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Review

Review of Geotechnical Properties of Reclaimed Asphalt Pavement for Reuse in Infrastructure

Catherine H. Dager, Robert H. Morro, Jonathan F. Hubler * and Kristin M. Sample-Lord

Department of Civil and Environmental Engineering, Villanova University, 800 Lancaster Ave., Villanova, PA 19085, USA
* Correspondence: jonathan.hubler@villanova.edu

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, owing 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. The gradation, specific gravity, density, moisture content, hydraulic conductivity, leaching, shear strength, and creep properties of different RAP sources are 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. Additionally, correlations between gradation properties (C_u, D_{10}, D_{85}), asphalt content, and the geotechnical properties of maximum dry density, saturated hydraulic conductivity, and shear strength were identified.

Keywords: Reclaimed Asphalt Pavement (RAP); creep; embankment; backfill

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1. Introduction

Reclaimed Asphalt Pavement (RAP), which is recycled pavement material consisting of coarse aggregates coated by asphalt cement that is generated when asphalt pavements are removed for construction purposes [1], is used worldwide in recycled pavement mixtures [2–7]. In Europe, RAP use as an aggregate in unbound layers is also significant, accounting for 17% of RAP use [2]. Generally, a RAP content range in new asphalt mixtures of 15–30% by weight is common practice, and in the 2019 United States construction season, the average percentage of RAP used in asphalt mixes was 21.1% [2,3,7]. In the United States, recycled pavement mixtures containing more than 25% RAP by weight are considered high-content RAP mixtures, and this practice is generally considered unpractical [2,4,5]. In contrast, in South Africa and Japan, the RAP content in recycled pavement mixtures is allowable up to 40% and 47% by weight, respectively [2].

Although RAP is commonly used in recycled pavement applications, there is still substantial excess RAP that is not being utilized. At the end of each construction season, significant amounts of RAP are left in stockpiles [2–5]. For example, in the 2019 construction season, an estimated 138 million tons of RAP was stockpiled in the United States [3]. Eventually, when stockpiles become overwhelmed, more RAP will have to be placed in landfills. Landfilling is costly and 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.

Although there has been an increase in RAP research around the world, RAP is highly variable, leading to variability in the geotechnical properties of the material [4,7–9]. The variability of RAP highlights the need to synthesize existing data and identify current knowledge gaps and research needs. Thus, this paper presents a comprehensive literature review that investigates the geotechnical properties of RAP. By compiling data for the geotechnical properties of RAP from throughout the world, recommendations on the reuse of this waste material beyond pavement applications can be made. The engineering properties of RAP are evaluated to provide recommendations on the use of RAP in alternative highway transportation infrastructure applications.

2. Background

RAP is created by the grinding or milling of an asphalt roadway to a specific depth, typically the top 50.8 mm (2 inches) of roadway [1]. The initial roadway milling creates RAP of variable size and quality, with some RAP particles exceeding 50 mm. 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 [2]. 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 25 mm) is used [2,8]. Processed RAP is commonly created because of its frequent application in hot and cold recycled asphalt mixes [1]. Figure 1 compares processed RAP to unprocessed RAP and Figure 2 provides a flowchart summarizing the process of creating RAP.

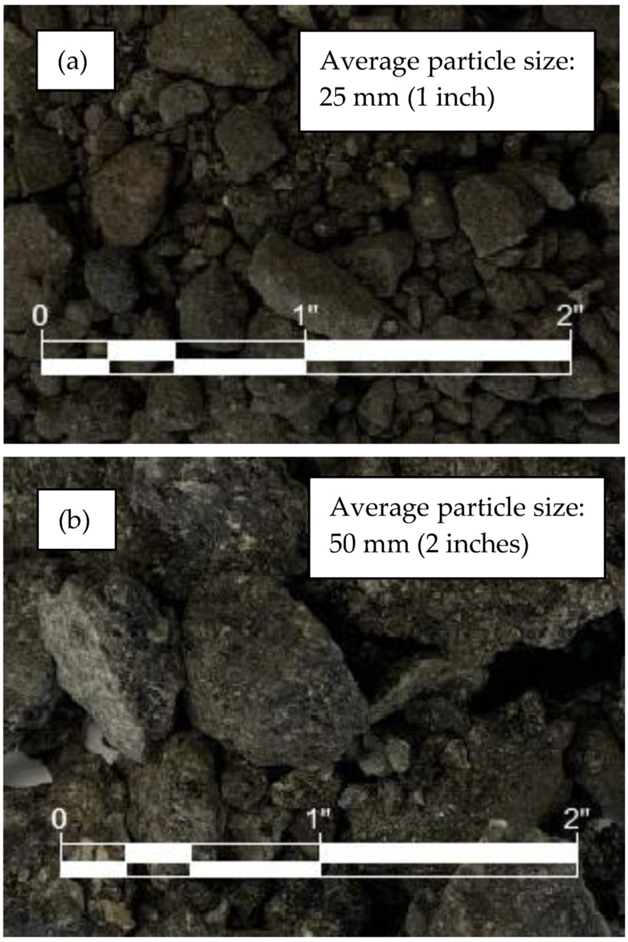

Figure 1. Photographs of: (**a**) processed and (**b**) unprocessed RAP.

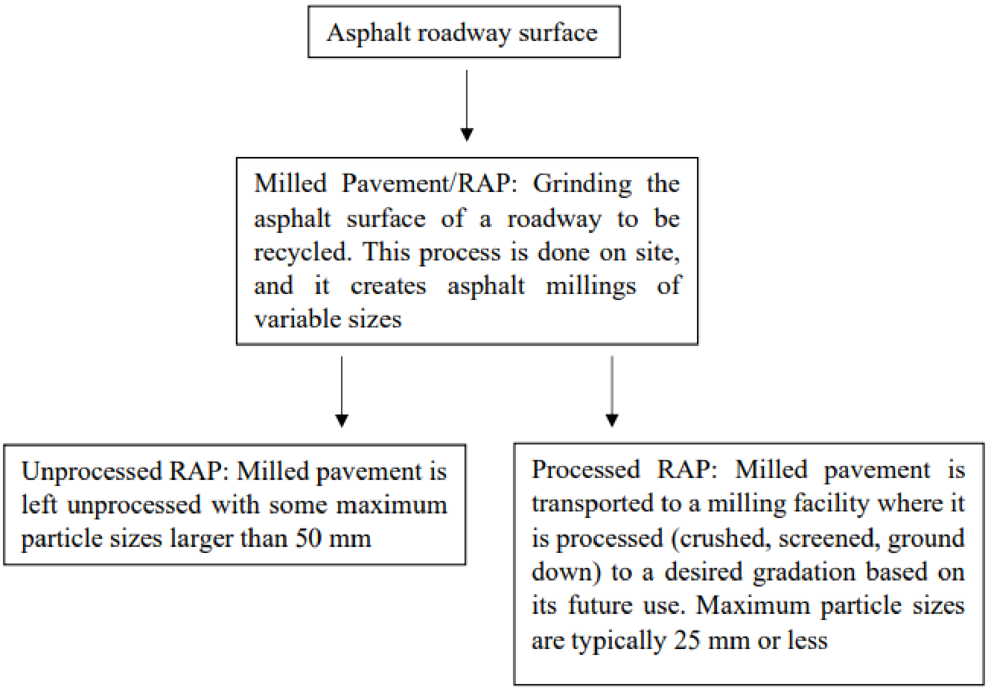

Figure 2. Process of creating RAP.

Research interest in RAP reuse has grown over the past three decades. Numerous experimental studies have focused on measuring and evaluating the engineering properties of RAP (e.g., see Table 1). As shown in Table 1, much of the existing literature on RAP is in reference to the further processed, smaller particle-sized material. Although processed RAP has been extensively studied by researchers worldwide, the properties such as the gradation, maximum dry density/optimum moisture content, hydraulic conductivity, and leaching of RAP can vary based on location because of the make-up of the initial asphalt pavement mixtures, the milling process, the use over a lifetime, and the stockpile management of the material [8,10]. For example, in Mijic et al. [11], RAP from seven highways in Maryland was evaluated, and it was found that there was variability within the same state between the distribution of fines, sand, and gravel, the maximum dry density, the saturated hydraulic conductivity, and the concentrations of chemicals that leached out of RAP.

Because of the 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 [12–18]. Furthermore, the effects of elevated temperatures on RAP's engineering behavior have been investigated [18–21]. 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.

Table 1 shows a compilation of studies used to evaluate the differences present in RAP properties throughout the world. Additionally, correlations between the asphalt content, the gradation properties of coefficient of uniformity and grain size diameters (D_{10}, D_{85}), and the engineering properties of maximum dry density, saturated hydraulic conductivity, and shear strength were identified and will be discussed.

Table 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
[8]	Texas	Processed	X						
[9]	Texas	Not Reported					X		
[10]	China	Processed	X						
[11,22,23]	Maryland	Processed	X	X	X	X	X		
[12–14,24,25]	Florida	Processed [a]	X	X	X	X	X	X	X
[15]	Egypt	Processed	X		X				
[16]	Iraq	Processed	X		X				
[17]	Pennsylvania	Processed	X	X	X	X		X	X
[18]	Illinois	Processed [c]	X		X	X		X	X
[19–21]	Wisconsin	Processed	X		X				X
[26–29]	Texas	Processed [a]	X	X	X	X		X	X
[30]	New Jersey	Processed	X			X			
[31]	Utah	Processed	X	X	X				
[32]	Australia	Processed	X		X	X		X	
[33]	Wisconsin	Processed	X	X					
[34]	Egypt	Processed	X	X	X	X		X	
[35]	Jordan	Unprocessed	X	X	X			X	
[36]	Singapore	Processed [b]	X	X	X	X		X	
[37]	Multiple [e]	Not Reported		X	X	X	X		
[38]	Colorado	Processed	X	X	X				
[39]	Multiple [e]	Not Reported					X		
[40]	Minnesota	Not Reported					X		
[41]	Florida	Not Reported					X		
[42]	California	Processed	X		X			X	
[43]	China	Processed	X					X	

Table 1. *Cont.*

Source	Location	RAP Type	Gradation	Specific Gravity	MDD/OMC	Hydraulic Conductivity	Leaching	Shear Strength	Creep
[44]	Kansas	Processed	X	X	X				X
[45]	Florida	Not Reported							X
[46]	Iran	Processed	X	X					X
[47]	France	Not Reported					X		
[48]	Denmark	Not Reported					X		
[49]	Sweden	Not Reported					X		
[50]	Multiple [d]	Processed	X	X					
[51]	Pennsylvania	Processed	X						
[52,53]	New Jersey	Processed	X				X		

[a]. Initial RAP was processed to be coarse-grained (≥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]. Initial RAP was unprocessed, but scalping RAP was conducted for laboratory testing. [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.

3. Geotechnical Properties Reported for RAP in Literature

The geotechnical properties of RAP are critical to resilient infrastructure design under varying conditions. This literature review evaluates the gradation, specific gravity, density and moisture content, hydraulic conductivity, leaching, shear strength, and creep properties of RAP.

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. Because of 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 50 mm, with most RAP gradations being 25 mm or less in particle size [1].

Based on the review of the literature, the gradation curves of the RAP investigated in Table 1 fell within a similar gradation band and had similar classifications. The particle size distribution curves from the studies evaluated are shown in Figure 3. From the literature studies that evaluated the gradation of RAP, nine of the most comprehensive studies were compiled in Table 2 to identify the common properties of RAP. These nine 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, RAP is typically classified as either well-graded sand (SW) or well-graded gravel (GW), based on the Unified Soil Classification System (USCS) and A-1-a material using the AASHTO system [11,12,17,26,30–34].

For the studies in Figure 3, it was found that there was no consistent maximum particle size between studies. This indicates that RAP gradation varies within the United States and throughout the world, and that the variation is most likely caused by the different milling processes. Although the studies identified different maximum particle sizes, the general shape of the gradation curves were similar. The majority of the studies in Figure 3 (30 out of 33 datasets) showed a relatively well-graded gradation curve with very little fines present. The RAP used in Abedalqadar et al. [35] was unprocessed; therefore, its gradation curve was uniformly graded and it varied from the other studies. Rahardjo et al. [36] 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, and this was because uniformly graded RAP is not preferable because of its lower compaction ability when compared to well-graded RAP.

3.2. Specific Gravity

Similar to gradation, the specific gravity of RAP shows variability across different studies, which is most likely caused by different milling processes. It was found that RAP has a lower specific gravity than typical coarse-grained aggregate materials, and values from seven of the most comprehensive studies are provided in Table 2. Overall, the range of specific gravity values of RAP from the literature evaluated was 2.17 to 2.63, with an average value of 2.41. This value is lower than the typical assumed values of 2.65–2.70 for soils and aggregates [20]. The lower value for RAP suggests that the asphalt binder coating the aggregate inhibits the ability for water to be absorbed in the aggregate pours, resulting in a smaller calculated specific gravity [27]. Although RAP does have a lower specific gravity than common 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.

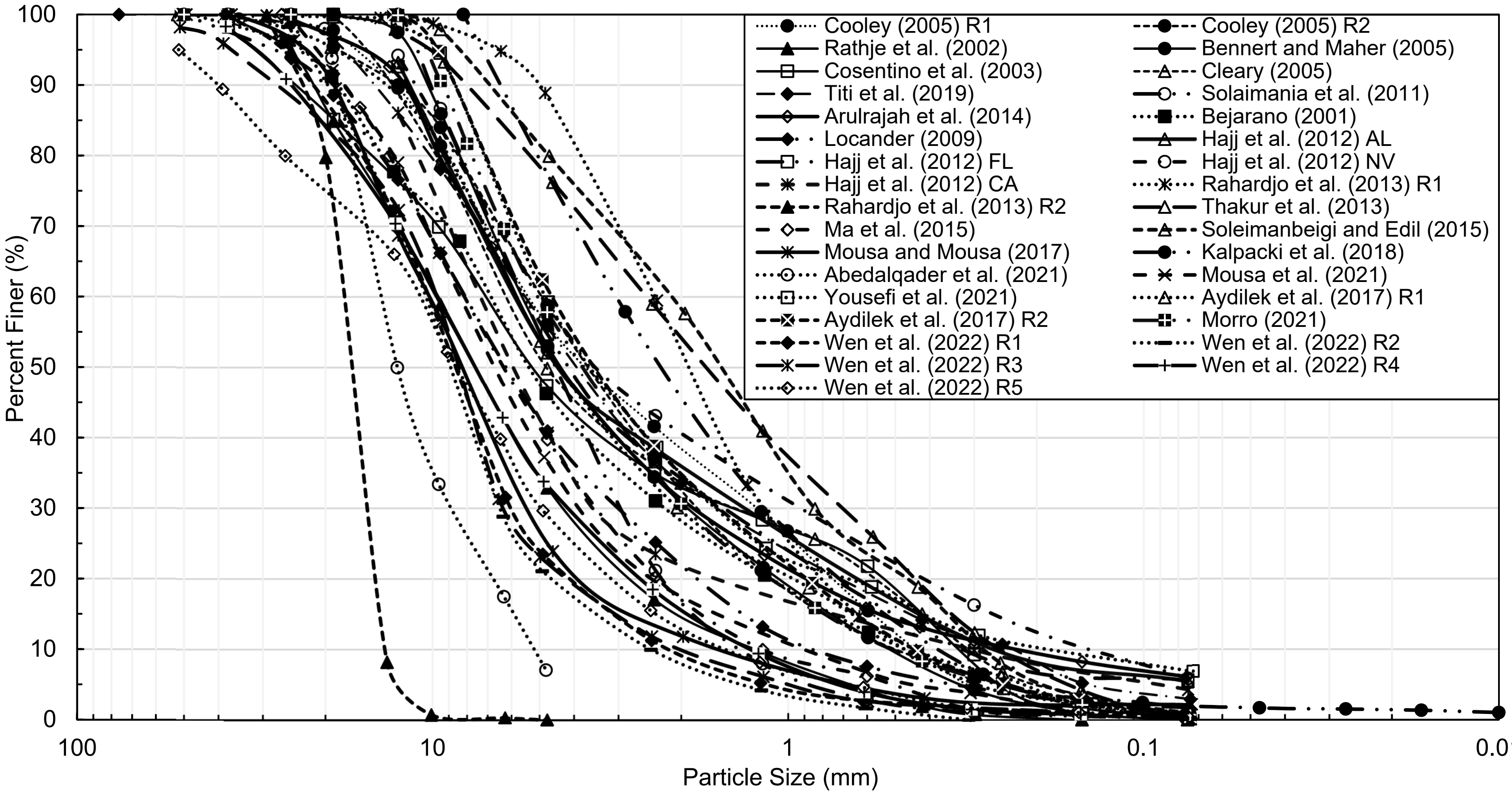

Figure 3. Gradation curves for RAP reported in the literature [12,15–19,22,24,26,30–36,38,44,46,51,52].

Table 2. Summary of geotechnical properties of RAP reported in nine experimental studies.

Parameter	[11]	[12]	[17]	[26]	[30]	[31] (R2)	[32]	[33]	[34]
Max Size (mm)	n/a	37.5	12.5	37.5	12.5	19	25	n/a	25.4
Percent Fines (Dry Sieve)	0.13 to 1.83	0	0.7	0	0.1	0	3	6.0	1.0
Percent Fines (Soil Wash)	n/a	n/a	1.7	n/a	n/a	0.5	0.99 to 17.1	n/a	n/a
D_{60} (mm) [a]	n/a	7	4.8	9.6	5.7	5	5.4	5.9	8
D_{30} (mm) [b]	n/a	1.5	1.9	4.2	1.9	1.8	1.6	1.9	3.5
D_{10} (mm) [c]	n/a	0.33	0.52	1.2	0.51	0.5	0.23	0.24	0.85
C_c [d]	1.03 to 1.79	0.97	1.4	1.53	1.22	1.3	2.06	2.5	1.80
C_u [e]	5.6 to 14.0	21.2	9.8	8.0	10.9	10.0	23.5	25.6	9.4
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	GW	SW	GW	SW	SW	SW	GW/GP	GW
AASHTO Classification	A-1-a	A-1-a	A-3-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a
Specific Gravity	2.35	2.19	2.62	2.33	n/a	2.47	2.28 to 2.77	n/a	2.24
Maximum Dry Density (kg/m^3)	1753.9 to 1996.8	1888.6	2047.2	1874.1	n/a	1846.9	n/a	2037.4	1988.9
Optimum Moisture Content (%)	5.7 to 8.2	8.0	7.8	3.0	n/a	5.8	n/a	8.0	6.0
Saturated Hydraulic Conductivity (cm/s)	6.3×10^{-3} to 1.6×10^{-2}	2.0×10^{-4}	1.7×10^{-3}	0.5×10^{-3} to 4.0×10^{-3}	6.0×10^{-3}	n/a	n/a	3.5×10^{-5}	3.3×10^{-2}

[a]. A total of 60% of soil particles are finer than this size. [b]. A total of 30% of soil particles are finer than this size. [c]. A total of 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; $C_u = \frac{D_{60}}{D_{10}}$.

3.3. Maximum Dry Density and Optimum Moisture Content

To determine the maximum dry density (MDD) and optimum moisture content (OMC) of RAP, the most common laboratory compaction test from the literature was the modified proctor test, with very few studies utilizing the standard proctor or other compaction methods. Additionally, it is also common to test compaction in the field using a nuclear gauge test. Because of 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 [18,26,53].

The MDD values from the literature using the modified proctor method ranged from 1847 kg/m^3 to 2158 kg/m^3, with the average being 2013 kg/m^3, and the OMC values ranged from 4% to 9%. Mijic et al. [11] and Wen et al. [18] were the only studies to utilize the standard Proctor method, and the MDDs from these studies ranged from 1754 kg/m^3 to 1997 kg/m^3, with the average being 1905 kg/m^3. The OMCs ranged from 6% to 9% [11,18]. The MDD results from seven comprehensive studies are summarized in Table 2. Compaction results indicate that RAP has a relatively flat compaction curve, and this is common for coarse-grained soils because of their high drainage capabilities [22,28].

Additionally, the generation of fines after compaction is an important characteristic to evaluate. Low particle breakage characteristics is critical in embankment and backfill 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 backfill construction. Results from the literature indicate that there was no significant particle breakage after compaction. In Rathje et al. [26], the increase in fines content was only 0.6%, which was less than the increase in fines content of 3.6% for other conventional fill materials.

3.4. Hydraulic Conductivity

The milling process and storage methods for RAP impacts the fines content, and correspondingly, the saturated hydraulic conductivity (k_{sat}). Values of k_{sat} reported in the literature for RAP ranged from 3.5×10^{-5} cm/s to 1.5×10^{-1} cm/s, with the average value being 4.1×10^{-2} cm/s [11,12,17,18,23,28,30,32,34,37,38]. 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 except for Arulrajah et al. [32] was classified as free draining based on the Casagrande and Fadum [54] requirement of a k_{sat} value greater than or equal to 1.0×10^{-4} cm/s. The results from seven of the literature studies that were investigated are provided in Table 2.

As previously mentioned, the use of free draining materials is important for embankment and backfill 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 [26]. Based on hydraulic conductivity information, RAP could be considered a viable option for use in embankment and backfill applications.

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 because of the manufacturing of the original asphalt, the application of RAP, the exposure during its lifespan as a roadway material, and the RAP storage length [40].

Herrara [40] 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 [40]. 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 [9,23,39,55]. These metals consisted of arsenic, manganese, iron, and selenium. Although the studies did find metal concentrations exceeding Washington's allowable limits, the exceedances generally occurred when water first passed through the RAP, with concentrations decreasing as more water was passed through [40]. The study concluded that the impact to the environment would be minimal if the RAP leachate was diluted and if soil assimilation occurred [40].

All metals that were tested in the Herrara [40] study as well as the additional literature studies were evaluated to determine which pollutants were most frequently tested during leaching investigations. A total of 11 studies were reviewed, with RAP being tested from multiple different sources. Table 3 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 3. 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.

Property or Species	Number of Sources	Sources
pH	10	[9,22,23,37,39,41,47–49,55]
Cadmium (Cd)	8	[9,22,23,37,39,41,47,55]
Chromium (Cr)	8	[9,22,23,37,39,41,47,55]
Copper (Cu)	**8**	[9,22,23,37,39,41,47,55]
Lead (Pb)	8	[9,22,23,37,39,41,47,55]
Nickel (Ni)	8	[9,22,23,37,39,41,47,55]
Zinc (Zn)	**8**	[9,22,23,37,39,41,47,55]
Barium (Ba)	7	[9,22,23,37,39,41,55]
Aluminium (Al)	6	[9,22,23,37,39,55]
Arsenic (As)	**6**	[9,22,23,37,39,55]
Manganese (Mn)	**6**	[9,22,23,37,39,55]
Iron (Fe)	5	[22,23,37,39,55]
Molybdenum (Mo)	5	[9,37,39,47,55]
Silver (Ag)	4	[9,22,37,55]
Beryllium (Be)	3	[9,39,55]
Selenium (Se)	**3**	[9,23,55]
Antimony (Sb)	2	[9,37]
Magnesium (Mg)	2	[23,37]
Mercury (Hg)	2	[9,47]
Thallium (Tl)	2	[23,55]
Potassium (K)	1	[37]
Silicon (Si)	1	[37]

Based on the literature reviewed, it was found that the leaching of metals does occur; however, it does not generally occur in levels significantly higher than standards set by the EPA. If MCLs were exceeded, after a few pore volumes of flow were flushed through the RAP, the concentration levels dropped below the MCL standards [22]. In both Brantley and Townsend [41] and Mehta et al. [55], when RAP leachates were permeated through natural soils, attenuation occurred and the contaminant concentrations dropped below EPA MCL standards. Mehta et al. [55] concluded that the reuse of RAP as an unbounded material was allowable in non-acidic environments. 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. The literature suggests that RAP does not pose a major leaching threat, and it could be used as embankment material or fill 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 [41,55].

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 because of the coarse-grained nature of RAP, triaxial testing has been more commonly used to evaluate shear strength in the literature.

As shown in Table 4, the results from the 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 general, the friction angles ranged from 42°–45°, with some outliers that were higher and lower [12,17,26,30,32,34,36,42,43]. The lowest friction angle that was evaluated was 37°, which was reported in Rathje et al. [26] and Rahardjo et al. [36]; however, a friction angle of 37° is still generally considered high strength.

Table 4. Shear strength and cohesion values for RAP from literature.

Source	Test	Friction Angle (°)	Cohesion (kPa)
[12]	Consolidated Drained	44	33.8
[17]	Consolidated Drained	41	34.5
[26]	Consolidated Drained	37	55.2
[30]	Not Reported	44.5	17.2
[32]	Consolidated Drained	37	53
[34]	Unconsolidated Undrained	39	97.9
[36]	Consolidated Drained	42	0
[42]	Consolidated Drained	52	0
[43]	Not Reported	49	126

The values of cohesion had more scatter, with most results showing some cohesion [12,17,26,30,32,34,36,43]; and Bejarano et al. [42] 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 [12,26]. Most tests did not display a distinct failure plane but instead it was observed that the specimens bulged radially during strain [26]. Shear strength and cohesion results from the literature are shown in Table 3 and a compilation of ranges of deviator stresses versus axial strain plots are plotted in Figure 4. At lower deviator stresses ranging from 0 to 199 kPa, 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 200 to 350 kPa, the peak deviator stress was attained at 9% axial strain or higher, and the deviator stress leveled off and did not decrease significantly [12,26,32].

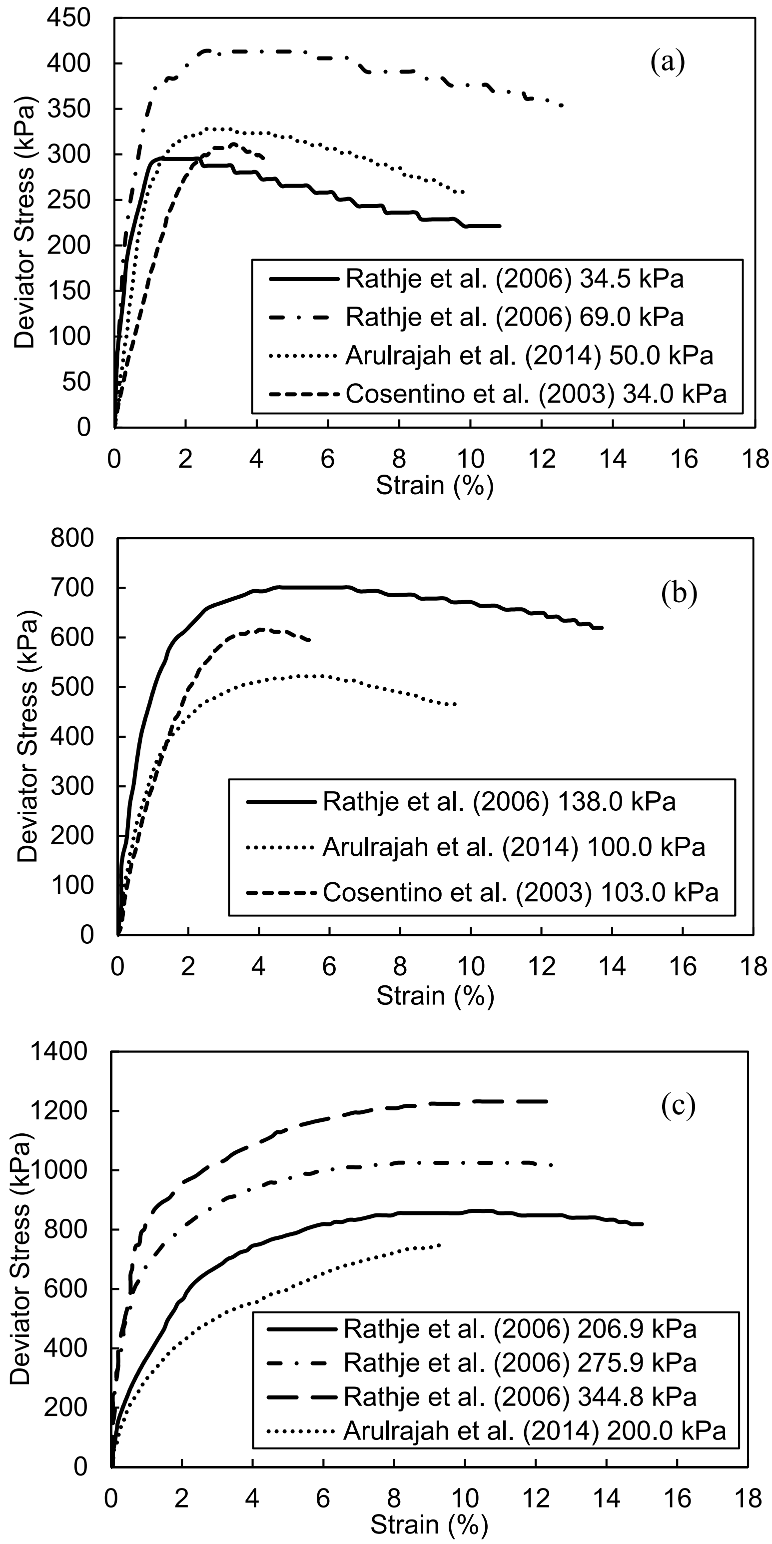

Figure 4. Deviator stress versus axial strain for RAP from the literature for (**a**) confining stress of 0–99 kPa, (**b**) confining stress of 100–199 kPa, and (**c**) confining stress of 200–350 kPa [12,27,32].

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 [12,44]. 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 [21]. This severely impairs RAP's potential to be used in fill applications and all the studies evaluated found that the creep of RAP poses a significant problem [12–14,17–19,21,24,27–29,44–46].

Viyanant [28] conducted CD triaxial tests at various percentages of the maximum deviator stress in accordance with methods described in Singh and Mitchell [56]. Testing conducted at different deviator stresses is done to achieve an m value which provides an indication of creep potential. A m value larger than 1.0 indicates that RAP will reach an asymptotic strain value, whereas a m value less than 1.0 will not achieve an asymptotic strain value and will experience a creep rupture [28]. The tests performed by Viyanant et al. [29] 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 1.0, indicating high creep susceptibility. Additionally, Viyanant et al. [29] observed that 3% axial strain was the limiting percentage of strain before creep rupture was observed.

Thakur et al. [44] investigated creep using plate loading tests and found that as the applied vertical stress on RAP was increased from 276 kPa to 552 kPa, the percent of axial creep strain was increased. Cosentino et al. [13] conducted 100% RAP tests at 41.3 kPa, 82.7 kPa, and 124.1 kPa and found that the axial strains at 82.7 kPa and 124.1 kPa stresses exceeded the strain limitation of 3% identified by Viyanant et al. [29]. Both studies concluded that at higher stresses, creep rupture is expected, and applications that experience high stresses may not be advisable for 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 because of its asphalt binder content, with high creep deformations likely at higher temperatures [27]. Yin et al. [21] concluded that if RAP is compacted and consolidated at higher temperatures, creep deformations are reduced.

Another way to improve upon RAP's creep is to confine the material or incorporate geosynthetics into the design. Thakur et al. [44] concluded that RAP crept more at lower degrees of confinement and incorporating geocell confinement into the design improved upon the RAP's creep tendencies. Furthermore, a few studies assessed blending RAP with other aggregate materials to improve upon its creep behavior [12,13,17,18]. Cosentino et al. [13] 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. [13] estimated 50-year settlement values for a typical 6.1-m high MSE wall and found that the total creep movement for the wall constructed with 100% RAP was 70.6 cm. The total creep movement for the same wall constructed with 80% RAP was reduced to 33 cm.

Based on the literature reviewed, 100% RAP is not recommended for structural fill applications. 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 structural fill applications.

4. Discussion

The geotechnical properties of RAP that were identified in the literature studies are useful when evaluating the ability of RAP to be reused in embankment and fill applications. Correlations between the different geotechnical properties can be used to evaluate the variability of RAP, and provide recommendations on the reuse of RAP in the applications of interest.

4.1. Geotechnical Property Correlations

The literature that was reviewed indicated that there is variability in RAP worldwide. This variability poses issues when using RAP in applications that require specific material properties to meet performance specifications; thus, it can be beneficial to evaluate correlations between geotechnical index properties and performance metrics. From the literature reviewed, correlations were identified between gradation properties of C_u, D_{10}, and D_{85}, and the geotechnical properties of maximum dry density and saturated hydraulic conductivity (Figures 5 and 6a,b). Additionally, a correlation between friction angle and the asphalt binder content of RAP was evaluated (Figure 7).

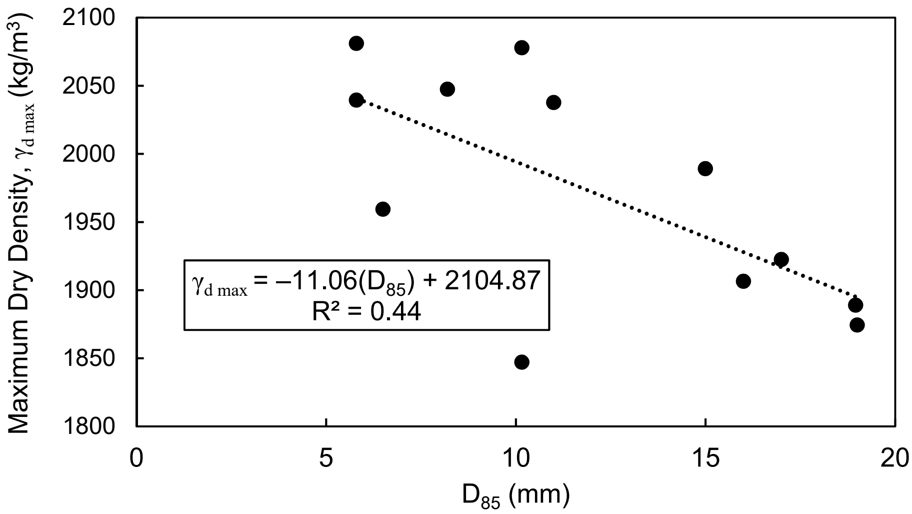

Figure 5. Maximum dry density (MDD) versus D_{85} for RAP from the literature [12,15–17,19,27,31,32,34,36,38,44].

The comparison of maximum dry density (MDD) and grain size diameter D_{85} followed a linear trend. As shown in Figure 5, when the D_{85} value of RAP increased, the MDD values decreased. Higher D_{85} values correspond to coarser-grained gradations. Larger particle sizes decrease the material's ability to pack together because it is harder for large particles to fill void spaces. This caused RAP's MDD values to decrease as its gradation became more coarse-grained.

Correlations between k_{sat} and the coefficient of uniformity (C_u) and the grain size diameter D_{10} are shown in Figure 6. In Figure 6a, as RAP becomes more well-graded (higher C_u), k_{sat} decreases. This was as expected because there is less void space for water to flow through in a well-graded material, thus decreasing the ability of liquid to flow through the saturated media. Similarly, when D_{10} values are larger, there is more void space within the gradation caused by larger particle sizes being unable to pack together as tightly, thus increasing the pathways for liquid to flow (Figure 6b). Eventually, as the D_{10} values become large enough, water is able to flow freely through the material, and increasing particle sizes no longer has an effect on the hydraulic conductivity [22].

For shear strength, as observed in Figure 7, there is a strong linear relationship between the asphalt content of the RAP and the friction angle. The literature showed a positive trend, with increasing amounts of asphalt binder content corresponding to higher friction angles [12,17,18,25]. This trend is likely caused by particle shape, with the asphalt binder creating more angular particles, thus increasing particle locking.

The asphalt binder content of RAP is a commonly evaluated property because the information is needed for reuse in recycled pavement mixtures. This relationship is useful because the commonly identified asphalt binder content of RAP can be used to provide an indication of the material's shear strength properties without having to run extensive laboratory tests.

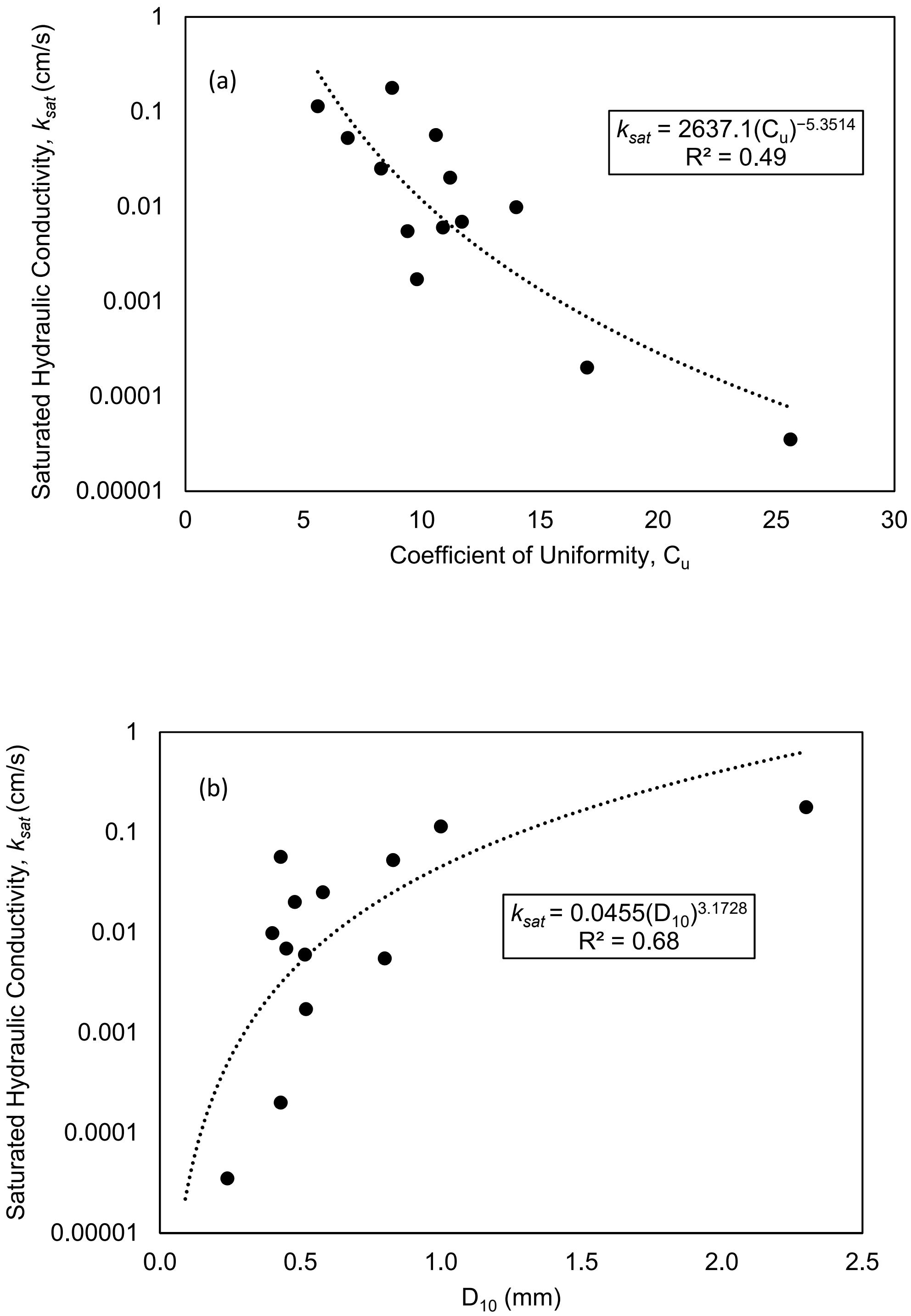

Figure 6. Saturated hydraulic conductivity (k_{sat}) versus (**a**) coefficient of uniformity (C_u) and (**b**) D_{10} for RAP from the literature [11,12,17,18,30,32,34].

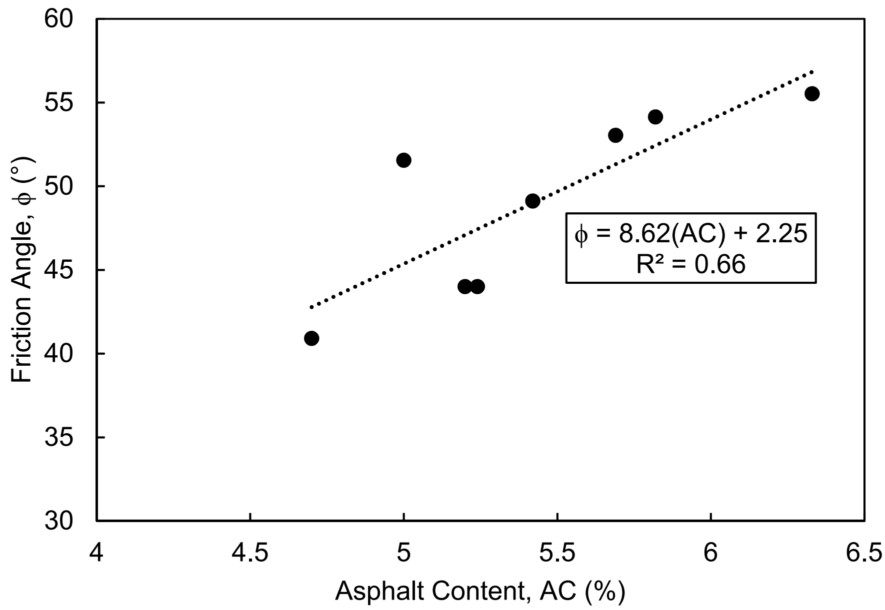

Figure 7. Asphalt content of the RAP versus friction angle [12,17,18,25].

For material used in embankment and fill applications, high shear strength and high compaction ability without significant particle breakage to maintain drainage through the material is required [1]. The correlations provided in Figures 5–7 indicate that when RAP had higher asphalt contents and smaller particle sizes, RAP displayed adequate shear strength, and good compaction ability. Although these properties are preferable characteristics in embankment and fill applications, these properties corresponded to decreasing hydraulic conductivities, which is not ideal. Although the comparison with k_{sat} showed that as RAP became more well-graded and had smaller particle sizes, the k_{sat} values decreased and, in general, RAP was still considered a free draining material. Because free drainage was maintained even at higher C_u and smaller D_{10} values, RAP was deemed acceptable for reuse in embankment and fill applications. Further laboratory study would be needed to identify threshold C_u and D_{10} values where the hydraulic conductivity would no longer be considered free draining.

The ability to evaluate the gradation properties/asphalt content of RAP and to gain an understanding of material performance without having to perform extensive laboratory tests would be useful to the geotechnical and construction community. This would minimize the concern over variability by providing a range of gradation properties that would yield optimal results. Moving forward, further research should focus on strengthening these correlations, and providing threshold values for gradation properties based on RAP's intended application.

4.2. Potential for Reuse for Processed RAP

Based on the geotechnical properties evaluated, processed RAP (particle size less than 25 mm) has the potential to be used in highway transportation infrastructure applications. If the material is left as-is, with no material adjustment, RAP may not be suitable in all applications. However, utilizing techniques such as scalping, mixing, temperature, and confinement, RAP may be suitable in embankment and fill applications.

In embankment and fill applications that have gradation requirements, adjustment of RAP's gradation may be necessary. Different milling processes can create RAP of variable sizes; therefore, it may be necessary to create a consistent gradation. Altering the gradation of RAP can be achieved through scalping, which involves removing particle sizes that are not suitable to the application of interest. Furthermore, mixing RAP with other materials such as sands and gravels can adjust the gradation. The gradation of RAP does not pose a significant problem for the reuse of RAP because if RAP does not fall within the applicable gradation standard for an application, the gradation can easily be adjusted to fit the specifications.

Studies in Figure 5 found that the maximum dry density of RAP was slightly lower than commonly used coarse aggregates; however, the MDD values of RAP fell within the expected range provided by FHWA for RAP use in embankment and fill materials. Additionally, after compaction, very few fines were generated, indicating particle breakage is not a concern. The compaction characteristics of RAP make it suitable for embankment and fill applications, and compaction does not limit RAP's potential for reuse. Similarly, all studies except for Arulrajah et al. [32] found that RAP was a free draining material yielding high k_{sat} values [11,12,17,18,22,23,28,30,32,34,37,38]. High k_{sat} values are suitable for embankment and fill applications, and because very little fines are generated after compaction, free drainage will be maintained post-construction.

There are environmental concerns regarding the leaching of RAP. For use in embankment and fill applications, additional measures may be necessary to ensure that the leaching of contaminants does not occur. Because of the variability of RAP, there are inconsistencies between what contaminants pose a problem with RAP; thus, prohibiting construction near water sources or allowing leachate to flow through natural soil may reduce leaching potential and allow for use in embankment and fill applications [9,12,22,23,39–41,47–50,55].

RAP has high shear strength characteristics similar to other coarse-grained materials, making it suitable for use in embankment/fill applications. In structural embankment/fill applications where high stresses are applied, deformations caused by creep are likely to occur, making RAP an unsuitable material. Aggregate mixtures, geosynthetic reinforcement, and an increase in construction temperatures during compaction may improve upon creep susceptibility. Further research on the reduction of creep is necessary to allow for the reuse of RAP in structural embankment and fill applications.

5. Recent and Future Directions

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.

5.1. Temperature Effects

Several studies have investigated the effect of temperature on the properties of RAP [18–21,35]. RAP is highly sensitive to the effects of temperature because of bituminous binder coating the coarse aggregate [18,20]. A study by Yin et al. [21] 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 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 [21].

A study by Wen et al. [18] conducted compaction and consolidation tests at varying temperatures. The study found that as temperature increased from 22 °C to 38 °C during compaction, the MDD values increased. It was concluded that this was caused by asphalt binder being softer and more easily deformed as it was heated [18]. 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 because of the softer and more deformable binder [18]. 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.

5.2. Aggregate Mixing

Many studies have investigated combining RAP with other aggregates to improve upon its properties [12–18,24]. 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. [12] found that the addition of sand improved upon density, bearing strength, and stiffness, whereas 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. Studies by Kalpacki et al. [15] and Mousa and Mousa [16] 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 the variability of RAP.

As previously discussed, RAP is highly susceptible to creep. The literature studies found that RAP–aggregate mixtures significantly improved upon the creep characteristics of RAP. As shown in Figure 8, a correlation was developed between the percent of RAP in RAP-aggregate mixtures, and the maximum axial strain at the conclusion of creep testing. An exponential relationship showed that as the percent of RAP in the mixture decreased, the axial strains decreased. This indicated that mixing RAP with aggregate materials is a viable option toward reducing the creep deformations of RAP. Although it is not recommended to use 100% RAP in embankment and fill applications, RAP–aggregate mixtures are a promising solution to allow for RAP's reuse in these applications.

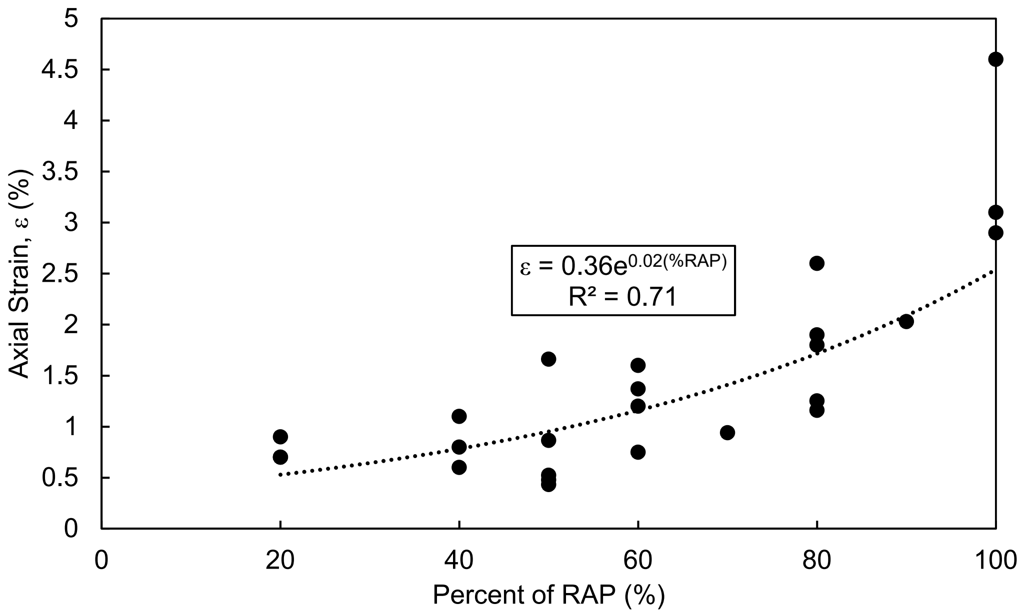

Figure 8. Percent of RAP in RAP-aggregate mixtures versus the maximum axial strain achieved at the conclusion of creep testing [13,17,18].

5.3. Challenges

In the future, certain challenges regarding the use of RAP must be addressed. Studies by Gao et al. [8] and Zhou et al. [10] 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.

An additional challenge associated with the reuse of RAP is the lack of literature on unprocessed RAP. The overwhelming majority of studies in the literature have evaluated processed RAP because of 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.

6. Conclusions

Several conclusions can be made from the literature that was reviewed. These conclusions are important because they may guide future RAP research programs and establish the properties of RAP that may be limiting the use of RAP in embankment and fill applications. RAP from the literature either fell within the required gradations set forth by various governing bodies such as US Departments of Transportation, US Departments of Environmental Protection, US Army Corp of Engineers, etc., or with gradation adjustment would meet the requirements necessary for the application. 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 embankment and fill applications. Additionally, correlations between the gradation properties of C_u, D_{10}, and D_{85}, and the geotechnical properties of MDD and k_{sat} were identified. Utilizing the correlations would minimize the concern over variability by providing a range of gradation properties that would yield optimal results. Moving forward, further research should focus on strengthening these correlations, and providing threshold values for the gradation properties based on its intended application.

RAP has a lower specific gravity than typical aggregate materials. The range of specific gravity values of RAP from the literature examined was 2.17 to 2.63, with an average value of 2.41. These values are lower than the typical assumed values of 2.65–2.70 for soils and aggregates. The lower specific gravity value for RAP is most likely caused by the bitumen coating around the aggregate; however, lower specific gravity values do not seem to significantly impact the use of RAP in embankment/fill applications.

RAP has a relatively flat compaction curve, which is common for coarse-grained materials. The MDDs from the literature using the modified proctor method ranged from 1743 kg/m^3 to 2147 kg/m^3, with an average of 1960 kg/m^3. The OMC ranged from 3% to 9%. 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.

RAP has high k_{sat} values ranging from 3.5×10^{-5} cm/s to 1.5×10^{-1} cm/s, which corresponds to high drainage capabilities. Embankment 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.

The literature suggests that RAP does not pose a major leaching threat; however, a few studies found that RAP leached metals over the required MCLs set by the EPA. When this occurred, the metal concentrations quickly dropped below the MCLs 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 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.

The results from the 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° with a few outliers. The high shear strength properties of RAP indicate that it could be used in embankment or fill applications.

RAP is likely to pose problems associated with creep. The low m values of RAP found in the 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 the creep in RAP. Further research is needed on reducing the creep susceptibility of RAP.

Both heating and mixture amendments have been investigated as potentials to enhance properties of RAP and reduce creep. Elevating the temperature of RAP during compaction 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. 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 values.

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References

1. FHWA (Federal Highway Administration) Research and Technology. *User Guidelines for Waste and Byproduct Materials in Pavement Construction*; Federal Highway Administration: Washington, DC, USA, 2016.
2. Tarsi, G.; Tataranni, P.; Sangiorgi, C. The challenges of using reclaimed asphalt pavement for new asphalt mixtures: A review. *Materials* **2020**, *13*, 4052. [CrossRef]
3. Williams, B.A.; Willis, J.R.; Shacat, J. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2019*; National Asphalt Pavement Association: Greenbelt, MD, USA, 2020.
4. Copeland, A. *Recycled Asphalt Pavement and in Asphalt Mixtures: State of Practices*; Federal Highway Administration: Mclean, VA, USA, 2011.
5. FHWA (Federal Highway Administration) Research and Technology. *Resource Responsible Use of Reclaimed Asphalt Pavement in Asphalt Mixtures*; Federal Highway Administration: Washington, DC, USA, 2021.
6. FHWA (Federal Highway Administration) Research and Technology. *Asphalt Pavement Recycling with Reclaimed Asphalt Pavement (RAP)*; Federal Highway Administration: Washington, DC, USA, 2020.
7. PennDOT (Pennsylvania Department of Transportation). *PennDOT Recycling Material Fact Sheet*; PennDOT: Harrisburg, PA, USA, 2020.
8. Zhou, F.; Das, G.; Scullion, T.; Hu, S. *RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines*; Texas Department of Transportation Research and Technology: Austin, TX, USA, 2010.
9. Morse, A.; Jackson, A.; Davio, R. Environmental characterization of traditional construction and maintenance materials. In Proceedings of the International Conference on Beneficial Use of Recycled Materials in Transportation Applications, Arlington, VA, USA, 13–15 November 2001.
10. Gao, J.; Yang, J.; Yu, D.; Jiang, Y.; Ruan, K.; Tao, W.; Sun, C.; Luo, L. Reducing the variability of multi-source reclaimed asphalt pavement materials: A practice in China. *Constr. Build. Mater.* **2021**, *278*, 122389. [CrossRef]
11. Mijic, Z.; Dayioglu, A.Y.; Hatipoglu, M.; Aydilek, A.H. Hydraulic and environmental impacts of using recycled asphalt pavement on highway shoulders. *Constr. Build. Mater.* **2020**, *234*, 117226. [CrossRef]

12. Cosentino, P.J.; Kalajian, E.H.; Shieh, C.S.; Mathurin, W.J.K.; Gomez, F.A.; Cleary, E.D.; Treeratrakoon, A. *Developing Specifications for Using Recycled Asphalt Pavement as Base, Subbase or General Fill Materials, Phase II, Final Report*; Florida Department of Transportation: Tallahassee, FL, USA, 2003.
13. Cosentino, P.J.; Kalajian, E.H.; Dikova, D.; Patel, M.; Sandin, C. *Investigating the Statewide Variability and Long-Term Strength Deformation Characteristics of RAP and RAP-Soil Mixtures, Final Report*; Florida Department of Transportation: Tallahassee, FL, USA, 2008.
14. Dikova, D. Creep Behavior of RAP–Soil Mixtures in Earthwork Applications. Master's Thesis, Florida Institute of Technology, Melbourne, FL, USA, 2006.
15. Mousa, R.M.; Mousa, M.R. Viability assessment of using reclaimed asphalt pavement—Sand blend in road construction: A case study in Egypt. In Proceedings of the 96th Transportation Research Board Annual Meeting, Washington, DC, USA, 8–12 January 2017.
16. Kalpakci, V.; Faeq, R.; Canakci, H. Compaction and CBR properties of RAP/sand blends in Iraq. *Arab. J. Geosci.* **2018**, *11*, 663. [CrossRef]
17. Morro, R.H. Characterization of Reclaimed Asphalt Pavement in Pennsylvania and Evaluation of Its Use in Geotechnical Infrastructure Applications. Master's Thesis, Department of Civil Engineering, Villanova University, Villanova, PA, USA, 2021.
18. Wen, H.; Barzegar, M.; Mivehchi, M.; Akin, I.; Edil, T.; Muhunthan, B. *Utilization and Limitations of Recycled Asphalt Pavement (RAP) as Roadway Embankment Material, Draft Final Report*; Illinois State Toll Highway Authority: Downers Grove, IL, USA, 2022.
19. Soleimanbeigi, A.; Edil, T.B. Thermal conditioning to improve geotechnical properties of recycled asphalt pavements. *Geotech. Test. J.* **2015**, *38*, 1–12. [CrossRef]
20. Yin, J.; Soleimanbeigi, A.; Warren, B.; Likos, W.; Edil, T. Creep behavior of recycled asphalt pavement at elevated temperatures. In Proceedings of the ASCE Geotechnical and Structural Engineering Congress 2016, Phoenix, AZ, USA, 14–17 February 2016; pp. 1426–1434.
21. Yin, J.; Soleimanbeigi, A.; Likos, W.J.; Edil, T.B. Effects of temperature on creep behavior of compacted recycled asphalt pavement. *J. Geotech. Geoenviron. Eng.* **2017**, *143*, 06016028. [CrossRef]
22. Aydilek, A.H.; Mijic, Z.; Seybou-Insa, O. *Hydraulic and Environmental Behavior of Recycled Asphalt Pavement in Highway Shoulder Applications, Final Report*; Maryland Department of Transportation: Hanover, MD, USA, 2017.
23. Seybou-Insa, O.; Dayioglu, A.Y.; Houlihan, M.; Aydilek, A.H. pH_{Stat} testing and geochemical modeling of inorganic compounds in recycled asphalt pavement used in highway shoulders. *Constr. Build. Mater.* **2021**, *313*, 125407. [CrossRef]
24. Cleary, E.D. Long-Term Behavior of RAP-Soil Mixtures for Use as Backfill Behind MSE Walls. Master's Thesis, Department of Civil Engineering, Florida Institute of Technology, Melbourne, FL, USA, 2005.
25. Gomez, F.A. Strength and Drainage Characteristics of RAP-Soil Mixtures in Highway Applications. Master's Thesis, Civil Engineering, Florida Institute of Technology, Melbourne, FL, USA, 2003.
26. Rathje, E.M.; Rauch, A.F.; Trejo, D.; Folliard, K.J.; Trejo, D.; Ogalla, M.; Viyanant, C.; Esfellar, M.; Jain, A. *Recycled Asphalt Pavement and Crushed Concrete Backfill: Results from Initial Durability and Geotechnical Tests*; Texas Department of Transportation Research and Technology: Austin, TX, USA, 2002.
27. Rathje, E.M.; Rauch, A.F.; Trejo, D.; Folliard, K.J.; Viyanant, C.; Esfellar, M.; Jain, A.; Ogalla, M. *Evaluation of Crushed Concrete and Recycled Asphalt Pavement as Backfill for Mechanically Stabilized Earth Walls*; Texas Department of Transportation Research and Technology: Austin, TX, USA, 2006.
28. Viyanant, C. Potential Use of Recycled Asphalt Pavement and Crushed Concrete as Backfill for Mechanically Stabilized Earth Walls. Ph.D. Thesis, University of Texas at Austin, Austin, TX, USA, 2006.
29. Viyanant, C.; Rathje, E.M.; Rauch, A.F. Creep of compacted recycled asphalt pavement. *Can. Geotech. J.* **2007**, *44*, 687–697. [CrossRef]
30. Bennert, T.; Maher, A. *The Development of a Performance Specification for Granular Base and Subbase Material*; New Jersey Department of Transportation: Ewing Township, NJ, USA, 2005.
31. Cooley, D.A. Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. Master's Thesis, Department of Civil Engineering, Brigham Young University, Provo, UT, USA, 2005.
32. Arulrajah, A.; Piratheepan, J.; Disfani, M.M.; Bo, M.W. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *J. Mater. Civ. Eng.* **2013**, *25*, 1077–1088. [CrossRef]
33. Titi, H.H.; Tabatabai, H.; Ramirez, J.; Sooman, M. *Evaluation of Recycled Base Aggregates*; Wisconsin Department of Transportation: Madison, WI, USA, 2019.
34. Mousa, E.; El-Badawy, S.; Azam, A. Evaluation of reclaimed asphalt pavement as base/subbase material in Egypt. *Transp. Geotech.* **2021**, *26*, 100414. [CrossRef]
35. Abedalqader, A.; Shatarat, N.; Ashteyat, A.; Katkhuda, H. Influence of temperature on mechanical properties of recycled asphalt pavement aggregate and recycled coarse aggregate concrete. *Constr. Build. Mater.* **2021**, *269*, 121285. [CrossRef]
36. Rahardjo, H.; Satyanaga, A.; Leong, E.; Wang, J. Unsaturated properties of recycled concrete aggregate and reclaimed asphalt pavement. *Eng. Geol.* **2013**, *161*, 44–54. [CrossRef]
37. Shedivy, R.; Meier, A.; Ma, J.; Tinjum, J.M.; Edil, T.B.; Benson, C.H.; Chen, J.; Bradshaw, S. *Leaching Characteristics of Recycled Asphalt Pavement Used as Unbound Road Base*; University of Wisconsin System Solid Waste Research Program: Madison, WI, USA, 2012.
38. Locander, R. *Analysis of Using Reclaimed Asphalt Pavement (RAP) as a Base Course Material*; Colorado Department of Transportation-Research: Denver, CO, USA, 2009.

39. Kang, D.H.; Gupta, S.; Ranaivoson, A.; Roberson, R.; Siekmeier, J. Recycled materials as substitutes for virgin aggregates in road construction: II. Inorganic contaminant leaching. *Soil Soc. Am. J.* **2011**, *75*, 1276–1284. [CrossRef]
40. Herrera Environmental Consultants, Inc. *Contaminant Leaching from Recycled Asphalt Pavement*; Thurston County Community Planning and Economic Development: Olympia, WA, USA, 2019.
41. Brantley, A.S.; Townsend, T. Leaching of pollutants from reclaimed asphalt pavement. *Environ. Eng. Sci.* **1999**, *16*, 105–116. [CrossRef]
42. Bejarano, M. *Evaluation of Recycled Asphalt Concrete Materials as Aggregate Base*; California Department of Transportation: Sacramento, CA, USA, 2001.
43. Ma, T.; Wang, H.; Zhao, Y.; Huang, X. Laboratory investigation on residual strength of reclaimed asphalt mixture for cold mix recycling. *Int. J. Pavement Res. Technol.* **2015**, *8*, 17–22.
44. Thakur, J.K.; Han, J.; Parsons, R.L. Creep behavior of geocell-reinforced recycled asphalt pavement bases. *J. Mater. Civ. Eng.* **2013**, *25*, 10. [CrossRef]
45. Bleakley, A.M.; Cosentino, P.J. Improving the properties of reclaimed asphalt pavement for roadway base applications through blending and chemical stabilization. *Transp. Res. Board* **2012**, *2335*, 20–28. [CrossRef]
46. Yousefi, A.; Behnood, A.; Nowruzi, A.; Haghshenas, H. Performance evaluation of asphalt mixtures containing warm mix asphalt (WMA) additives and reclaimed asphalt pavement (RAP). *Constr. Build. Mater.* **2021**, *268*, 121200. [CrossRef]
47. Legret, M.; Odie, L.; Demare, D.; Jullien, A. Leaching of heavy metals and polycyclic aromatic hydrocarbons from reclaimed asphalt pavement. *Water Res.* **2005**, *39*, 3675–3685. [CrossRef]
48. Birgisdottir, H.; Gamst, J.; Christensen, T. Leaching of PAHs from hot mix asphalt pavements. *Environ. Eng. Sci.* **2007**, *24*, 1409–1422. [CrossRef]
49. Norin, M.; Strömvall, A.-M. Leaching of organic contaminants from storage of reclaimed asphalt pavement. *Environ. Technol.* **2004**, *25*, 323–340. [CrossRef] [PubMed]
50. Yang, Q.; Yin, H.; He, X.; Chen, F.; Ali, A.; Mehta, Y.; Yan, B. Environmental impacts of reclaimed asphalt pavement on leaching of metals into groundwater. *Transp. Res. Part D Transp. Environ.* **2020**, *85*, 102415. [CrossRef]
51. Hajj, E.Y.; Sebaaly, P.E.; West, R.; Morian, N.; Luis Loria, L. Recommendations for the characterization of RAP aggregate properties using traditional testing and mixture volumetrics. *Road Mater. Pavement Des.* **2012**, *13*, 209–233. [CrossRef]
52. Solaimanian, M.; Milander, S.; Boz, I.; Stoffels, S. *Development of Guidelines for Usage of High Percent RAP in Warm-Mix Asphalt Pavements*; Pennsylvania Department of Transportation: Harrisburg, PA, USA, 2011.
53. McGarrah, E.J. *Evaluation of Current Practices of Reclaimed Asphalt Pavement/Virgin Aggregate as Base Course Material*; Washington State Department of Transportation: Seattle, WA, USA, 2007.
54. Casagrande, A.; Fadum, R.E. *Notes on Soil Testing for Engineering Purposes*; Harvard Soil Mechanics, Series No. 8; Harvard University: Cambridge MA, USA, 1940.
55. Mehta, Y.M.; Ayman, A.; Yan, B.; McElroy, A.; Huiming, Y. *Environmental Impacts of Reclaimed Asphalt Pavement (RAP)*; New Jersey Department of Transportation: Trenton, NJ, USA, 2017.
56. Singh, A.; Mitchell, J.K. General stress-strain-time function for soils. *J. Soil Mech. Found. Div. Proc. ASCE* **1968**, *94*, 21–46. [CrossRef]