

LITERATURE REVIEW

CONTAMINANT LEACHING FROM RECYCLED ASPHALT PAVEMENT

Prepared for
Thurston County
Community Planning & Economic Development

Prepared by
Herrera Environmental Consultants, Inc.



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Prepared for
Community Planning and Economic Development
2000 Lakeridge Drive Southwest
Olympia, Washington 98502

Prepared by
Herrera Environmental Consultants, Inc.
1220 Fourth Avenue Northeast
Olympia, Washington 98506
Telephone: 360-754-1344

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CONTENTS

Executive Summary	iii
Introduction.....	1
Methods.....	2
Summary of Selected Literature	4
Hydraulic and Environmental Behavior of Recycled Asphalt Pavement in Highway Shoulder Applications (Aydilek et al. 2017)	4
Leaching of Heavy Metals and Polycyclic Aromatic Hydrocarbons from Reclaimed Asphalt Pavement (Legret et al. 2005)	6
Environmental Impacts of Reclaimed Asphalt Pavement (RAP) (Mehta et al. 2017).....	8
Leaching of PAHs from Hot Mix Asphalt Pavements (Birgisdottir et al. 2007).....	10
Leaching of Organic Contaminants from Storage of Reclaimed Asphalt Pavement (Norin and Strömvall 2004)	12
Recycled Materials as Substitutes for Virgin Aggregates in Road Construction: II. Inorganic Contaminant Leaching (Kang et al. 2011).....	14
Environmental Characteristics of Traditional Construction and Maintenance Materials: Final Report (Morse et al. 2001).....	15
Leaching of Pollutants from Reclaimed Asphalt Pavement (Brantley and Townsend 1999)	15
Comparison of Studies to Expected Conditions in Nisqually.....	17
Comparison of Study Results to Standards	18
Summary and Conclusions.....	20
References.....	33

APPENDICES

- Appendix A Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement
- Appendix B Copies of Selected Literature

TABLES

Table 1. Summary of Batch Test Results from the Eight Research Studies Reviewed.23

Table 2. Summary of Column Test Results from the Eight Research Studies Reviewed.....27

Table 3. Water Quality Standards Comparison.....31

EXECUTIVE SUMMARY

Recycled asphalt pavement (RAP) is typically asphalt that has been removed from roadways or parking lots during repair and replacement of the roadway surface. It is then reused extensively in the creation of new roadway surfaces. Concerns over possible leaching of pollutants from RAP stem from the original composition of the asphalt as well as from the pollutants added during its use, for example, when the RAP has been taken from roadways where it has been exposed to vehicle traffic and the metals and petroleum products that are associated with that use.

Between the time when RAP is removed and when it is reused, it must be stockpiled. When stockpiled, precipitation falling onto the stockpile can result in contaminants leaching from the RAP. These contaminants can then be transported to nearby surface waters or infiltrated to groundwater. The purpose of this study was to review available research on leaching of pollutants from RAP. The study was purposely constrained to a review of research on direct measurements of leachate from RAP; no research that evaluated application of Best Management Practices (BMPs) to reduce contaminant loading or that assessed fate and transport of contaminants once the leachate reaches the environment were considered in this literature review.

After an assessment of over 100 articles initially identified, eight highly rated studies were selected for this literature review. They were selected because they were directly applicable to the objectives of this study, and the research was of high quality in terms of the number of tests, quality assurance, and in the detail provided for this review.

Key conclusions of the literature review are:

- As a source of contaminants, RAP is highly variable. Factors contributing to variability in leachate from RAP appear to include how the asphalt was originally manufactured (e.g., the sources of crude oil and aggregate or whether coal tar or bitumen was used), how the RAP was used, the duration and degree to which it has weathered and been exposed to traffic or other pollution generating sources, and how long it is stored.
- Laboratory testing indicated that there were typically some contaminants leached from RAP at concentrations that exceeded state groundwater quality standards. There were five polycyclic aromatic hydrocarbons (PAHs) that were measured above state groundwater quality standards with some frequency (i.e., in 50 percent or more of the studies where detection limits were adequate). Some metals were also leached, primarily in tests run under low pH environments.
- Testing indicated that there is a distinct, initial flush of contaminants from RAP that can result in concentrations exceeding Washington State groundwater quality standards, but that these peak concentrations decrease quickly to below detection limits as more water is flushed through the RAP.

INTRODUCTION

Recycled asphalt pavement (RAP) is typically asphalt that has been removed from roadways or parking lots during repair and replacement of the roadway surface. It is then re-used extensively in the creation of new roadway surfaces. Concerns over possible leaching of pollutants from RAP stem from the original composition of the asphalt as well as the pollutants added by vehicle traffic. Asphalt can be composed of bitumen, coal tar, mineral aggregate, and fillers such as adhesives and polymers. Bitumen and coal tar are derived from crude oil and contain metals and polycyclic aromatic hydrocarbons (PAHs). The composition of the crude oil is also highly variable in terms of these pollutants, which is why some of the studies summarized in this report have compared different sources of RAP. Mineral aggregate can be a natural source of heavy metals in RAP, and vehicle traffic contributes metals and PAHs from wear and tear of vehicle parts and from gasoline and lubricants.

Between the time when RAP is removed and when it is reused, it must be stockpiled. When stockpiled, precipitation falling onto the stockpile can result in contaminants leaching from the RAP. These contaminants can then be transported to nearby surface waters or infiltrated to groundwater. The latter is especially a concern in areas where the groundwater is more vulnerable to contamination due to fast-draining soils and where it is used as a drinking water supply, such as in the Nisqually area of Thurston County. Because of concerns about RAP leaching contaminants while it is stockpiled, the Nisqually Sub-Area plan of the Thurston County Comprehensive Plan specifically prohibits the use of mined-out gravel pits for the reprocessing of asphalt due to water quality concerns.

The purpose of this study by Herrera Environmental Consultants, Inc. (Herrera) was to review available research on leaching of pollutants from RAP. The study scope was specifically constrained to summarizing research on direct leaching of pollutants. For example, it does not account for use of best management practices (BMPs) such as covering the material to reduce the amount of precipitation that comes into contact with the RAP, thereby limiting leachate formation. It also does not address fate and transport as leached materials move over or through ground and water. Such practices and processes could be evaluated in a subsequent phase of study, if warranted.

Most of the laboratory studies reviewed can be grouped into two different methods of simulating pollutant leaching: batch-leaching tests (referred to herein as batch tests) and water column leaching tests (referred to herein as column tests).

Batch tests are those in which prepared samples of RAP are placed in containers with water, which is sometimes acidified, and allowed to soak for a fairly short period, usually on the order of hours or days. The samples are typically agitated during the soaking period to maximize surface area contact. The samples are filtered, and the filtrate is tested for pollutants. The objective of a batch test is to evaluate the short-term leaching potential of water-soluble contaminants. Batch tests are small-scale tests used to provide quick estimates of maximum

potential leaching behavior; the low water volume, high contact time, and agitation do not simulate the conditions likely to exist in the field, where water continually flows through the material. There are many variations in how batch tests are performed, such as how the samples are prepared, size of the test containers, the ratio of liquids to solids (L:S ratio), the duration of the test, and the character and pH of the water used as the extractant. The extractant in the studies reviewed varied from neutralized deionized water, to slightly acidified water, to more strongly acidified solutions. The more acidic the solution, the more aggressive the leaching of most contaminants. In the United States (US), there are two standard protocols that are typically followed for performing these tests: the Toxicity Characteristic Leaching Procedure (TCLP) and the Synthetic Precipitation Leaching Procedure (SPLP). The TCLP test was designed to simulate conditions that might be experienced by materials exposed for many years to the acidic environment of a landfill. The SPLP is used to better simulate conditions in a more natural environment but under acid rainfall conditions. Even the studies done in Europe often use these protocols from the US Environmental Protection Agency (US EPA).

Column tests involve placing compacted samples into a column and delivering water to the column at a specified flow rate for a specific period of time, typically a number of weeks. For column tests, water samples are collected from the columns at multiple times during the test to allow assessment of changes in contaminant leaching over time. In addition to the type, quantity, and source of RAP used, the rate that the water is delivered to the column, the total amount of water sent through the column (which affects the L:S ratio), and the sampling intervals are important variables in column tests. As with the batch tests, the pH of the water used for the test is also critical. There are no standard protocols for conducting column tests.

As described below, the literature review began with identification of 101 information sources to consider. Through initial sorting and reviewing, eight studies were identified that were of high quality in terms of how the research was performed and for which the research was most applicable to the objective of this report. This report includes a brief synopsis of the findings of each of the eight studies.

METHODS

During the first phase of this project, a list of preliminarily identified studies was created. At project onset, Thurston County provided a list of 88 information sources that were identified by project stakeholders over the years and submitted to Thurston County. As a first step in development of this literature review, a reference library search was completed to identify additional information sources; this resulted in the addition of 13 references to the database, for a total of 101 information sources. Then, studies dated before 1995 were eliminated to remove sources with outdated analytical techniques. The remaining sources were sorted with the objective of including only those that serve as primary data sources; studies that did not contain data or that summarized data collected by others were excluded. As a result, 33 of the 101 information sources were retained for further evaluation.

During the second phase of the project, a closer examination of the study methods and objectives used in each of the 33 studies was completed; and each of the studies was rated as low, medium, or high in terms of its appropriateness for inclusion in this report. There were initially 5 studies rated as high, and they were the only studies included in an early (October 2018) draft of this literature review. The studies rated as low were not considered further. In most cases, those rated as low did not appear to specifically address RAP, although some were given low ratings because they did not provide data or because the author(s) had completed a more recent study that superseded the preceding one. In general, the studies rated as moderate were either: 1) older and had higher detection limits than those currently in use, 2) done by undergraduate students and did not have rigorous review, or 3) did not specifically address the objective of this study. However, the results and conclusions of the moderate-rated studies were reviewed to evaluate whether they used a testing approach or contained unusual findings that should be considered. None of the studies rated as moderate had findings notably different than the highly rated studies.

One concern identified during review of the early (October 2018) draft of the document was that too many of the highly rated studies were done outside the U.S. where coal tar has been used in the processing of asphalt for many years beyond when it stopped being used in the U.S. Because coal tar has many times more PAHs than the bitumen used in the U.S., it could be expected that the character of the RAP and leachate would be different. A second search of the literature and review of reference sections of the other reports was done in an effort to identify additional U.S.-based research. As a result, two additional highly rated studies were identified and included in this evaluation. A third study, which had been included in the list of 33 studies but removed from consideration due to its age, was also added to the list of literature to be reviewed because it was done in the U.S. and was considered one of the preeminent studies of RAP. This resulted in a total of 35 studies. Appendix A contains a list of the 35 studies that were considered in this second phase and provides the rating rationale for each.

In the end, eight studies were highly rated because they were directly applicable to the objectives of this study and the research was of high quality in terms of the number of tests, quality assurance, and detail provided for the analysis. Each of these studies is described individually below.

Tables 1 and 2 (following the *Summary and Conclusions* section of this report) provide a comparison of key data provided in the eight studies. The intent of these tables was not to list all of the data but to focus on those data of most interest and frequently reported. For the Total Metals category, all 13 US EPA priority pollutant metals have been included plus a few others that were commonly measured in the different studies. No elements were left out if they were commonly detected or if they were detected in any study at a problem concentration. The data for Polycyclic Aromatic Hydrocarbons (PAHs) is limited to the US EPA's list of 16 priority pollutant PAHs. With the exception of one study that assessed 29 PAHs, the remaining seven studies evaluated the list of 16 or a subset of these.

Tables 1 and 2 provide a comparison of study results to Washington State Groundwater Quality Standards (Washington Administrative Code [WAC] Chapter 173-200-040). These standards are

the most applicable because Thurston County refers to them for groundwater monitoring under its mineral extraction and asphalt production code (Thurston County Code 17.20.210) and because the literature reviewed relies on direct measurements in discharge. State drinking water standards would have been applied if the measurements had been made in the groundwater. Table 3 provides a comparison of the state groundwater quality standards to the Washington State Drinking Water Standards for Group A Public Water Supplies (WAC 246-290-310). These are standards that would apply under the Sanitary Code for Thurston County-Article III and are applicable to assessments of domestic water supply. The drinking water standards are provided for comparison purposes only.

SUMMARY OF SELECTED LITERATURE

In the research reports summarized below, the authors used a variety of standards for comparison, including European Community (EU) drinking water standards, Danish groundwater standards, US EPA standards, and state-specific standards, because the studies were done in different countries and states. In the summary of each report, provided below, the authors' conclusions related to the standards they used are included. For the purposes of this review, the groundwater quality standards in Washington State are the standards that are of most interest and that would be applied in Nisqually. Therefore, in the *Comparisons of Study Results to Standards* section of this report the data from all of the studies is compared to Washington State groundwater quality standards. In that section, the authors' conclusions related to the standards they applied are summarized again so that all of those conclusions related to standards exceedances are in one place.

Hydraulic and Environmental Behavior of Recycled Asphalt Pavement in Highway Shoulder Applications (Aydilek et al. 2017)

This was an extensive study done by researchers at the University of Maryland for the Maryland Department of Transportation. The objective of the testing was to evaluate RAP from seven different sources in Maryland to reflect differences in original source materials (e.g., crude oil and aggregate) and roadway use characteristics. The study included three different phases: hydraulic behavior, environmental behavior, and pH relationships with leaching. The information gained from the testing was used to develop models to predict fate and transport of contaminants in surface water and through the ground.

For the purposes of this review, the second phase of the testing that examined environmental behavior was most applicable. For those studies, the seven RAP samples, as well as three or four control samples consisting of either aggregate base, stone, or topsoils, were tested. The tests included batch and column tests.

Batch Tests

Batch tests, which used deionized water with a low amount of salt as the extractant (likely close to neutral pH), were done in triplicate. A total of 15 elements were analyzed, including most of the heavy metals. Aluminum (Al), arsenic (As), barium (Ba), copper (Cu), iron (Fe), sodium (Na), and zinc (Zn) were measured at detectable concentrations in one or more of the seven RAP samples; the rest of the elements tested were below the detection limits for all samples. Of those elements detected, Al, Ba, and Cu were detected at levels that exceeded either a US EPA or Maryland State standard. Copper was detected in four of the seven samples, with two results slightly exceeding the US EPA Water Quality Limits (US EPA WQLs), and all results exceeded Maryland's Aquatic Toxicity Limits (ATLs) for fresh water. Aluminum was detected in five of the seven RAP samples; all five results were well below the US EPA WQLs but well above Maryland's ATLs. Barium was detected in three of the seven samples, with all three results above Maryland's ATLs; there is no US EPA WQL for barium. The authors do not specifically discuss the arsenic results; however, all three of the RAP samples where arsenic was measured at detectable concentrations exceeded Maryland's ATL. The detection limit for the remaining four samples exceeded the Maryland's ATL standard; therefore, it is unknown how they compare to them. Similarly, lead (Pb), Chromium (Cr), Cobalt (Co), Nickel (Ni) and Vanadium (V) were below detection in all samples, but again the detection limit was higher than Maryland's ATL for these elements; however, they were all below US EPA WQLs.

Column Tests

The same seven RAP samples used in the batch tests, were tested in flow-through column tests. The column tests involved pumping a constant flow of water (pH 6.0 to 6.5) through the columns and collecting samples at regular intervals that represented different pore volume exchanges. Approximately 15 to 20 samples were collected from each column, representing pore volume exchanges from approximately 1 to 250. In the column tests, peak concentrations exceeded Maryland's ATL standards for:

- Aluminum (Al) (in three of the seven RAP samples)
- Boron (B) (in all seven samples)
- Barium (Ba) (in all seven samples)
- Cobalt (Co) (in one of seven samples)
- Copper (Cu) (in four of seven samples)
- Manganese (Mn) (in six of seven samples)
- Nickel (Ni) (in four of seven samples)
- Zinc (Zn) (in one of the seven)

The peak concentrations for Zn and Cu exceeded the US EPA WQLs (each in one of the seven RAP samples) but decreased to below the US EPA WQLs very quickly. All As, Pb, Cr, and V concentrations were below the detection limit, but the limit was higher than the ATL; thus, it is unknown how the concentrations compare to Maryland's ATL standard. However, the detection limits are well below the US EPA WQL; thus, those standards were met. Almost all of the analytes tested exhibited a strong first-flush characteristic; that is, peak concentrations occurred early in the testing and then concentrations dropped precipitously. With the exception of one RAP sample, which had very high (relative to the other RAP samples) aluminum (Al) concentration to begin with, Al did not exhibit a first-flush characteristic. Instead, Al concentrations began to increase late in the experiment and coincident with a pH increase. This result fits with what is understood about the solubility of Al within the neutral range of pH.

As stated by the study authors, if any kind of a weighted average were to be applied to the results, the concentrations for all constituents would be well below the most stringent standards. The authors concluded that RAP from sources in Maryland does not release excessive amounts of toxic elements, as determined through either the batch or column tests.

Leaching of Heavy Metals and Polycyclic Aromatic Hydrocarbons from Reclaimed Asphalt Pavement (Legret et al. 2005)

This study was completed by researchers in France and funded by the French Public Works Ministry. The objective was to evaluate potential environmental concerns associated with leaching of contaminants from RAP. In this study, RAP samples were collected during a repaving project on a heavily used highway. Batch and column tests were done on composite samples collected from a stockpile of the RAP. Testing was also performed on core samples taken from the roadway. All leachate samples were analyzed for heavy metals, total hydrocarbons, and PAHs. The study authors compared results to European Community (EC) drinking water standards, Dutch target (intervention) levels for groundwater, and US EPA standards. The research included batch tests and column tests, as well as column tests completed with core samples.

Batch Tests

Batch tests were performed on four composite samples collected from a stockpile of RAP. A series of three extractions, done in a succession of 16-hour periods, were run on three RAP samples. Deionized water was used as the extractant. Of the eight metals analyzed, only Zn and mercury (Hg) were measured at levels above detection limits. Zinc was detected during only the first of the three extractions in the 16-hour series test, but the concentration was below US EPA standards. Mercury was detected during all three extractions but always at or near the detection limit. Metals detected were all well below the maximum contaminant level (MCL). Total hydrocarbons were detected slightly above the Dutch intervention level for groundwater during the initial extraction but below the detection limit for the remaining extractions. Of the 16 PAHs

analyzed, all were near or below the detection limit except phenanthrene, which was measured at or just above the detection limit but well below the Dutch intervention level.

The last composite sample was tested over one, 24-hour extraction period in parallel with a sample of new asphalt (as opposed to RAP). Heavy metals were below detection in both the RAP and the new asphalt. Total hydrocarbons were higher in the RAP sample. Of the six PAHs tested, only benzo(a)pyrene and fluoranthene were measured above detection limits in the RAP leachate; neither were above Dutch groundwater intervention levels. None of the six PAHs were detected in the new asphalt sample.

The researchers also ran a two-stage batch test that included a first stage at neutral pH (7) and a second stage at low pH (4). No data tables were provided for this test, but the researchers noted that Zn, Ni, chromium (Cr), and cadmium (Cd) were released at the lower pH, while Cu and lead (Pb) were not. All the elements tested were below the EC limits for drinking water.

Column Tests

Column tests were performed on two of the composite RAP samples. One unique aspect of these column tests was that the bottom of each sample was submerged at all times to simulate saturated conditions that might occur in some roadway configurations. The column tests were conducted by adding 1.5 liters of water to the columns every day for 75 days. Samples were collected five times during that period (on Days 2, 10, 25, 50, and 75) to represent increasing volumes of water passing through the columns and corresponding to an L:S ratio ranging from 0.5 to 30.

Similar to other studies, there was a definite first-flush effect for some analytes. Only five heavy metals were tested: Cu, Pb, Zn, molybdenum (Mo), and Hg. Copper and Zn were detectable in the initial test samples (Day 2) but at low concentrations, and Zn was detected again at even lower concentrations on Day 10. Lead and Mo were below detection for all samples. Mercury was not detected until Days 50 and 75 and was detected at concentrations just above the detection limit. The total hydrocarbon concentration was above the EC drinking water standards but well below the Dutch groundwater intervention level until Day 10; it was not detected after that. Of the 16 PAHs tested, 10 were below detection in all samples. The remaining six PAHs showed classic, first-flush characteristics, with detectable concentrations during the Day 2 test and in a few cases during the Day 10 test, but concentrations were generally below detection after Day 10. Only benzo(a)pyrene slightly exceeded the EC drinking water standard during the first two tests (Day 2 and Day 10). All PAHs were below detection by Day 20.

Core Samples

This study also included collection of four core samples: two from a pavement with 10 percent RAP and two from a pavement with 20 percent RAP. The four core samples were placed in columns and, after saturating them under pressure, 4 liters of deionized water was passed through them and analyzed. Six heavy metals were tested. However, since the authors noted

that the metal analyses may have been confounded by some of the equipment that was used, no summary of those results is provided herein. As with the column tests, the concentration of total hydrocarbons was significantly high as compared to the Dutch target value for groundwater. Among the six PAHs analyzed, one (fluoranthene) was at a detectable level, and its concentration was just above the detection limit.

The authors concluded that pollutant leaching is rather weak for most of the studied parameters. Concentrations in the solutions derived from batch tests generally remained below EC limits for drinking water. Column experiments showed higher concentrations in the initial leaching stages that rapidly decreased to values below detection limits. The authors recommended that the laboratory experiments be followed by field experiments to evaluate real-world hydrologic conditions and scaling.

Environmental Impacts of Reclaimed Asphalt Pavement (RAP) (Mehta et al. 2017)

This study was funded by the New Jersey Department of Transportation and performed by researchers from the State University of New York and Columbia University. The objective of the study was to investigate levels of 32 elements and PAHs in leachate from RAP (using batch and column tests), as well as to evaluate how weathering might affect leachate characteristics. The study also included toxicity testing. Three RAP sources from different areas in New Jersey were used in the study, as well as a "fresh" hot mix asphalt sample (which had not been used in roadways) as a control.

Batch Tests

Batch extraction experiments, using acidified water (pH 4.93) as the extraction fluid, were performed on all samples (from all three RAP sources and the fresh asphalt, each in four different weathered forms) and were analyzed for 32 major and trace elements, including most of the heavy metals. The purpose of using a low pH extractant was to simulate a very aggressive leaching environment, such as would occur in a landfill. The study authors summarized that, overall, no elements except Pb exceeded US EPA drinking water MCLs. Lead was close to or higher than the MCL for a number of the weathered samples, but all of them came from the same RAP source (i.e., "NORTHRAP"). The elevated Pb was attributed to historical use of lead in gas and white road paint. The control sample had significantly lower concentrations of most elements, indicating that the source of the contaminants was related to road exposure. Weathering of the control samples did not affect these findings, indicating that aging and oxidation of the RAP did not lead to contamination.

The PAH testing included evaluating the acidified water-soluble fraction as well as the total organic extractable fraction of 29 PAH compounds. The total organic extractable fraction used a strong solvent (dichloromethane) as the extractant. The acidified water-soluble fraction represents the portion that would be released into solution under more aggressive leaching

conditions (e.g., in landfills) than would be expected with natural rainwater (i.e., rainwater with a pH of approximately 5.6), while the total organic extractable PAH represents the maximal amount of organic compounds that could be leached from the RAP under extreme conditions.

Acidified water extracted little, if any, PAHs from the samples. The water leaching process, on average, mobilized less than 1 percent of the total PAHs. Again, the one RAP source (NORTHRAP) and its weathering products showed the highest concentrations for most PAHs, while samples from the fresh asphalt and the other RAP sources often had concentrations below detection. The authors noted that benzo(a)anthracene was the only PAH detected at levels of concern. (This was based on 1995 US EPA human health advisory levels.)

For the 8 PAHs for which specific data was provided, the total extractable PAH concentrations were magnitudes higher than what was extracted with acidified water, as would be expected. The fresh asphalt source and its weathering products had the lowest concentrations for most PAHs. The NORTHRAP source and its weathering products had the highest PAH concentrations.

Column Tests

Water column experiments were performed to investigate both leaching and the attenuation effect of soil on contaminants leached. The columns had two stages—the first column contained the RAP samples and the second contained a local sandy loam soil—to test leaching as well as attenuation in the soil. The column experiments were done as a time series with samples collected eight times over a 4-day period. Synthetic rain water (pH close to 5) was used as the extractant. The RAP samples selected for testing included the sample with the consistently highest concentrations of contaminants from previous testing (NORTHRAP) in weathered and unweathered form, and the fresh asphalt, which had consistently low concentrations of contaminants in weathered and unweathered form. As with the batch experiments, samples from the column experiments were analyzed for 32 major and trace elements. No major or trace elements were found to exceed US EPA's primary drinking water MCL. The authors summarized that, compared to the strong dissolution capacity of the more acidic water used in the batch testing, the synthetic rain water used in the column experiments was less capable of eluting elements. Most of the major and trace elements exhibited higher release from the soil than from the asphalt, but in both stages (RAP and soil stage) the contaminants were leached out quickly. The elements that were released from the asphalt column were attenuated in the soil column.

Overall, PAHs in the column experiments were detected at concentrations less than the 1995 US EPA guidelines cited by the authors. Some of the PAHs appeared to be generated by the soil stage of the columns. The weathered RAPs generally generated more PAHs, but the concentrations were still below the US EPA guidelines and decreased to below detection after attenuation through the soil.

Toxicity Testing

This study also included extensive testing of toxicity using multiple test types and assay organisms. Overall, the results did not identify significant toxicity associated with the solutions emanating from fresh or weathered RAP. However, there were problems associated with the testing, including that the extracting fluid itself exhibited toxicity and that fungal growth in the soil may have affected some of the tests. The authors caution that minor toxicity could have been obscured by these problems.

The authors included the following conclusions:

- Leaching of some PAHs and Pb may occur under acidic environments such as landfills, but typical New Jersey rainfall is expected to elute negligible contaminants.
- Column testing indicated that weathered RAP can leach PAHs; however, the contaminants were attenuated in the soil and reached baseline levels.
- New Jersey soils can be a source of contamination for both metals and PAHs; thus, soil testing may be important in some usages.

Based on these findings, the authors made recommendations on use of RAP. They recommended that it could be used as an unbound material in all environments except those which are highly acidic ($\text{pH} < = 4$), such as mines or landfills. (Note: the assumption is that the authors are referring to coal- and metal-type mines and not gravel-type mines since the former can result in acidic drainage waters.) The authors listed acceptable, beneficial uses of unbound RAP in addition to use in hot mix asphalt applications as including surface materials for parking lots, farm roads, or pathways; for quarry reclamation; as non-vegetative cover underneath guidrails; and mixed with other materials for subbase or base materials.

Leaching of PAHs from Hot Mix Asphalt Pavements (Birgisdottir et al. 2007)

This study was performed by researchers at the University of Denmark. The underlying question for the research was whether the source of elevated PAHs measured in soils near paved roads originated from the asphalt. The researchers used laboratory results to inform model parameters (e.g., diffusion coefficients for PAHs) and then to evaluate scenarios of PAHs moving to the adjacent roadway soils. The research included testing of two core samples collected from different paved surfaces: a gas station in operation since 1980 and a roadway constructed in 2001. Because the cores were collected in 2002, the samples represent more than 20 years of potential contaminant accumulation for the gas station but only about 1 year of the same for the roadway. The two core samples were subdivided to include a "wear course" (the upper portion of the pavement core) and a "base course," resulting in a total of four samples. Two types of tests were run. The first used a column-based set up, but the methods and objectives

were more similar to the batch tests done by other researchers; the second was a tank leaching test, and those methods were more similar to column testing done by others.

Batch Type Test

The batch type tests (called availability tests in the paper) were done using columns, but the leachate was recirculated through the system for a 7-day period. Deionized water was used for the elutriate; the pH was not reported but presumably it would be near neutral. The total content of PAHs was found to be higher in the wear course than in the base course for both samples. This supports the findings of other studies indicating that the source of contaminants was from pavement use (e.g., contaminants from vehicles or vehicle emissions) rather than from the original asphalt material. The portion of the total PAHs that was calculated to be available through leaching was 3 percent to 11 percent. In terms of availability of individual PAHs in the wear course, they ranged from 0.5 to 75 percent available; naphthalene and phenanthrene had the highest availability at 33 to 75 percent and 4 to 36 percent, respectively.

Column Tests

The column tests in this study were done in large tanks over a 64-day leaching period. Samples were collected eight times over that period, and the water was replaced each time samples were collected. The extractant was deionized water stabilized with sodium-azide with a close to neutral pH. The sample from the wear course of the gas station exhibited the highest concentrations for all PAHs detected. Generally, in all four samples the highest concentrations were measured for naphthalene and phenanthrene. However, in the wear course sample from the gas station, 8 of the 16 PAHs were measured at detectable concentrations at some point over the 64-day leaching period.

The cumulative leaching measured during the 64-day test was used to develop diffusion coefficients for naphthalene and phenanthrene; those diffusion coefficients were applied to hypothetical scenarios for leaching from a roadway. The authors concluded that leaching of PAHs from asphalt would only slightly influence the concentration of PAHs in soil near roads.

The authors concluded that, for three of the four samples (all except the gas station wear course), the total content of PAHs in the samples were below the Danish soil quality criteria; the wear course from the gas station sample exceeded the criteria. Based on this study and the modeling, the authors also concluded that only a minor portion of the PAHs present in the asphalt is available to be leached during 25 years of leaching and it is very unlikely that leaching of PAHs from the asphalt causes roadside soils to exceed Danish soil criteria. However, the authors also noted that their conclusions were reliant upon the determination of PAH availability and that further studies should be conducted due to uncertainty in that parameter.

Leaching of Organic Contaminants from Storage of Reclaimed Asphalt Pavement (Norin and Strömvall 2004)

This study was done by researchers at Chalmers University of Technology in Sweden. The purpose of this study was to evaluate the leaching mechanism of organic contaminants including how the leaching may be impacted during temporary storage or stockpiling of the material. Of the sources reviewed, this may be the most directly applicable to this report because its purpose was to characterize runoff from outdoor stockpiles of RAP. However, it must also be noted that in Sweden coal tar was used as an additive in asphalt until 1975; and coal tar contains 10^3 to 10^5 times more PAH than the bitumen used today (Norin and Strömvall 2004). Coal tar has not been similarly used in the U.S. since World War II (Lakeside Industries. Letter to Thurston County Community Planning and Economic Development. November 6, 2018).

In addition to the testing of exposed stockpiles, column tests were carried out in laboratory settings. (Batch tests were completed during an earlier phase of the study [Larson 1998]; some of that data was provided in the report and therefore is included in Table 1; but generally, this data was not summarized in this 2004 report and therefore is not summarized in this review.)

Stockpile Testing

Two stockpiles of RAP were designed and set up specifically to allow collection of leachate samples from different places in each stockpile, such as from the center of the stockpile, where the L:S ratio was lowest, and from near the outer edges of the stockpile, where the L:S ratio was much higher. One stockpile comprised "scarified" RAP, which was asphalt collected from the top 3 centimeters (cm) of a highly used highway (called the wear course in other studies) and milled into fine gravel (average diameter of approximately 2 millimeters). The second stockpile comprised "dug" RAP, which consisted of coarse pieces (diameter of 20 to 50 cm) collected to a depth of 10 cm from the same highway; it includes material from both the wear and base courses. The stockpiles were uncovered and, therefore, exposed to precipitation. Precipitation in the west coast of Sweden, where the study occurred, has an approximate pH of 4.5 and a chloride content of 4 to 20 milligrams per liter. The authors describe it as representing "a relatively aggressive leaching environment."

Rainfall leachate samples from the two stockpiles were collected monthly for a year and were analyzed for total organic carbon (TOC), which was used as a surrogate measure for all organic contaminants; PAHs; and semi-volatile organics.

Thirty semi-volatile organic compounds (which includes PAHs) were identified in the stockpile samples. The number of semi-volatile compounds identified, and their concentrations were highest in leachate collected from the inner portions of both stockpiles. Leachate from the inner part of the piles had the longest vertical transport time and drained through the thickest part of the stockpiles, providing a lower L:S ratio and more contact between the percolating water and the RAP. Leachate from the stockpile of scarified RAP exhibited higher concentrations of semi-volatile organics than leachate from the stockpile of dug RAP. The authors attributed the

differences between scarified and dug RAP to the scarified RAP's greater exposure to pollutants contributed from the roadway (because the scarified RAP was sourced from wear course only; the dug RAP came from the wear and base courses) and the higher contact area of the more-finely-ground scarified material.

Six of the 30 compounds identified occurred with the most frequency; they were naphthalene, butylated hydroxytoluene (BHT), dibutylphthalate (DBP), N-butyl-benzenesulfonamide, dibenzylhydrozylamine, and di(2-ethylhexyl)phthalate (DEHP). The concentration of total PAHs in leachate from both stockpiles (scarified and dug RAPs) exceeded the threshold set by Sweden for groundwater in polluted soils at gas stations.

Column Test

A column test was done using the same scarified asphalt source to compare "unstored" (i.e., removed from the roadway and immediately tested) RAP to "stored" RAP, which had been stockpiled for 2 years. Acidified water (pH 4) was continuously pumped through the columns. Samples were collected early in the test, representing an L:S ratio of 0.05, and at the end of the test, representing an L:S ratio of 1.0.

The highest concentrations and amounts of TOC were measured in the unstored sample at the highest L:S ratio. The amount of TOC released by the stored samples decreased by more than 50 percent, although TOC concentrations remained high. The concentration of total PAHs followed the same leaching trend as TOC. However, as the authors noted, total PAHs accounted for only 0.005 percent of the TOC, indicating that nearly all the organic compounds leached were from unidentified organic compounds of unknown origin. Where PAHs were detected, the unstored RAP sample had higher concentrations, compared to the stored RAP sample. Comparison of the total PAHs leached in the column tests with the total available for leaching (based on a batch test previously performed by Larsson [1998] with an L:S ratio of 100), indicated that less than <0.4 percent of the total available PAH amount leached during the column tests. Naphthalene was by far the dominant PAH released, representing 85 percent of the total PAH released. Naphthalene and other lower-weight, more volatile PAHs decreased considerably over the 2 years of storage, while PAHs with higher molecular weights increased.

For semi-volatile organics, the trend was opposite that of TOC and PAHs; the stored sample had higher concentrations than the unstored sample, but the concentration difference was not great.

Comparison of Stockpile and Column Test Results

Norin and Strömvall (2004) compared results of the stockpile and column tests. The number and concentration of semi-volatile organic compounds was much lower in leachate samples collected in the column test than were measured in the stockpiles. The total cumulative loading of semi-volatile organics leached from the columns was approximately only 25 percent of what was calculated from the inner section of the scarified RAP stockpile. Further, the leaching in the columns continued for a few days while in the stockpiles it continued for a year. Due to these

differences, the authors cautioned that it is crucial to do further studies and measurements of field leachates because column test results for PAHs and other semi-volatile organics are typically under or near detection limits (as demonstrated by many of the other studies reviewed herein).

The authors attributed the differences in test results to the disparities between the L:S ratios, especially the low ratios for leachate collected from the center (i.e., the deepest part) of the stockpile, and to the cumulative effect of contaminants leaching over a longer period of time in the stockpile test versus the column test. Consequently, the study authors considered the leachate test results from the column tests to be less reliable than those from the stockpile tests.

The authors concluded that their findings “clearly show that the release of organic pollutants from asphalt storage could cause environmental problems.” The cumulative amounts of organic contaminants (as total PAHs) were high in leachates from both fresh and stored RAP in the stockpile study and exceeded the Swedish recommended values for groundwater in polluted soils at gas stations. The dominant contaminants identified were naphthalene, BHT, and DBP. The authors note that these contaminants occur in urban groundwater, and their high emission rates and persistent structures make them potentially hazardous.

Recycled Materials as Substitutes for Virgin Aggregates in Road Construction: II. Inorganic Contaminant Leaching (Kang et al. 2011)

This study was done by researchers at the University of Minnesota in cooperation with the Minnesota Pollution Control Agency and Minnesota Department of Transportation. It is one part of a larger study to evaluate the suitability of fly ash, RAP, recycled cement material, and foundry sand mixed with virgin aggregates as base and subbase materials in roadways. Part I of the study was focused on hydraulic and mechanical characteristics of the materials and mixtures; Part II evaluated contaminant leaching. The study included both batch and column style testing; however, most of the testing was on mixtures of materials and therefore not strictly representative of RAP. A few of the batch tests included evaluation of 100 percent RAP and those results are summarized in Table 1. Some findings from the column studies are described as they related to evidence of leaching patterns, but no column testing data is included in Table 2 because there were no column studies with 100 percent RAP.

Batch Tests

Batch tests were completed with 100 percent RAP using Mili-q® (ultra-pure) water as the elutriate at an L:S ratio of 20. The pH of Mili-q water is reported as 6.998. The researchers were more focused on fly ash than the other components, and therefore they did not formulate many conclusions related to RAP. However, relevant results for metals for 100 percent RAP are summarized in Table 1. Arsenic was detected at a concentration at the MCL, but no other measured metals had high concentrations. Except for sodium, which was only moderately

elevated, the 100 percent RAP sample had lower concentrations of all inorganic elements detected than 100 percent fly ash and 100 percent aggregate materials.

Column Test

Column tests were performed on six mixtures of three different materials (i.e., fly ash, RAP, and aggregate). No column tests were performed on 100 percent RAP, but the mixtures contained 25 percent to 75 percent RAP. Initial leaching of some contaminants did occur; those mixtures with the highest portion of fly ash (i.e., 15 percent) exhibited the most significant initial leaching. This was attributed in part to the higher water residence time (contact time) of those columns that contained high fly ash. The authors' conclusions were primarily focused on use of fly ash and were not relevant to this review. No column test results are included in Table 2 because there were no column tests on 100 percent RAP.

Environmental Characteristics of Traditional Construction and Maintenance Materials: Final Report (Morse et al. 2001)

This Texas Tech University study was done for the Texas Department of Transportation. The purpose of the study was to determine the concentration of contaminants that would be released into the environment from traditional construction and maintenance materials. RAP was one of eight materials tested. The testing was limited to batch type tests that used the SPLP method to evaluate the mobility of contaminants.

Batch Tests

RAP samples from three different districts in Texas were tested. The experiments used deionized water (pH 5) as the extractant and were mixed by rotating for an 18-hour period at an L:S ratio of 20. Samples were analyzed for 19 major and trace elements, including most of the heavy metals. Organic compounds were also tested in this study, but not on RAP samples. In this study analyte concentrations were compared to the Texas Risk Reduction Standard 2 (RRS2) to evaluate whether the leachate concentrations exceed the values specified by TxDOT. RAP samples exceeded RRS2 regulatory concentrations for at least one of the three samples for antimony, barium, and lead. The average concentration exceeded RRS2 concentrations for barium and lead. Table 1 provides a comparison of their results with groundwater standards applicable in Washington, which were exceeded in one or more samples for antimony, lead, and manganese.

Leaching of Pollutants from Reclaimed Asphalt Pavement (Brantley and Townsend 1999)

This University of Florida study was done for the Florida Center for Solid and Hazardous Waste and the Florida Department of Transportation. The purpose of the study was to address some of

the environmental concerns related to possible leaching of pollutants from RAP. Testing was performed on six RAP samples collected from six different asphalt plants in Florida. Both batch tests and column tests were performed. The testing focused on volatile organic compounds (VOCs), PAHs, and heavy metals. Although this is a dated study, it is considered one of the preeminent RAP leaching studies and therefore was included in this review. The results are summarized here, but it should be noted that the detection limits achieved during this study were very high. In nearly all cases, the detection limits were higher than the state groundwater quality standards, which means the data are not useful for determining whether the contaminant is present at a level that exceeds the standards.

Batch Tests

Three batch type tests were performed on all six samples: TCLP, SPLP, and a test following the same procedures but using unacidified deionized water. None of the 53 VOCs or 16 PAHs tested were found above detection limits, and no heavy metals were detected above Florida's drinking water standards that were in place at that time.

Column Tests

Column tests were performed to simulate two different environmental scenarios: saturated and unsaturated. In the saturated condition, the samples were completely submerged in a SPLP solution for the entire 6-week experiment; the column was drained and refilled every 14 days, and the elutriate was tested. This resulted in a total of three sampled "events" over the course of the experiment. For the unsaturated condition, a liter was drained from the columns every 2 days and tested, and a new liter of SPLP solution was added to the columns. This resulted in a total of 21 sampled events over the 6-week period. Column tests based on general water quality parameters (total dissolved solids was the example used in the report) indicated the "typical leaching curve" of higher concentrations of chemicals during the first 10 to 20 days of the experiment. All of the PAHs were below detection limits. All heavy metals were below detection limits except for lead. Lead exceeded drinking water standards in one of the samples under unsaturated conditions and in three of the samples under saturated conditions. Based on other sample characteristics measured, the samples with the higher measured lead were indicated to be samples of older RAP material; thus, the authors suggest that the older samples likely contained more lead as a result of longer exposure to traffic and emissions.

The authors concluded that few if any priority pollutant chemicals leached from the RAP samples collected and that under most regulatory policies RAP would pose minimal risk from a leaching standpoint. In terms of the lead results, they concluded that under most reuse circumstances where some degree of dilution and attenuation would occur, even if lead was encountered at levels of the highest concentrations measured in the study, the concentrations in the environment would be below acceptable regulatory levels of drinking water. An exception they noted was under saturated conditions with minimal dilution.

COMPARISON OF STUDIES TO EXPECTED CONDITIONS IN NISQUALLY

With the exception of the Norin and Strömvall (2004) study, all of the studies are based on controlled laboratory conditions. For at least three of the eight studies, batch test results followed protocols designed to test leaching under what were considered acidic environments (i.e., pH levels at about 5 and below). However, the pH of precipitation in the Puget Sound region can be very low; in one study mean rainwater pH in the Puget Sound region was reported as 4.5 (Harrison et al. 1977), and the United States Geological Survey (<<https://pubs.usgs.gov/gip/acidrain/2.html>>) indicates a pH for most of Washington State as 5.3. Therefore, the acidic test conditions used in the batch tests are not too low to represent expected conditions in Nisqually. For the other four studies, testing conditions were close to a neutral pH and therefore represent a less acidic (less leaching) environment than would occur in Nisqually. The one recent study (therefore with improved detection limits), performed at lower pH conditions (Metha 2017) did appear to exhibit higher leaching of metals. In the column tests there were only a few studies that used lower pH elutriates, and there was very little data for metals (the contaminants that would be most impacted by pH) so it is difficult to draw any relationships from those tests.

The Norin and Strömvall (2004) study was the only research conducted in an outdoor setting in the west coast of Sweden where the precipitation has a pH of 4.5 and was considered by the authors to be a “relatively aggressive leaching environment.” As noted above, this is similar to the mean pH of precipitation in the Puget Sound region, so from a pH perspective the study results are applicable to this region. The larger concern with the Swedish study is related to the quality and type of asphalt used in Europe versus the U.S. In Europe the asphalt manufacturing process (e.g., the presence of coal tar in European pavement), the make and model of vehicles, and other factors (e.g., use of studded tires and winter de-icing solutions) could influence the type of contaminants found in the RAP (Lakeside Industries. Letter to Thurston County Community Planning and Economic Development. November 6, 2018). As noted by the study authors, in Sweden tar was used as an additive in asphalt until 1975; and tar contains 10^3 to 10^5 times more PAH than bitumen, which is what has been used in the U.S. since World War II. The PAH results from the Norin and Strömvall (2004) study were the highest concentrations measured, especially for naphthalene and phenanthrene, likely an indication of the quality of the original asphalt. Thus, the basic findings of the Norin and Strömvall (2004) study, that is that RAP from roadway wear course exhibits more leaching than base course RAP and that leaching is highest at the beginning of storage, are likely applicable to the Nisqually area; but the concentrations of contaminants measured may not be representative.

The most consistent trend in all of the studies was that most of the contaminant leaching occurred during the early stages of flushing, whether in batch or column tests or at neutral and low pH. In the Puget Sound region, summer and early fall are typically dry; and storm events that do occur are small, likely too small to completely soak a large stockpile of RAP. Therefore, leaching from stockpiles stored in Nisqually would likely occur during the first large storm

events of the season when the stockpiles are first exposed to heavy rainfall. This is the period when the greatest potential for leaching of contaminants would likely exist.

COMPARISON OF STUDY RESULTS TO STANDARDS

Tables 1 and 2 provide a summary of the most relevant data from each of the selected studies and a comparison to current Washington State Groundwater Quality Standards. Batch test results are presented in Table 1, and column test results are presented in Table 2. All data in these tables reflect testing on 100 percent RAP. Ranges are shown where there was a range of RAP materials tested. For example, seven different RAP sources were tested in one study (Aydilek et al. 2017), and, therefore, Tables 1 and 2 include the range for all the test data from that study. **Bolded** results in the tables indicate where that standard was exceeded. Results are *Italicized* in cases where the detection limit was higher than the state groundwater quality standard. This means that the concentration of the contaminant could have exceeded the standard, or it could have been zero, and makes the results meaningless for evaluating against the standard.

As indicated by Table 1, in four of the eight studies there was at least one metal detected at a level that exceeded the standard. In the one study performed in a low pH (acidic) environment and where detection limits were low enough to compare to the standards (Mehta et al. 2017), four metals were detected at peak concentrations that exceeded a standard. In tests performed under more neutral pH conditions only two metals exceeded a standard. PAHs were only tested at appropriate detection limits (i.e., above groundwater standards) in four of the batch type studies. Thirteen, of the sixteen PAHs were measured at detectable concentrations in at least one of the four studies with appropriate detection limits. At least one PAH above groundwater standards was measured in each of the four studies. Acenaphthene, fluoranthene, naphthalene, benzo(a)pyrene, and pyrene exceeded groundwater standards in at least two (50 percent) of the studies where detection limits were adequate.

Table 2 summarizes the study results from column tests. Metals data are largely lacking for comparison between studies, due to high detection limits and the fact that only a few of the studies evaluated metals in column tests. There was only one metal (manganese) that was measured at a concentration that exceeded the Washington State groundwater standard. For PAHs, all 16 analytes exceeded the standard in at least one of the four studies where they were tested at appropriate detection limits. There were eight PAHs that were measured above the standard in at least two (50 percent) of the studies. These were acenaphthene, dibenzo(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-c,d)pyrene, naphthalene, phenanthrene, and pyrene.

Table 3 provides a comparison of the state groundwater quality standards to the state drinking water quality standards. As shown, for all metals and PAH's reviewed in this study, the groundwater quality standards (those included in Tables 1 and 2) are the most stringent. However, there are three metals for which there are drinking water standards but no groundwater quality standards; beryllium, nickel, and thallium. With the exception of one case

where thallium slightly exceeded the state drinking water standard, all other measurements of these metals were below the standard.

The following standards comparisons have been excerpted from each of the report summaries above and relate to the standards used by the various authors rather than Washington State standards:

1. Aydilek et al. (2017) reported that Cu, Al, B, Ba, Co, Mn, Ni, and Zn exceeded Maryland's ATLS in either batch or column tests. Of those, Cu and Zn also exceeded US EPA WQLs. Most of the exceedances occurred during initial flushing, after which concentrations of all the elements quickly fell below detection.
2. In column tests by Legret et al. (2005), total hydrocarbon concentrations were measured above the EC target level for groundwater, and benzo(a)pyrene slightly exceeded the EC drinking water standard. In both cases, the highest measured concentrations occurred during initial flushing and concentrations were below detection in later tests.
3. Lead was close to or higher than US EPA drinking water standards for a number of the weathered NORTHRAP samples in batch tests done by Mehta et al. 2017. In the same study, benzo(a)anthrazene was detected at levels of concern based on 1995 US EPA human health advisory levels. In the experiments conducted with a strong solvent, many of the PAHs exceeded US EPA 2016 Clean Water Act criteria.
4. In Birgsdotter et al. (2007) the total content of PAHs in the wear course sample from a gas station exceeded Danish soil quality criteria.
5. In Norin and Strömvall (2004), the concentration of total PAHs in leachate from stockpiles of scarified, wear-course RAP and dug, wear- and base-course RAP, both collected from a highly used highway, exceeded the threshold set by Sweden for groundwater in polluted soils at gas stations. The dominant contaminants identified were naphthalene, BHT, and DBP.
6. In Morse et al. (2003), RAP samples exceeded Texas regulatory standards for at least one of the three samples for antimony, barium, and lead. The average concentration exceeded Texas standards for barium and lead.
7. In Kang et al. (2011), there was little testing on 100 percent RAP, and only metals were assessed. Arsenic was measured at the MCL, but no other measured metals had high concentrations as per the standards they were using.
8. In Brently and Townsend (1999), lead exceeded Florida's drinking water standards in a number of the samples during column testing.

SUMMARY AND CONCLUSIONS

There was a wide range in testing materials and protocols used in these studies, and they represent a wide range in conditions. For example, in Europe the asphalt manufacturing process (e.g., the presence of coal tar in European pavement), the make and model of vehicles, and other factors (e.g., use of studded tires and winter de-icing solutions) could influence the type of contaminants found in the RAP (Lakeside Industries. Letter to Thurston County Community Planning and Economic Development. November 6, 2018). The issue of the manufacturing process is emphasized in one of the studies from Sweden where it was noted that in Sweden tar was used as an additive in asphalt until 1975 and that tar contains 10^3 to 10^5 times more PAH than bitumen (Norin and Strömvall 2004). In comparison, coal tar has not been used in the U.S. since World War II (Lakeside Industries. Letter to Thurston County Community Planning and Economic Development. November 6, 2018). As a result of this and other sources of variability, only broad summaries can be drawn from the research. The following points summarize basic findings from the literature reviewed.

- As a source of contaminants, RAP is highly variable. Factors contributing to variability in leachate from RAP appear to include the asphalt manufacturing process, the RAP source, the duration and degree to which it has weathered and been exposed to pollution generating sources, and how long it is stored.
- Both batch and column tests indicated that there were typically some contaminants leached from RAP at concentrations that exceeded Washington State groundwater quality standards. Typically, these exceedances occurred during initial flushing of the RAP.
 - Acenaphthene, fluoranthene, naphthalene, and pyrene were measured above groundwater standards with the most frequency (in 50 percent or more of the studies where detection limits were adequate) in both batch and column tests.
 - Metals data from batch testing indicated that increased release should be expected under acidic (low pH) conditions.
- Although this literature review specifically did not include an assessment of potential environmental impact from fate and transport of these contaminants, a number of the researchers suggested that the impact to the environment would be negligible if dilution and assimilation were considered.
- While some portion of the contaminants is likely generated from components of the asphalt itself, exposure to roadways (and traffic) was identified as a major contributor of contaminants that were available for leaching in three of the studies (Mehta et al. 2017; Birgisdottir et al. 2007; and Norin and Strömvall 2004).
- Batch and column laboratory tests, while informative, are not necessarily representative of what can be expected under field conditions. In the one study that evaluated leachate

collected from outdoor stockpiles (Norin and Strömvall 2004) the results indicated that the total cumulative loading of semi-volatile organics leached during laboratory-based column studies was approximately only 25 percent of what was calculated from leachate collected from the inner section (where the most leaching occurred) of the RAP stockpile. The authors attributed this to differences between the L:S ratios, and to the cumulative effect of contaminants leaching over a longer period of time in the stockpile versus the column test. The authors emphasized the need for field testing as a follow up to laboratory studies.

Table 1. Summary of Batch Test Results from the Eight Research Studies Reviewed.

Constituent	Washington Groundwater Quality Standards ^a	Aydilek et al. 2017 ^b	Legret et al. 2005 ^c	Mehta et al. 2017 ^d	Birgisdottir et al. 2007 ^e	Norin and Strömvall 2004 ^f	Morse et al. 2001 ^g	Brantley and Townsend 1999 ^h	Kang et al. 2011 ⁱ
pH	-	7	7.2 to 7.8	4.93	~7	Not reported	5	4.9 to 5.2	7
Liquid:Solids Ratio	-	20:1	10:1 to 30:1	-	100	100	20:1	20:1	20:1
Total Metals (ug/L)									
Aluminum	-	<5 - 272	-	~30 - 800	-	-	<2,000 - <2,000	-	37
Arsenic	0.05	<50 - 39.5	-	~0.4 - 0.6	-	-	<25 - <25	-	10
Antimony	-	-	-	-	-	-	5.2 - 6.3	-	-
Barium	1,000	<5 - 29.3	-	~0.08 - 300	-	-	<2,000 - <2,000	<500 - <500	70
Beryllium	-	-	-	~0.08 - 0.5	-	-	<1 - <1	-	BDL
Cadmium	10	<2 - <5	<0.01 - <0.01	~0.04 - 0.8	-	-	1.2 - 1.8	<5 - <5	BDL
Chromium	50	<5 - <25	<1 - <1	~0.4 - 1.5	-	-	<5 - 6.0	<100 - <100	BDL
Copper	1,000	<5 - 28.4	<5 - <5	~0.5 - 750	-	-	<100 - <100	<500 - <500	BDL
Iron	300	<5 - 10.2	-	~1.4 - 1,100	-	-	-	-	410
Lead	50	<5 - <25	<5 - <5	~0.08 - 20	-	-	20.4	<10 - <10	BDL
Manganese	50	<5 - <5	-	~0.08 - 1,000	-	-	<100 - 113	-	30
Mercury	2	-	0.1 - 0.2	-	-	-	<2 - <2	-	-
Molybdenum	-	-	<5 - <5	~0.05 - 0.8	-	-	<10 - <10	-	BDL
Nickel	-	<5 - <5	<2 - <2	~0.08 - 20	-	-	<50 - <50	<100 - <100	BDL
Selenium	10	-	-	~4 - 12	-	-	<25 - <25	-	-
Silver	50	<5 - <5	-	~0.01 - 0.03	-	-	<100 - <100	-	-
Thallium	-	-	-	~0.03 - 0.2	-	-	-	-	-
Zinc	5,000	<5 - 8.90	<10 - 115	~6 - 500	-	-	290 - 977	<500 - <500	BDL

Bold values represent detected results that exceed Washington groundwater quality standards.

Italics represent when the detection limit is as high or higher than one of the groundwater quality criteria.

- = Not reported or not available.

µg/L = Micrograms per liter.

BDL = Below detection limit (used when detection limit was not reported).

< = Indicates the analyte was below detection; the adjacent number is the reported detection limit.

~ = Indicates approximate value

^a Washington Groundwater Quality Standards (WAC 173-200-040).

^b The numbers shown provide the range from all seven RAP samples tested.

^c Three extractions at increasing liquid to solid (L:S) ratios were done in these experiments. These data show the range measured in those extractions.

^d Data reflect range of three unweathered RAP samples from supply sources in New Jersey. Raw data for metals were not provided but were grossly interpolated from graphics. These are shown as approximate (~) values.

^e These results show the range in concentrations from the wear course of RAP removed from a gas station that had been in use for 20 years as well as the wear course from a highway that had only been in use a few years.

^f Results reported are from batch tests performed during previous research (Larsson 1998) that were performed on finely ground material.

^g The results shown represent the range of concentrations measured from three or four samples over two experiments as reported in Appendix B of the report.

^h The results represent TCLP, SPLP, and deionized water batch tests for six RAP samples. Results were taken from Townsend and Brantley (1998) since only select data was reported in the referenced literature report (i.e., Brantley and Townsend 1999).

ⁱ Results are from testing of one RAP sample.

Table 1 (continued). Summary of Batch Test Results from the Eight Research Studies Reviewed.

Constituent	Washington Groundwater Quality Standards ^a	Aydilek et al. 2017 ^b	Legret et al. 2005 ^c	Mehta et al. 2017 ^d	Birgisdottir et al. 2007 ^e	Norin and Strömvall 2004 ^f	Morse et al. 2001 ^g	Brantley and Townsend 1999 ^h	Kang et al. 2011 ⁱ
Polycyclic Aromatic Hydrocarbons (PAHs) (in µg/L)									
Acenaphthene	0.01	–	<0.05 – <0.05	BDL – 0.20	BDL – 0.05	0.057	–	<5 – <5	–
Acenaphthylene	0.01	–	<0.05 – <0.05	–	BDL – BDL	0.338	–	<5 – <5	–
Anthracene	0.01	–	0.030 – 0.030	–	BDL – BDL	<0.018	–	<5 – <5	–
Benzo(a)anthracene	0.01	–	<0.025 – <0.025	BDL – BDL	0.06 – 0.08	–	–	<5 – <5	–
Benzo(a)pyrene	0.008	–	<0.010 – 0.020	–	BDL – 0.02	<0.071	–	<0.025 – <0.025	–
Benzo(b)fluoranthene	0.01	–	<0.025 – <0.025	–	–	<0.053	–	<1 – <1	–
Benzo(k)fluoranthene	0.01	–	<0.025 – <0.025	–	BDL – 0.04	<0.036	–	<2.5 – <2.5	–
Benzo(g,h,i)perylene	0.01	–	<0.025 – 0.030	–	BDL – 0.01	<0.036	–	<5 – <5	–
Chrysene	0.01	–	<0.025 – <0.025	BDL – BDL	BDL – BDL	0.249^j	–	<5 – <5	–
Dibenzo(a,h)anthracene	0.01	–	<0.025 – <0.025	–	BDL – BDL	<0.036	–	<2.5 – <2.5	–
Fluoranthene	0.01	–	0.050 – 0.060	0.0039 – 0.0087	0.07 – 0.20	<0.036	–	<5 – <5	–
Fluorene	0.01	–	0.030 – 0.040	BDL – BDL	BDL – 0.01	0.057	–	<1 – <1	–
Indeno(1,2,3-cd)pyrene	0.01	–	<0.025 – <0.025	–	BDL – BDL	<0.053	–	<1 – <1	–
Naphthalene	0.01	–	<0.100 – <0.100	–	0.08 – 0.50	3.92	–	<1 – <1	–
Phenanthrene	0.01	–	0.250 – 0.300	–	0.10 – 0.50	0.012	–	<2.5 – <2.5	–
Pyrene	0.01	–	<0.025 – <0.025	BDL – 0.019	0.07 – 0.09	0.062	–	<.5 – <.5	–

Bold values represent detected results that exceed Washington groundwater quality standards.

Italics represent when the detection limit is as high or higher than the groundwater quality standard.

– = Not reported or not available.

µg/L = Micrograms per liter.

BDL = Below detection limit (used when detection limit was not reported).

< = Indicates the analyte was below detection; the adjacent number is the reported detection limit.

~ = Indicates approximate value interpreted from figures

^a Washington Groundwater Quality Standards (WAC 173-200-040).

^b The numbers shown provide the range from all seven RAP samples tested.

^c Three extractions at increasing liquid to solid (L:S) ratios were done in these experiments. These data show the range measured in those extractions.

^d Data reflect range of three unweathered RAP samples from supply sources in New Jersey. Raw data for metals were not provided but were grossly interpolated from graphics. These are shown as approximate (–) values.

^e These results show the range in concentrations from the wear course of RAP removed from a gas station that had been in use for 20 years as well as the wear course from a highway that had only been in use a few years.

^f Results reported are from batch tests performed during previous research (Larsson 1998) that were performed on finely ground material.

^g The results shown represent the range of concentrations measured from three or four samples over two experiments as reported in Appendix B of the report.

^h The results represent TCLP, SPLP, and deionized water batch tests for six RAP samples. Results were taken from Townsend and Brantley (1998) since only select data was reported in the referenced literature report (i.e., Brantley and Townsend 1999).

ⁱ Results are from testing of one RAP sample.

^j Chrysene concentration represents both chrysene and benzo(a) anthracene as reported in the study.

Table 2. Summary of Column Test Results from the Eight Research Studies Reviewed.

Constituent	Washington Groundwater Quality Standards ^a	Aydilek et al. 2017 ^b	Legret et al. 2005 ^c	Mehta et al. 2017 ^d	Birgisdottir et al. 2007 ^e	Norin and Strömvall 2004 ^f		Morse et al. 2001	Brantley and Townsend 1999	Kang et al. 2011
						Scarified Recycled Asphalt Pavement				
						Not Stored	Stored			
pH	-	6.0 – 6.5	~7 (deionized water)	~5 (artificial rain water)	8	4.5	4	4	~7	
Liquid:Solids Ratio		25:1	30:1		100	0.05	0.07			
Total Metals (ug/L)										
Aluminum	-	<5 – 320	-	-	-	-	-	-	-	-
Arsenic	0.05	<25 – <25	-	<10	-	-	-	-	-	-
Antimony	-	-	-	-	-	-	-	-	-	-
Barium	1,000	14.2 – 172	-	<2,000	-	-	-	-	<500	-
Beryllium	-	-	-	-	-	-	-	-	-	-
Cadmium	10	<2 – <5	-	<5	-	-	-	-	<5	-
Chromium	50	<5 – <25	-	<100	-	-	-	-	<100	-
Copper	1,000	<5 – 16.1	13	<1,300	-	-	-	-	<500	-
Iron	300	<25 – 224	-	-	-	-	-	-	-	-
Lead	50	<25 – <25	<5	<15	-	-	-	-	<10 – 38	-
Manganese	50	<5 – 426	-	-	-	-	-	-	-	-
Mercury	2	-	<0.1	-	-	-	-	-	-	-
Molybdenum	-	-	<5	-	-	-	-	-	-	-
Nickel	-	<5 – 108	-	-	-	-	-	-	<100	-
Selenium	10	-	-	-	-	-	-	-	-	-
Silver	50	-	-	-	-	-	-	-	-	-
Zinc	-	23 – 213	71	-	-	-	-	-	<500	-

Bold values represent detected results that exceed Washington groundwater quality standards.

Italics represent when the detection limit is as high or higher than the groundwater quality standard.

- = Not reported or not available.

µg/L = micrograms per liter.

BDL = Below detection limit (used when detection limit was not reported).

< = Indicates the analyte was below detection; the adjacent number is the reported detection limit.

^a Washington Groundwater Quality Standards (WAC 173-200-040).

^b This is the range in peak concentrations across seven recycled asphalt pavement (RAP) samples.

^c This study was done over a 75-day period at increasing L:S ratios. These results are from Day 2 (the first testing day), and therefore reflect the highest concentrations measured for all parameters except mercury and total hydrocarbons which peaked later in the testing.

^d Raw data for metals were not provided but were reported as less than maximum contaminant level (<MCL). The MCLs (or in the case of copper and lead, US EPA-designated Action Levels) are shown in the table.

^e Range shown represents results of testing the wear course of RAP from a gas station that had been in use for 20 years and a highway that had been in service for approximately a year. They reflect the range in concentrations measured over the 64-day test period.

^f Results for a laboratory column test where compounds were leached from two RAP samples: scarified asphalt that was not stored and scarified asphalt that was stored for 2 years. Both samples came from the same highway road surface at 3 cm of depth that had been in use for 11 years.

Table 2 (continued). Summary of Column Test Results from the Eight Research Studies Reviewed.

Constituent	Washington Groundwater Quality Standards ^a	Aydilek et al. 2017 ^b	Legret et al. 2005 ^c	Mehta et al. 2017 ^d	Birgisdottir et al. 2007 ^e	Norin and Strömvall 2004 ^f		Morse et al. 2001	Brantley and Townsend 1999	Kang et al. 2011
						Scarified Recycled Asphalt Pavement				
						Not Stored	Stored			
Polycyclic Aromatic Hydrocarbons (PAHs) (in µg/L)										
Acenaphthene	0.01	–	<0.05	BDL – 0.09	<0.015 – 0.070	3.0	0.7	–	<5	–
Acenaphthylene	0.01	–	<0.05	–	<0.015 – <0.003	0.5	0.4	–	<5	–
Anthracene	0.01	–	<0.025	–	–	0.5	0.1	–	<5	–
Benzo(a)anthracene	0.01	–	<0.025	BDL	0.015 – 0.180	<0.01	<0.01	–	<5	–
Benzo(a)pyrene	0.008	–	0.020	–	<0.024 – <0.050	<0.01	<0.01	–	<0.25	–
Benzo(b)fluoranthene	0.01	–	0.025	–	–	<0.01	<0.01	–	<1	–
Benzo(k)fluoranthene	0.01	–	<0.025	–	0.150 – 0.830	<0.01	<0.01	–	<2.5	–
Benzo(g,h,i)perylene	0.01	–	0.080	–	<0.024 – <0.050	<0.01	<0.01	–	<5	–
Chrysene	0.01	–	0.045	BDL	–	<0.01	<0.01	–	<5	–
Dibenzo(a,h)anthracene	0.01	–	0.055	–	<0.024 – 0.043	0.04	0.20	–	<2.5	–
Fluoranthene	0.01	–	<0.025	BDL	0.015 – 0.078	0.1	0.1	–	<5	–
Fluorene	0.01	–	<0.025	BDL – 0.03	<0.015 – <0.030	2.1	0.5	–	<1	–
Indeno(1,2,3-cd)pyrene	0.01	–	0.050	–	0.024 – 0.200	0.02	0.04	–	<1	–
Naphthalene	0.01	–	<0.100	–	0.310 – 0.320	28	9.2	–	<1	–
Phenanthrene	0.01	–	<0.025	–	0.026 – 0.120	1.8	0.7	–	<2.5	–
Pyrene	0.01	–	<0.025	BD L – 0.19	<0.015 – 0.054	0.1	0.1	–	<0.5	–

Bold values represent detected results that exceed Washington groundwater quality standards.

Italics represent when the detection limit is as high or higher than the groundwater quality standard.

– = Not reported or not available.

µg/L = micrograms per liter.

BDL = Below detection limit (used when detection limit was not reported).

< = Indicates the analyte was below detection; the adjacent number is the reported detection limit.

^a Washington State Groundwater Quality Standards (WAC 173-200-040).

^b This is the range in peak concentrations across seven recycled asphalt pavement (RAP) samples.

^c This study was done over a 75-day period at increasing L:S ratios. These results are from Day 2 (the first testing day), and therefore reflect the highest concentrations measured for all parameters except mercury and total hydrocarbons which peaked later in the testing.

^d Raw data for metals were not provided but were reported as less than US EPA's maximum contaminant level (<MCL). The MCLs (or in the case of copper and lead, US EPA-designated Action Levels) are shown in the table.

^e Range shown represents results of testing the wear course of RAP from a gas station that had been in use for 20 years and a highway that had been in service for approximately a year. They reflect the range in concentrations measured over the 64-day test period.

^f Results for a laboratory column test where compounds were leached from two RAP samples: scarified asphalt that was not stored and scarified asphalt that was stored for 2 years. Both samples came from the same highway road surface at 3 cm of depth that had been in use for 11 years.

Table 3. Water Quality Standards Comparison.		
Constituent	Washington Groundwater Quality Standards ^a	Drinking Water Standards ^b
Total Metals (in micrograms per liter [µg/L])		
Aluminum	–	–
Arsenic	0.05	10
Antimony	–	6
Barium	1,000	2,000
Beryllium	–	4
Cadmium	10	5
Chromium	50	100
Copper	1,000	1,300 ^c
Iron	300	–
Lead	50	15 ^c
Manganese	50	–
Mercury	2	2
Molybdenum	–	–
Nickel	–	100
Selenium	10	50
Silver	50	–
Thallium	–	2
Zinc	5,000	–
Polycyclic Aromatic Hydrocarbons (PAHs) (in micrograms per liter [µg/L])		
Acenaphthene	0.01	–
Acenaphthylene	0.01	–
Anthracene	0.01	–
Benzo(a)anthracene	0.01	–
Benzo(a)pyrene	0.008	0.20 ^d
Benzo(b)fluoranthene	0.01	–
Benzo(k)fluoranthene	0.01	–
Benzo(g,h,i)perylene	0.01	–
Chrysene	0.01	–
Dibenzo(a,h)anthracene	0.01	–
Fluoranthene	0.01	–
Fluorene	0.01	–
Indeno(1,2,3-cd)pyrene	0.01	–
Naphthalene	0.01	–
Phenanthrene	0.01	–
Pyrene	0.01	–

– = Not reported or not available

^a Washington State Groundwater Quality Standards (WAC 173-200-040)

^b Washington State Drinking Water Standards for Group A Public Water Supplies (WAC 246-290-310)

^c Although the state board of health has not established maximum contaminant levels for copper and lead, there is sufficient public health significance connected with copper and lead levels to require inclusion in inorganic chemical and physical source monitoring. For copper and lead, the US EPA has established distribution-system-related levels at which a system is required to consider corrosion control. These Action Levels are 0.015 mg/L for lead and 1.3 mg/L for copper (WAC 246-290-310).

^d US EPA Drinking Water Standard

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APPENDIX A

Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement

Appendix A: Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement

Author	Title	Date	Overall Rating	Rating Rationale
Aydilek, Ahmet H.; Mijic, Zorana; Seybou-Insa, Ousmane	Hydraulic and Environmental Behaviour of Recycled Asphalt Pavement in Highway Shoulder Applications	2017	High	Direct testing of leaching 7 different RAP. High quality study.
Birgisdottir, H.; Gamst, J; Christensen, T. H.	Leaching of PAHs From Hot Mix Asphalt Pavements	2007	High	Direct testing of different RAP sources. High quality study.
Brantley, A.S.; Townsend, T.G.	Leaching of Pollutants from Reclaimed Asphalt Pavement	1999	High	Laboratory batch and column tests of 6 different RAP samples. Detection limits were high, limiting the value of this study.
Kang, Dong Hee; Gupta, Satish C; Ranaivoson, Andry Z; Roberson, Ruth; Siekmeier, John A.	Recycled Materials as Substitutes for Virgin Aggregates in Road Construction: II. Inorganic Contaminant Leaching	2011	High	Focus of testing is fly ash and mixtures but one test sample is 100% RAP.
Legret, M.; Odie, L.; Demare, D.; Jullien, A.	Leaching of heavy metals and polycyclic aromatic hydrocarbons from reclaimed asphalt pavement	2005	High	Direct testing of RAP. High quality study.
Mehta, Yusuf; Ayman, Ali; Beizhan, Yan; McElroy, Anne E.; Huiming, Yin	Environmental Impacts of Reclaimed Asphalt Pavement	2017	High	High quality study. Assessed various RAP sources including "fresh" RAP and evaluated affects of weathering.
Morse, A., A.M. Jackson, and R. Davio	Environmental Characterization of Traditional Construction and Maintenance Materials	2001	High	Direct testing of RAP from 3 different districts in Tx was tested following std SPLP protocol.
Norin, Malin; Strömvall, A-M.	Leaching of Organic Contaminants from Storage of Reclaimed Asphalt Pavement	2004	High	Direct testing of RAP. High quality study
Arulrajah, A.; Piratheepan, J.; Disfani, M. M.	Reclaimed Asphalt Pavement and Recycled Concrete Aggregate Blends in Pavement Subbases: Laboratory and Field Evaluation	2014	Low	Testing is related to its physical properties and therefore RAP use as a subbase material.
Azah, Edmund; Kim, Hwidong; Townsend, Timothy	Assessment of Direct Exposure and Leaching Risk from PAHs in Roadway and Stormwater System Residuals	2017	Low	Not about RAP. Samples were from stormwater maintenance operations.
Beyers, C; Clifton, M.	Land use planning and the impacts of odour emissions from waste recycling in asphalt production	2017	Low	Testing was based on manufacturing of product not impacts of recycled product. Comparison of odor emissions from hot mix and RAP facilities.
Brandt, H.C.A; de Groot, P.C.	Aqueous Leaching of Polycyclic Aromatic Hydrocarbons From Bitumen and Asphalt	2001	Low	Not about RAP but about petroleum bitumens that make up asphalt and one asphalt product.
Cai, Hongmei; Wei, Jianming; Zhang, Yuzhen; Changtai, Jin	The Research on the Potential Leachability of Asphalt	2011	Low	Testing is of 5 types of asphalt binders not RAP.

Appendix A: Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement

Author	Title	Date	Overall Rating	Rating Rationale
Harrington, Joseph T.; Wagter, James M; R., Kevin	Toxicity of Milled Asphalt Pavement to Aquatic Organisms and its Effect on Stream Substrates in Deep Creek, San Bernardino County	1996	Low	Could not acquire this report. The age of the study would have limited its usefulness due to poor detection limits and likely false negatives.
Jullien, A., Monéron, P., Quaranta, G. and Gaillard, D.	Air emissions from pavement layers composed of varying rates of reclaimed asphalt	2006	Low	Testing of air emissions during newly laid (hot mix) asphalt pavement with different ratios of RAP. Results are related to air emissions during roadway building and for hot asphalt. Not related to RAP storage.
Kang, Dong Hee; Gupta, Satish C; Ranaivoson, Andry Z; Roberson, Ruth; Siekmeier, John A.	Leaching Characteristics of Fly Ash, Recycled Asphalt, and Aggregate Mixtures	2010	Low	Testing was of fly ash and RAP mixes. Therefore any results would be biased by fly ash component.
Kayhanian, M., Vichare, A., Green, P.G. and Harvey, J.	Leachability of dissolved chromium in asphalt and concrete surfacing materials	2009	Low	Leaching test on different pavement types but doesn't appear to be RAP in any of the mixes.
Kayhanian, Masoud; Vichare, Akshay; Green, Peter G.; Alaimo, Chris; Hwang, Hyun-Min; Signore, James M.; Troxler, Mark; Jones, David; Harvey, John	Water Quality Evaluation of Leachate Produced from Pavement Specimens Under Controlled Laboratory Conditions	2011	Low	Testing is of different new roadway materials, many w an asphalt component but not directly pertaining to RAP.
Kriech, A.J.; Kurek, J.T.; Osborn L.V, et al.	Determination of Polycyclic Aromatic Compounds in Asphalt and in Corresponding Leachate Water	2002	Low	Research on "virgin" asphalts from 6 sources. Not about recycled asphalt. No contaminants from its use in the roadway would have been tested.
Licbinsky, R.; Huzlik, J.; Provalilova, I.; Jandova, V.; Licbinska, M.	Groundwater Contamination Caused by Road Construction Materials	2012	Low	Testing is done on boreholes in existing roadway. RAP may or may not be part of the roadway structure. Either way, the results would not reflect RAP alone.
Lopez, S; Sanchez, F; Kosson, D S	Evaluation of the impact of environmental conditions on constituent leaching from granular materials during intermittent infiltration	2001	Low	Did not test asphalt or RAP
Mitchel, M.R.; Link, R.E.; Hongmei, Cai; Xiaosheng, Huang; Peng, Wang; Yuzhen, Zhang	Factors Influencing the Leaching of Asphalt Components	2009	Low	Testing is of asphalt binders not RAP. Precursor to 2011 report.

Appendix A: Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement

Author	Title	Date	Overall Rating	Rating Rationale
Nelson, P.O., Eldin, N.N., Huber, W.C., Lundy, J.R., Williamson, K.J., Quigley, M.M., Azizian, M.F., Thayumanavan, P., and Frey, K.M.	Environmental impact of construction and repair materials on surface and ground waters. <i>Final report</i> , 4, pp.25-9.	2000	Low	This report was superceded by NCHRP 448 listed above.
Nielsen, E. et al	Processing and RA management at the mixing plant. Final report. Deliverable 4.6 of Re-Road – End of life strategies of asphalt pavements	2012	Low	Not about environmental impacts but about maximizing use of RAP in pavements.
Ogunro, Vincent O.; Inyang, Hillary I.	Relating Batch and Column Diffusion Coefficients for Leachable Contaminants in Particulate Waste Materials	2003	Low	Leaching test was asphalt mixed with municipal waste. Results would be biased by municipal waste component.
The Recycled Materials Resource Center – Dr. David Kosson of Vanderbilt University	Project 11 – Leaching from Granular Materials Used in Highway Construction During Intermittent Wetting	2006	Low	Test objective was looking at impact of freeze/thaw cycles on leaching on recycled concrete
Townsend, Timothy G.	Leaching Characteristics of Asphalt Road Waste	1998	Low	Graduate study. Laboratory batch and column tests of 6 different RAP samples. See Brantly and Townsend for reviewed paper
Unknown	Asphalt Test Show Little Leachate	1998	Low	News summary. No data. Superceded by Brantly and Townsend study.
Ventura, A. Jullien, A., and P. Moneron.	Polycyclic aromatic hydrocarbons emitted from a hot-mix drum, asphalt plant: study of the influence from use of recycled bitumen	2007	Low	Testing was based on air emissions from manufacturing of product not impacts of recycled product or leaching from RAP.
Norrman, Jenny; Rosén, Lars; Norin, Malin	Decision Analysis for Storage for Reclaimed Asphalt	2005	Moderate	This is about storage and fate/transport. Refers to Norin paper as source of original leachate tests.
Sadecki, Roger W., et al.	An Investigation of Water Quality In Runoff From Stockpiles of Salvaged Concrete And Bituminous Paving	1996	Moderate	Comparison of leaching from stockpiles of concrete and RAP in field application. Just a few heavy metals were sampled and PAHs; however the tests were done in mid-1990s and no information on detection limits was provided. Age of study and likely high detection limits, limit its value.

Appendix A: Literature Considered for Phase 2 of the Literature Review for Contaminant Leaching from Recycled Asphalt Pavement

Author	Title	Date	Overall Rating	Rating Rationale
Student Investigators: Nemeth, Andrew F.; Ward, Devon A.; Woodington, Walter G. Advisor: Mathisen, Paul P.	The Effect of Asphalt Pavement on Stormwater Contamination	2010	Moderate	Methods appear to be good and it is specifically about RAP. However, it is undergraduate student work. Doesn't appear to have had much review. Does not meet test of having met peer review standards.
Student Investigators: Shedivy, Ryan F.; Meier, Amara Advisors: Edil, Tuncer B.; Tinjum, James M.; Benson Craig H.	Leaching Characteristics of Recycled Asphalt Pavement Used as Unbound Road Base	2012	Moderate	Methods appear to be good and it is specifically about RAP. However, it appears to be undergraduate student work. Doesn't appear to have had much review. Does not meet test of having met peer review standards.
NCHRP	Environmental Impact of Construction and Repair Materials on Surface and Ground Waters: Summary of Methodology, Laboratory Results, and Model Development	2001	Moderate	Extensive study but RAP was only tested in initial toxicity phase. Because there was no toxic effect it was eliminated from further testing.
Thayumanavan, P., Nelson, P., Azizian, M., Williamson, K., and Lundy, J.	Environmental impact of construction and repair materials on surface water and groundwater: Detailed evaluation of waste-amended highway materials	2001	Moderate	Looked at leaching from a wide range of recycled materials and impacts in aquatic environment. RAP was tested RAP during the first phase of aquatic toxicity testing, since No Toxic Effect was observed, it was not included in follow up testing.

APPENDIX B

Copies of Selected Literature

The contents of this appendix will be
provided separately.
