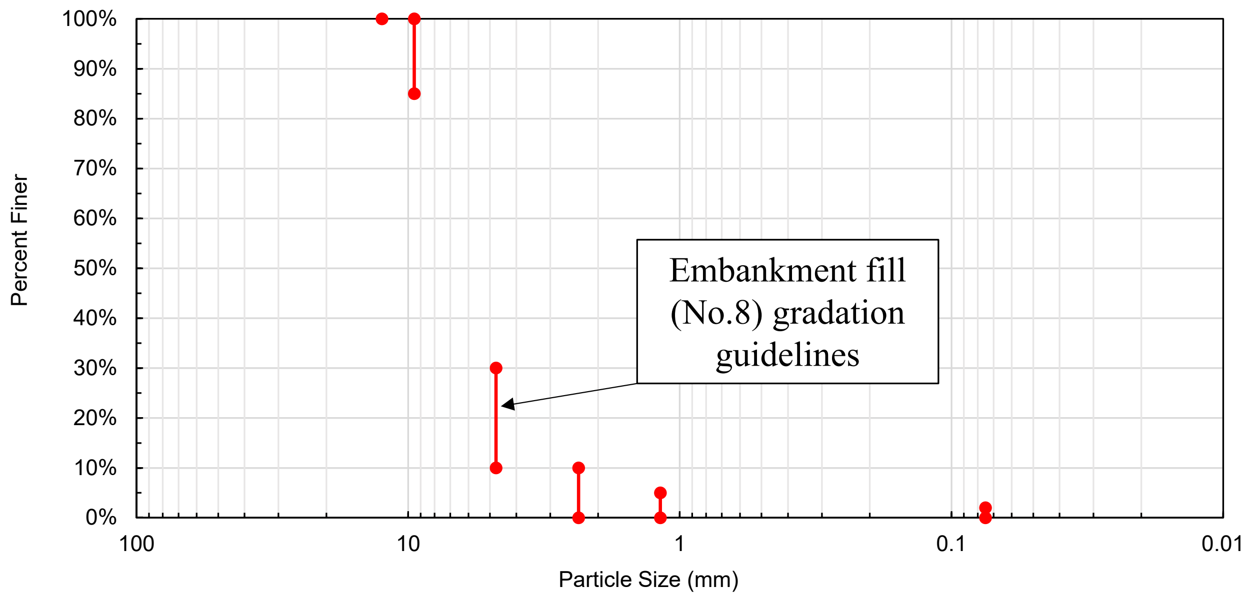


Figure 4. PennDOT Publication 408 embankment fill (No.8) gradation envelope.

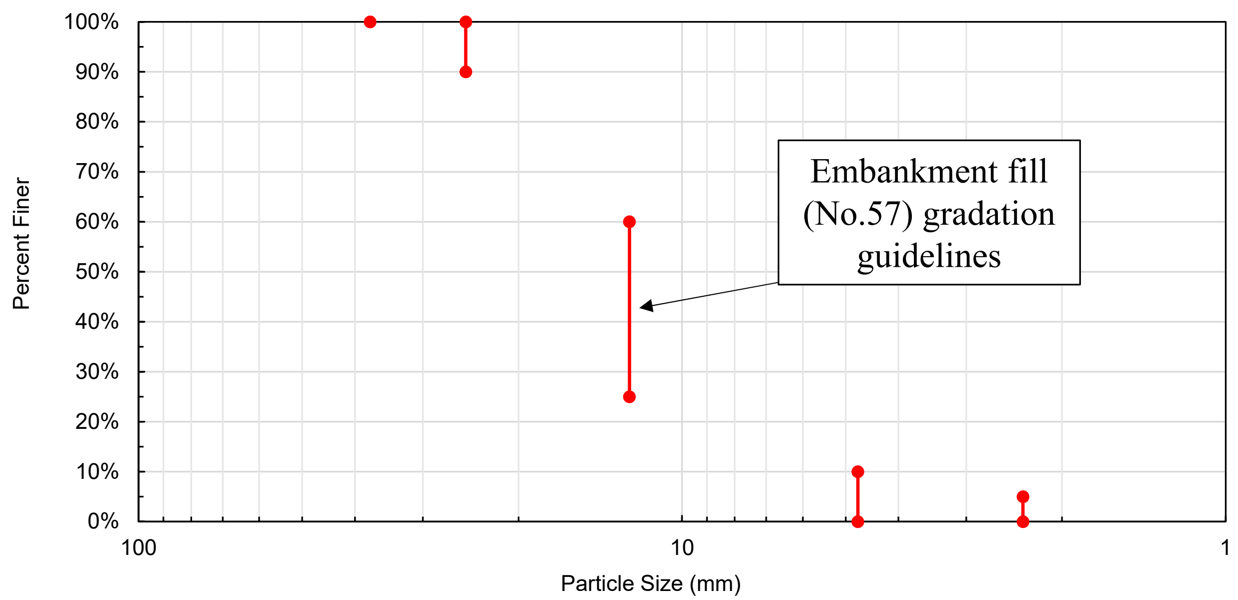


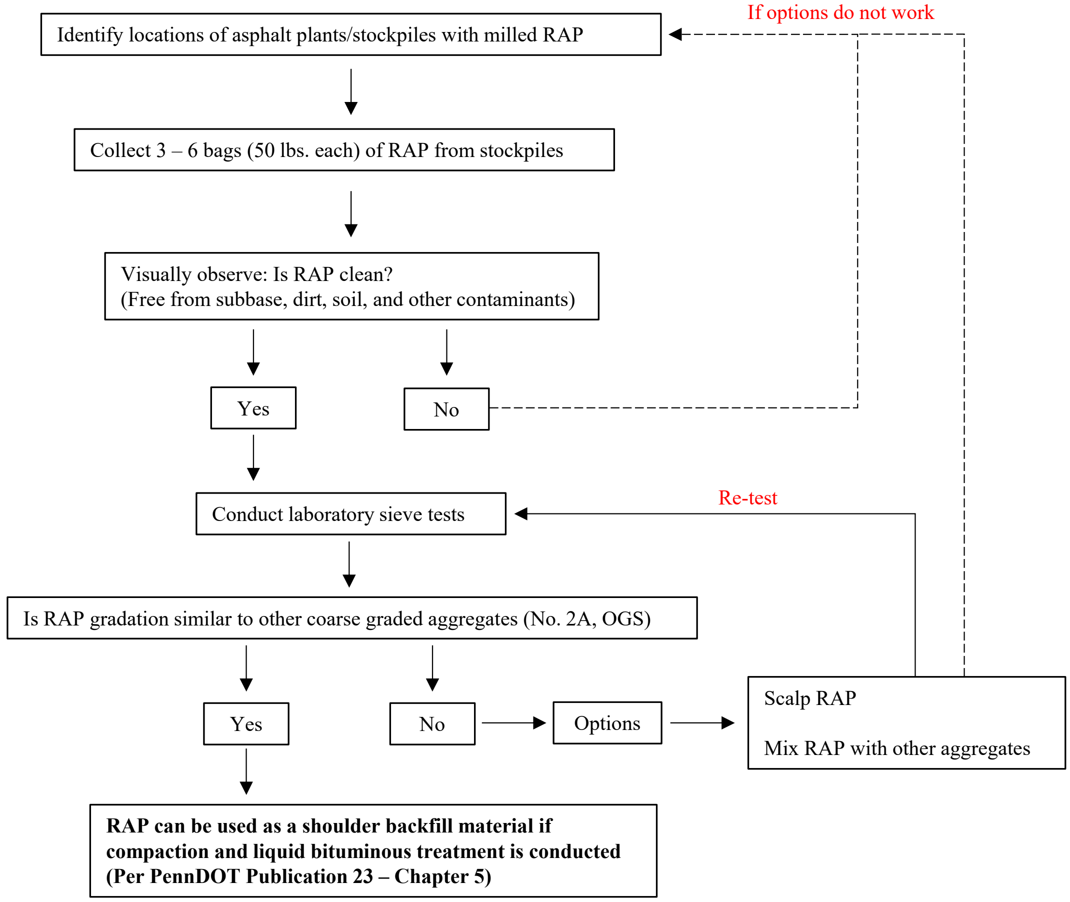
Figure 5. PennDOT Publication 408 embankment fill (No.57) gradation envelope.

Table 1. Required gradations for embankment fill.

Requirement	2RC (% Passing)	2A (% Passing)	OGS (% Passing)	No.8 (% Passing)	No.57 (% Passing)
50 mm (2")	100	100	100		
37.5 mm (1 1/2")					100
25 mm (1")					90-100
19 mm (3/4")		52-100	52-100		
12.5 mm (1/2")				100	25-60
9.5 mm (3/8")		36-70	36-65	85-100	
4.75 mm (No. 4)	15-60	24-50	8-40	10-30	0-10
2.36 mm (No. 8)		16-38		0-10	0-5
1.18 mm (No. 16)		10-30	0-12	0-5	
150 μm (No. 100)	0-30				
0.75 μm (No. 200)		0-2	0-2	0-2	

RAP Reuse as Shoulder Backfill Flowchart

Laboratory Testing Method
Sieve – PTM 616 (modification of AASHTO T-27)



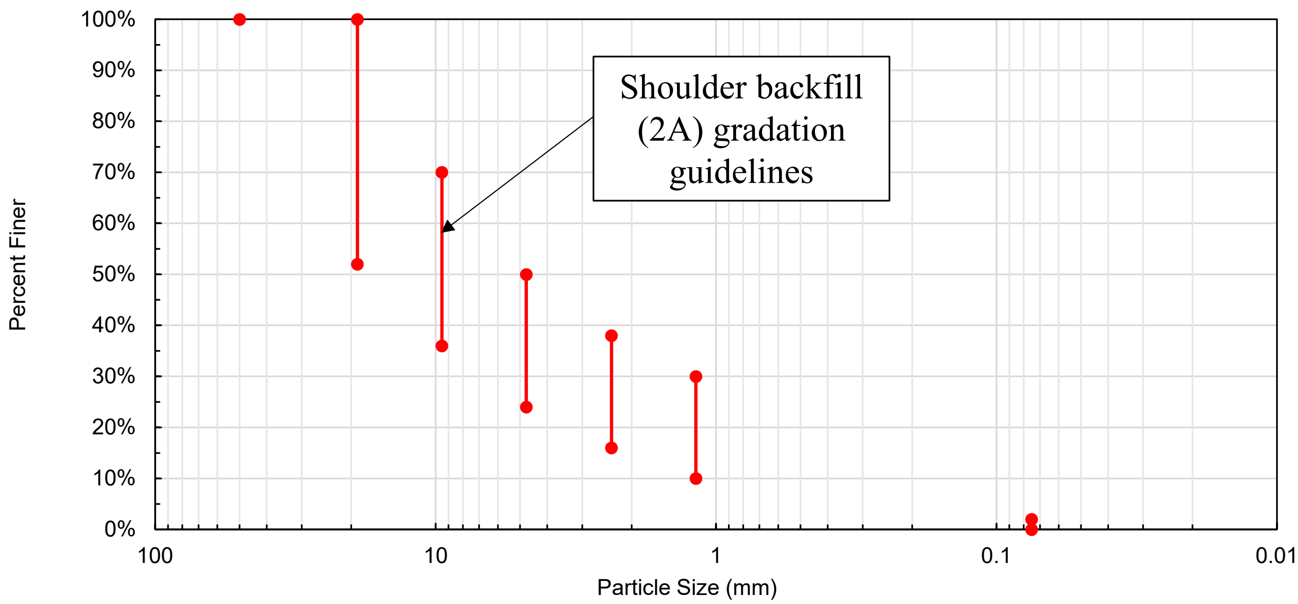


Figure 6. PennDOT Publication 408 shoulder backfill (2A) gradation envelope.

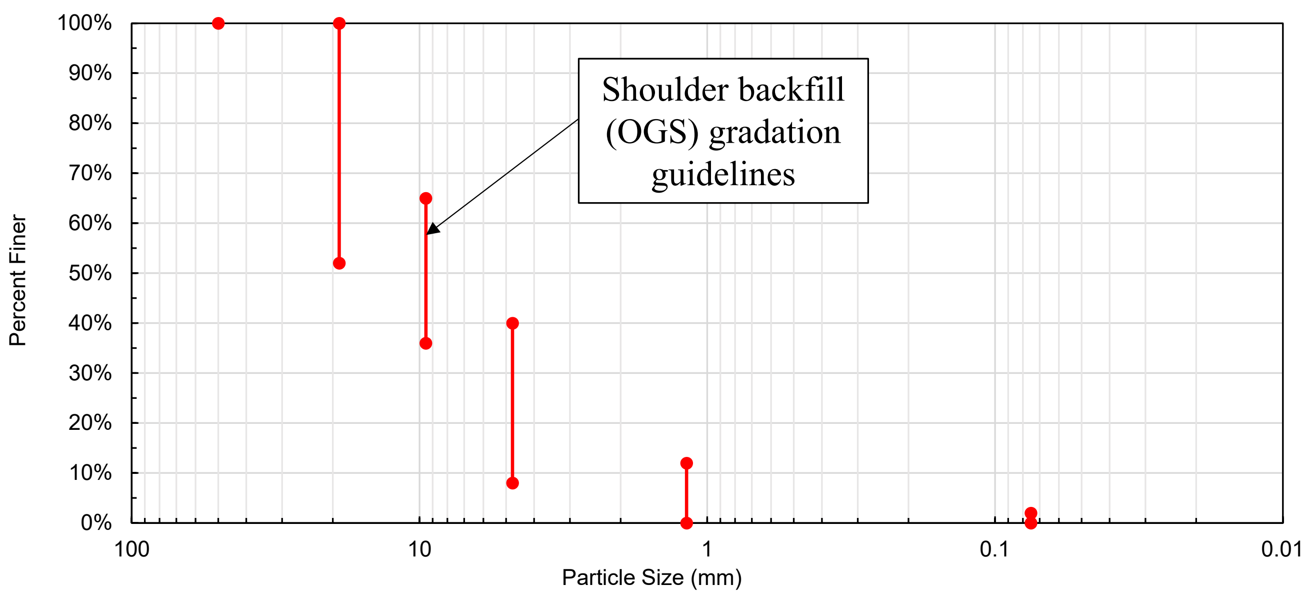


Figure 7. PennDOT Publication 408 shoulder backfill (OGS) gradation envelope.

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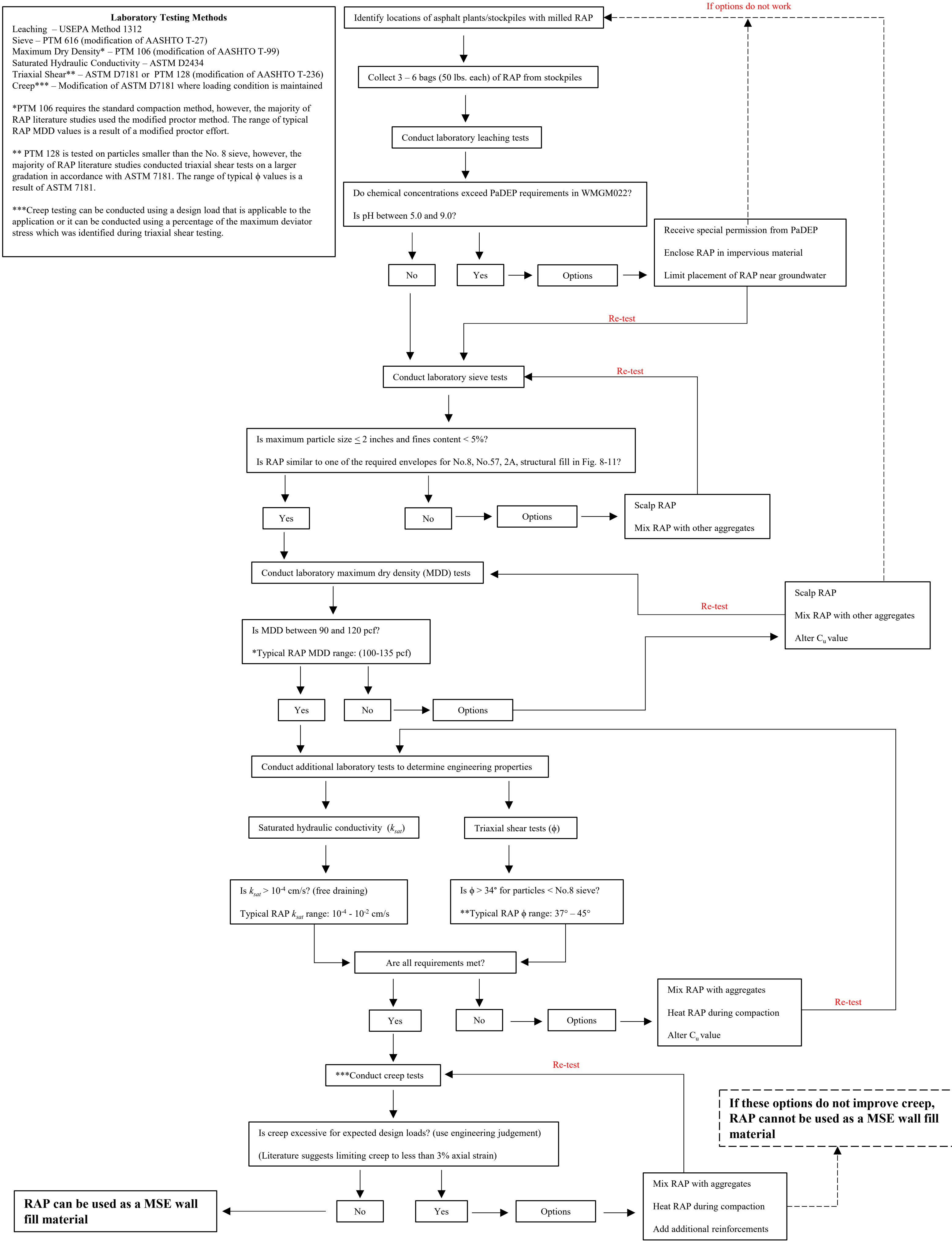
Table 2. Required gradations for shoulder backfill.

Requirement	2A (% Passing)	OGS (% Passing)
50 mm (2")	100	100
19 mm (3/4")	52-100	52-100
9.5 mm (3/8")	36-70	36-65
4.75 mm (No. 4)	24-50	8-40
2.36 mm (No. 8)	16-38	
1.18 mm (No. 16)	10-30	0-12
0.75 µm (No. 200)	0-2	0-2

RAP Reuse as MSE Wall Flowchart



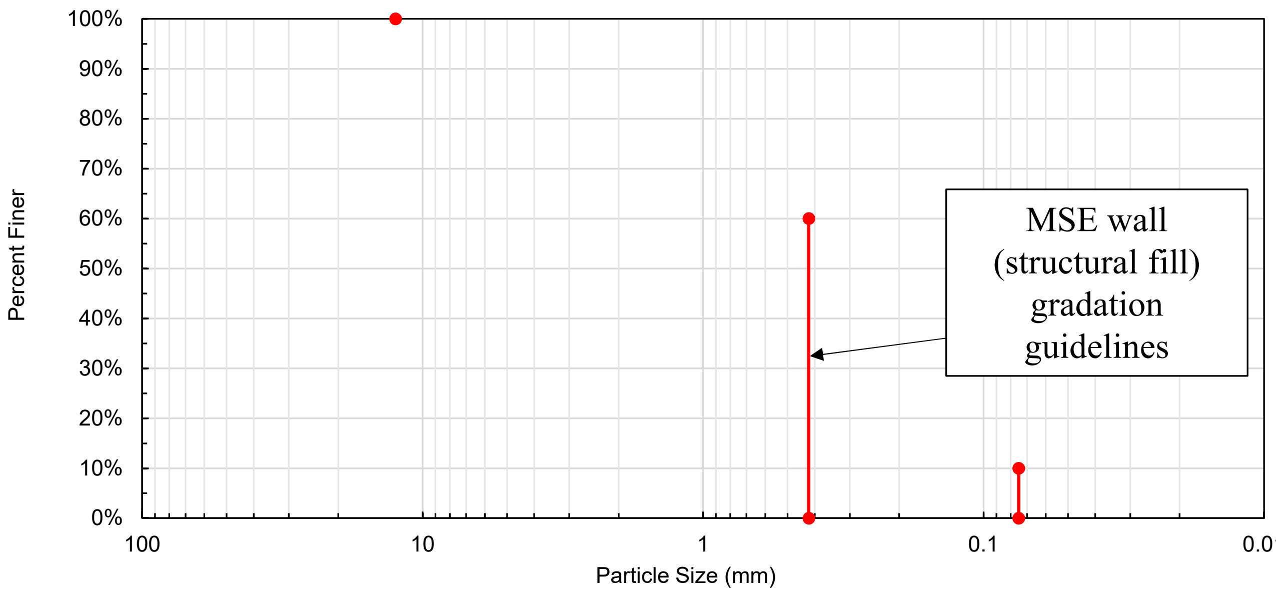


Figure 8. PennDOT Publication 408 MSE Wall (structural fill) gradation envelope.

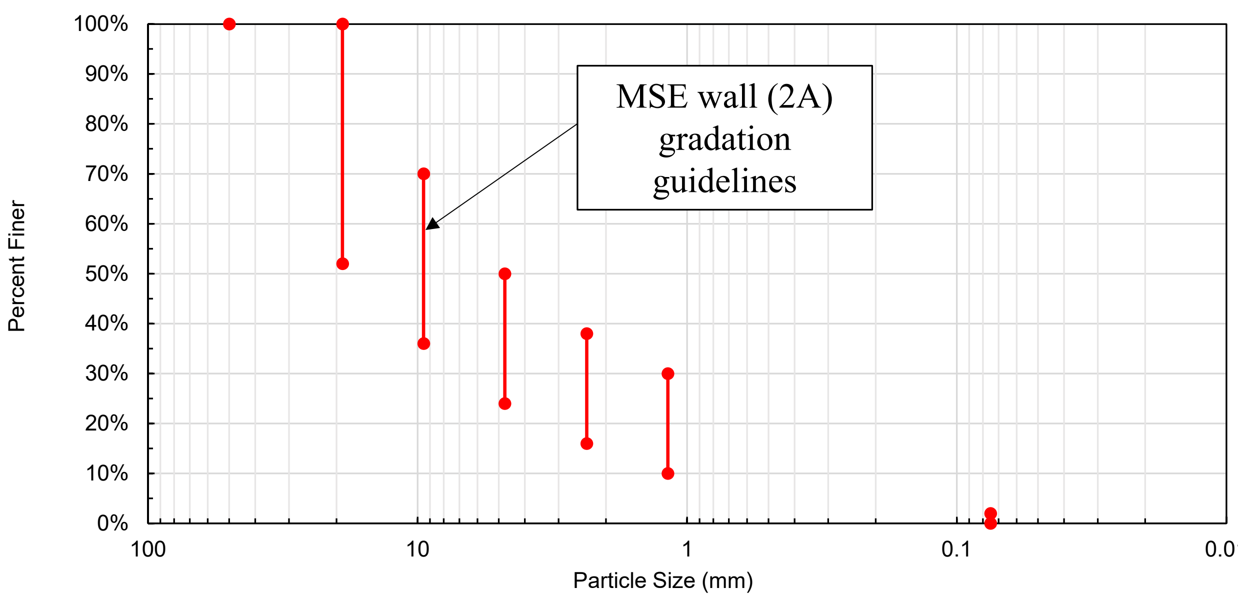


Figure 9. PennDOT Publication 408 MSE wall (No. 2A) gradation envelope.

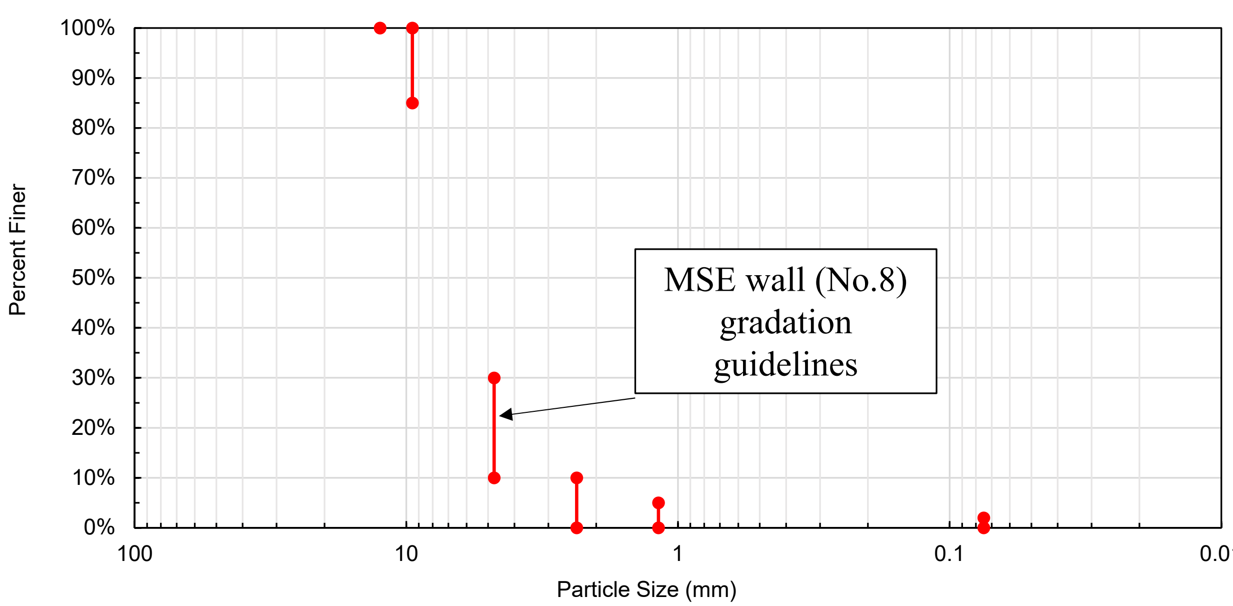


Figure 10. PennDOT Publication 408 MSE wall (No. 8) gradation envelope.

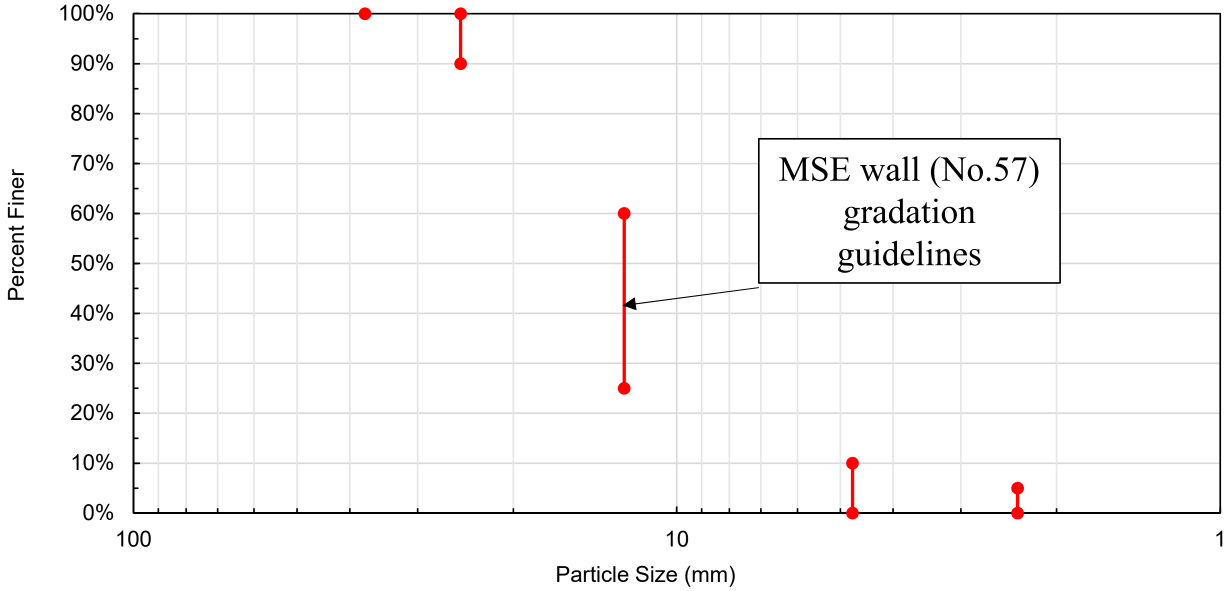
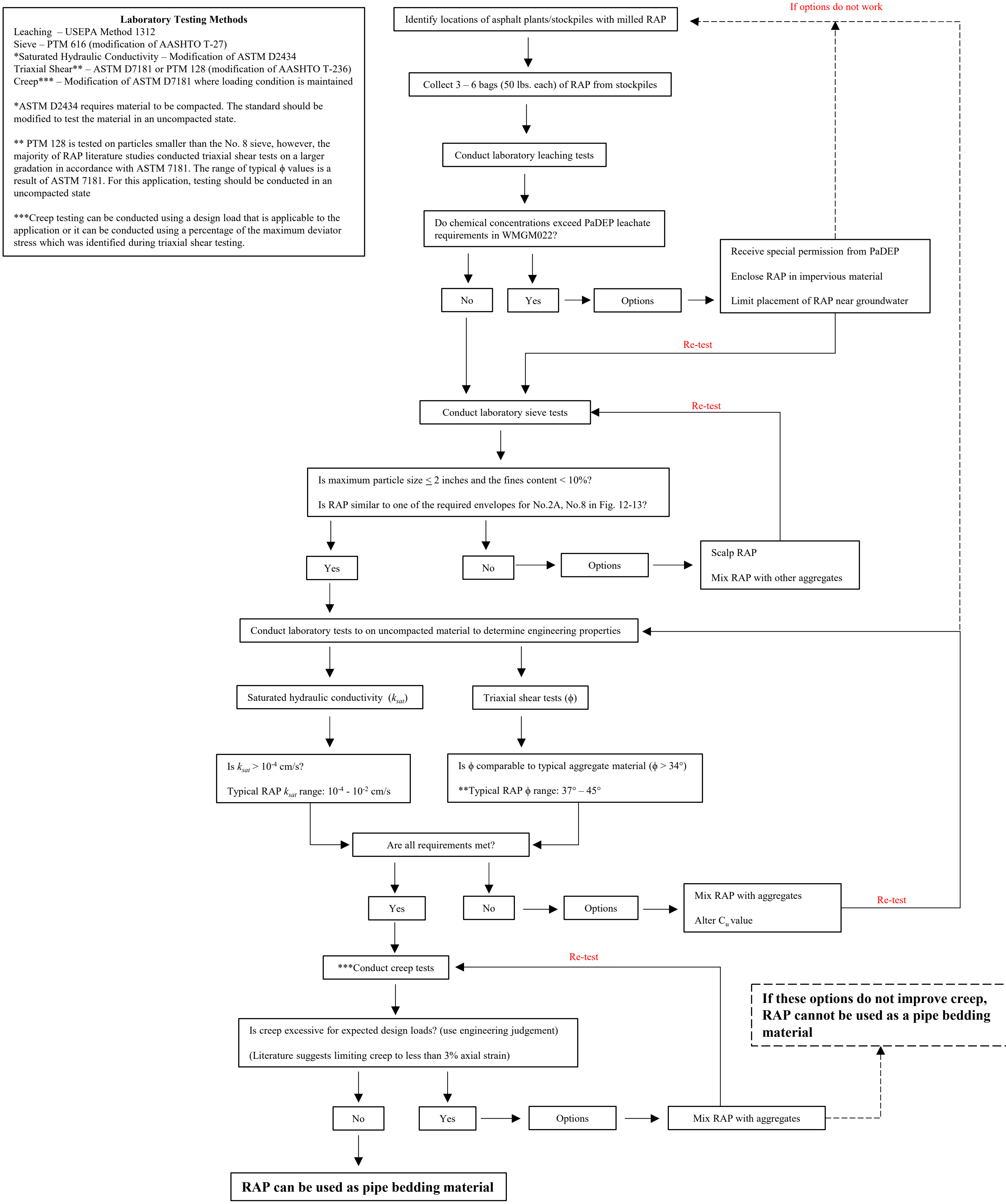


Figure 11. PennDOT Publication 408 MSE wall (No. 57) gradation envelope.

Table 1. Required gradations for MSE Walls.

Requirement	Structural Fill (% Passing)	2A (% Passing)	No.8 (% Passing)	No.57 (% Passing)
50 mm (2")		100		
37.5 mm (1 1/2")				100
25 mm (1")				90-100
19 mm (3/4")		52-100		
12.5 mm (1/2")	100		100	25-60
9.5 mm (3/8")		36-70	85-100	
4.75 mm (No. 4)		24-50	10-30	0-10
2.36 mm (No. 8)		16-38	0-10	0-5
1.18 mm (No. 16)		10-30	0-5	
450 μm (No. 40)	0-60			
0.75 μm (No. 200)	0-10	0-2	0-2	

RAP Reuse Pipe Bedding Flowchart



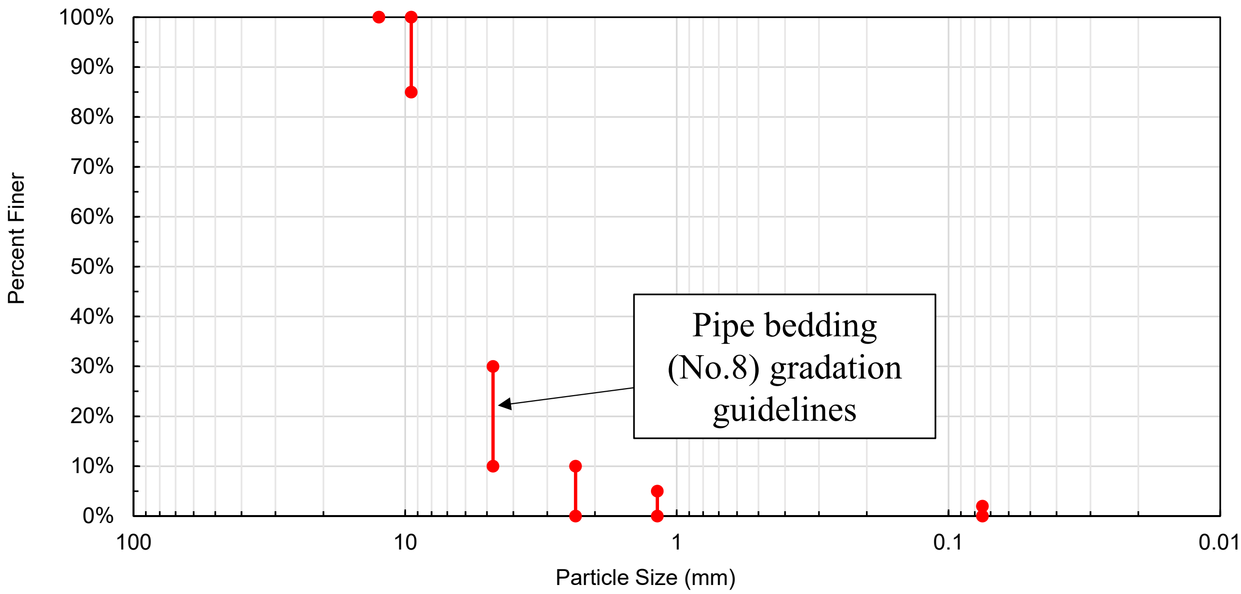


Figure 12. PennDOT Publication 408 gradation envelope for pipe bedding for concrete pipes (No.8).

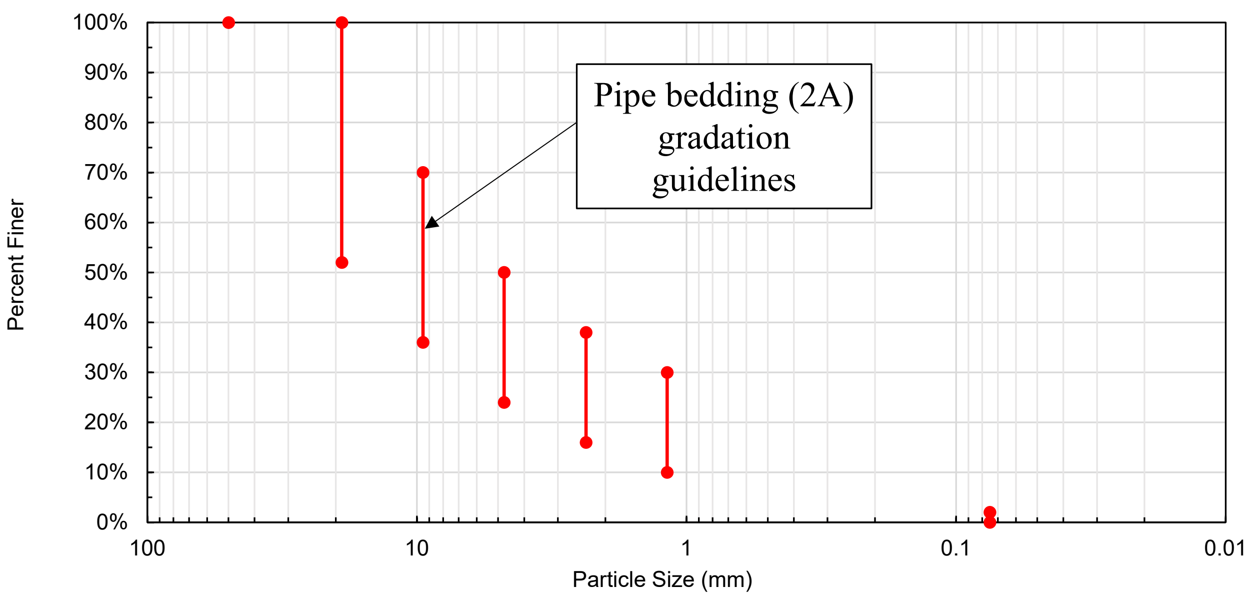


Figure 13. PennDOT Publication 408 gradation envelope for pipe bedding for concrete pipes (No.2A).

Table 1. Required gradations for pipe bedding.

Requirement	2A (% Passing)	No.8 (% Passing)
50 mm (2")	100	
19 mm (3/4")	52-100	
12.5 mm (1/2")		100
9.5 mm (3/8")	36-70	85-100
4.75 mm (No. 4)	24-50	10-30
2.36 mm (No. 8)	16-38	0-10
1.18 mm (No. 16)	10-30	0-5
0.75 µm (No. 200)	0-2	0-2

A.2 Specific Gravity

Table A.2.1 Coarse-grained Delaware Valley RAP specific gravity raw data.

Sample	1								**Avg.**
Pan ID	1	2	3	4	5	6	7	8	
Mass OD (g)	989.2	987.2	988.9	986.2	994.8	988.7	991.7	986.8	**989.2**
Mass SSD (g)	999.4	1000.7	999.0	995.2	1007.0	1010.0	1007.0	1013.4	**1003.9**
Mass Submerged (g)	607.8	610.2	615.5	592.5	623.6	607.5	615.1	612.8	**610.6**
SG (OD)	2.53	2.53	2.58	2.45	2.60	2.50	2.53	2.46	**2.52**
SG (SSD)	2.55	2.56	2.61	2.47	2.63	2.51	2.57	2.53	**2.55**
Apparent SG	2.60	2.62	2.65	2.51	2.68	2.60	2.63	2.64	**2.61**
Absorption (%)	1.03	1.37	1.02	0.91	1.18	2.11	1.58	2.70	**1.49**

Table A.2.2 Fine-grained Delaware Valley RAP specific gravity raw data.

Sample	1		**Avg.**
Pan ID	1	2	
Mass OD (g)	580.1	565.4	**572.8**
Mass SSD (g)	590.7	572.1	**581.4**
Mass Submerged (g)	342.0	332.6	**337.3**
SG (OD)	2.33	2.36	**2.35**
SG (SSD)	2.38	2.39	**2.38**
Apparent SG	2.44	2.43	**2.43**
Absorption (%)	1.83	1.19	**1.51**

Table A.2.3 Coarse-grained Erie RAP specific gravity raw data.

Sample	1									**Avg.**
Pan ID	1	2	3	4	5	6	7	8	9	
Mass OD (g)	1026	976	1015	1003	1035	1007	1035	1026	1028	**1017**
Mass SSD (g)	1039	989	1027	1013	1047	1021	1047	1040	1041	**1023**
Mass Submerged (g)	633	602	622	618	640	622	639	629	632	**626**
SG (OD)	2.53	2.52	2.51	2.54	2.54	2.52	2.54	2.50	2.51	**2.52**
SG (SSD)	2.56	2.56	2.54	2.57	2.57	2.56	2.56	2.53	2.54	**2.55**
Apparent SG	2.61	2.61	2.58	2.60	2.62	2.61	2.61	2.58	2.59	**2.60**
Absorption (%)	1.23	1.31	1.16	0.91	1.16	1.38	1.13	1.32	1.20	**1.20**

Table A.2.4 Fine-grained Erie RAP specific gravity raw data.

Sample	1		2		3		4	**Avg.**
Pan ID	1	2	3	4	5	6	7	
Mass OD (g)	504	560	416	542	501	502	491	**502**
Mass SSD (g)	514	575	429	560	520	518	509	**518**
Mass Submerged (g)	302	336	249	325	301	299	294	**301**
SG (OD)	2.38	2.34	2.31	2.31	2.29	2.29	2.28	**2.32**
SG (SSD)	2.43	2.41	2.39	2.38	2.38	2.37	2.37	**2.39**
Apparent SG	2.50	2.50	2.49	2.50	2.51	2.47	2.49	**2.49**
Absorption (%)	2.08	2.66	3.10	3.32	3.71	3.19	3.61	**3.10**

Table A.2.5 Coarse-grained Glen Mills RAP specific gravity raw data.

Sample	1		2		3		4		5		**Avg.**
Pan ID	1	2	3	4	5	6	7	8	9	10	
Mass OD (g)	1028	1000	1000	1002	849	880	941	830	866	831	**923**
Mass SSD (g)	1039	1011	1010	1013	854	885	947	835	871	836	**930**
Mass Submerged (g)	649	631	632	634	540	563	600	527	549	525	**585**
SG (OD)	2.63	2.63	2.64	2.64	2.70	2.73	2.71	2.70	2.69	2.67	**2.68**
SG (SSD)	2.66	2.66	2.67	2.67	2.72	2.75	2.73	2.71	2.71	2.69	**2.70**
Apparent SG	2.71	2.71	2.71	2.72	2.75	2.78	2.76	2.74	2.73	2.72	**2.73**
Absorption (%)	1.05	1.07	0.99	1.03	0.59	0.64	0.70	0.54	0.58	0.63	**0.78**

Table A.2.6 Fine-grained Glen Mills RAP specific gravity raw data.

Sample	1		2		**Avg.**
Pan ID	1	2	3	4	
Mass OD (g)	477	481	491	491	**485**
Mass SSD (g)	493	505	511	519	**507**
Mass Submerged (g)	290	291	300	298	**295**
SG (OD)	2.35	2.25	2.33	2.22	**2.29**
SG (SSD)	2.43	2.36	2.42	2.35	**2.39**
Apparent SG	2.55	2.53	2.57	2.54	**2.55**
Absorption (%)	3.25	4.88	4.01	5.64	**4.45**

Table A.2.7 Course-grained Glasgow RAP specific gravity raw data.

Sample	1		2		**Avg.**
Pan ID	1	2	3	4	
Mass OD (g)	989.2	992.4	987.9	988.9	**989.6**
Mass SSD (g)	1002	1002.6	1003.3	1004.9	**1003.2**
Mass Submerged (g)	620.6	620.7	627.5	622.4	**622.8**
SG (OD)	2.59	2.60	2.63	2.59	**2.60**
SG (SSD)	2.63	2.63	2.67	2.63	**2.64**
Apparent SG	2.68	2.67	2.74	2.70	**2.70**
Absorption (%)	1.29	1.03	1.56	1.62	**1.37**

Table A.2.8 Fine-grained Glasgow RAP specific gravity raw data.

Sample	1		2		**Avg.**
Pan ID	1	2	3	4	
Mass OD (g)	493.1	490.7	617	528.3	**532.3**
Mass SSD (g)	496.7	500.4	639.3	618.5	**563.7**
Mass Submerged (g)	294.2	293.9	364.7	314.7	**316.9**
SG (OD)	2.44	2.38	2.25	1.74	**2.20**
SG (SSD)	2.45	2.42	2.33	2.04	**2.31**
Apparent SG	2.48	2.49	2.45	2.47	**2.47**
Absorption (%)	0.73	1.98	3.61	17.07	**5.85**

Table A.2.9 Course-grained Highway Materials RAP specific gravity raw data.

Sample	1				**Avg.**
Pan ID	1	2	3	4	
Mass OD (g)	989.8	985.5	989.1	990.1	**988.6**
Mass SSD (g)	1000	995.4	999.7	1001.9	**999.3**
Mass Submerged (g)	613.4	612.5	620.1	616.5	**615.6**
SG (OD)	2.56	2.57	2.61	2.57	**2.58**
SG (SSD)	2.59	2.60	2.63	2.60	**2.60**
Apparent SG	2.63	2.64	2.68	2.65	**2.65**
Absorption (%)	1.03	1.00	1.07	1.19	**1.07**

Table A.2.10 Fined-grained Highway Materials RAP specific gravity raw data.

Sample	1				**Avg.**
Pan ID	1	2	3	4	
Mass OD (g)	479.4	491.4	491.1	558.5	**505.1**
Mass SSD (g)	479.7	495.7	506.7	566.9	**512.3**
Mass Submerged (g)	278.3	289.6	292.8	319.3	**295.0**
SG (OD)	2.38	2.38	2.30	2.26	**2.33**
SG (SSD)	2.38	2.41	2.37	2.29	**2.36**
Apparent SG	2.38	2.44	2.48	2.33	**2.41**
Absorption (%)	0.06	0.88	3.18	1.50	**1.40**

A.3 Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)

Table A.3.1 Glen Mills RAP compaction raw data.

Modified Proctor ASTM D1557											
Glen Mills Compaction	1	2	3	4	5	6	7	8	9	10	11
Mass of Mold, Plate and sample (kg)	10.8	11.1	11.2	11.2	11.4	11.4	11.4	11.2	11.2	10.7	10.6
Weight of compacted sample (kg)	4.2	4.4	4.5	4.5	4.7	4.7	4.7	4.6	4.6	4.9	4.8
Moisture Content (%)	0.9	3.1	4.5	5.8	7.1	9.6	7.3	5.5	5.4	8.5	7.3
Dry Density (kg/m^3)	1930.6	2003.9	2020.8	1997.7	2059.5	2014.0	2056.0	2024.7	2026.0	2067.0	2068.3
Wet Density (kg/m^3)	1948.4	2065.7	2112.7	2112.7	2206.6	2206.6	2206.6	2136.2	2136.2	2242.3	2219.1
Dry Density (lb/ft^3)	120.5	125.1	126.2	124.7	128.6	125.7	128.4	126.4	126.5	129.0	129.1
Wet Density (lb/ft^3)	121.6	129.0	131.9	131.9	137.8	137.8	137.8	133.4	133.4	140.0	138.5

Table A.3.2 Glen Mills RAP gradation raw data before and after compaction.

Sieve	Sieve opening size (mm)	Pre-Compaction Percent Finer	Post-Compaction Percent Finer
2"	50	100%	100%
1-1/2"	37.5	100%	100%
1"	25	100%	100%
3/4"	19	100%	100%
1/2"	12.5	100%	100%
3/8"	9.5	90%	92%
5/16"	8	81%	85%
1/4"	6.3	69%	74%
4	4.75	58%	63%
10	2	31%	35%
20	0.85	16%	20%
40	0.425	9%	12%
100	0.15	2%	4%
200	0.075	1%	2%
Pan	-	0%	0%

A.4 Saturated Hydraulic Conductivity (k_{sat})

Table A.4.1 Malvern k_{sat} Test 1.

Measurement	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	360	360	0.66	0.66	-
3	4	720	360	0.66	1.32	0%
4	6	1070	350	0.64	1.96	3%
5	8	1420	350	0.64	2.60	0%
6	10	1790	370	0.68	3.27	-6%
7	12	2150	360	0.66	3.93	3%
8	14	2510	360	0.66	4.59	0%
9	16	2870	360	0.66	5.25	0%
10	18	3220	350	0.64	5.89	3%
11	20	3570	350	0.64	6.53	0%

Table A.4.2 Malvern k_{sat} Test 2.

Measurement	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	400	400	0.73	0.73	-
3	4	810	410	0.75	1.48	-3%
4	6	1200	390	0.71	2.19	5%
5	8	1600	400	0.73	2.93	-3%
6	10	1990	390	0.71	3.64	3%
7	12	2390	400	0.73	4.37	-3%
8	14	2770	380	0.69	5.07	5%
9	16	3150	380	0.69	5.76	0%
10	18	3540	390	0.71	6.47	-3%
11	20	3920	380	0.69	7.17	3%

Table A.4.3 Malvern k_{sat} Test 3.

Measurement	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	520	520	0.95	0.95	-
3	4	1050	530	0.97	1.92	-2%
4	6	1560	510	0.93	2.85	4%
5	8	2070	510	0.93	3.79	0%
6	10	2570	500	0.91	4.70	2%
7	12	3070	500	0.91	5.61	0%
8	14	3560	490	0.90	6.51	2%
9	16	4070	510	0.93	7.44	-4%
10	18	4560	490	0.90	8.34	4%
11	20	5050	490	0.90	9.23	0%

Table A.4.4 Malvern k_{sat} Test 4.

Measurement	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	450	450	0.82	0.82	-
3	4	950	500	0.91	1.74	-11%
4	6	1420	470	0.86	2.60	6%
5	8	1920	500	0.91	3.51	-6%
6	10	2390	470	0.86	4.37	6%
7	12	2850	460	0.84	5.21	2%
8	14	3320	470	0.86	6.07	-2%
9	16	3780	460	0.84	6.91	2%
10	18	4230	450	0.82	7.73	2%
11	20	4670	440	0.80	8.54	2%

Table A.4.5 Malvern k_{sat} Test 5.

Measurement	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	340	340	0.62	0.62	-
3	4	670	330	0.60	1.23	3%
4	6	1030	360	0.66	1.88	-9%
5	8	1400	370	0.68	2.56	-3%
6	10	1770	370	0.68	3.24	0%
7	12	2130	360	0.66	3.89	3%
8	14	2490	360	0.66	4.55	0%
9	16	2840	350	0.64	5.19	3%
10	18	3200	360	0.66	5.85	-3%
11	20	3550	350	0.64	6.49	3%

Table A.4.6 Erie k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	430	430	0.79	0.79	-
3	4	860	430	0.79	1.57	0%
4	6	1270	410	0.75	2.32	5%
5	8	1690	420	0.77	3.09	-2%
6	10	2100	410	0.75	3.84	2%
7	12	2500	400	0.73	4.57	2%
8	14	2880	380	0.69	5.27	5%
9	16	3270	390	0.71	5.98	-3%
10	18	3650	380	0.69	6.67	3%
11	20	4040	390	0.71	7.39	-3%
12	22	4420	380	0.69	8.08	3%
13	24	4800	380	0.69	8.78	0%
14	26	5190	390	0.71	9.49	-3%
15	28	5570	380	0.69	10.19	3%
16	30	5960	390	0.71	10.90	-3%

Table A.4.7 Erie k_{sat} Test 2.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	2	480	480	0.88	0.88	-
3	4	970	490	0.90	1.77	-2%
4	6	1440	470	0.86	2.63	4%
5	8	1925	485	0.89	3.52	-3%
6	10	2370	445	0.81	4.33	8%
7	12	2832	462	0.84	5.18	-4%
8	14	3272	440	0.80	5.98	5%
9	16	3722	450	0.82	6.81	-2%
10	18	4197	475	0.87	7.67	-6%
11	20	4657	460	0.84	8.52	3%
12	22	5107	450	0.82	9.34	2%
13	24	5537	430	0.79	10.12	4%
14	26	5965	428	0.78	10.91	0%
15	28	6400	435	0.80	11.70	-2%
16	30	6827	427	0.78	12.48	2%

Table A.4.8 Highway Materials k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	58	58	0.11	0.11	-
3	10	114	56	0.10	0.21	3%
4	15	168	54	0.10	0.31	4%
5	20	223	55	0.10	0.41	-2%
6	25	276	53	0.10	0.50	4%
7	30	329	53	0.10	0.60	0%
8	35	381	52	0.10	0.70	2%
9	40	433	52	0.10	0.79	0%
10	45	489	56	0.10	0.89	-8%
11	50	543	54	0.10	0.99	4%
12	55	595	52	0.10	1.09	4%
13	60	647	52	0.10	1.18	0%

Table A.4.9 Highway Materials k_{sat} Test 2.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	108	108	0.20	0.20	-
3	10	214	106	0.19	0.39	2%
4	15	320	106	0.19	0.59	0%
5	20	428	108	0.20	0.78	-2%
6	25	536	108	0.20	0.98	0%
7	30	644	108	0.20	1.18	0%
8	35	752	108	0.20	1.38	0%

Table A.4.10 Delaware Valley Asphalt k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	156	156	0.29	0.29	-
3	10	306	150	0.27	0.56	4%
4	15	452	146	0.27	0.83	3%
5	20	596	144	0.26	1.09	1%
6	25	736	140	0.26	1.35	3%
7	30	876	140	0.26	1.60	0%

Table A.4.11 Delaware Valley Asphalt k_{sat} Test 2.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	114	114	0.21	0.21	-
3	10	226	112	0.20	0.41	2%
4	15	328	102	0.19	0.60	9%
5	20	430	102	0.19	0.79	0%
6	25	532	102	0.19	0.97	0%
7	30	634	102	0.19	1.16	0%
8	35	734	100	0.18	1.34	2%
9	40	834	100	0.18	1.53	0%

Table A.4.12 Glasgow k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	32	32	0.06	0.06	-
3	10	62	30	0.05	0.11	6%
4	15	93	31	0.06	0.17	-3%
5	20	124	31	0.06	0.23	0%
6	25	154	30	0.05	0.28	3%
7	30	185	31	0.06	0.34	-3%
8	35	216	31	0.06	0.39	0%
9	40	247	31	0.06	0.45	0%
10	45	279	32	0.06	0.51	-3%
11	50	310	31	0.06	0.57	3%
12	55	340	30	0.05	0.62	3%
13	60	371	31	0.06	0.68	-3%
14	65	401	30	0.05	0.73	3%
15	70	433	32	0.06	0.79	-7%
16	75	464	31	0.06	0.85	3%
17	80	495	31	0.06	0.91	0%
18	85	527	32	0.06	0.96	-3%
19	90	558	31	0.06	1.02	3%
20	95	589	31	0.06	1.08	0%

Table A.4.13 Glasgow k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	38	38	0.07	0.07	-
3	10	72	34	0.06	0.13	11%
4	15	108	36	0.07	0.20	-6%
5	20	142	34	0.06	0.26	6%
6	25	178	36	0.07	0.33	-6%
7	30	212	34	0.06	0.39	6%
8	35	246	34	0.06	0.45	0%
9	40	282	36	0.07	0.52	-6%
10	45	318	36	0.07	0.58	0%
11	50	352	34	0.06	0.64	6%
12	55	386	34	0.06	0.71	0%
13	60	422	36	0.07	0.77	-6%
14	65	456	34	0.06	0.83	6%
15	70	490	34	0.06	0.90	0%
16	75	526	36	0.07	0.96	-6%
17	80	560	34	0.06	1.02	6%
18	85	596	36	0.07	1.09	-6%

Table A.4.14 Glen Mills k_{sat} Test 1.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	160	160	0.28	0.28	-
3	10	300	140	0.24	0.52	13%
4	15	440	140	0.24	0.77	0%
5	20	590	150	0.26	1.03	-7%
6	25	740	150	0.26	1.29	0%
7	30	890	150	0.26	1.55	0%
8	35	1040	150	0.26	1.82	0%
9	40	1190	150	0.26	2.08	0%
10	45	1330	140	0.24	2.32	7%
11	50	1480	150	0.26	2.59	-7%
12	55	1640	160	0.28	2.87	-7%

Table A.4.15 Glen Mills k_{sat} Test 2.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	290	290	0.53	0.53	-
3	10	550	260	0.48	1.01	10%
4	15	810	260	0.48	1.48	0%
5	20	1100	290	0.53	2.01	-12%
6	25	1360	260	0.48	2.49	10%
7	30	1640	280	0.51	3.00	-8%
8	35	1890	250	0.46	3.46	11%

Table A.4.16 Glen Mills k_{sat} Test 3.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	210	210	0.38	0.38	-
3	10	360	150	0.27	0.66	29%
4	15	510	150	0.27	0.93	0%
5	20	610	100	0.18	1.12	33%
6	25	820	210	0.38	1.50	-110%
7	30	970	150	0.27	1.77	29%
8	35	1160	190	0.35	2.12	-27%
9	40	1310	150	0.27	2.40	21%
10	45	1470	160	0.29	2.69	-7%
11	50	1620	150	0.27	2.96	6%
12	55	1770	150	0.27	3.24	0%
13	60	1920	150	0.27	3.51	0%

Table A.4.17 Glen Mills k_{sat} Test 4.

Measurement ID	Time Interval (mins)	Cumulative Flow (mL)	Flow Volume (mL)	PVF Volume	Cumulative PVF Volume	Percent difference
1	0	0	0	-	-	-
2	5	480	480	0.88	0.88	-
3	10	870	390	0.71	1.59	19%
4	15	1300	430	0.79	2.38	-10%
5	20	1740	440	0.80	3.18	-2%
6	25	2190	450	0.82	4.00	-2%
7	30	2600	410	0.75	4.75	9%
8	35	2920	320	0.59	5.34	22%
9	40	3330	410	0.75	6.09	-28%
10	45	3790	460	0.84	6.93	-12%
11	50	4240	450	0.82	7.75	2%
12	55	4710	470	0.86	8.61	-4%
13	60	5160	450	0.82	9.44	4%

A.5 Triaxial Shear Testing

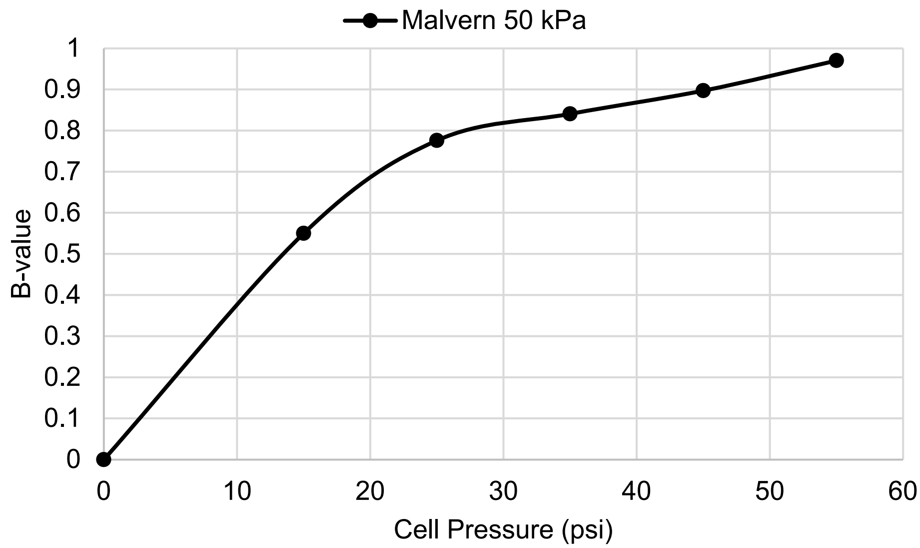


Figure A.5.1 Malvern 50 kPa B-value.

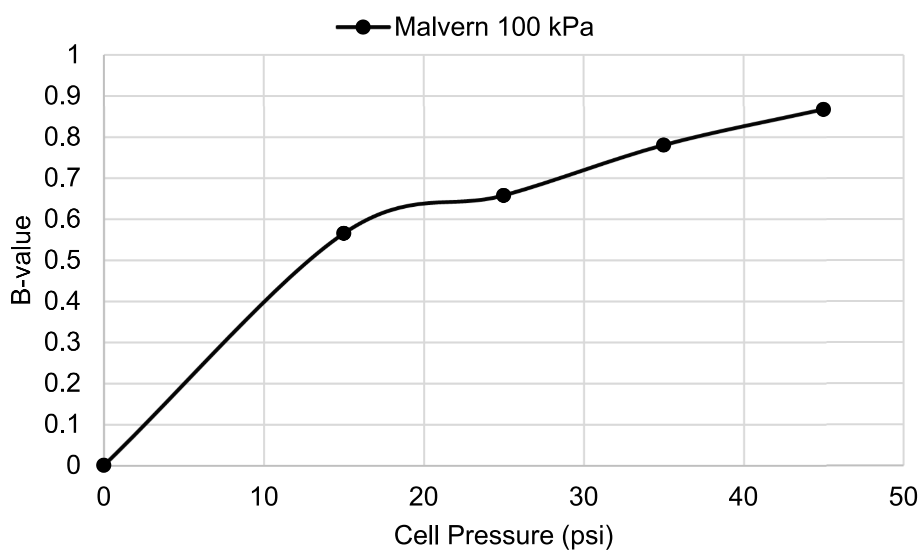


Figure A.5.2 Malvern 100 kPa B-value.

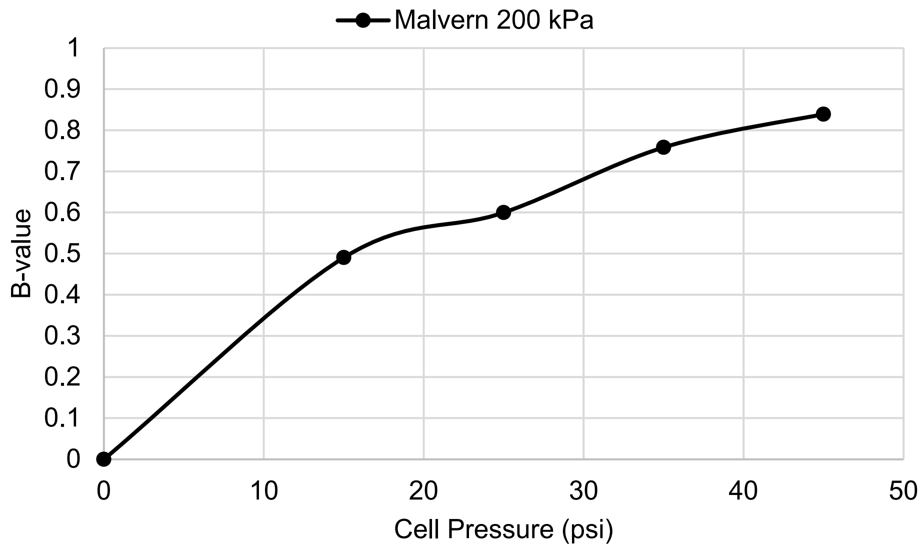


Figure A.5.3 Malvern 200 kPa B-value.

Table A.5.1 Malvern B-values.

Test	Final B-Value
50 kPa	0.97
100 kPa	0.87
200 kPa	0.84

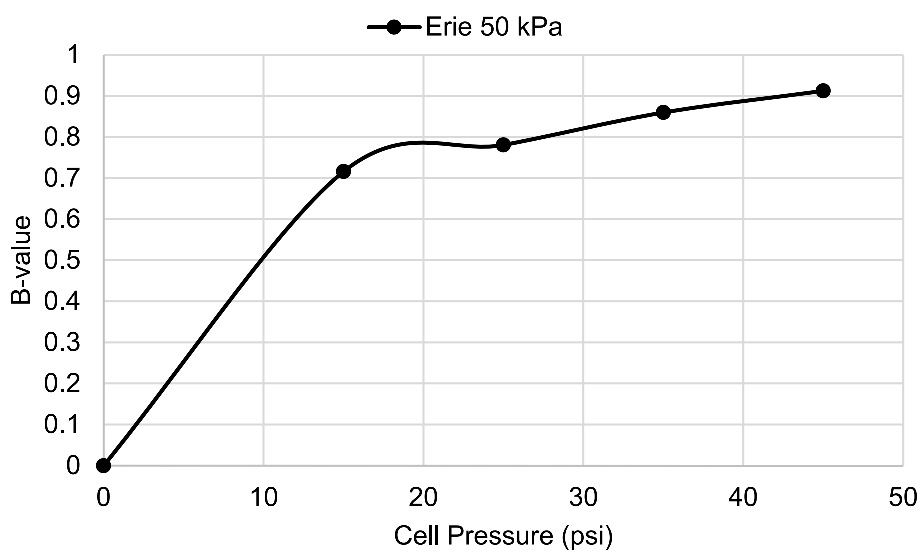


Figure A.5.4 Erie 50 kPa B-value.

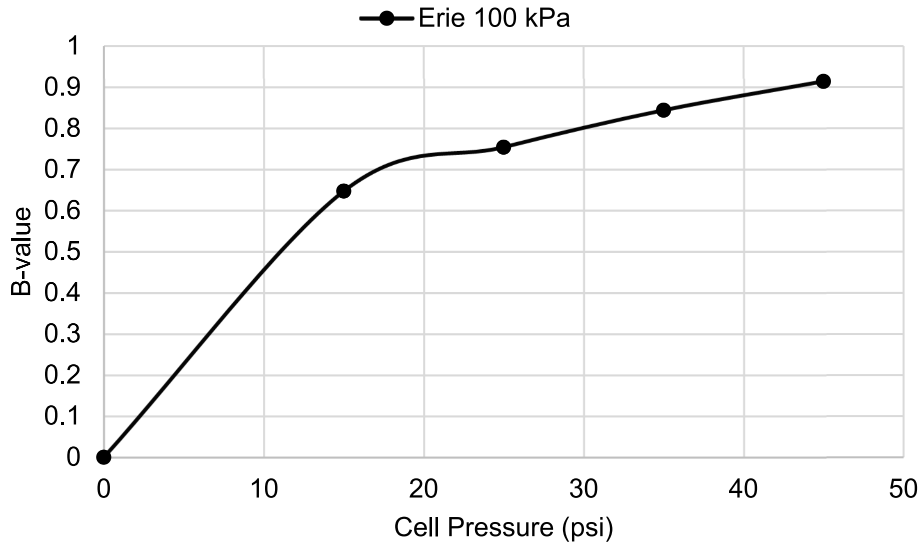


Figure A.5.5 Erie 100 kPa B-value.

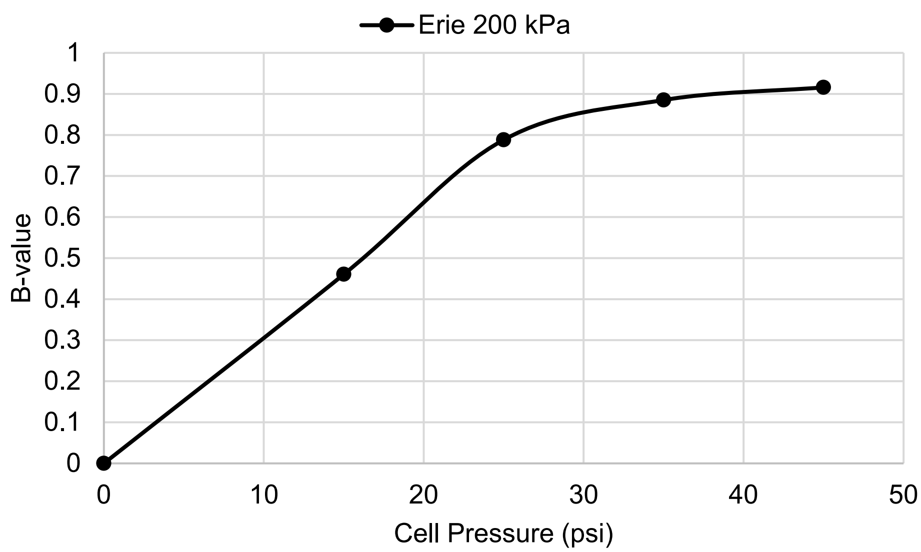


Figure A.5.6 Erie 200 kPa B-value.

Table A.5.2 Erie B-values.

Test	Final B-Value
50 kPa	0.91
100 kPa	0.91
200 kPa	0.92

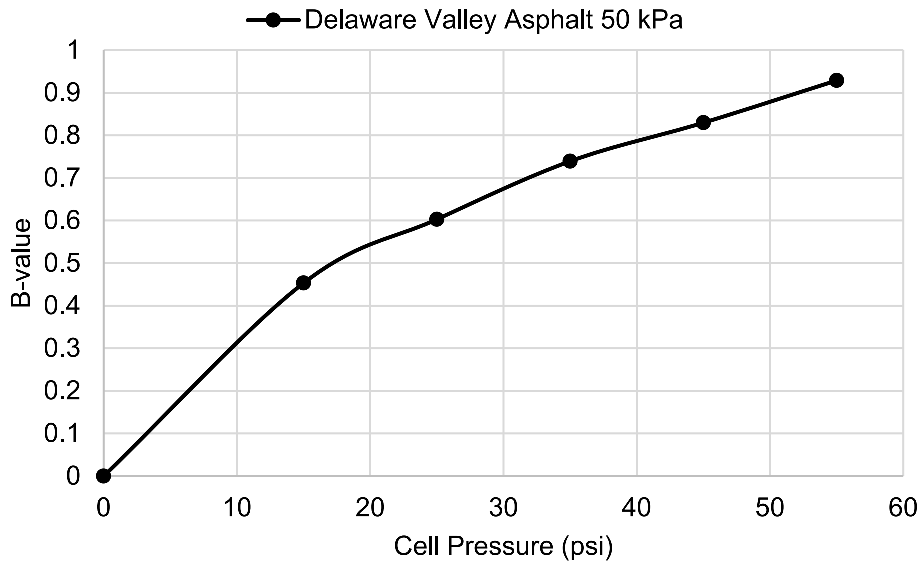


Figure A.5.7 Delaware Valley Asphalt 50 kPa B-value.

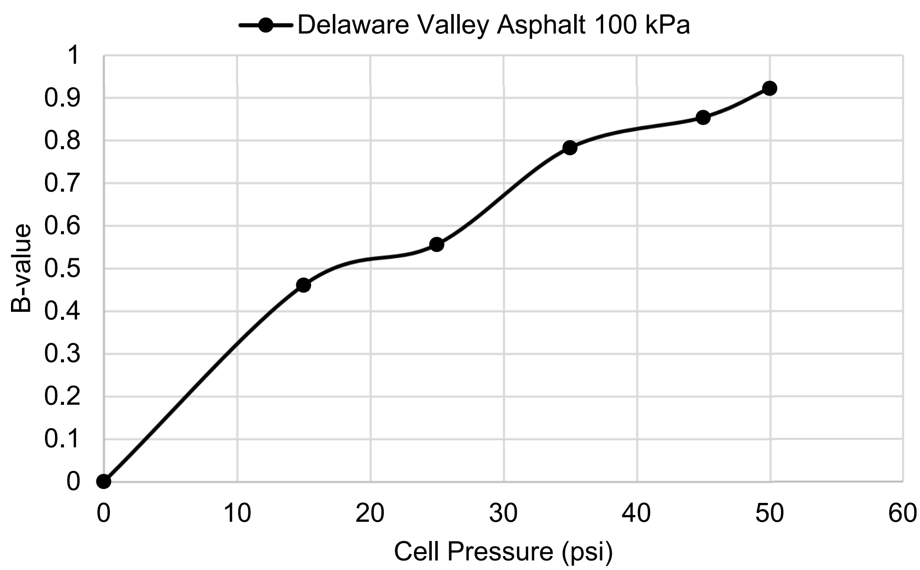


Figure A.5.8 Delaware Valley Asphalt 100 kPa B-value.

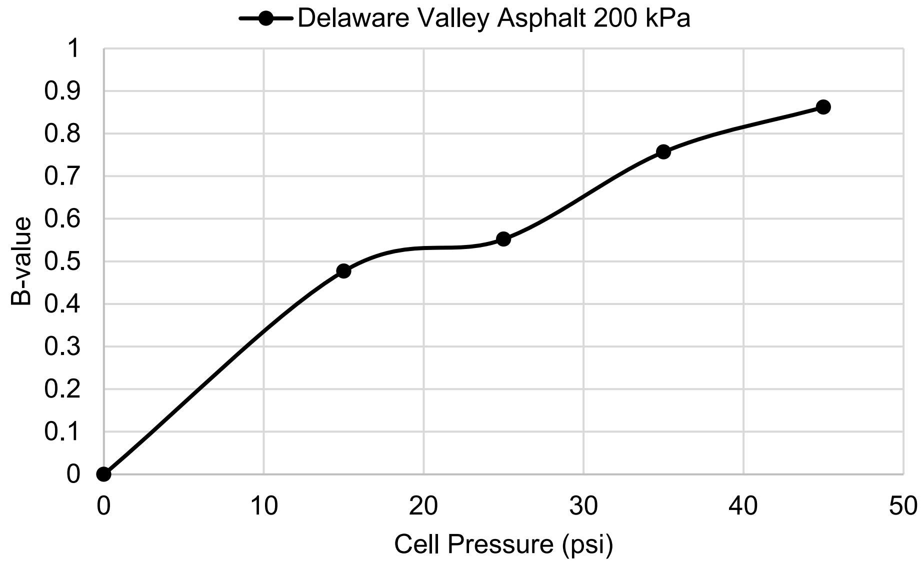


Figure A.5.9 Delaware Valley Asphalt 200 kPa B-value.

Table A.5.3 Delaware Valley Asphalt B-values.

Test	Final B-Value
50 kPa	0.93
100 kPa	0.92
200 kPa	0.86

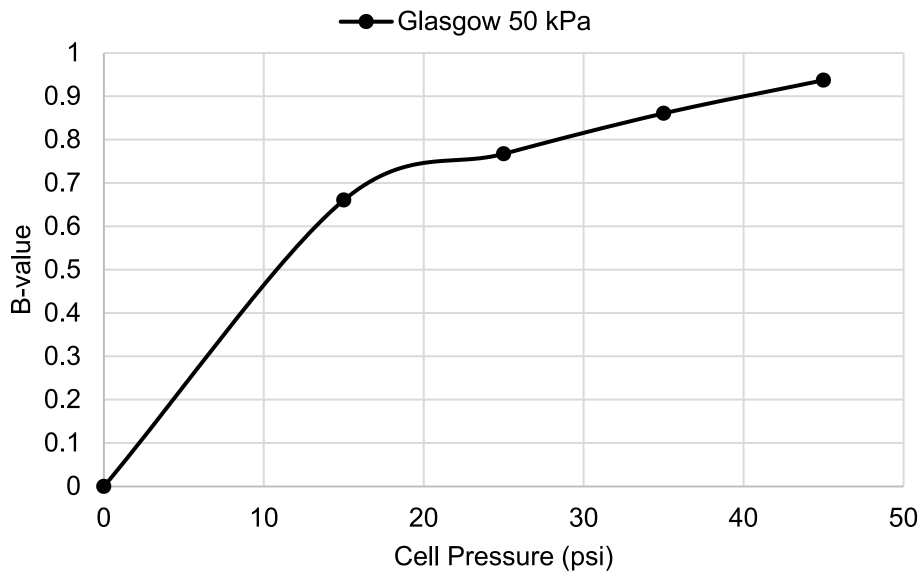


Figure A.5.10 Glasgow 50 kPa B-value.

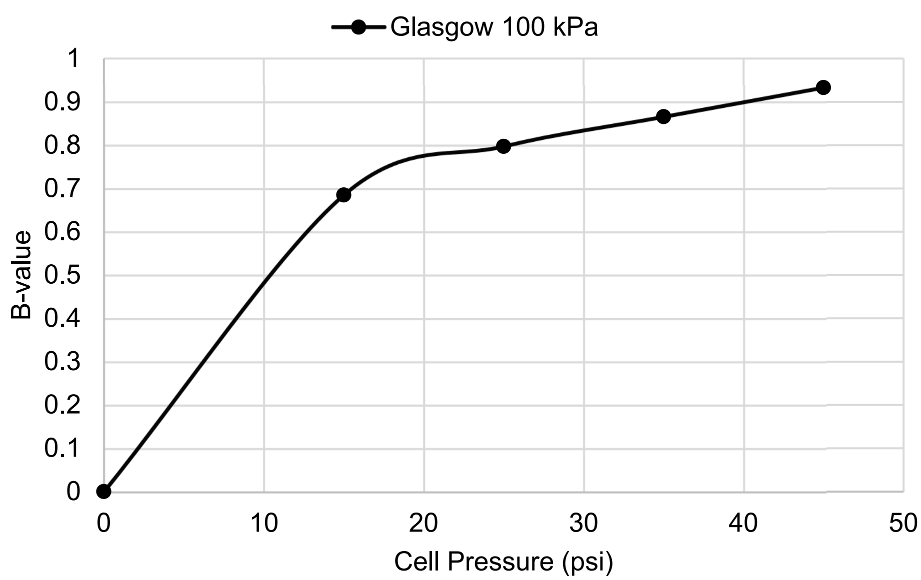


Figure A.5.11 Glasgow 100 kPa B-value.

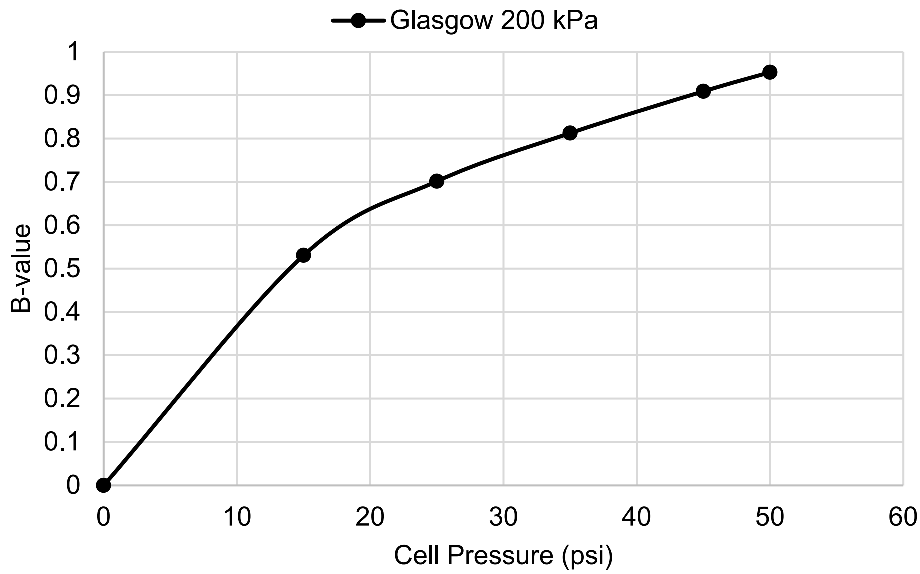


Figure A.5.12 Glasgow 200 kPa B-value.

Table A.5.4 Glasgow B-values.

Test	Final B-Value
50 kPa	0.94
100 kPa	0.93
200 kPa	0.95

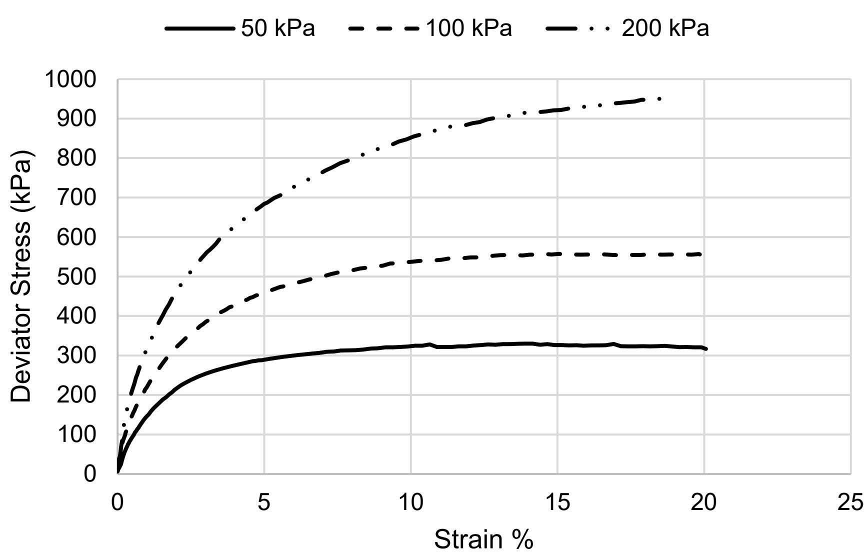


Figure A.5.13 Malvern stress-strain curve.

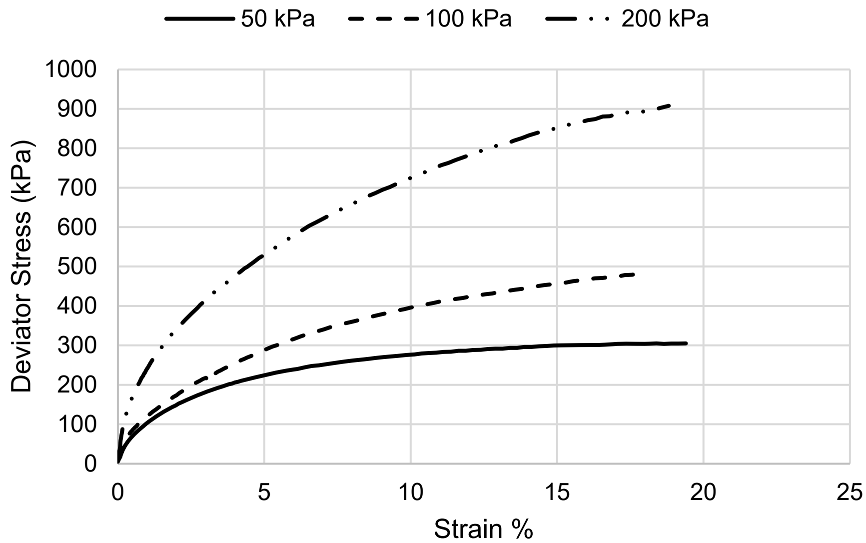


Figure A.5.14 Erie stress-strain curve.

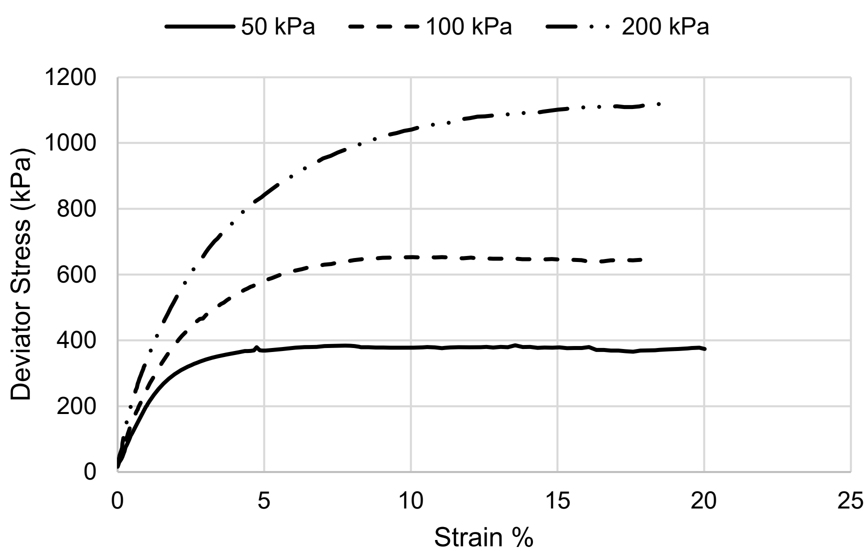


Figure A.5.15 Delaware Valley Asphalt stress-strain curve.

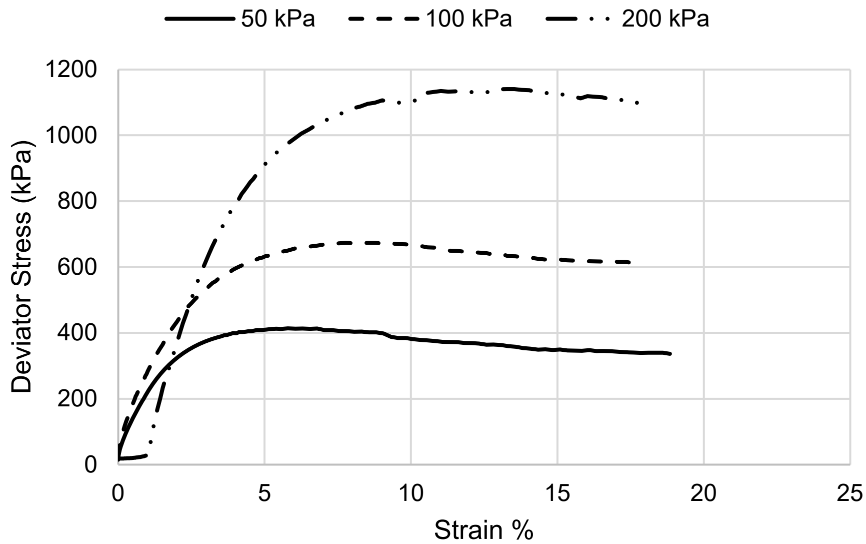


Figure A.5.16 Glasgow stress-strain curve.

A.6 Creep Triaxial Testing

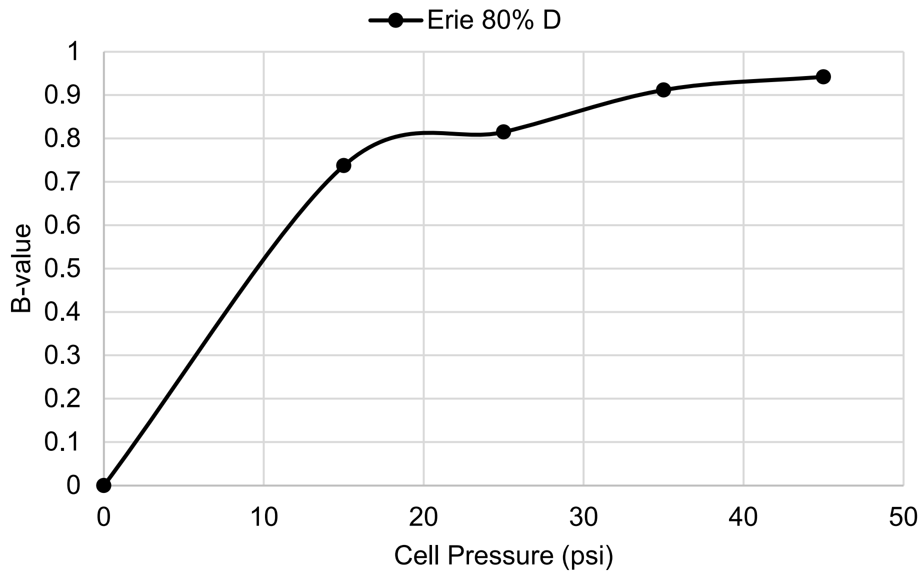


Figure A.6.1 Erie 80% maximum deviator stress B-value.

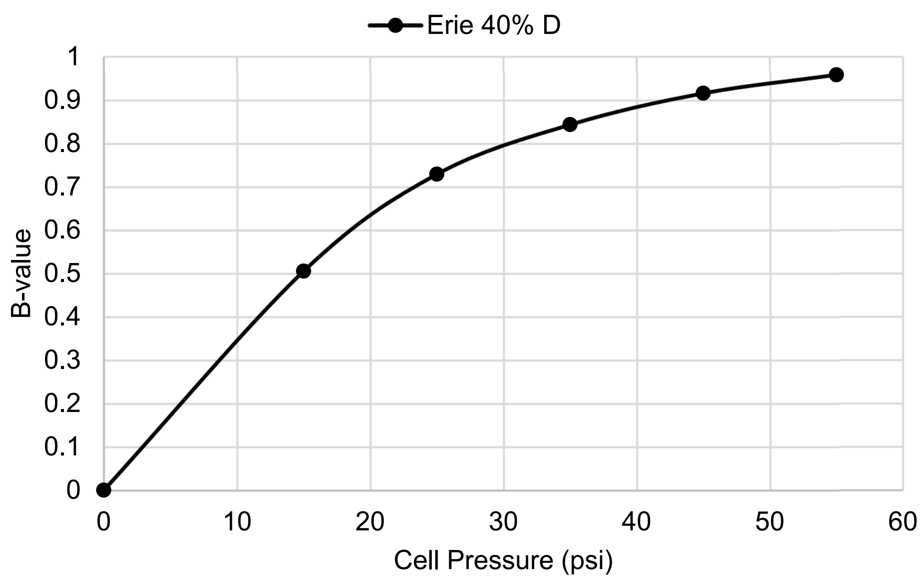


Figure A.6.2 Erie 40% maximum deviator stress B-value.

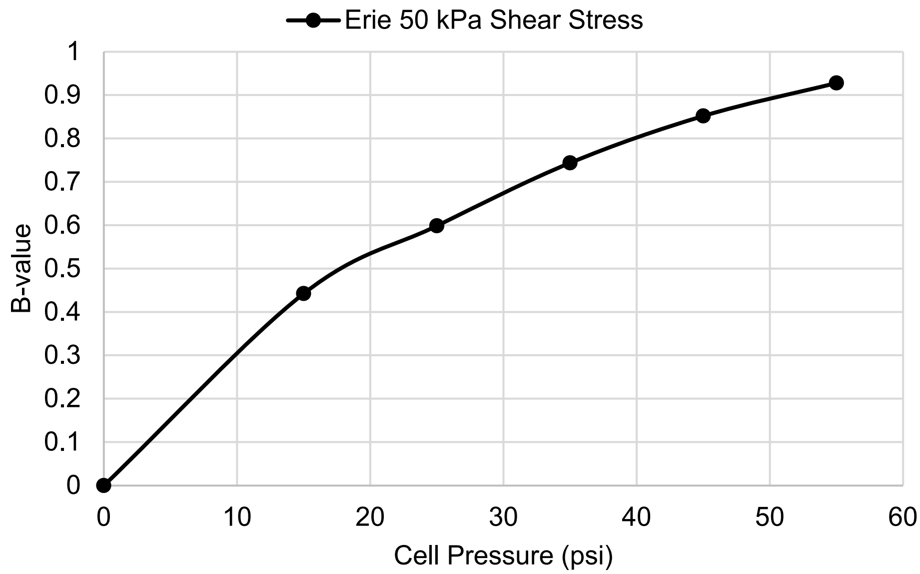


Figure A.6.3 Erie 50 kPa shear stress B-value.

Table A.6.1 Erie creep B-values.

Test	Final B-Value
80% D	0.94
50% D	0.96
50 kPa Shear Stress	0.93

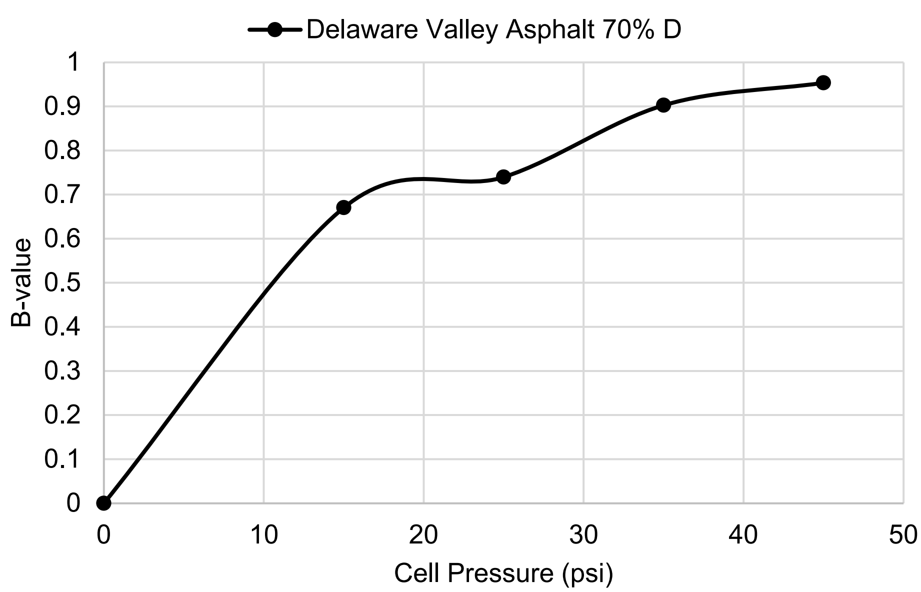


Figure A.6.4 Delaware Valley Asphalt 70% maximum deviator stress B-value.

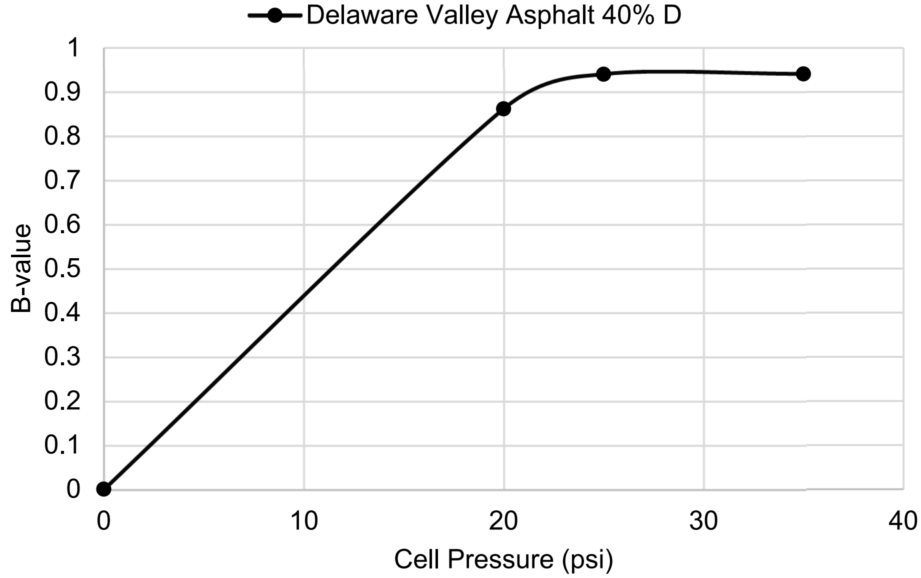


Figure A.6.5 Delaware Valley Asphalt 40% maximum deviator stress B-value.

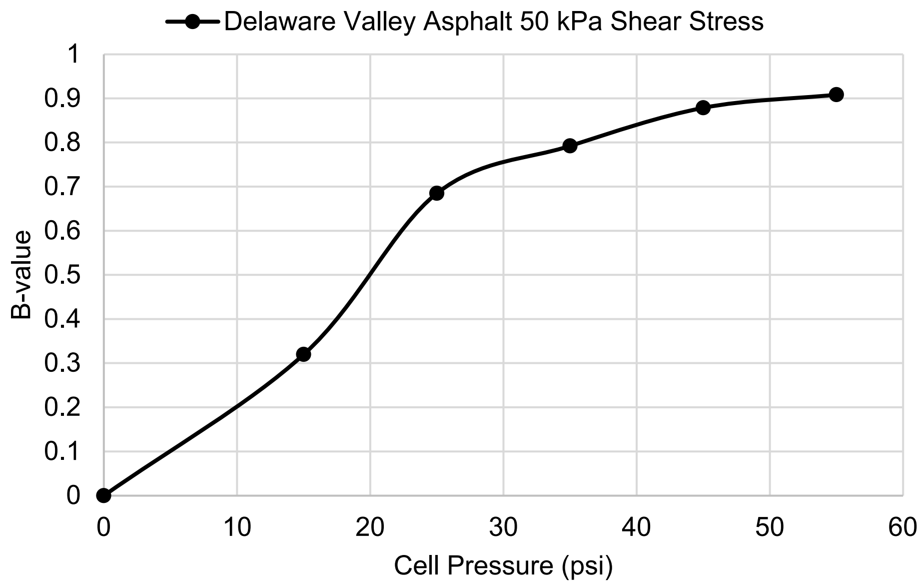


Figure A.6.6 Delaware Valley Asphalt 50 kPa shear stress B-value.

Table A.6.2 Delaware Valley Asphalt creep B-values.

Test	Final B-Value
80% D	0.95
50% D	0.94
50 kPa Shear Stress	0.91

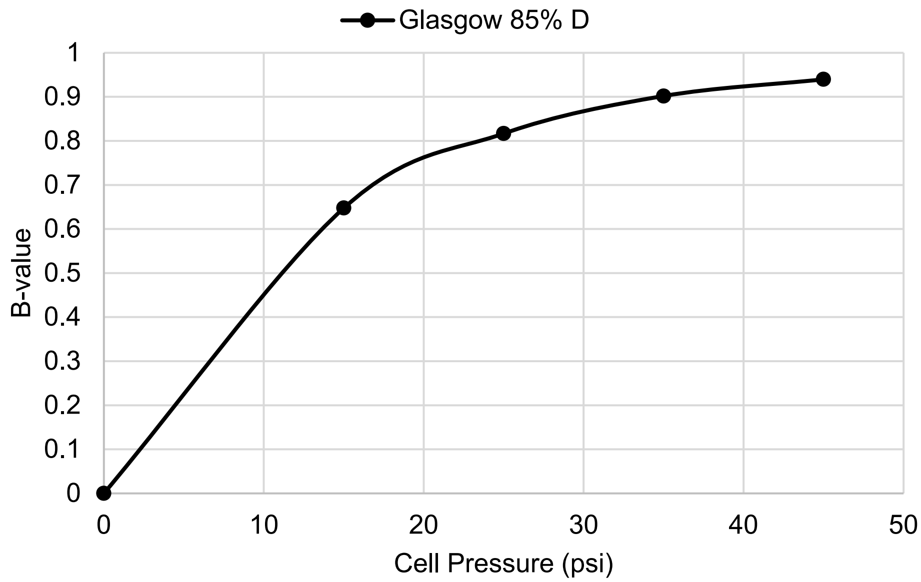


Figure A.6.7 Glasgow 85% maximum deviator stress B-value.

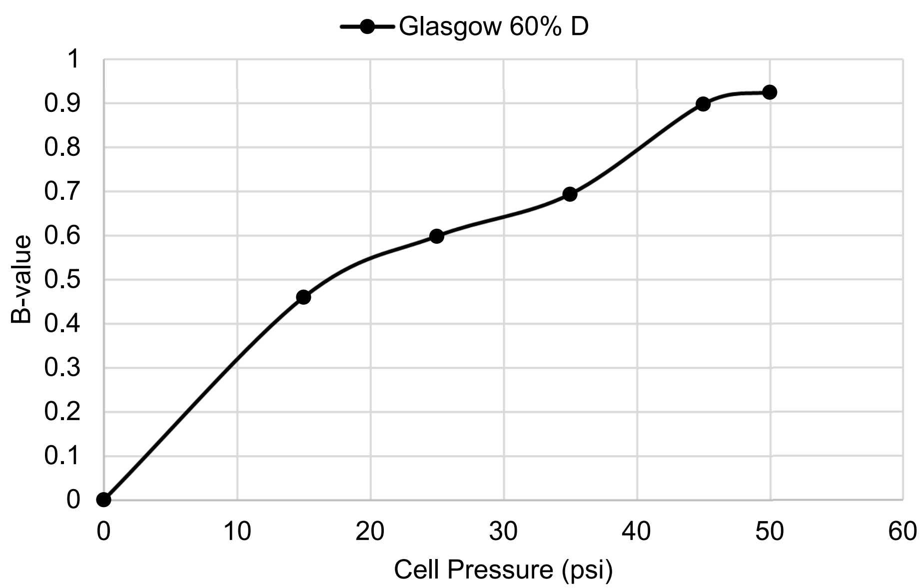


Figure A.6.8 Glasgow 60% maximum deviator stress B-value.

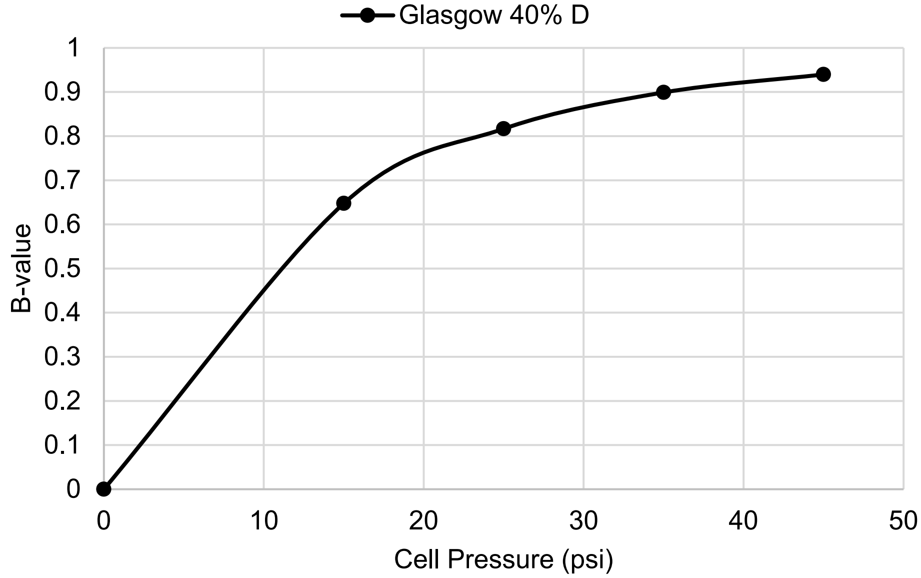


Figure A.6.9 Glasgow 40% maximum deviator stress B-value.

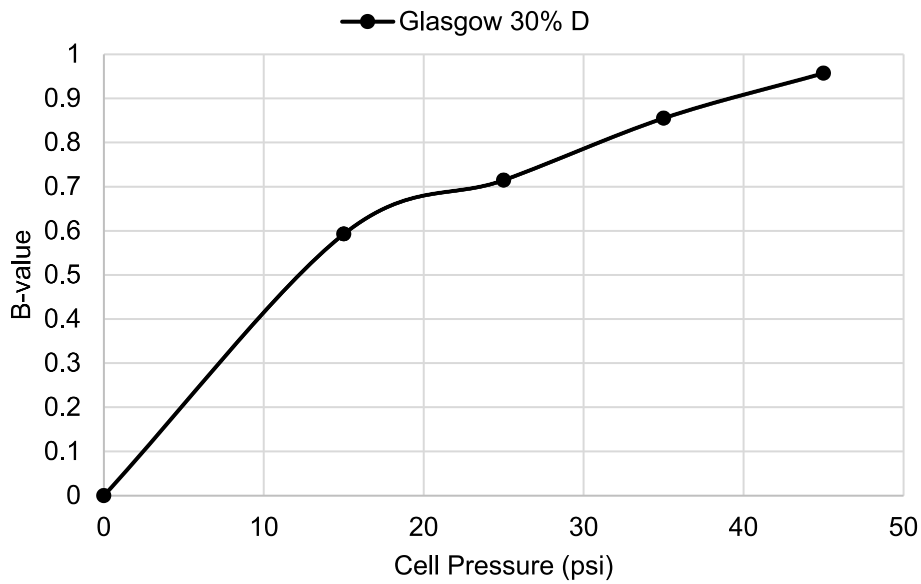


Figure A.6.10 Glasgow 30% maximum deviator stress B-value.

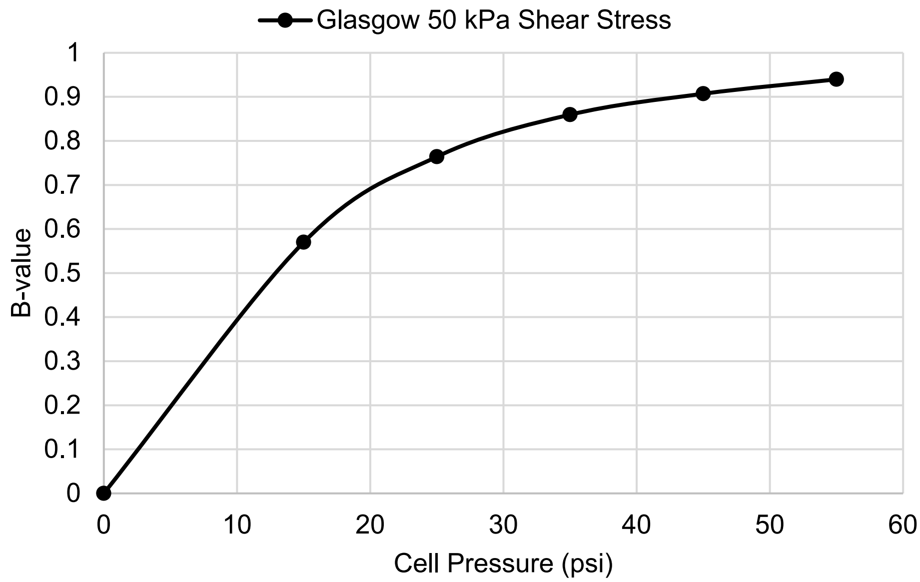


Figure A.6.11 Glasgow 50 kPa shear stress B-value.

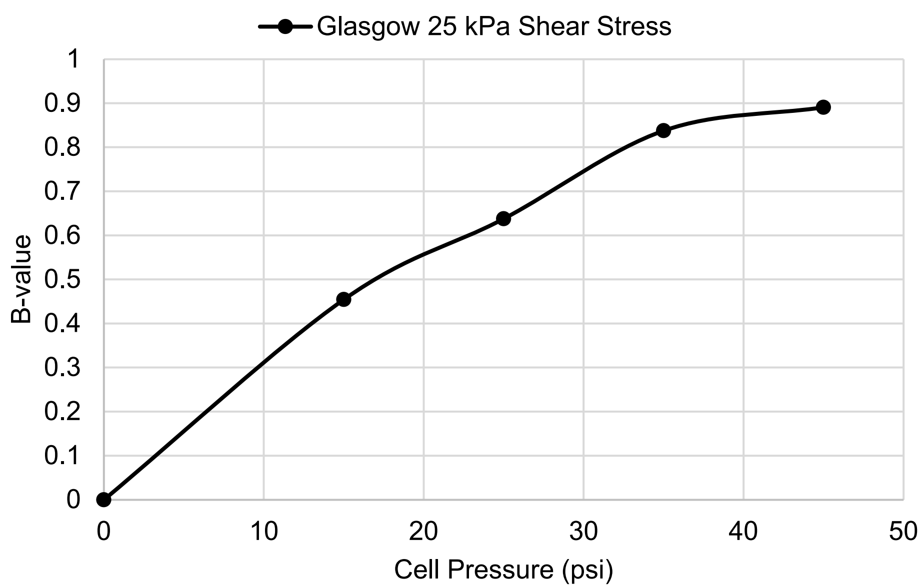


Figure A.6.12 Glasgow 25 kPa shear stress B-value.

Table A.6.3 Glasgow creep B-values.

Test	Final B-Value
85% D	0.94
60% D	0.92
40% D	0.96
30% D	0.91
50 kPa Shear Stress	0.94
25 kPa Shear Stress	0.89

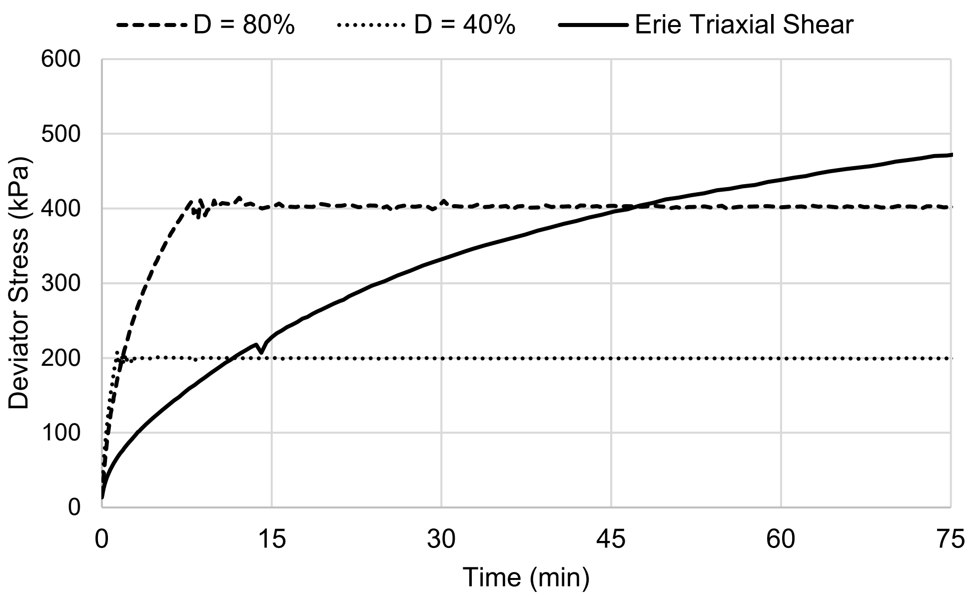


Figure A.6.13 Erie RAP at 40% and 80% of the material's maximum deviator stress.

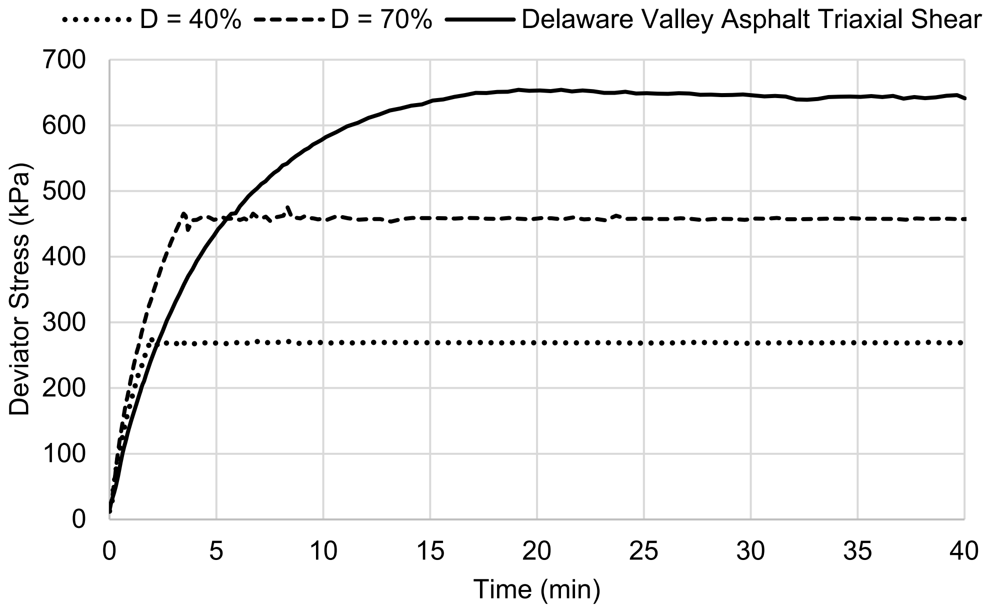


Figure A.6.14 Delaware Valley Asphalt RAP at 40% and 70% of the material's maximum deviator stress.

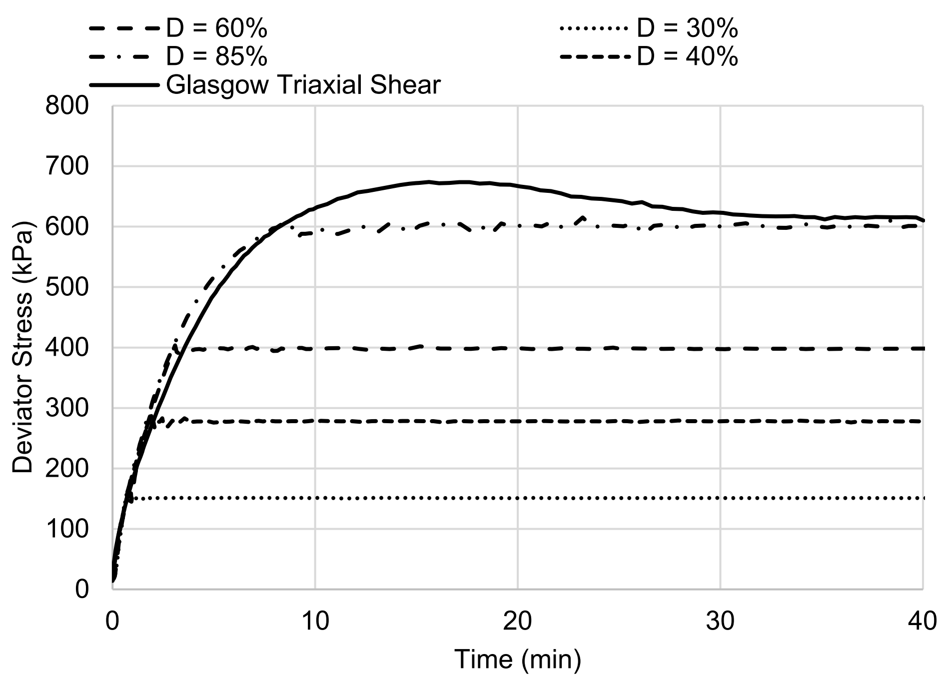


Figure A.6.15 Glasgow RAP at 30%, 40%, 60%, and 85% of the material's maximum deviator stress.

Table A.6.4 100% Erie RAP free weight creep raw data.

100% Erie RAP						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.784	0.000	0
	15	15	0.25	0.780	0.004	0.09
	30	30	0.5	0.776	0.008	0.17
	45	45	0.75	0.775	0.009	0.20
	60	60	1	0.774	0.010	0.22
Minutes	2	120	2	0.769	0.015	0.33
	4	240	4	0.762	0.022	0.48
	8	480	8	0.755	0.029	0.63
	15	900	15	0.749	0.035	0.76
	30	1800	30	0.741	0.043	0.94
Hours	1	3600	60	0.733	0.051	1.11
	2	7200	120	0.724	0.060	1.31
	24	86400	1440	0.697	0.087	1.90
	2	172800	2880	0.691	0.093	2.03
Days	5	432000	7200	0.683	0.101	2.20
	6	518400	8640	0.683	0.101	2.20
	8	691200	11520	0.682	0.102	2.23
	9	777600	12960	0.682	0.102	2.23
	10	864000	14400	0.682	0.102	2.23
	11	950400	15840	0.682	0.102	2.23
	14	1209600	20160	0.682	0.102	2.23
	15	1296000	21600	0.682	0.102	2.23
	17	1468800	24480	0.682	0.102	2.23

Table A.6.5 100% Highway Materials RAP 1 free weight creep raw data.

100% Highway Materials RAP 1						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.550	0.000	0
	15	15	0.25	0.550	0.000	0
	30	30	0.5	0.549	0.001	0.02
	45	45	0.75	0.549	0.001	0.02
	60	60	1	0.548	0.002	0.04
Minutes	2	120	2	0.547	0.003	0.06
	4	240	4	0.545	0.005	0.09
	8	480	8	0.544	0.006	0.11
	15	900	15	0.541	0.009	0.17
	30	1800	30	0.538	0.012	0.22
Hours	1	3600	60	0.534	0.016	0.30
	2	7200	120	0.532	0.018	0.33
	4	14400	240	0.532	0.018	0.33
	24	86400	1440	0.532	0.018	0.33
Days	2	172800	2880	0.532	0.018	0.33
	5	432000	7200	0.532	0.018	0.33
	6	518400	8640	0.532	0.018	0.33
	8	691200	11520	0.532	0.018	0.33

Table A.6.6 100% Highway Materials RAP 2 free weight creep raw data.

100% Highway Materials RAP 2						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.505	0.000	0
	15	15	0.25	0.505	0.000	0
	30	30	0.5	0.505	0.000	0
	45	45	0.75	0.505	0.000	0
	60	60	1	0.505	0.000	0
Minutes	2	120	2	0.505	0.000	0
	4	240	4	0.504	0.001	0.02
	8	480	8	0.502	0.003	0.06
	15	900	15	0.501	0.004	0.08
	30	1800	30	0.498	0.007	0.13
Hours	1	3600	60	0.495	0.010	0.19
	2	7200	120	0.492	0.013	0.25
	4	14400	240	0.489	0.016	0.30
	24	86400	1440	0.481	0.024	0.46
Days	4	345600	5760	0.474	0.031	0.59
	5	432000	7200	0.473	0.032	0.61
	6	518400	8640	0.473	0.032	0.61
	8	691200	11520	0.472	0.033	0.63
	12	1036800	17280	0.471	0.034	0.65
	14	1209600	20160	0.470	0.035	0.66
	17	1468800	24480	0.470	0.035	0.66
	18	1555200	25920	0.470	0.035	0.66

Table A.6.7 100% Delaware Valley Asphalt RAP 1 free weight creep raw data.

100% Delaware Valley Asphalt RAP 1						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.494	0.000	0
	15	15	0.25	0.490	0.004	0.09
	30	30	0.5	0.488	0.006	0.13
	45	45	0.75	0.485	0.009	0.20
	60	60	1	0.484	0.010	0.22
Minutes	2	120	2	0.469	0.025	0.55
	4	240	4	0.464	0.030	0.65
	8	480	8	0.457	0.037	0.81
	15	900	15	0.450	0.044	0.96
	30	1800	30	0.441	0.053	1.16
Hours	1	3600	60	0.435	0.059	1.29
	2	7200	120	0.428	0.066	1.44
	9	32400	540	0.409	0.085	1.85
	24	86400	1440	0.399	0.095	2.07
Days	2	172800	2880	0.391	0.103	2.25
	4	345600	5760	0.390	0.104	2.27
	5	432000	7200	0.387	0.107	2.33
	6	518400	8640	0.387	0.107	2.33
	7	604800	10080	0.380	0.114	2.49
	12	1036800	17280	0.377	0.117	2.55
	13	1123200	18720	0.377	0.117	2.55
	14	1209600	20160	0.377	0.117	2.55
	15	1296000	21600	0.377	0.117	2.55
	16	1382400	23040	0.376	0.118	2.57
	17	1468800	24480	0.375	0.119	2.60
	19	1641600	27360	0.375	0.119	2.60
	20	1728000	28800	0.374	0.120	2.62
	23	1987200	33120	0.373	0.121	2.64
	24	2073600	34560	0.373	0.121	2.64
	25	2160000	36000	0.373	0.121	2.64
	27	2332800	38880	0.373	0.121	2.64
	31	2678400	44640	0.373	0.121	2.64
	33	2851200	47520	0.371	0.123	2.68
	36	3110400	51840	0.371	0.123	2.68
	37	3196800	53280	0.371	0.123	2.68

Table A.6.8 100% Delaware Valley Asphalt RAP 2 free weight creep raw data.

100% Delaware Valley Asphalt RAP 2						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.615	0.000	0
	15	15	0.25	0.612	0.003	0.07
	30	30	0.5	0.610	0.005	0.11
	45	45	0.75	0.608	0.007	0.15
	60	60	1	0.604	0.011	0.24
Minutes	2	120	2	0.598	0.017	0.37
	4	240	4	0.591	0.024	0.52
	8	480	8	0.585	0.030	0.65
	15	900	15	0.579	0.036	0.79
	30	1800	30	0.576	0.039	0.85
Hours	1	3600	60	0.569	0.046	1.00
	2	7200	120	0.565	0.050	1.09
	4	14400	240	0.562	0.053	1.16
	24	86400	1440	0.547	0.068	1.48
Days	2	172800	2880	0.544	0.071	1.55
	5	432000	7200	0.542	0.073	1.59
	6	518400	8640	0.540	0.075	1.64
	8	691200	11520	0.538	0.077	1.68
	9	777600	12960	0.536	0.079	1.72
	10	864000	14400	0.536	0.079	1.72
	13	1123200	18720	0.535	0.080	1.75
	14	1209600	20160	0.534	0.081	1.77
	16	1382400	23040	0.534	0.081	1.77
	17	1468800	24480	0.533	0.082	1.79
	19	1641600	27360	0.533	0.082	1.79
	20	1728000	28800	0.533	0.082	1.79
	21	1814400	30240	0.533	0.082	1.79
	23	1987200	33120	0.533	0.082	1.79

Table A.6.9 100% Glasgow RAP 1 free weight creep raw data.

100% Glasgow RAP 1						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.453	0.000	0
	15	15	0.25	0.453	0.000	0
	30	30	0.5	0.453	0.000	0
	45	45	0.75	0.453	0.000	0
	60	60	1	0.453	0.000	0
Minutes	2	120	2	0.453	0.000	0
	4	240	4	0.453	0.000	0
	8	480	8	0.452	0.001	0.02
	15	900	15	0.451	0.002	0.04
	30	1800	30	0.450	0.003	0.07
Hours	1	3600	60	0.447	0.006	0.13
	2	7200	120	0.445	0.008	0.17
	6.5	23400	390	0.440	0.013	0.28
	24	86400	1440	0.429	0.024	0.52
Days	2	172800	2880	0.426	0.027	0.59
	2.25	194400	3240	0.425	0.028	0.61
	3	259200	4320	0.423	0.030	0.65
	6	518400	8640	0.421	0.033	0.71
	7	604800	10080	0.420	0.033	0.72
	8	691200	11520	0.420	0.034	0.73
	9	777600	12960	0.418	0.035	0.76
	10	864000	14400	0.418	0.035	0.76
	11	950400	15840	0.418	0.035	0.76
	13	1123200	18720	0.4175	0.036	0.77
	14	1209600	20160	0.418	0.036	0.77
	15	1296000	21600	0.418	0.036	0.77
	16	1382400	23040	0.418	0.036	0.77
	21	1814400	30240	0.4175	0.036	0.77

Table A.6.10 100% Glasgow RAP 2 free weight creep raw data.

100% Glasgow RAP 2						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.480	0.000	0
	15	15	0.25	0.470	0.010	0.22
	30	30	0.5	0.460	0.020	0.44
	45	45	0.75	0.459	0.021	0.46
	60	60	1	0.458	0.022	0.48
Minutes	2	120	2	0.454	0.026	0.57
	4	240	4	0.451	0.029	0.63
	8	480	8	0.448	0.032	0.70
	15	900	15	0.442	0.038	0.83
	30	1800	30	0.438	0.042	0.92
Hours	1	3600	60	0.436	0.044	0.96
	2	7200	120	0.434	0.046	1.00
	24	86400	1440	0.430	0.050	1.09
Days	2	172800	2880	0.428	0.052	1.13
	3	259200	4320	0.427	0.053	1.16
	4	345600	5760	0.426	0.054	1.18
	6	518400	8640	0.424	0.056	1.22
	7	604800	10080	0.423	0.057	1.24
	11	950400	15840	0.421	0.059	1.29
	12	1036800	17280	0.420	0.060	1.31
	13	1123200	18720	0.420	0.060	1.31
	16	1382400	23040	0.420	0.060	1.31
	17	1468800	24480	0.420	0.060	1.31
	18	1555200	25920	0.420	0.060	1.31
	19	1641600	27360	0.420	0.060	1.31

A.7 Mixtures

Table A.7.1 50/50 Erie RAP – 57 Stone compaction raw data.

50/50 Erie - 57 Blend						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.615	0.000	0
	15	15	0.25	0.615	0.000	0
	30	30	0.5	0.615	0.000	0
	45	45	0.75	0.615	0.000	0
	60	60	1	0.614	0.001	0.02
Minutes	2	120	2	0.613	0.002	0.04
	4	240	4	0.612	0.003	0.07
	8	480	8	0.611	0.004	0.09
	15	900	15	0.610	0.005	0.11
	30	1800	30	0.610	0.005	0.11
Hours	1	3600	60	0.610	0.005	0.11
	2	7200	120	0.610	0.005	0.11
	4	14400	240	0.610	0.005	0.11
	24	86400	1440	0.610	0.005	0.11
Days	2	172800	2880	0.610	0.005	0.11
	5	432000	7200	0.610	0.005	0.11
	6	518400	8640	0.610	0.005	0.11
	8	691200	11520	0.610	0.005	0.11
	9	777600	12960	0.610	0.005	0.11
	13	1123200	18720	0.610	0.005	0.11
	14	1209600	20160	0.610	0.005	0.11
	16	1382400	23040	0.610	0.005	0.11

Table A.7.2 50/50 Highway Materials RAP – 57 Stone compaction raw data.

50/50 Highway Materials RAP – 57 Stone						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.689	0.000	0
	15	15	0.25	0.687	0.002	0.04
	30	30	0.5	0.686	0.003	0.07
	45	45	0.75	0.686	0.003	0.07
	60	60	1	0.685	0.004	0.09
Minutes	2	120	2	0.684	0.005	0.11
	4	240	4	0.682	0.007	0.15
	8	480	8	0.681	0.008	0.17
	15	900	15	0.679	0.010	0.22
	30	1800	30	0.677	0.012	0.26
Hours	1	3600	60	0.674	0.015	0.33
	2	7200	120	0.671	0.018	0.39
	24	86400	1440	0.669	0.020	0.44
Days	2	172800	2880	0.667	0.022	0.48
	3	259200	4320	0.666	0.023	0.50
	4	345600	5760	0.665	0.024	0.52
	6	518400	8640	0.664	0.025	0.55
	7	604800	10080	0.664	0.025	0.55
	11	950400	15840	0.664	0.025	0.55
	12	1036800	17280	0.664	0.025	0.55
	13	1123200	18720	0.664	0.025	0.55
	16	1382400	23040	0.663	0.026	0.57
	17	1468800	24480	0.663	0.026	0.57
	18	1555200	25920	0.663	0.026	0.57
	19	1641600	27360	0.663	0.026	0.57

Table A.7.3 50/50 Delaware Valley Asphalt RAP – 57 Stone compaction raw data.

50/50 Delaware Valley Asphalt - 57 Blend						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.741	0.000	0
	15	15	0.25	0.739	0.002	0.04
	30	30	0.5	0.739	0.002	0.04
	45	45	0.75	0.738	0.003	0.07
	60	60	1	0.738	0.003	0.07
Minutes	2	120	2	0.738	0.003	0.07
	4	240	4	0.737	0.004	0.09
	8	480	8	0.736	0.005	0.11
	15	900	15	0.735	0.006	0.13
	30	1800	30	0.734	0.007	0.15
Hours	1	3600	60	0.733	0.008	0.17
	2	7200	120	0.728	0.013	0.28
	4	14400	240	0.728	0.013	0.28
	24	86400	1440	0.725	0.016	0.35
Days	2	172800	2880	0.722	0.019	0.41
	5	432000	7200	0.718	0.023	0.50
	6	518400	8640	0.717	0.024	0.52
	8	691200	11520	0.717	0.024	0.52
	9	777600	12960	0.716	0.025	0.55
	12	1036800	17280	0.715	0.026	0.57
	13	1123200	18720	0.715	0.026	0.57
	14	1209600	20160	0.715	0.026	0.57
	16	1382400	23040	0.715	0.026	0.57
	20	1728000	28800	0.714	0.027	0.59
	22	1900800	31680	0.714	0.027	0.59
	25	2160000	36000	0.714	0.027	0.59

Table A.7.4 50/50 Glasgow RAP – 57 Stone compaction raw data.

50/50 Glasgow - 57 Blend						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.634	0.000	0
	15	15	0.25	0.634	0.000	0
	30	30	0.5	0.634	0.000	0
	45	45	0.75	0.634	0.000	0
	60	60	1	0.634	0.000	0
Minutes	2	120	2	0.633	0.001	0.02
	4	240	4	0.632	0.002	0.04
	8	480	8	0.631	0.003	0.07
	15	900	15	0.630	0.004	0.09
	30	1800	30	0.627	0.007	0.15
Hours	1	3600	60	0.624	0.010	0.22
	2	7200	120	0.621	0.013	0.28
	8.5	30600	510	0.619	0.015	0.33
	24	86400	1440	0.618	0.016	0.35
	29.5	106200	1770	0.618	0.016	0.35
Days	2	172800	2880	0.618	0.016	0.35
	5	432000	7200	0.618	0.016	0.35
	6	518400	8640	0.618	0.016	0.35
	7	604800	10080	0.618	0.016	0.35
	8	691200	11520	0.618	0.016	0.35

Table A.7.5 70/30 Glasgow RAP – 57 Stone compaction raw data.

70/30 Glasgow - 57 Blend						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.780	0.000	0
	15	15	0.25	0.778	0.002	0.04
	30	30	0.5	0.777	0.003	0.07
	45	45	0.75	0.776	0.004	0.09
	60	60	1	0.775	0.005	0.11
Minutes	2	120	2	0.774	0.006	0.13
	4	240	4	0.771	0.009	0.20
	8	480	8	0.769	0.011	0.24
	15	900	15	0.767	0.013	0.28
	30	1800	30	0.765	0.015	0.33
Hours	1	3600	60	0.762	0.018	0.39
	2	7200	120	0.762	0.018	0.39
	9	32400	540	0.762	0.018	0.39
	24	86400	1440	0.761	0.019	0.41
Days	2	172800	2880	0.761	0.019	0.41
	4	345600	5760	0.760	0.020	0.44
	5	432000	7200	0.760	0.020	0.44
	6	518400	8640	0.760	0.020	0.44
	7	604800	10080	0.760	0.020	0.44

A.8 Thermal Conditioning Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)

Table A.8.1 Erie RAP thermal conditioning compaction raw data.

Modified Proctor ASTM D1557				
Erie Compaction	1	2	3	4
Mass of Mold, Plate, and sample (kg)	9.75	10.01	10.2	10.1
Weight of compacted sample (kg)	4.5	4.76	4.95	4.85
Moisture Content (%)	1.82	3.61	5.49	5.51
Dry Density (kg/m^3)	1923.30	1999.25	2041.98	2000.41
Wet Density (kg/m^3)	1958.22	2071.37	2154.05	2110.53
Dry Density (lb/ft^3)	120.07	124.81	127.48	124.88
Wet Density (lb/ft^3)	122.25	129.31	134.47	131.76

Table A.8.2 Erie RAP thermal conditioned gradation raw data before and after compaction.

Sieve	Sieve opening size (mm)	Pre-Compaction Percent Finer	Post-Compaction Percent Finer
2"	50	100%	100%
1-1/2"	37.5	100%	100%
1"	25	100%	100%
3/4"	19	100%	100%
1/2"	12.5	100%	100%
3/8"	9.5	94%	94%
5/16"	8	87%	87%
1/4"	6.3	75%	76%
4	4.75	65%	65%
10	2	36%	36%
20	0.85	18%	18%
40	0.425	9%	10%
100	0.15	2%	4%
200	0.075	0%	2%
Pan	-	0%	0%

Table A.8.3 Highway Materials RAP thermal conditioned with oven compaction raw data.

Modified Proctor ASTM D1557					
Erie Compaction	1	2	3	4	5
Mass of Mold, Plate, and sample (kg)	10.05	10.2	10.3	10.35	10.4
Weight of compacted sample (kg)	4.8	4.95	5.05	5.1	5.15
Moisture Content (%)	2.17	3.73	4.87	6.48	10.64
Dry Density (kg/m^3)	2044.47	2076.59	2095.57	2084.33	2025.49
Wet Density (kg/m^3)	2088.77	2154.05	2197.56	2219.32	2241.08
Dry Density (lb/ft^3)	127.63	129.64	130.82	130.12	126.45
Wet Density (lb/ft^3)	130.40	134.47	137.19	138.55	139.91

Table A.8.4 Highway Materials RAP thermal conditioned with oven gradation raw data before and after compaction.

Sieve	Sieve opening size (mm)	Pre-Compaction Percent Finer	Post-Compaction Percent Finer
2"	50	100%	100%
1-1/2"	37.5	100%	100%
1"	25	100%	100%
3/4"	19	100%	100%
1/2"	12.5	100%	100%
3/8"	9.5	94%	94%
5/16"	8	87%	87%
1/4"	6.3	75%	76%
4	4.75	65%	65%
10	2	36%	36%
20	0.85	18%	18%
40	0.425	9%	10%
100	0.15	2%	4%
200	0.075	0%	2%
Pan	-	0%	0%

Table A.8.5 Highway Materials RAP thermal conditioned with outside heating compaction raw data.

Modified Proctor ASTM D1557						
Erie Compaction	1	2	3	4	5	6
Mass of Mold, Plate, and sample (kg)	9.95	10.00	10.20	10.35	10.40	10.40
Weight of compacted sample (kg)	4.7	4.75	4.95	5.10	5.15	5.15
Moisture Content (%)	1.97	1.94	3.72	5.26	9.12	8.12
Dry Density (kg/m^3)	2005.83	2027.59	2076.76	2108.48	2053.78	2072.84
Wet Density (kg/m^3)	2045.26	2067.01	2154.05	2219.32	2241.08	2241.08
Dry Density (lb/ft^3)	125.22	126.58	129.65	131.63	128.21	129.40
Wet Density (lb/ft^3)	127.68	129.04	134.47	138.55	139.91	139.91

Table A.8.6 Highway Materials RAP thermal conditioned with outside heating gradation raw data before and after compaction.

Sieve	Sieve opening size (mm)	Pre-Compaction Percent Finer	Post-Compaction Percent Finer
2"	50	100%	100%
1-1/2"	37.5	100%	100%
1"	25	100%	100%
3/4"	19	100%	100%
1/2"	12.5	100%	100%
3/8"	9.5	94%	95%
5/16"	8	87%	89%
1/4"	6.3	75%	81%
4	4.75	65%	71%
10	2	36%	42%
20	0.85	18%	23%
40	0.425	9%	13%
100	0.15	2%	4%
200	0.075	0%	2%
Pan	-	0%	0%

Table A.8.7 Highway Materials RAP thermal conditioned free weight creep compaction raw data.

Heated 100% Highway Materials RAP - 35 C						
Time		Time (s)	Time (min)	Dial Gauge Reading	Cumulative Deformation (in)	Strain (%)
Seconds	0	1	0.017	0.371	0.000	0
	15	15	0.25	0.371	0.000	0
	30	30	0.5	0.370	0.001	0.02
	45	45	0.75	0.370	0.001	0.02
	60	60	1	0.370	0.001	0.02
Minutes	2	120	2	0.370	0.001	0.02
	4	240	4	0.369	0.002	0.04
	8	480	8	0.366	0.005	0.11
	15	900	15	0.366	0.005	0.11
	30	1800	30	0.365	0.006	0.13
Hours	1	3600	60	0.362	0.009	0.20
	2	7200	120	0.360	0.011	0.24
	24	86400	1440	0.351	0.020	0.44
Days	2	172800	2880	0.349	0.022	0.48
	5	432000	7200	0.346	0.025	0.55
	6	518400	8640	0.346	0.025	0.55
	7	604800	10080	0.345	0.026	0.57
	12	1036800	17280	0.343	0.028	0.61
	13	1123200	18720	0.343	0.028	0.61
	14	1209600	20160	0.343	0.028	0.61
	15	1296000	21600	0.342	0.029	0.63
	16	1382400	23040	0.342	0.029	0.63
	21	1814400	30240	0.342	0.029	0.63