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RESEARCH

2009-27

Use of Fly Ash for Reconstruction of Bituminous Roads

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Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2009-27		

4. Title and Subtitle	5. Report Date
Use of Fly Ash for Reconstruction of Bituminous Roads	August 2009
	6.
7. Author(s) C. Benson, T. Edil, A. Ebrahimi, B. Kootstra, L. Li, and P. Bloom	8. Performing Organization Report No.
9. Performing Organization Name and Address Dept. of Civil and Environmental Engineering University of Wisconsin Madison, WI 53706 Dept. of Soil, Water, and Climate University of Minnesota St. Paul, MN 55108	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 89261 (wo) 5
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/200927.pdf
Appendices can be found in report number 2009-27A:
http://www.lrrb.org/pdf/200927A.pdf

16. Abstract (Limit: 250 words)

Recycling part or all of the pavement materials in an existing road during reconstruction is an attractive construction alternative. When reconstructing roads surfaced with hot mix asphalt (HMA), the HMA, underlying base, and a portion of the existing subgrade often are pulverized to form a new base material referred to as recycled pavement material (RPM). Compacted RPM is overlain with a new HMA layer to create a reconstructed or rehabilitated pavement. This process is often referred to as full-depth reclamation. Similarly, when an unpaved road with a gravel surface is upgraded to a paved road, the existing road surface gravel (RSG) is blended and compacted to form a new base layer that is overlain with an HMA surface. Recycling pavement and road materials in this manner is both cost effective and environmentally friendly. However, recycled base materials may contain asphalt binder, fines, and/or other deleterious materials that can adversely affect strength and stiffness. To address this issue, chemical stabilizing agents can be blended with RPM or RSG. Use of industrial material resources for stabilization (e.g., cementitious coal fly ash) is particularly attractive in the context of sustainability. The purpose of this study was to develop a practical method to design local roadways using stabilized RPM or SRSG as the base layer and Class C fly ash as the stabilizing agent. The design method was developed in the context of the "gravel equivalency" (GE) design methodology employed for local roads in Minnesota.

17. Document Analysis/Descriptors	18. Availability Statement
Recycled materials, sustainability, gravel, full-depth reclamation, modulus of resilience, design methods, field tests, environmental impact analysis, environmental modeling, fly ash, pavement maintenance, environmental risk assessment	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	32	

Use of Fly Ash for Reconstruction of Bituminous Roads

Final Report

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August 2009

Published by

Minnesota Department of Transportation
Research Services Section
Transportation Bldg.
395 John Ireland Boulevard, Mail Stop 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

The Minnesota Local Road Research Board (LRRB) provided financial support for this study. Supplementary support was provided by the US Department of Energy's Combustion Byproducts Recycling Consortium (CBRC), Great River Energy, Inc., and Lafarge, Inc. Endorsement by LRRB, CBRC, Great River Energy, and Lafarge is not implied and should not be assumed. Tim Brown (City of Waseca, MN), Fred Salisbury (City of Waseca, MN), Joe Triplett (Chisago County, MN), and Bill Malin (Chisago County, MN) assisted with the study. John Siekmeier of the Minnesota Department of Transportation (Mn/DOT) managed the project for the LRRB. The assistance of each of these individuals is gratefully acknowledged.

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EXECUTIVE SUMMARY

Recycling part or all of the pavement materials in an existing road during rehabilitation and reconstruction is attractive. For roads surfaced with hot mix asphalt (HMA), the HMA, underlying base, and a portion of the existing subgrade often are pulverized to form a new base material referred to as recycled pavement material (RPM). Compacted RPM is overlain with a new HMA layer to create a reconstructed or rehabilitated pavement. This process is often referred to as full-depth reclamation (FDR). Similarly, when an unpaved road with a gravel surface is upgraded to a paved road, the existing road surface gravel (RSG) is blended and compacted to form a new base layer that is overlain with a surface of HMA. Recycling pavement and road materials in this manner is cost effective, environmentally friendly, and more sustainable.

Recycled base materials may contain asphalt binder, fines, and/or other deleterious materials that can adversely affect strength and stiffness. To address this issue, chemical stabilizing agents such as cement, asphalt emulsions, lime, cement kiln dust (CKD), or cementitious fly ash can be blended with RPM or RSG to increase the strength and stiffness. This "stabilized" material is referred to as SRPM or SRSG. Use of industrial material resources for stabilization, such as cementitious coal fly ash, is particularly attractive in the context of sustainability.

The purpose of this study was to develop a practical method to design local roadways using SRPM or SRSG as the base layer and Class C fly ash as the stabilizing agent in the context of the "gravel equivalency" (GE) design methodology employed for local roads in Minnesota. The project consisted of four major elements: (i) laboratory testing, (ii) prototype pavement evaluation, (iii) field assessment of two existing roadways constructed with SRPM and SRSG, and (iv) assessment of potential impacts to ground water. Findings from the study are described in a summary report and a set of detailed appendices focused on individual elements of the study. The summary report contains a step-by-step design procedure along with practical implications relevant to implementation.

The design procedure was developed using a three-pronged approach that used analysis to couple findings from (i) laboratory bench-scale testing, (ii) prototype-scale testing, and (iii) field monitoring. Laboratory tests were conducted on conventional test specimens to evaluate how fly ash content, curing time, and freeze-thaw cycling affect the strength and stiffness of RPM, RSG, SRPM, and SRSG. Prototype-scale tests were conducted to understand the stiffness of RPM, RSG, SRPM, and SRSG operative in full-scale pavement profiles under cyclic loading representative of field conditions. Results of these prototype-scale tests were used to develop the design procedure. Pavement monitoring was conducted at two field sites employing SRPM and SRSG to confirm that the pavements were performing satisfactorily when subjected to full-scale loading under realistic conditions, including exposure to severe weather conditions imposed by winter in Minnesota.

The bench-scale and field-scale testing program was conducted with three different base course materials: (i) a granular base comparable to Class 5 base used in Minnesota, (ii) RPM from a FDR project in Madison, WI, and (iii) a simulated RSG. SRPM and SRSG were created by blending the RPM and RSG with Class C fly ash from Columbia Power Station in Portage, Wisconsin. The fly ash content was maintained at 10% in the prototype evaluation due to the high level of effort associated with prototype-scale testing. However, 10% is the common fly ash content used in practice.

The design procedure is used to select the thickness of SRPM or SRSG base that has equivalent structural capacity as conventional Class 5 base course. The steps are as follows:

1. Create a conventional pavement design with Class 5 base material (or comparable aggregate base) using methods published by MnDOT or using local experience.

2. Determine the gravel equivalency factor for the recycled base material using the thickness of Class 5 base material from the conventional design (D_c) and design equations in the report.

3. Compute the thickness of the alternative base course (D_a) as $D_a = D_c(a_a^{-1})$, where a_a is the gravel equivalency factor for the stabilized base material (SRPM or SRSG)

Methods to account for fly ash contents other than 10% are also described as are the implications of freeze-thaw cycling and long-term curing. Field data from two sites in Minnesota are used to illustrate the efficacy of using SRPM and SRSG on actual projects.

Environmental monitoring was conducted at the two field sites, environmental testing was conducted in the laboratory, and environmental modeling was conducted to assess how ground water might be affected by trace elements leaching from the fly ash. This effort showed that trace elements in water percolating from the base of a roadway with SRPM or SRSG can have concentrations exceeding drinking water standards. However, these concentrations diminish over time, and the effects of dilution and attenuation prevent concentrations above drinking water standards at the limits of the right of way during the service life of a roadway.

CHAPTER 1. INTRODUCTION

Recycling part or all of the pavement materials in an existing road during rehabilitation and reconstruction is an attractive construction alternative. For roads with a hot mix asphalt (HMA) surface, the HMA, underlying base, and a portion of the existing subgrade often are pulverized to form a new base material referred to as recycled pavement material (RPM). Compacted RPM is overlain with a new HMA layer to create a reconstructed or rehabilitated pavement. This process is often referred to as full-depth reclamation (FDR). Similarly, when an unpaved road with a gravel surface is upgraded to a paved road, the existing road surface gravel (RSG) is blended and compacted to form a new base layer that is overlain with an HMA surface. Recycling pavement and road materials in this manner is both cost effective and environmentally friendly.

Recycled base materials may contain asphalt binder, fines, and/or other deleterious materials that can adversely affect strength and stiffness. To address this issue, chemical stabilizing agents such as cement, asphalt emulsions, lime, cement kiln dust (CKD), or cementitious fly ash can be blended with RPM or RSG to increase the strength and stiffness. This "stabilized" material is referred to as SRPM or SRSG. Use of industrial material resources for stabilization, such as CKD or fly ash, is particularly attractive in the context of sustainability.

The purpose of this study was to develop a practical method to design local roadways using SRPM or SRSG as the base layer and Class C fly ash as the stabilizing agent in the context of the "gravel equivalency" (GE) design methodology employed for local roads in Minnesota. The project consisted of four major elements: (i) laboratory testing (Appendix B), (ii) prototype pavement evaluation (Appendix C), (iii) field assessment of two existing roadways constructed with SRPM and SRSG (Appendix D), and (iv) assessment of potential impacts to ground water (Appendix E and F). This summary report was created as a design guide and includes step-by-step design procedures along with practical implications relevant to implementation. A summary of a similar study conducted by MnDOT and the Waseca County Highway Department at CSAH 8 in Waseca, MN is included in the appendix to this report. The URL to the appendices of this report is: http://www.lrrb.org/pdf/200927A.pdf.

CHAPTER 2. METHODOLOGY

The design methodology presented in this report was developed using a three-pronged approach:

- Laboratory tests were conducted on conventional test specimens to evaluate how fly ash content, curing time, and freeze-thaw cycling affect the strength and stiffness of RPM, RSG, SRPM, and SRSG.

- Prototype-scale tests were conducted to understand the stiffness of RPM, RSG, SRPM, and SRSG operative in full-scale pavement profiles under cyclic loading representative of field conditions. Results of these prototype-scale tests were used to develop the design procedure.

- Pavement monitoring was conducted at two field sites employing SRPM and SRSG to confirm that the pavements were performing satisfactorily when subjected to full-scale loading under realistic conditions, including exposure to severe weather conditions imposed by winter in Minnesota. These field sites were also instrumented to evaluate potential impacts to ground water.

The testing program was conducted with three different base course materials: (i) a granular base comparable to Class 5 base used in Minnesota, (ii) RPM from a FDR project in Madison, WI, and (iii) a simulated RSG created by blending commercially available soil and aggregates to form a test material having characteristics of RSG meeting the criteria in AASHTO M 147. SRPM and SRSG were created by blending the RPM and RSG with Class C fly ash from Columbia Power Station in Portage, Wisconsin. The fly ash content was maintained at 10% in the prototype evaluation due to the high level of effort associated with prototype-scale testing. However, 10% is the common fly ash content used in practice.

Properties of the materials are summarized in Tables 1 and 2. Their particle size distribution curves are shown in Fig. 1. These materials have characteristics similar to materials employed in actual projects in Minnesota. Thus, the findings and procedures reported in this study are believed to have general applicability for design of local roads in Minnesota.

The prototype-scale tests were conducted in the large-scale model experiment (LSME) at the University of Wisconsin-Madison. The LSME is a testing facility where full-scale pavement profiles can be evaluated under cyclic loading conditions simulating the field condition (Fig. 2). Previous studies have shown that pavement moduli obtained by analyzing LSME data are representative of full-scale conditions. Background on the LSME and detailed information on the LSME tests conducted in this study are available in the aforementioned project reports linked electronically to this document.

CHAPTER 3. DESIGN PROCEDURE

3.1 Background on Gravel Equivalency

The GE procedure for design of local roads employs GE factors that are similar conceptually to the layer coefficients employed when designing flexible pavements using the AASHTO *Guide for Design of Pavement Structures*. The GE method provides a means of equating the structural performance of all bituminous and aggregate layers constituting a pavement structure with respect to the structural performance of MnDOT's Class 5 and 6 aggregate bases. GE of a pavement structure is computed as:

$$GE = a_1D_1 + a_2D_2 + a_3D_3 \quad (1)$$

where D_1, D_2, and D_3 are thicknesses of the HMA surface, the granular base course, and a granular subbase course (if present) and a_1, a_2, and a_3 are corresponding GE factors. Type of pavement material is used to define each of the GE factors using tables published by MnDOT.

3.2 Equivalency-Based Design

The design procedure developed in this study is based on the premise that the pavement constructed with the alternative base material has equivalent structural capacity as the pavement constructed with conventional base course. The conventional pavement is assumed to consist of a HMA layer and a MnDOT Class 5 base course layer (no subbase). Thickness of the alternative base course is selected to ensure that the pavement with alternative materials has equivalent structural capacity.

The GE of the pavement structure using the conventional Class 5 base is:

$$GE_c = a_1 D_1 + a_c D_c \quad (2)$$

where the subscript ‘c’ denotes the conventional Class 5 base (Fig. 3). Similarly, for the alternative recycled base material:

$$GE_a = a_1 D_1 + a_a D_a \quad (3)$$

where the subscript ‘a’ denotes the alternative recycled base course (Fig. 3). For an equivalent pavement structure, $GE_a = GE_c$. If the HMA thickness is assumed to be the same for both pavements, the relationship between thicknesses and GE factors for the conventional and recycled base materials is:

$$\frac{a_a}{a_c} = \frac{D_c}{D_a} \quad (4)$$

A similar procedure can be carried out with the AASHTO design method based on structural number. For the AASHTO method, the ratio of the thicknesses is:

$$\frac{D_c}{D_a} = \frac{0.249 \log Mr_a - 0.977}{0.249 \log Mr_c - 0.977} \quad (5)$$

where Mr_a (in psi, note: 100 psi = 0.69 MPa.) is the summary resilient modulus of the alternative recycled base course and Mr_c (psi) is the summary resilient modulus of the conventional Class 5 base course. Eq. 5 can be used to determine the thickness of an alternative base course of recycled material using the resilient modulus of the alternative and conventional base course materials:

$$D_a = D_c \frac{0.249 \log Mr_c - 0.977}{0.249 \log Mr_a - 0.977} \quad (6)$$

Alternatively, the GE factor for an alternative recycled base material can be obtained by combining Eqs. 4 and 5:

$$a_a = \frac{0.249 \log Mr_a - 0.977}{0.249 \log Mr_c - 0.977} \quad (7)$$

In Eq. 7, $a_c = 1.0$ as stipulated in the GE design method.

Eqs. 6 and 7 require that the summary resilient modulus of the Class 5 base course and the alternative recycled material as input. LSME testing was conducted to obtain these summary resilient moduli for conditions operative at field scale. These moduli vary with thickness for the granular materials (Class 5 base, RPM, and RSG), but are independent of thickness for the stabilized materials (SRPM and SRSG) (Fig. 4). These relationships can be used with Eq. 7 to define the GE factor for each alternative recycled material (Fig. 5).

As shown in Fig. 5, the GE for RSG (a_{RSG}) is less than that of Class 5 base ($a_{RSG} < a_c = 1.0$), the GE factor for RPM ($a_{RSG} = 1.07$) is essentially the same as the GE factor for Class 5 base, and the GE factor for SRPM and SRSG is greater than that of Class 5 base. In addition, the GE factors for SRPM and SRSG are nearly identical, and can be described by a single equation. RPM is the only alternative material that has a constant GE factor. This occurs because the resilient modulus of RPM and Class 5 gravel vary with layer thickness in a similar manner (Fig. 4).

Given the lack of field experience with this method, the following recommendations are made when applying the equations shown on Fig. 5:

- Stabilized materials should have a minimum UCS_{7day} of 1000 kPa.
- Maintain a_{SRPM} and a_{SRSG} within the range of 1.0 to 1.5.
- Use $a_{RPM} = 1.0$.

3.3 Alternative Base Course Selection Procedure

The following procedure is recommended for selecting the thickness of an alternative base course:

1. Create a conventional pavement design with Class 5 base material (or comparable aggregate base) using methods published by MnDOT or using local experience.

2. Determine the gravel equivalency factor for the recycled base material using the thickness of Class 5 base material from the conventional design (D_c) and the equations in Fig. 5. If a_{SPRM} or a_{SRSG} exceeds 1.5, set it at 1.5. Similarly, if a_{SPRM} or a_{SRSG} is less than 1.0, set it at 1.0.

3. Compute the thickness of the alternative base course (D_a) using

$$D_a = \frac{1}{a_a} D_c \tag{8}$$

where $a_a = a_{SPRM}$, a_{SRSG}, a_{RPM}, or a_{RSG} (depending on the material selected).

The following example illustrates the calculation procedure. A deteriorated two-lane asphalt road with low traffic volume will be reconstructed using SRPM as base course. The old HMA will be pulverized and mixed with underlying base and subgrade to create RPM. Fly ash (10% by weight) will be blended with the RPM to increase its strength and stiffness. The following steps are performed to determine the required thickness of the SRPM base layer.

1. Determine the thickness of base course required if the road is reconstructed using conventional Class 5 base course (D_c). This can be accomplished using one of the thickness design procedures described in MnDOT's "Best Practices for the Design and Construction of Low Volume Roads," such as the soil factor design method or the R-value method. For this example, assume that this design procedure employing Class 5 base course yields D_c = 0.30 m (12 in).

2. Determine the gravel equivalency factor for SRPM using D_c = 0.30 m in the appropriate equation from Fig. 5:

$$a_{SRPM} = 0.69(0.30)^{-0.58} = 1.39$$

Since a_{SRPM} is less than 1.5 and greater than 1.0, use the calculated 1.39.

3. The thickness of the alternative base course (D_a) is calculated using Eqn. 8:

$$D_a = \left(\frac{1}{1.39}\right)0.30 = 0.22$$

This computation yields a SRPM base course that is 0.22 m thick (8.7 in). For practical purposes specify a construction thickness of 0.23 m (9 in).

CHAPTER 4. PRACTICAL IMPLICATIONS

4.1 Fly Ash Content

Bench-scale testing conducted in this study on conventional test specimens showed that the summary resilient modulus of SRPM and SRSG increases significantly as the fly ash content is increased (Fig. 6). This behavior is significantly different from that observed in stabilized subgrades, where little increase in modulus is obtained for fly ash contents > 10%.

Although 10% fly ash is most common in practice, designers may wish to increase the fly ash content to increase the modulus of SRPM and SRSG. The following procedure can be used to account for this increase in modulus due to higher fly ash content:

1. Conduct resilient modulus tests on specimens of SRPM and SRSG at 10% fly ash content and the desired fly ash content using AASHTO TP46-94 or the locally adopted method.

2. Determine the summary resilient modulus at 10% fly ash content (SMr_{10}) and at the desired fly ash content (SMr_X at X%). If resilient modulus testing is impractical, conduct unconfined compression tests and estimate the summary resilient modulus using:

   $$SM_{rx} = 3280\ UCS \tag{9}$$

   where SM_{rx} is in MPa and UCS is the unconfined compressive strength (MPa). Eq. 9 was obtained from bench-scale tests on conventional specimens of SRPM and SRSG, as shown in Fig. 7.

3. Compute the gravel equivalency factor for X% fly ash (a_X) using:

   $$a_x = a_{10}\frac{0.249\ \log SMr_x - 0.977}{0.249\ \log SMr_{10} - 0.977} \tag{10}$$

   where a_a is the layer coefficient for 10% fly ash and the summary resilient moduli are in psi. If a_x computed with Eq. 9 exceeds 1.5, set $a_X = 1.5$.

4. Compute the thickness of the alternative base course with X% fly ash (D_X) using:

   $$D_x = \frac{1}{a_x}D_{10} \tag{11}$$

4.2 Curing Time

The LSME tests used to develop the design method described in this report were conducted after 28 d of curing. However, the hydration reactions associated with fly ash in SRPM or SRSG continue for many weeks after initial hydration, resulting in greater cementation and increasing modulus. This effect is shown in Fig. 8, which shows data from bench-scale tests on conventional test specimens of SRPM and SRSG cured for various periods of time.

At this time, there is insufficient information to confirm that increases in modulus occurring in the field are of comparable magnitude as those observed in the laboratory. Thus, no correction for curing time is recommended. Neglecting the temporal increase in modulus due to curing also makes the design method described in Section 3 conservative.

4.3 Freeze-Thaw Deterioration

Freeze-thaw cycling causes volume change and movement of particles in base courses and subgrades, and has the potential to cause a reduction in modulus due to breaking of cement bonds between particles. The effect of freeze-thaw cycling on modulus of SRPM and SRSG was evaluated by conducting bench-scale tests on conventional test specimens that were subjected to 5 cycles of freeze-thaw cycling. This testing regime was selected based on prior studies, which showed that reductions in modulus due to freeze-thaw cycling occur within 5 cycles.

Results of the freeze-thaw tests are summarized in Table 3. Reductions in modulus due to freeze-thaw cycling for SRPM and SRSG ranged between 5 and 15%. These reductions likely are offset by gains in modulus due to additional hydration. Thus, no correction for the effect of freeze-thaw cycling is recommended.

4.4 Field Performance

Mechanical and environmental monitoring data were collected and evaluated at field sites in Waseca, MN and Chisago County, MN where fly ash was used to stabilize recycled alternative base materials. The field site in Waseca employed SRPM as part of a reconstruction project for a city street with an HMA surface. At Chisago County, SRSG was used as base course for an HMA pavement when upgrading a gravel road. Falling weight deflectometer (FWD) tests were conducted at both field sites to assess the modulus of the SRPM and SRSG over time.

For the Waseca site, data from the FWD surveys indicated that the field moduli remained stable over 4 yr, despite several seasons of freezing and thawing. For the Chisago site, FWD testing indicated that the modulus of the SRSG decreased slightly during the first year, but remained stable thereafter at about 350 MPa. These findings indicate that the properties of SRPM and SRSG generally are maintained in the field, even under the severe winter conditions in Minnesota. Periodic monitoring of these field sites with a FWD is recommended to assess the long-term performance of the stabilized recycled base materials.

CHAPTER 5. ENVIRONMENTAL CONSIDERATIONS

5.1 Field Observations

Pan lysimeters were installed beneath the pavement at the field sites in Waseca and Chisago County, MN to measure the rate at which liquid is transmitted by pavement structures and to determine chemical constituents in the liquid that is transmitted (referred to as leachate). Leachate from both sites was analyzed for 20 MPCA soil leaching value (SLV) elements. Column tests were also conducted in the laboratory on samples of the SRPM and SRSG from the field sites. Data from these column tests were used as input when modeling potential ground water impacts at the field sites.

Data were collected from the Waseca lysimeter from 2004 to 2008, with a hiatus in 2006 between funding mechanisms. During the monitoring period, the pavement transmitted approximately 20 mm/yr of leachate. The lysimeter at Chisago County was periodically flooded by perched ground water during snowmelt events. This unanticipated condition rendered data from the Chisago County lysimeter unreliable. Consequently, data collection from the Chisago lysimeter was terminated within one year after installation.

Chemical analysis of leachate from the Waseca lysimeter showed that concentrations of many trace elements were reasonably steady towards the end of the monitoring period, or were decreasing (Fig. 9). During the monitoring period, concentrations of most elements were below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs) established by the Minnesota Dept. of Public Health. Concentrations exceeding MCLs and/or HRLs at least one time included As (MCL exceeded), Pb (MCL exceeded), Sb (MCL and HRL exceeded), and Tl (MCL and HRL exceeded). There is no MCL or HRL for lead (Pb) but there is an “action level” of 15 μg/L that was exceeded. Similarly, there is no MCL or HRL for Mn, but USEPA lists a secondary (nuisance) limit of 50 μg/L that was exceeded. These exceedances were infrequent, only modestly above the MCL or HRL, and were measured at the bottom of the SRPM layer (not in ground water). Thus, these exceedances do not reflect ground water conditions or impacts to ground water. In fact, modeling showed that exceeding MCLs or HRLs in ground water concentration at the edge of the right of way is highly unlikely under most conditions (see Sec 5.2).

5.2 Potential Ground Water Impacts

Potential impacts to ground water were evaluated by conducting simulations with two different programs: WiscLEACH and the Seasonal Soil Compartment Model (SESOIL). WiscLEACH is used in Midwestern states to evaluate potential impacts to ground water from leaching associated with industrial material resources used in roadway construction, including fly ash used to stabilize recycled base materials. SESOIL was used by the Minnesota Pollution Control Agency (MPCA) to develop Soil Leaching Value (SLV) limits that are used to set upper limits in polluted soils to protect groundwater. The MPCA SLV worksheets are used in the Screening Tool for Using Waste Materials in Paving Projects (STUWMPP), which was developed in a previous LRRB project for use in projects considering subgrade stabilization with fly ash.

Simulations were conducted with WiscLEACH in two steps: calibration and assessment. Calibration consisted of simulations of the Waseca site where the seepage velocity was adjusted until reasonable agreement was obtained between concentrations predicted by WiscLEACH and concentrations measured in the lysimeter. Leaching data from column tests conducted on samples of SRPM collected during construction were used as input.

Calibration showed that good agreement between predicted and measured concentrations was obtained using the 75th percentile seepage velocity measured in the field. The calibration was then checked by comparing predictions made for As and Sb concentrations observed in the lysimeter. Good agreement was obtained between these predicted and measured concentrations as well.

Assessment consisted of making predictions of maximum ground water concentrations at the right of way for the Waseca site over a 100-yr period. These simulations showed that concentrations above the MCL at the point of compliance were obtained only for Sb, and these concentrations were only slightly above the MCL. Thus, the potential for ground water impacts at the Waseca site is very small.

Two simulations were conducted using SESOIL. The first was to predict the concentrations for leaching from the SRPM layer and the second was to predict the concentration that is delivered to a water table at a 2 m depth. The SESOIL model, which uses the total concentrations of the elements in the SRPM, over-predicts concentrations in the lysimeter leachate at Waseca, except for Pb and Sb. For many of the more highly mobile elements, the model greatly over predicts leachate concentrations because all of the elements are assumed to be in their most mobile form (adsorption or binding within the mineral structures in the SRPM is not considered).

Modeling of attenuation due to leaching through the subsoil to a depth of 2 m showed that maximum concentrations were reduced by a factor of 8 due to sorption. If the attenuation factor of 8 is applied to the measured concentrations from the lysimeter all of the concentrations are less than the MCL/HRL limits except for Mn and Tl. Both are within a factor of 3.5 of the limit and dilution in the ground water would readily decrease these elements to the MCL/HRL limits. The MPCA uses a default dilution attenuation factor of 10. The redox status of the unsaturated soil zone and the groundwater will be a very important factor in determining Mn concentrations, and air movement into the unsaturated zone under the road will oxidize the mobile Mn^{2+} to immobile MnO_2. As with the WiscLEACH modeling, the SESOIL model results indicate the potential for groundwater impacts at the Waseca site is very small.

5.3 Effect of Site Conditions

Parametric simulations were conducted with WiscLEACH and SESOIL to evaluate how site specific factors affect trace element concentrations in ground water caused by leaching from recycled base materials stabilized with fly ash. Independent variables were varied one at a time in a systematic manner, with all other variables held constant. Input data for the Waseca site were used to define the variables held constant.

Results of these simulations were used to identify conditions that result in lower peak concentrations at the edge of a right of way. The following conditions were identified:

- lower peak concentrations are expected at sites with greater depth to ground water,

- presence of a less permeable layer within the pavement profile (e.g., HMA with low air voids content, fine-grained subgrade, etc.) will reduce peak concentrations in ground water,

- use of a thinner layer of SRPM, when practical, will result in lower peak concentrations, and

- application to narrower roadways, such as city streets and secondary highways, has less impact on ground water than applications on wide highway pavements.

Lower concentrations are also expected at sites where ground water flows more rapidly due to increased dilution. Given the number of factors that may affect peak concentrations at the right of way, site-specific assessments are recommended.

TABLES

Table 1. Index properties for Class 5 base, RPM, and RSG.

Material	D_{50} (mm)	C_u	C_c	G_s	w_{opt} (%)	$\gamma_{d\,max}$ (kN/m^3)	Asphalt Content (%)	LL (%)	PL (%)	Gravel Content (%)	Sand Content (%)	Fines Content (%)	USCS Symbol	AASHTO Symbol
Class 5 Base	2.25	33.3	0.7	2.72	5.0	20.9	-	NP	NP	36.6	59.3	4.1	SP	A-1-a
RPM	3.89	89.5	2.5	2.64	7.5	21.2	4.6	NP	NP	46.0	43.0	10.6	GW-GM	A-1-a
RSG	0.80	40.0	1.0	2.73	7.5	22.6	-	21	14	28.6	59.0	12.4	SC-SM	A-2-4
SRPM	-	-	-	-	8.5	20.4	-	-	-	-	-	-	-	-
SRSG	-	-	-	-	6.6	22	-	-	-	-	-	-	-	-

D_{50} = median particle size, C_u = coefficient of uniformity, C_c = coefficient of curvature, G_s = specific gravity, w_{opt} = optimum water content, $\gamma_{d\,max}$ = maximum dry density, LL = liquid limit, PL = plastic limit, NP = non-plastic.

Note: Particle size analysis conducted following ASTM D 422, G_s determined by ASTM D 854, $\gamma_{d\,max}$ and w_{opt} determined by ASTM D 698, USCS classification determined by ASTM D 2487, AASHTO classification determined by ASTM D 3282, asphalt content determined by ASTM D 6307, and Atterberg limits determined by ASTM D 4318.

Table 2. Physical properties and chemical composition of Columbia fly ash.

Parameter	Columbia	Typical Class C
SiO_2 , %	31.1	40
Al_2O_3 , %	18.3	17
Fe_2O_3 , %	6.1	6
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	55.5	63
CaO , %	23.3	24
MgO , %	3.7	2
SO_3 , %	-	3
CaO/SiO_2	0.8	0.6
$CaO/(SiO_2+Al_2O_3)$	0.4	0.4
Loss on Ignition, %	0.7	6
Fineness (retained on #325 sieve) %	12	-

Table 3. Change in SRM due to freeze-thaw cycling.

Material	Fly Ash Content (%)	Change in SRM (%)
Class 5 base	0	-7.0
RPM	0	14
RSG	0	1.0
RPM	10	-15
RSG	10	-5.0

FIGURES

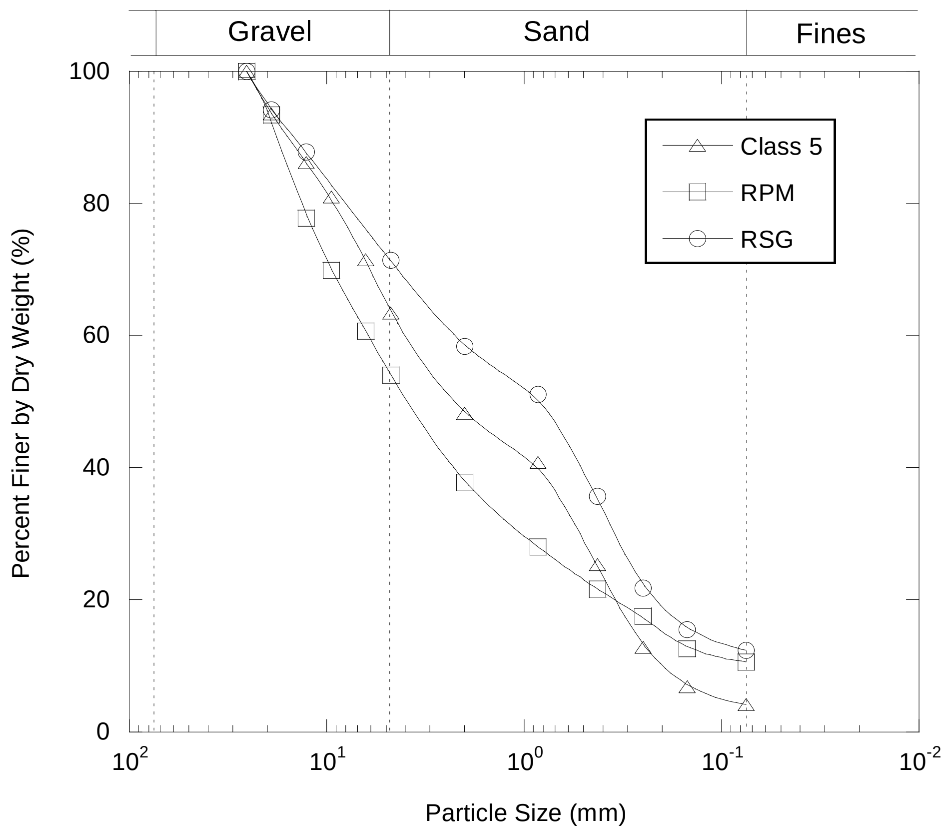

Figure 1. Particle size distributions of Class 5 base, RPM, and RSG used in study.

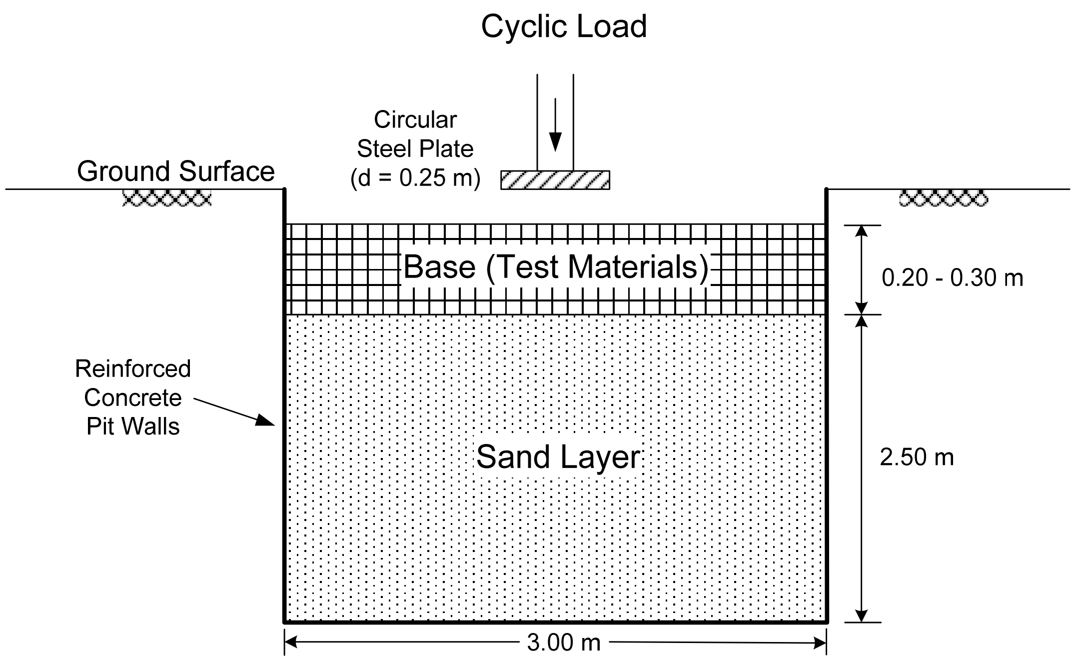

Figure 2. Schematic of LSME used for prototype testing and evaluation.

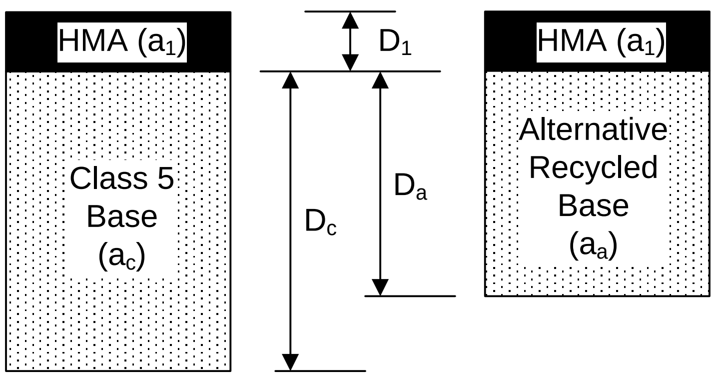

Figure 3. Schematic of profiles for conventional pavement and alternative with recycled base material.

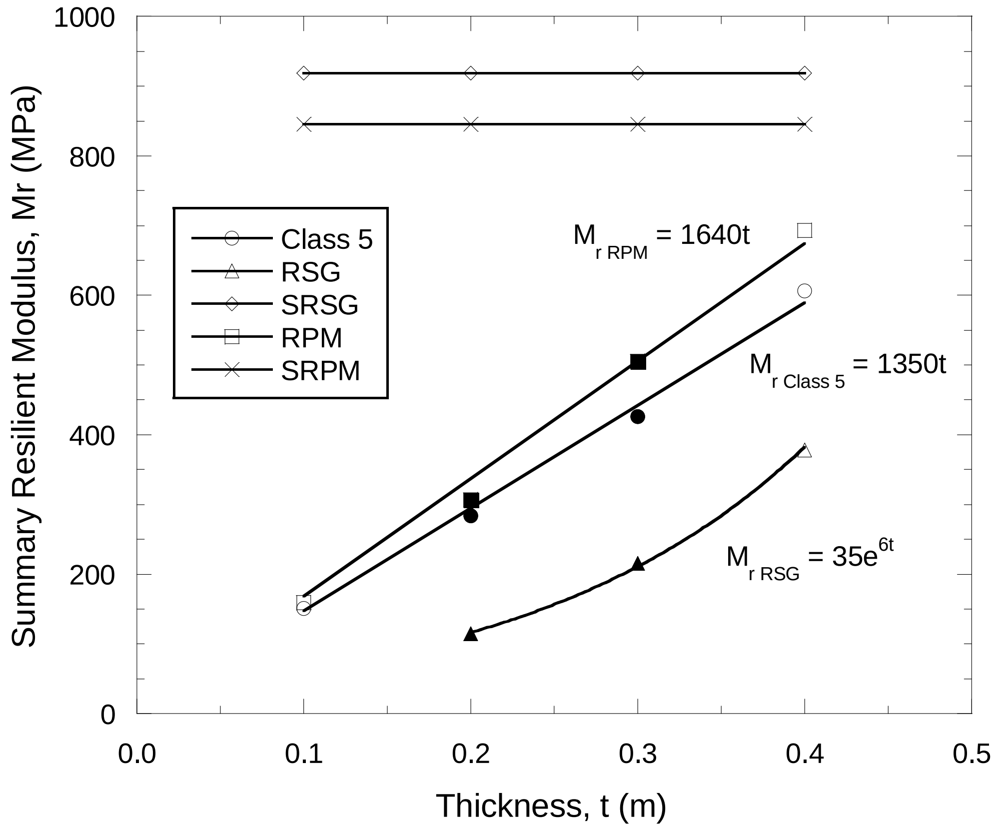

Figure 4. Summary resilient modulus of Class 5 base, RPM, RSG, SRPM, and SRSG as a function of base course thickness.

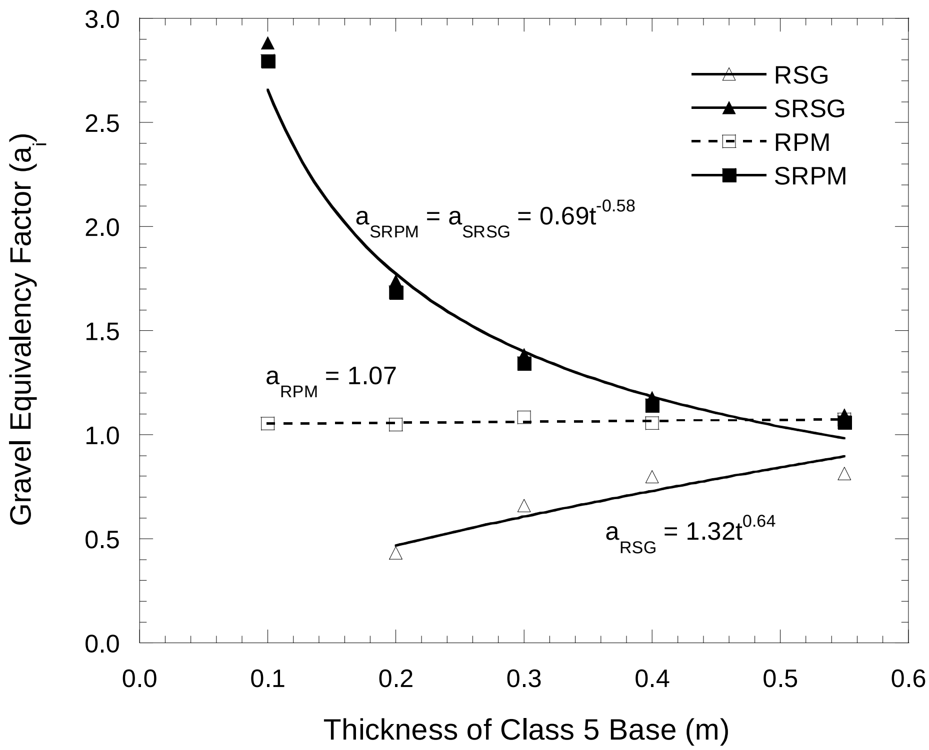

Figure 5. Gravel equivalency factor for RPM, RSG, SRPM, and SRSG as a function of thickness of Class 5 base.

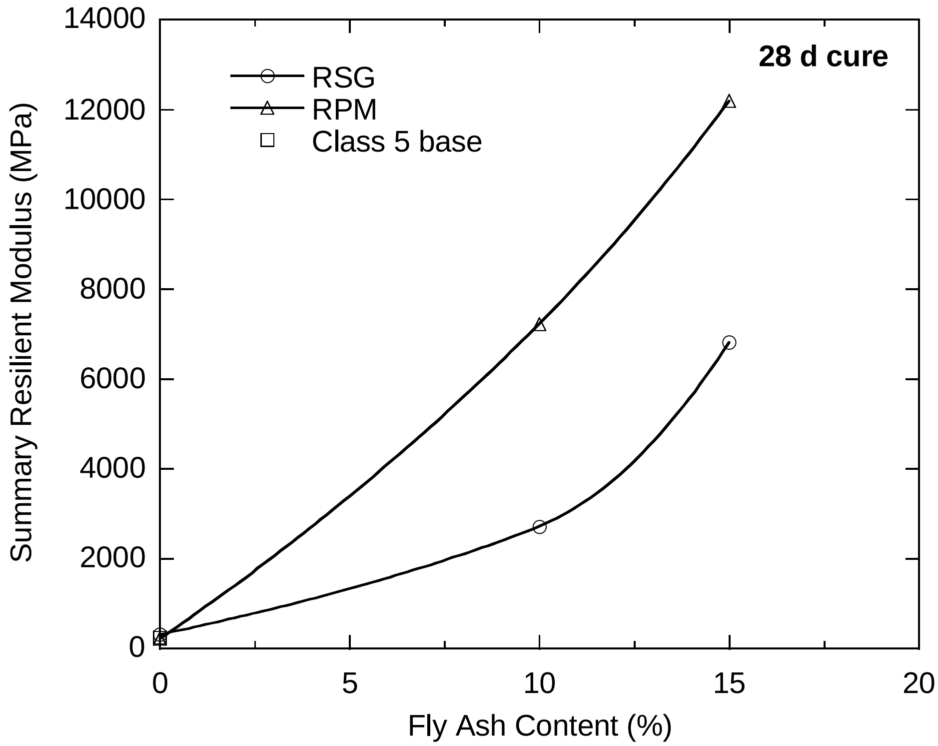

Figure 6. Summary resilient modulus as function of fly ash content for SRPM and SRSG.

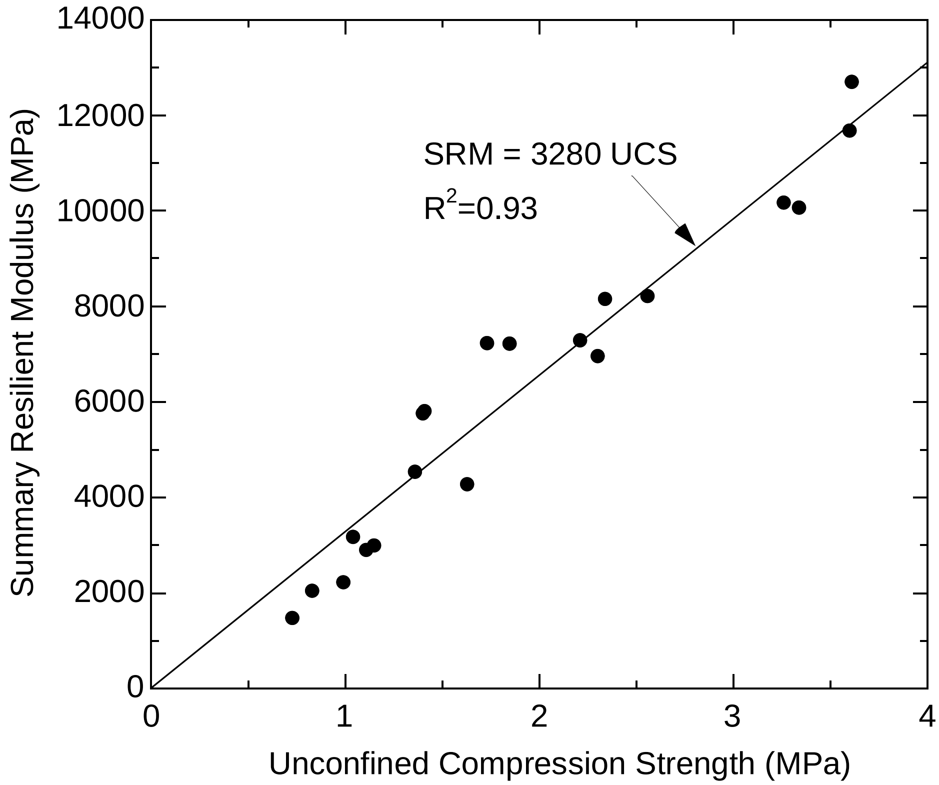

Figure 7. Summary resilient modulus of SRPM and SRSG as a function of unconfined compressive strength.

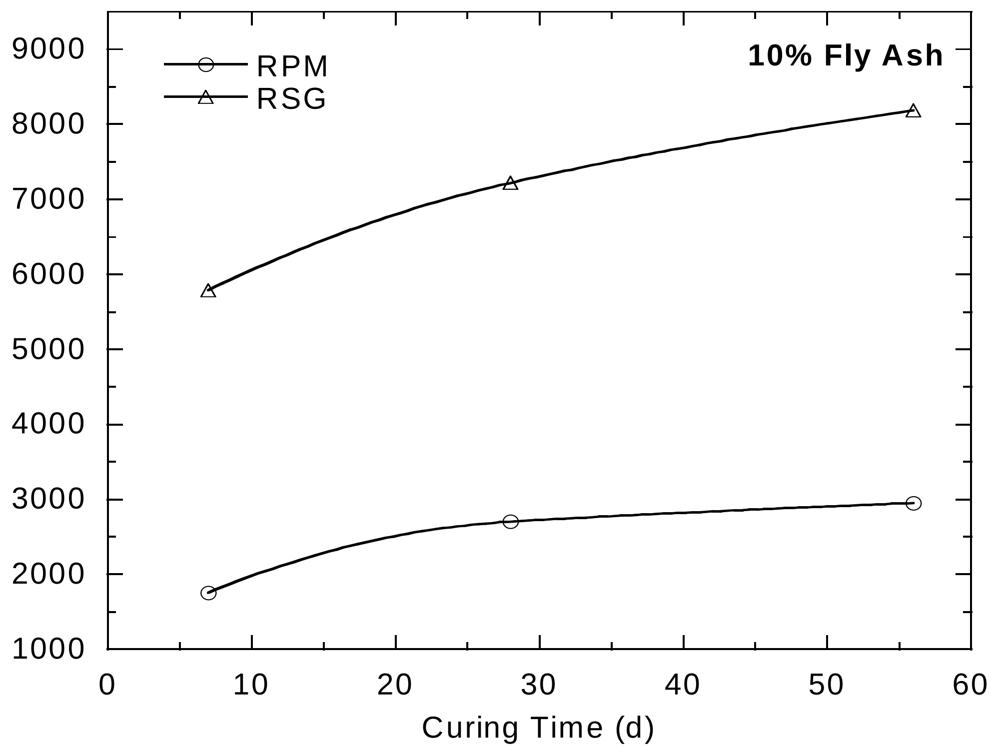

Figure 8. Summary resilient modulus as function of curing time for SRPM and SRSG.

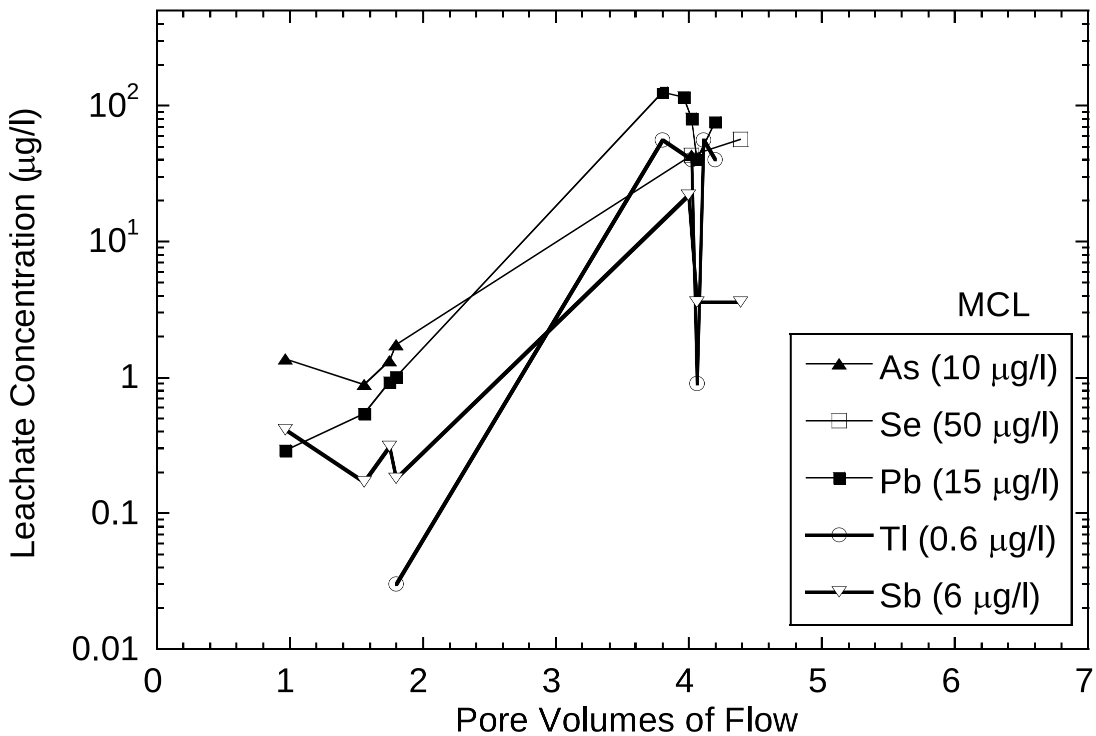

Figure 9. Concentrations of select trace elements in lysimeter at Waseca site.