COAL ASH UTILIZATION IN GRAVEL ROADS AND RECYCLED PAVED ROADS

by

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EXECUTIVE SUMMARY

This report describes two field sites where cementitious fly ashes (Class C and off-specification) were used to stabilize recycled pavement materials (RPM) and road-surface gravel (RSG) to form a base during reconstruction of a city street in Waseca, MN and construction of a flexible pavement in a segment of gravel country road, CR 53 in Chisago County, MN, respectively. The construction method is well established and requires minimal specialty equipment. Construction proceeded smoothly for both projects with experienced specialty contractors. The process is reported to be cost-effective by the project owners.

The projects consisted of mixing fly ash (10% by dry weight) and adding water into the RPM pulverized to a depth of 300 mm and into RSG to a depth of 254 mm, compacting the mixture to form a firm base, and placing an hot mix asphalt surface. California bearing ratio (CBR) and resilient modulus (M_r) tests were conducted on the RPM and RSG alone and fly-ash stabilized RPM (S-RPM) and RSG (S-RSG) mixed in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. *In situ* testing was also conducted on the subgrade and the S-RPM and S-RSG with a soil stiffness gauge (SSG) and dynamic cone penetrometer (DCP). Falling weight deflectometer (FWD) tests were conducted after paving on two different occasions. A pan lysimeter was installed beneath the pavement in each project to monitor the rate of drainage and trace element concentrations in the leachate. Column leaching tests were also conducted on samples of S-RPM and S-RSG collected during construction. Column leach tests were conducted in the laboratory for comparison.

The most important mechanical property of a layer in the pavement structure is its modulus. It is concluded that addition of Class C (self-cementitious) fly ash (typically about 10% by dry weight) improves the stiffness and strength of the base materials, whether RPM, RSG or subgrade soil, significantly. The stabilized material has typically a mean modulus at the end of construction (roughly within 7 days of curing) that is about 1.7-3 times higher than that of the

untreated material for a variety of base materials, that is the material stabilized with fly ash. It is recommended that modulus obtained from laboratory mixed specimens during mix design stage to be reduced by 1/4 to 1/3 to estimate the target resilient modulus obtainable during construction. SSG and DCP can be used as a means of monitoring construction quality. A resilient modulus of minimum 50 MPa appears safe to assume irrespective of the base material at the end of construction due to fly ash stabilization. However, moduli of 100 MPa or more can also be achieved with certain materials.

Modulus developed during construction, however, is likely to change with time due to continuing hydration reactions on one hand and due to environmental exposure such as frost action. The degree of resilient modulus reduction appear to be no more than 50% in the laboratory due to 12 cycles of freeze-thaw for a range of fly ash-stabilized materials although it was less than that for the RPM and RSG. There is no evidence of frost-induced degradation in the field based on FWD surveys over a single season of winter. However, longer term monitoring using FWD surveys is important.

Chemical analysis of the draining leachate from the fly ash-stabilized layers showed that the concentrations of many trace elements were reasonably steady toward the end of the monitoring period. Longer-term monitoring is needed to fully understand the potential for leaching of trace elements during the service life of a pavement. However, during the monitoring period, all of the concentrations (with the exception of Mn) were below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs) established by the Minnesota Department of Public Health. Additional study is also needed to define laboratory leach testing protocols that can more accurately simulate leaching of trace elements from fly ash-stabilized materials.

These field cases show that fly ash stabilization provides an effective and economical means of providing a base for asphalt paving using existing roadway materials.

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1. INTRODUCTION

Utilization of byproducts is becoming a common method to improve the ride quality and structural capacity of roads. Use of self-cementitious fly ash in stabilizing the existing roads (gravel roads or recycled paved roads) to form a stable base for hot mixed asphalt layer is of great interest as this reconstruction approach costs significantly less compared to traditional reconstruction where road surface materials are replaced with new aggregate base (estimated to be 1/3 of the traditional total reconstruction), more rapid and convenient. This approach was implemented in two projects in Minnesota. The first project took place in the City of Waseca, MN and involved reconstruction of a city street (7th Street and 7th Avenue) by fly ash stabilization of recycled pavement materials. The second project involved the conversion of a gravel road (CR 53) to a paved road in Chisago County, MN. The detailed findings related to each of these projects were submitted as individual reports and are attached to this report. This report reviews the data collected at these two sites as well as other fly ash stabilization projects that the investigators monitored in Wisconsin to arrive at some general observations and conclusions. The material descriptions, the tests methods used both in the laboratory and the field, the field data collection and monitoring are described in the attached individual reports and are not repeated here.

2. MODULUS

The most important mechanical property of a layer in the pavement structure is its modulus. As pavement design moves to mechanistic-empirical pavement design methods, as proposed in NCHRP Project 1-37A (*The Mechanistic-Empirical Design Guide for New and Rehabilitated Pavement Structures*), input parameters for fly ash stabilized base materials must be developed for use in this design practice.

2.1. Modulus measured in the Laboratory

There are no standards available for resilient testing of fly ash-stabilized or chemically stabilized materials. Resilient modulus tests on the fly ash–stabilized materials have been conducted by the investigators following the methods described in AASHTO T292. Irrespective of the nature of the base material stabilized by fly ash, the final product becomes essentially “cohesive” due to chemical stabilization. Therefore, the loading sequence for cohesive soils is used. Laboratory resilient modulus tests performed on Class C fly ash-stabilized materials generally showed small dependency on bulk or deviator stresses and can be considered stress-independent for the typical range of stresses expected in the base layer of the type of asphalt paved roads considered here. Therefore, the resilient modulus at the initial stress state of 21 kPa is reported as “modulus”.

Preparation of laboratory specimens of fly ash-stabilized materials, during the mix design phase typically involve mixing of air-dry base material with the desired percentage of fly ash on dry weight basis, addition of the appropriate amount of water, allowing 1-2 hours for reactions (simulating the typical delay in the field), and compaction in special split PVC mold to the desired density or by the standard compaction effort.

The specimen, thus prepared, is cured for a minimum of 7 d but also for longer periods in a 100% relative humidity room in the mold. A 14-d curing period, intended to reflect the condition when most of the hydration is complete, is probably a better indicator of expected modulus but only 7 d of curing is also employed to compare laboratory modulus with the field measurements done after a similar period. After curing, the specimen is removed from the mold and subjected to resilient testing.

While this approach produces reasonably uniform and reproducible specimens (Tastan 2005), there are questions regarding how well it represents the field conditions, especially relative to mixing, curing, and inherent variability of base materials and construction operations. Tube sampling of fly ash-stabilized materials is difficult and often results in sample damage. Therefore, as an alternative, field mixed specimens are used. In this approach the material is sampled immediately after it is mixed during construction. After 1 hour (simulating field operations), the sample is compacted in the resilient modulus specimen mold (and/or CBR mold as appropriate) to the same density measured in that area of the field-compacted stabilized layer. Following the same curing and testing procedures as the laboratory mix specimen, its modulus is determined. Field-mix samples reflect the mixing, moisture, and density conditions that are occurring in the field as closely as possible. Field curing conditions, however, are not replicated. Field experience shows curing takes place rapidly in the field and always is achieved eventually.

The laboratory measured moduli on field-mix specimens of three types of Class C fly ash-stabilized materials are shown in Fig. 1. In this type of box plot, each box encloses 50% of the data with the median value of the variable displayed as a line. The mean value is written in the box. The top and bottom of the box mark the limits of ± 25% of the variable population. The lines extending from the top and bottom of each box mark the minimum and maximum values within the data set that fall within an acceptable range. Any value outside of this range, called an outlier, is displayed as an individual point.

The data in Fig. 1 were obtained from specimens that were made along the project route and incorporate the variability of the base material and construction process. The material in Waseca is a recycled pavement material consisting of a mixture of asphalt, base course, and subgrade materials encountered in the top 300 mm of an existing street. It consists of mostly sand and gravel-size particles, which reflects the presence of the pulverized asphalt and the original base course. The fines were mostly less than 10%. The material in Chisago is road-surface gravel consisting of well-graded gravelly sand with fines in the range of 11 to 14%, the sand content consistently around 60%, and the gravel content about 25%. The data from US 12 from Wisconsin are also presented in Fig. 1 to show the response of natural subgrade soils to fly ash treatment (Edil et al. 2006a). US 12 material consists of natural subgrade soils (classified as CL, SC, and SM according to the USCS or A-7-6, A-6, and A-2-6 according to AASHTO. In each case a Class C fly ash was used (10% by dry weight of Riverside fly ash in Waseca and Chisago and 12% by dry weight of Columbia fly ash in US 12). Water content of the base material also plays a role on mechanical properties. Too dry materials may not have moisture to complete the hydration process and on the other hand excess amount of water (typical of very soft subgrade soils) may result in reduction of mechanical properties. The water contents after mixing fly ash during construction of Waseca, Chisago, and US 12 materials were 7-8%, 6-7%, and 7-15%, respectively. These were the moisture contents measured during construction. All specimens were compacted to the densities achieved in the field during construction. The resilient modulus of the specimens was measured after 7-d curing (14-d for US 12) in a 100% relative humidity room.

The data in Fig. 1 indicate that fly ash stabilized recycled pavement materials and subgrade soils have a resilient modulus in the range of 50-100 MPa whereas road-surface gravels markedly higher (130-180 MPa). It should be remembered water content of US 12 subgrade soil, having more fines and wet conditions during construction was markedly higher than that of Waseca and Chicago materials although they were cured for 14 days. On the other hand, recycled pavement materials may tend to have lower strength gain as a result of fly ash stabilization due to the presence of asphalt in some particles. In a study of recycled pavement materials stabilized by off-specification fly ashes, it was reported that laboratory mixed materials had resilient moduli ranging from 60 to 90 MPa (Wen et al. 2007). In a laboratory study on a wide range of fine-grained subgrade soils in Wisconsin (from high plasticity clays to low plasticity silts and clays), it was reported that resilient modulus depended on soil characteristics such as expressed by group index and water content (Edil et al. 2006b). Such materials can have a wide range of water contents in situ. For the soils (i.e., without fly ash) compacted at optimum water content, M_r varied between 13 to 80 MPa. Resilient moduli of the soil-fly ash mixtures prepared with 10% fly ash at 7% wet of optimum water content typically fall below the moduli of the soils compacted at optimum water content. At 18% fly ash content, however, M_r of the soil-fly ash mixtures at 7% wet of optimum water content were in the range of 50-90 MPa and up to 2.5 times higher than the modulus of the soils compacted at optimum water content. That is, addition of 18% fly ash to a soft and wet subgrade soil results in comparable or higher M_r than the same subgrade soil dried and compacted at optimum water content.

According to a Wisconsin Highway Research Program study (Eggen 2004), the resilient modulus of a wide-variety of crushed aggregate base course materials at a bulk stress of 83-100 kPa (approximate value at the base course level as recommended by NCHRP 1-28A, 2003) varied between about 48 and 110 Mpa. The resilient modulus based on field-mix fly ash-stabilized materials cured and tested in the laboratory, fall in this range for recycled pavement material and is significantly higher for road-surface gravel when stabilized with fly ash. The mean modulus for field-mix and laboratory-mix materials from a variety of projects is tabulated in Table 1. In some cases, only California bearing ratio (CBR) is available. Except for road-surface gravel in Chisago, in all case the field-mix results in lower (60-75%) modulus than the laboratory-mix. The modulus measured on tube samples was available at only one site (US 12) and given in Table 1 (designated undisturbed). The modulus of the field-mix samples (mean=71 MPa) is reasonably close to that of the undisturbed tube samples (mean =82 MPa) within the context of the variation observed in each group. Thus, the field-mix approach can be considered to be an effective method of assessing the *in situ* soil stiffness during construction.

The average laboratory resilient modulus of the unstabilized base material is also given for some projects in Table 1. Adding fly ash increased the modulus of both the recycled pavement material and the road-surface gravel by 1.7 to 3 times.

2.2. Modulus Measured in the Field

Stiffness (or modulus) of the fly ash-stabilized base was measured in the field with a soil stiffness gauge (SSG), a dynamic cone penetrometer (DCP), and a falling weight deflectometer (FWD). There are standards for SSG and DCP and were followed. SSG and DCP can be performed only when the surface of the stabilized base is still uncovered. FWD is an indirect method, however, can be performed any time after the surface is paved and thus allows an assessment of time-dependent changes in the integrity of the materials. It allows monitoring of combined impacts of continuing curing, climatic conditions (moisture and temperature changes), frost action, and continuing traffic loading. Testing with the SSG and DCP was conducted directly on the stabilized surface after approximately 7 d of curing. FWD testing was conducted several times after the HMA was placed and will be continued in coming years.

The results of the SSG and DCP surveys are given in Fig. 2 for both sites. The effect of stabilization and curing is evident in Fig. 2 (SSG stiffness increases and DPI decreases with stabilization). It is possible to calculate an elastic modulus based on the measured SSG stiffness (essentially requires and assumption of Poisson's ratio). The elastic moduli back-calculated from the FWD surveys are given in Fig. 3 for the fly-ash stabilized recycled pavement material in Waseca and road-surface gravel in Chisago at two different times. The field moduli measured in November of the same year of construction (i.e., 2004 for Waseca and 2005 for Chisago) shown in Fig. 3 follow the laboratory moduli measured on field-mix specimens given in Fig. 1, i.e., Chisago moduli are markedly higher than Waseca moduli. The FWD surveys conducted in the year following construction, i.e., August 2005 and May 2006; respectively for Waseca and Chisago are markedly lower than the first survey performed in November. This is consistent with the field temperature and moisture conditions and frost penetration monitored at each site. It is early to make major conclusions. However, the lowest mean field FWD moduli are higher than the mean moduli measured in the field-mix specimens in the laboratory only after 7-d curing. It appears additional time for field curing compensates for the impacts of environmental conditions at least during the first year.

To place the moduli measured by different methods (and also different times), the data are presented in Fig. 4. Moduli obtained from field-mix specimens tested in the laboratory and SSG moduli from the field after 7-d curing and the FWD moduli corresponding to additional curing and exposure are given. Moduli obtained from the resilient modulus test on field-mix samples are lower than those obtained in the field by the SSG or the FWD. It appears that operating moduli of at least 100 MPa can be used for both materials.

2.3. Frost Effect on Modulus

A significant concern in northern climates is frost action on pavement materials. Fly ash-stabilized materials have not been used widely in such frost areas to draw conclusions regarding their long-term performance. On one hand it is argued that materials stronger to begin with will have a greater resistance to the damaging action of frost penetration. Fly ash, being a silt-size material, implies greater propensity for frost action. However, the particles of Class C fly ash, a self-cementitious material like cement, hydrate in the presence of water and bind base material grains together. So it is not likely that the individual size characteristics of unhydrated fly ash will remain and act like silt-soil particles. Addition of fly ash is expected to lower the drainage capability of the base materials. In other words, the fly ash-stabilized base is not likely to have the same drainage capability and ability to shed water as natural base course aggregate.

There is no standard laboratory test to evaluate the effect of freeze-thaw cycles on the mechanical properties such as resilient modulus of soils or fly ash-stabilized soils. There are procedures for soil-cement or concrete products where weight loss and volume change are monitored. Such procedures are aimed at evaluating the potential of such rigid materials to spall and disintegrate. A new procedure, similar to ASTM D 6035 *Standard Test Method for Determining the Effect of Freeze-Thaw on Hydraulic Conductivity of Compacted or Undisturbed Soil Specimens Using a Flexible Wall Permeameter*, is adopted here, in which identical resilient modulus specimens are prepared and subjected to cycles of freeze-thaw and tested for resilient modulus. Weight, volume, and moisture change of these specimens at the end of each freeze-thaw cycle are also monitored. The steps in the procedure are shown in Fig. 5. The freezing temperature was chosen after determining the freezing point depression for each material in accordance with ASTM D 5918 *Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils*. The freezing point depression was -12 °C for Chisago road-surface gravel stabilized with 10% Riverside 8 fly ash and -8.7 to -9.4 °C for Waseca recycled pavement materials stabilized with 10% Riverside 7 fly ash. A standard -15 °C was then applied in each freeze-thaw cycle and resilient modulus tests (and subsequent unconfined compression tests on the same specimens) were performed without freeze-thaw and at the end of 1st, 3rd, and 5th cycles of freeze-thaw on identically prepared specimens. Typically, the changes in modulus take place over 5 cycles based on observations made on fly ash-stabilized soils (Rosa 2006). The base material being granular with relatively low water content (about 7%), the compacted specimens were soaked before the freeze-thaw cycles to generate a conservative moisture condition. This resulted in about 4-5% water content gain. The volume of all specimens increased by about 2.5% at the end of 5 cycles of freeze-thaw.

In Fig. 6, resilient moduli of the base materials (without fly ash addition and without freeze-thaw but soaked) are given along with moduli obtained after fly ash stabilization (without freeze-thaw) and after the last freeze-thaw cycle (5th cycle) of the fly ash stabilized base materials (one road-surface gravel sample from Chisago and two recycled pavement materials from Waseca) are presented. A general trend of higher resilient modulus when the base materials are stabilized with fly ash even after freeze-thaw cycles compared to unstabilized soils without freeze-thaw cycles is clearly observed. Both base materials showed decrease in resilient modulus after soaking and subjecting them to freeze-thaw cycles.

Resilient modulus of the specimens that were subjected to freeze-thaw cycles were normalized by the resilient modulus of the specimen that was not subjected to any freeze-thaw cycles to determine the loss of property due to freeze-thaw. The results, shown in Fig. 6, indicate that resilient modulus drop by 17% after 5 cycles of freeze-thaw for fly ash-stabilized road-surface gravel and 25-42% for recycled pavement material. Rosa (2006) performed freeze-thaw tests on a variety of materials including fine-grained soils alone and stabilized with fly ash. The degree of resilient modulus reduction varied with the type of material but remained to be no more than 50%. From these results can be concluded that for highway design, the safest way to represent the effect of freeze-thaw cycling on the resilient modulus of the fly ash stabilized materials is dividing the modulus of the material not subjected to freeze-thaw by 2. However, one also needs to take into account the time-dependent modulus gain due to continuing hydration reactions.

Previous research published that reduction on stiffness after freeze-thaw cycles can be attributed to that the freezing temperatures dominate and retard the cementitious/ pozzolanic reactions. When no variation or minimal variation in stiffness is observed after freeze-thaw cycles is attributed to that the freezing and thawing temperatures compensates each other producing a balance in the cementitious/pozzolanic reactions. And increase on stiffness after freeze-thaw cycles is also observed and attributed to that the thawing temperatures dominates and accelerates the cementitious/pozzolanic reactions.

2.4. Correlation of Modulus with Other Properties and Tests

Laboratory assessment of the resilient modulus of the fly ash stabilized materials was supplemented additional laboratory and field tests. The relationship of the resilient modulus of field-mix specimens to the CBR of similarly field-mixed specimens is shown in Fig. 8 for Chisago and Waseca but also two other sites in Wisconsin where natural soils were stabilized with Class C fly ash (US 12). There is a general tendency of increasing modulus with increasing CBR but correlation for different materials is different. Empirical correlations between modulus and CBR have been proposed for natural soils by a number of researchers. For example, Powell et al. (1984) developed an equation relating the elastic modulus obtained by wave propagation techniques and CBR. After accounting for stress and strain level characteristic of pavements, Powell et al. (1984) obtained:

$$E = 17.6\ CBR^{0.64} \tag{1}$$

where E (essentially equivalent of resilient modulus) is in MPa and CBR is in percent. Another well-known relationship that is widely used in North America was proposed by Heukelom and Foster (1960):

$$M_r = 10\ CBR \tag{2}$$

where M_r is the resilient modulus in MPa. Eq. 2 is included in the AASHTO (1993) guide for design of pavements.

Eqs. 1 and 2 are shown with the data reported for soil-fly ash mixtures in Fig. 8. Both equations, developed using natural soils, over-predicted M_r for soil-fly ash mixtures, with the over-prediction being much greater for Eq. 2. Sawangsuriya and Edil (2004) also report that Eq. 2 tends to over-predict M_r appreciably for natural soils. A better prediction was obtained by Edil et al. (2006b) with:

$$M_r = 3\ CBR \tag{3}$$

which was obtained by linear least-squares regression of the data based of a range of laboratory-mix fly ash-stabilized fine-grained soils by Edil et al. (2006b). Eq. 3 also represents Waseca and Chisago data reasonably well.

To assess the structural properties of the pavement materials, the DCP penetration index (DPI) values are usually correlated with the CBR of the pavement materials. Extensive research has been conducted to develop an empirical relationship between CBR and DPI for a wide range of pavement and subgrade materials. These include research by Livneh (1987), Kleyn (1975), Harisson (1987), Webster et al. (1992), and others. Based on their researches, many of the relationships between CBR and DPI can be quantitatively presented in the form of:

$$\log(\mathrm{CBR}) = \alpha + \beta \log(\mathrm{DPI}) \tag{4}$$

where α and β are coefficients ranging from 2.44 to 2.56 and -1.07 to -1.16, respectively, which are valid for a wide range of pavement and subgrade materials. Note also that CBR is in percent and DPI is in millimetres per blow (mm/blow). For a wide range of granular and cohesive materials, the US Army Corps of Engineers use the coefficients α and β of 2.46 and -1.12, which have been also adopted by several agencies and researchers and is in general agreement between the various sources of information. Livneh et al. (1995) also show that there exists a universal correlation between CBR and DPI for a wide range of pavement and subgrade materials, testing conditions, and technologies. In addition, the relationship between CBR and DPI is independent of water content and dry unit weight since both water content and dry unit weight equally influence CBR and DPI.

The CBR-DPI data collected at Waseca and Chisago projects are plotted in Fig. 9 along with similar data from three projects in Wisconsin where subgrade soils were stabilized by Class C fly ash (US 12, Scenic Edge, and STH 60). Also plotted is the relationship given in Eq. 4 with α and β coefficients 2.46 and -1.12, respectively. Although there is some scatter, this relationship appears to represent also the CBR-DPI relationship for a wide variety of fly ash-stabilized base materials.

The relationship of resilient modulus measured on field-mix specimens compared to SSG stiffness measured in the field at the vicinity of the location (i.e., station) where the resilient modulus specimen was made is shown in Fig. 10 for Waseca and Chicago projects as well as US 12 where subgrade soils were stabilized with fly ash. There is a general correlation but also significant scatter. The data indicate that resilient modulus is mostly larger than 50 MPa and SSG stiffness is greater than 12 for fly stabilized materials.

3. ENVIRONMENTAL SUITABILITY

Fly ash, being an industrial by-product, its use is subject to environmental regulation. Minnesota Pollution Control Agency permits use of fly ash in various applications and typically the agency permits individual fly ash for use based on the chemical composition provided by the producer. A computer mixing model that uses the total composition in fly ash–soil mixtures and compares total concentrations to Minnesota Pollution Control Agency (MPCA) guidance for residential cleanup using Soil Reference Values (SRV) and Soil Leaching Values (SRV) worksheets has been developed by Dr. Paul Bloom of the University of Minnesota. The SRV values provide guidance for protection of human health assuming some stabilized subsoil could, in the distant future, be used in a residential area. The SRV guidance, which is based on leaching of ions and compounds (predicted by the SESOIL transport model), is designed for the protection of groundwater. Earlier Bloom and Gollany (2001) conducted a field investigation of runoff from fly ash stabilized soils and found that the runoff is not high in problematic elements. A user-friendly computer model (WiscLEACH) was developed to predict the maximum concentration of contaminants in groundwater adjacent to roadways using fly ash stabilization (Li, Hatipoglu, Benson, and Edil 2006). Analyses with WiscLEACH showed that in most cases where fly ash is placed above the groundwater table, impacts to groundwater are negligible. However, the level of impact depends on the type and amount of metals in the fly ash, nature of the base material being stabilized (i.e., sorption capacity), and the type of soils in the vadose zone, and depth and velocity of groundwater.

To provide actual field data of the leachate from the fly-ash stabilized layer in this project, an environmental monitoring program that consists of monitoring the volume of water draining from the pavement, concentrations of trace elements in the leachate, temperatures and water contents within the pavement profile, and meteorological conditions (air temperature, humidity, and precipitation) was initiated. Monitoring of the pavement began in October 2004 in Waseca and October 2005 in Chisago and is still being conducted.

Leachate draining from the pavement was monitored using a pan lysimeter installed under the fly ash-stabilized layer in both projects. The lysimeter is 4 m wide, 4 m long and 200 mm deep and is lined with 1.5-mm-thick linear low density polyethylene geomembrane. The base of the lysimeter was overlain by a geocomposite drainage layer (geonet sandwiched between two non-woven geotextiles). Water collected in the drainage layer is directed to a sump plumbed to a 120-L polyethylene collection tank buried adjacent to the roadway. The collection tank is insulated with extruded polystyrene to prevent freezing. Leachate that accumulates in the collection tank is removed periodically with a pump. The volume of leachate removed is recorded with a flow meter, a sample for chemical analysis is collected, and the pH and Eh of the leachate are recorded. The sample is filtered, preserved, and analyzed.

3.1 Trace Elements in Lysimeter Drainage

Approximately 1.8 and 16 pore volumes of flow (PVF) have passed through the fly ash-stabilized layers during the monitoring period, in Waseca and Chisago (Waseca was monitored for two years whereas Chisago one year and is much drier than

Chisago), respectively. During this period, pH of the drainage has been near neutral and oxidizing conditions have prevailed.

Concentrations of trace elements in drainage from the lysimeter in Waseca are shown in Fig. 11 as a function of PVF. Elements with peak concentrations between 3 and 102 μg/L are shown in Fig. 11a, whereas those with peak concentrations less than 2.5 μg/L are shown in Fig. 11b. Elements not shown in Fig. 11 include those below the detection limit (Be, Ag, Hg, Se, and Tl) and elements not typically associated with health risks (Ca and Mn). All of the concentrations are below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs). The exception is Mn (not shown in Fig. 11), which typically had concentrations between 1 and 2 mg/L. The Minnesota HRL for Mn currently is 100 μg/L, but plans exist to increase the HRL to 1.0-1.3 mg/L (www.pca.state.mn.us). USEPA does not have a MCL for Mn.

Most of the concentrations appear to be increasing, with a more rapid increase towards the end of the monitoring. Thus, higher concentrations are likely to be observed for many of the elements as the lysimeter is monitored in the future. However, concentrations of some elements appear to be decreasing (Mo and Sr) or remaining steady (Sb and Sn). The lack of a steady-state condition or clearly diminished concentrations for most of the trace elements highlights the need for longer term monitoring of the lysimeter.

Concentrations of trace elements in drainage from the lysimeter in Chisago are shown in Fig. 12 as a function of PVF. Fig. 12 Fig. 12is divided into three parts: high concentration, moderate and persistent, and low and diminishing concentration. Elements not shown in Fig. 12 include those below the detection limit (Be, Ag, Hg, and Tl) and elements not typically associated with health risks (e.g., Ca). All of the concentrations are below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs). The exception is Mn, which had a maximum concentration of 3,682 ug/L and exceeded the Minnesoata HRL of 100 ug/L. However, the Minnesota Department of Health no longer recommends the HRL value and plans exist to increase the HRL to 1,000 to 1,300 ug/L (www.pca.state.mn.us). USEPA does not have a primary criterion for Mn although there is a secondary criterion. Most of the concentrations appear to be stabilizing and persistent. Concentrations of some elements appear to be low and decreasing (Pb, Sb and Sn).

3.2 Trace Elements in Column Leaching Tests Effluent

A column leaching test (CLT) test was performed using material from field mix in Waseca. The elution behavior observed in the CLT effluent follows two patterns: (i) delayed response (Co, Cr, Pb, Se, Cu, and Zn), where the concentration initially increases and then falls, and (ii) persistent leaching (B, Ba, Sr, Mo, As, and V), where the concentration initially increases and then remains relatively constant. The data indicate that the trace element concentrations in the CLT effluent typically are higher than concentrations in the drainage collected in the field (Fig. 11). The poor agreement suggests that the CLT test method that was used may not be appropriate for evaluating leaching of trace elements from S-RPM, unless a conservative estimate of the trace element concentrations is acceptable. Despite the higher concentrations obtained from the CLT, most of the elements have concentrations below USEPA MCLs and Minnesota HRLs. The exceptions are for B, Pb, Se, and Sr. The peak Mn concentration was also above the current Minnesota HRL for Mn, but is less than the proposed HRL.

Two column leaching tests were performed using material from field mix in Chisago. The elution behavior observed in the CLT effluent follows two patterns: (i) first-flush response, where the concentration falls from an initially high value and then remains nearly constant, and (ii) persistent leaching, where the concentration initially increases and then remains relatively constant. The trace element concentrations in the CLT effluent typically are higher than concentrations in the drainage collected in the field in the lysimeters (Fig. 12). The poor agreement suggests that the CLT test method that was used may not be appropriate for evaluating leaching of trace elements from S-RSG, unless a conservative estimate of the trace element concentrations is acceptable. Despite the higher concentrations obtained from the CLT, most of the elements have concentrations below USEPA MCLs and Minnesota HRLs. The exceptions are for B, Be, Cr, Ba,As, and Se. Additional study is also needed to define laboratory leach testing protocols that can more accurately simulate leaching of trace elements from S-RSG.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Two field case histories have been described where Class C and off-specification cementitious fly ashes (10% by weight) were used to stabilize recycled pavement material (RPM) and road-surface gravel (RSG) during construction of a flexible pavement. The construction method is well established and requires minimal specialty equipment. Construction proceeded smoothly for both projects with experienced specialty contractors. The process is reported to be cost-effective by the project owners.

California bearing ratio (CBR) and resilient modulus (M_r) tests were conducted on the RPM and RSG alone and on the fly-ash stabilized RPM (S-RPM) and RSG (S-RSG) mixed in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. *In situ* testing was also conducted on the subgrade and S-RSG with a soil stiffness gauge (SSG) and dynamic cone penetrometer (DCP). Falling weight deflectometer (FWD) test were conducted after paving on two different occasions. A pan lysimeter was installed beneath the pavement in each project to monitor the rate of drainage and trace element concentrations in the leachate. Column leaching tests were also conducted on samples of S-RPM and S-RSG collected during construction.

The most important mechanical property of a layer in the pavement structure is its modulus. As pavement design moves to mechanistic-empirical pavement design methods, as proposed in NCHRP Project 1-37A (*The Mechanistic-Empirical Design Guide for New and Rehabilitated Pavement Structures,*), input parameters for fly ash stabilized base materials must be developed for use in this design practice. Therefore, resilient modulus data as measured or inferred by a variety of methods are analyzed from both projects as well as a number of other fly ash stabilization projects available to the investigators. It is concluded that addition of Class C (self-cementitious) fly ash (typically about 10% by dry weight) improves the stiffness and strength of the base materials, whether RPM, RSG or subgrade soil, significantly. The stabilized material has typically a mean modulus at the end of construction (roughly within 7 days of curing) that is about 1.7-3 times higher than that of the untreated material for a variety of base materials. Fly ash stabilization reduces variability in measured modulus compared to the variability encountered in natural soils. Resilient modulus of fly ash stabilized materials does not exhibit the non-linear stress dependency typical of soils for the typical range of bulk and deviator stresses expected in the pavement structure and in future a single modulus can be used simplifying the design.

Measurement of the modulus of fly ash stabilized materials, however, is not easy because of the difficulty of obtaining undamaged tube samples. Field mixed specimens typically give a modulus that is only 60 to 75% of that of laboratory mixed specimens. It is recommended that modulus obtained from laboratory mixed specimens during mix design stage to be reduced by 1/4 to 1/3 to estimate the target resilient modulus obtainable during construction. SSG modulus obtained in situ during construction within 7 days of curing is 50% or higher than resilient modulus measured in the laboratory on field mix specimens made during construction. This reflects to a certain degree the lower strain amplitude employed in SSG compared to resilient modulus test. There is a general correlation of resilient modulus to SSG modulus so SSG can be used as a means of monitoring construction quality. Because of general inverse correlation of DPI and SSG stiffness, DPI can also be used for monitoring quality control during construction. Resilient modulus of fly ash stabilized materials is also correlated with their CBR and therefore with DPI in a manner similar to those correlations observed in natural soils. Therefore, such tests can be used for fly ash stabilized materials and the data provided in this report provide a basis of specifying acceptable levels in terms of these tests. A resilient modulus of minimum 50 MPa appears safe to assume irrespective of the base material at the end of construction due to fly ash stabilization. However, moduli of 100 MPa or more can also be achieved with certain materials.

Modulus developed during construction, however, is likely to change with time due to continuing hydration reactions on one hand and due to environmental exposure such as frost action. At a Wisconsin site (STH 60) where low plasticity silty and clayey subgrade soils were stabilized by fly ash, FWD moduli continued to increase over six years of monitoring. The degree of resilient modulus reduction appear to be no more than 50% in the laboratory due to many freeze-thaw cycles for a range of fly ash-stabilized materials although it was less than that for the RPM and RSG. There is no evidence of frost-induced degradation in the field based on FWD surveys over a single season of winter. However, longer term monitoring using FWD surveys is important to understand the behavior of these new materials with which there is limited field record. Currently, another 2 years of monitoring is assured through new projects of the investigators.

Chemical analysis of the draining leachate from the fly ash-stabilized layers showed that the concentrations of many trace elements were reasonably steady toward the end of the monitoring period. Longer-term monitoring is needed to fully understand the potential for leaching of trace elements during the service life of a pavement. However, during the monitoring period, all of the concentrations (with the exception of Mn) were below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs) established by the Minnesota Dept. of Public Health. The trace element concentrations in the column leaching test (CLT) effluents typically are higher than concentrations in the drainage collected in the field in the lysimeters. The poor agreement suggests that the CLT test method that was used may not be appropriate for evaluating leaching of trace elements from fly ash-stabilized materials, unless a conservative estimate of the trace element concentrations is acceptable. Despite the higher concentrations obtained from the CLT, most of the elements have concentrations below USEPA MCLs and Minnesota HRLs. Additional study is also needed to define laboratory leach testing protocols that can more accurately simulate leaching of trace elements from fly ash-stabilized materials.

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Table 1 Resilient modulus gain by fly ash stabilization and comparison of field and laboratory-mix specimens from various projects

Project	Base Material	Fly Ash Content (%)	Lab-Mix M_r (MPa)	Field-Mix M_r (MPa)	Undis-turbed M_r (MPa)	Field-Mix/Lab-Mix M_r Ratio	Base Material M_r (MPa)	M_r Gain due to Fly Ash Stabilization
Waseca	RPM	10	104	78		0.75	47	1.7
Chisago	RSG	10	112	153		0.73	51	3
US 12	SS*	12	-	73	82		38	1.9
STH 32	SS	10	13.4	21		0.63	12.4	1.7
STH60	SS	10	99 (CBR 32)	(CBR 23)		0.72	Very soft	High
Scenic Edge	SS	12	115 (CBR 37)	(CBR 28)		0.76	Very soft	High

* subgrade soil

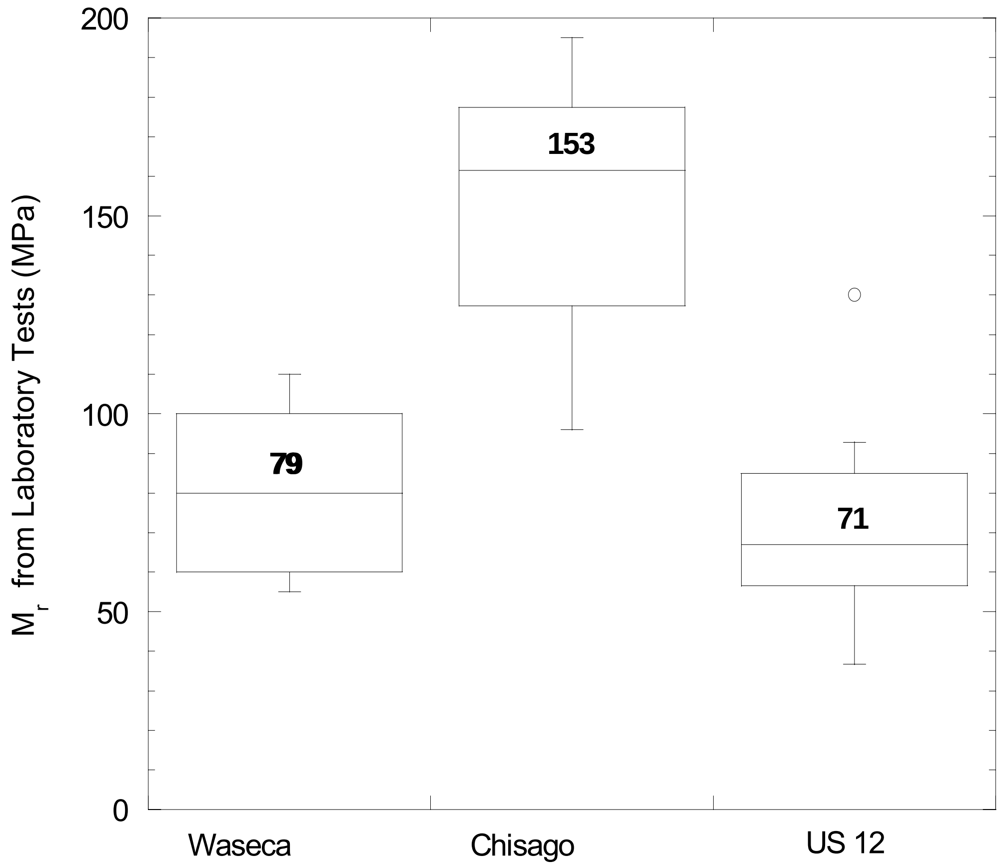

Fig. 1 Laboratory Mr of field-mix fly ash-stabilized materials (numbers on the boxes indicate mean modulus)

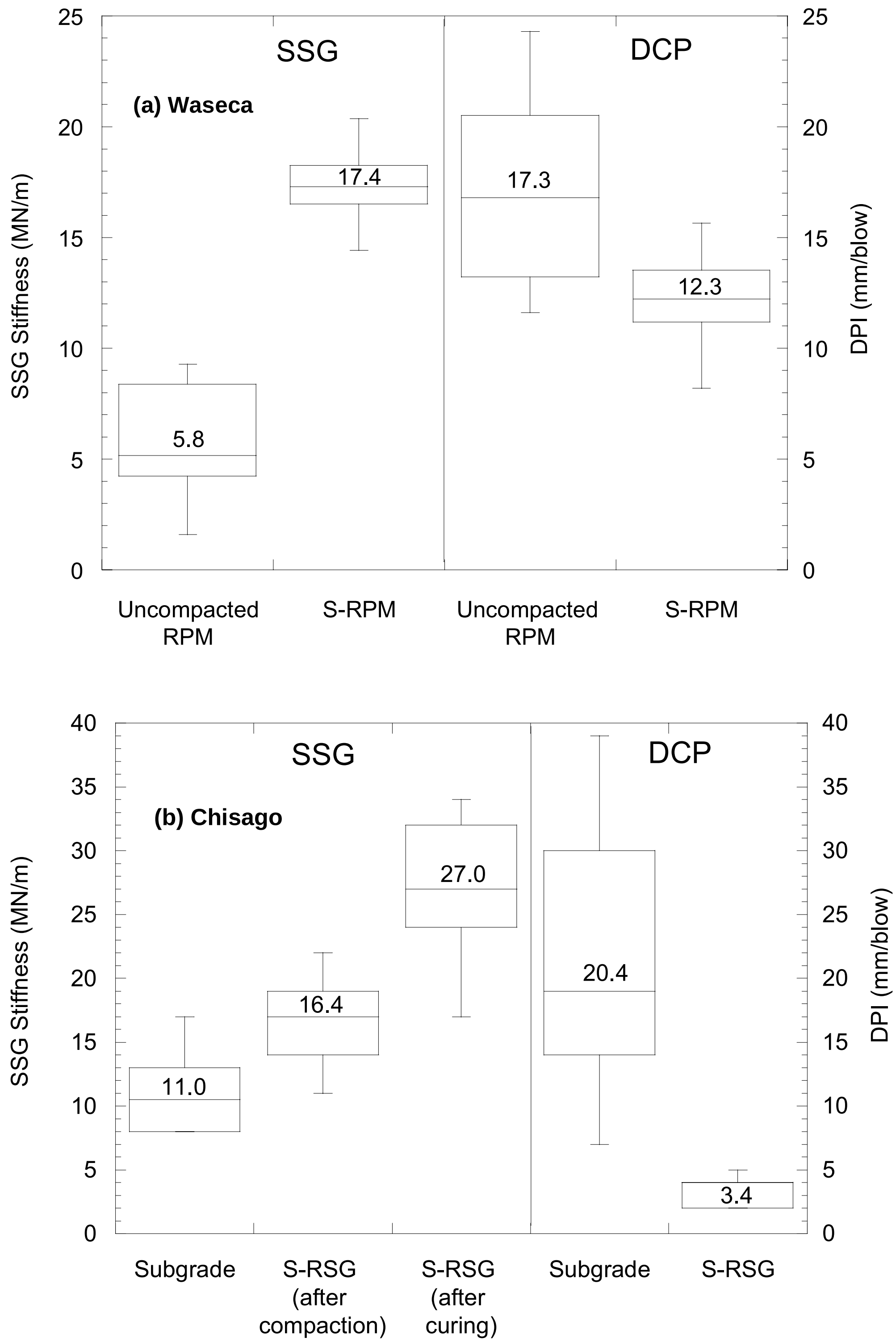

Fig. 2 Stiffness and DPI of base material and fly ash-stabilized recycled pavement material and road surface gravel (numbers on the boxes indicate mean value)

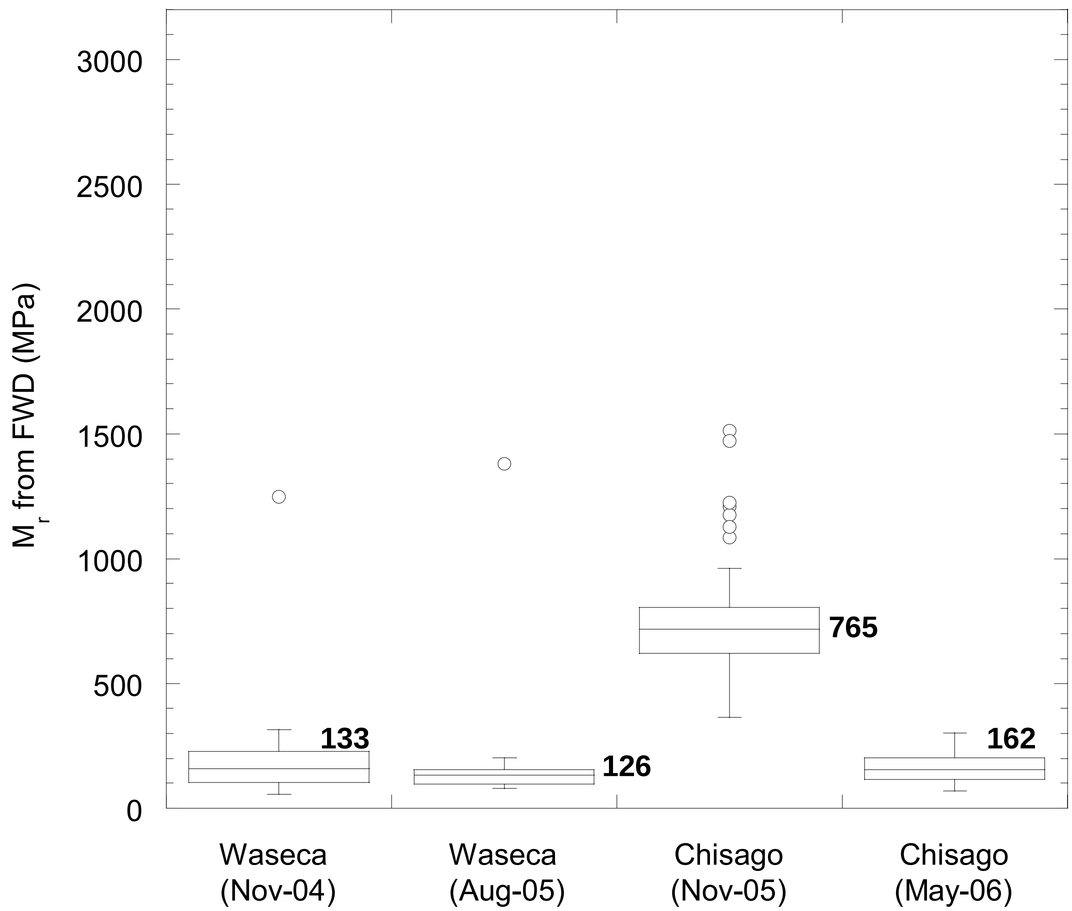

Fig. 3 Back-calculated Mr of fly ash-stabilized layer from FWD data at Waseca and Chisago projects (numbers on the boxes indicate mean modulus)

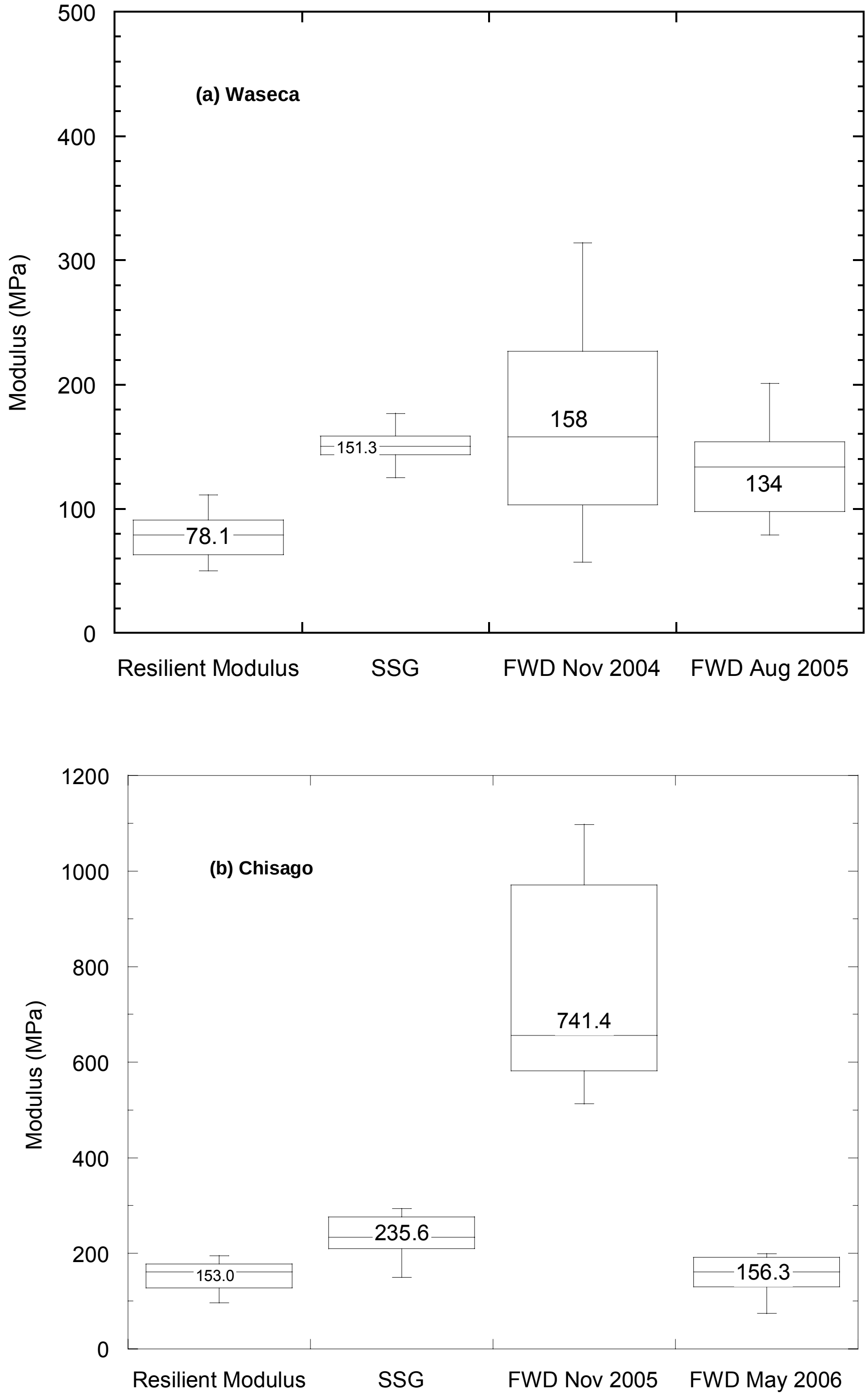

Fig. 4 Modulus as determined by different methods (numbers on the boxes indicate mean modulus)

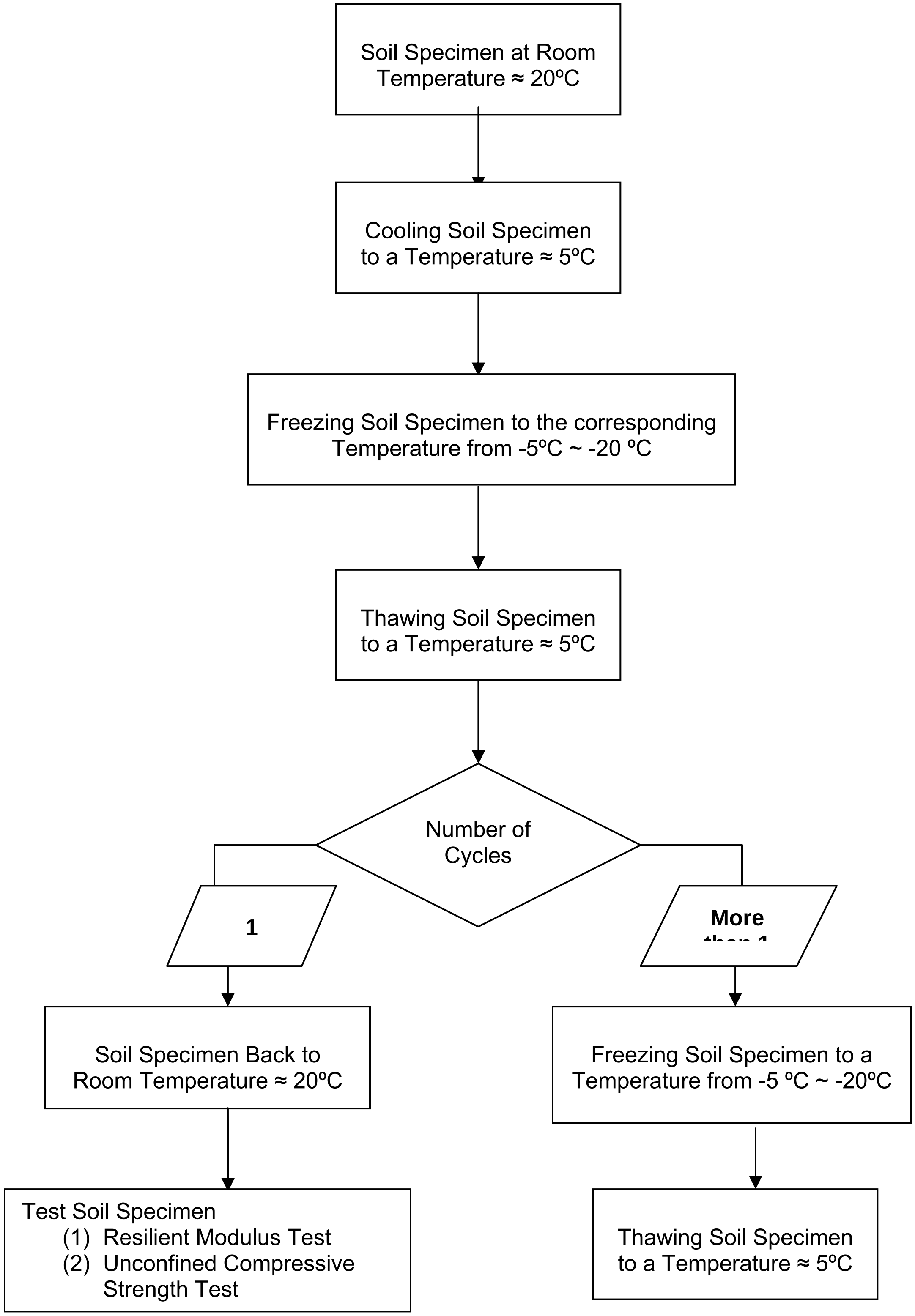

Fig. 5 Description of the process used for freeze-thaw cycling

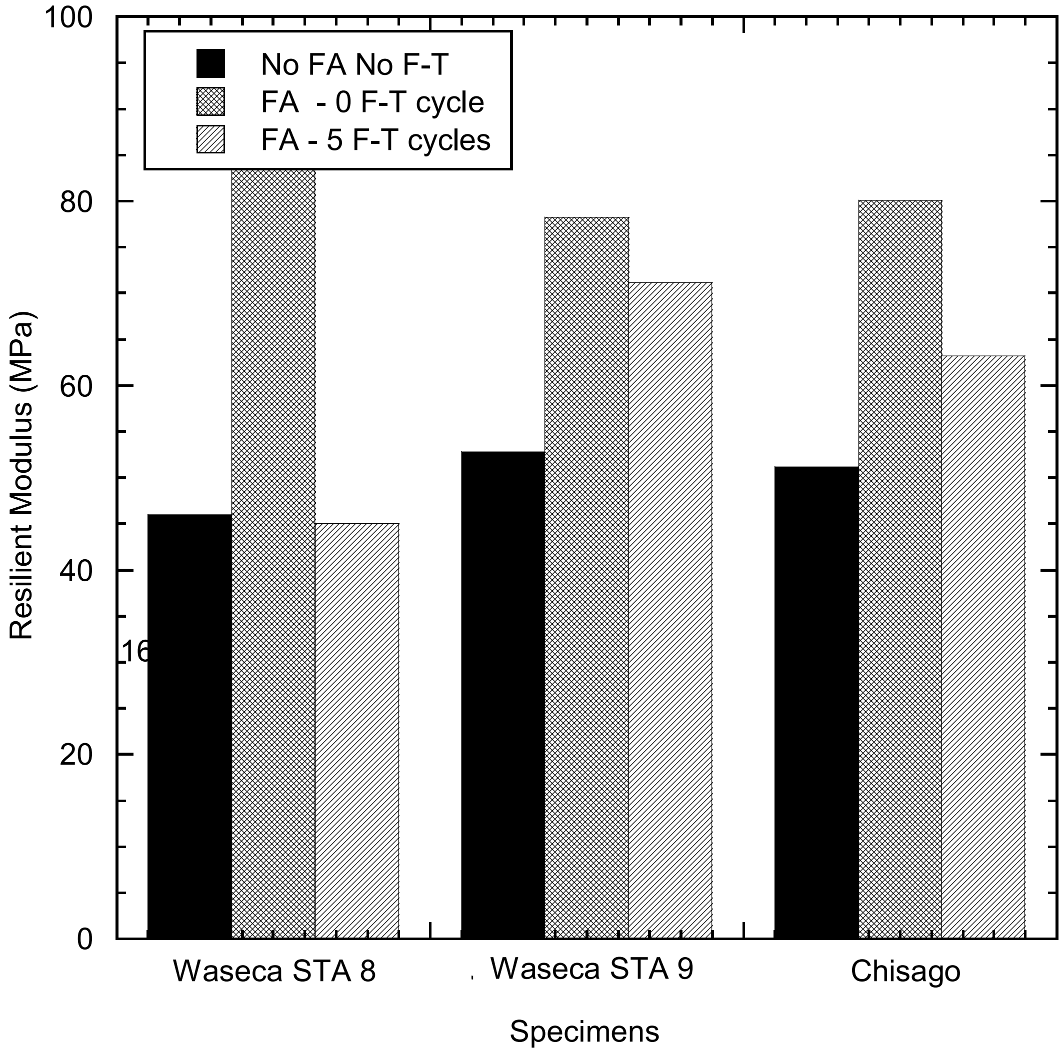

Fig. 6 Comparison of the resilient modulus values without fly ash and unfrozen with the resilient modulus of the fly ash-stabilized base materials after 5 of freeze-thaw

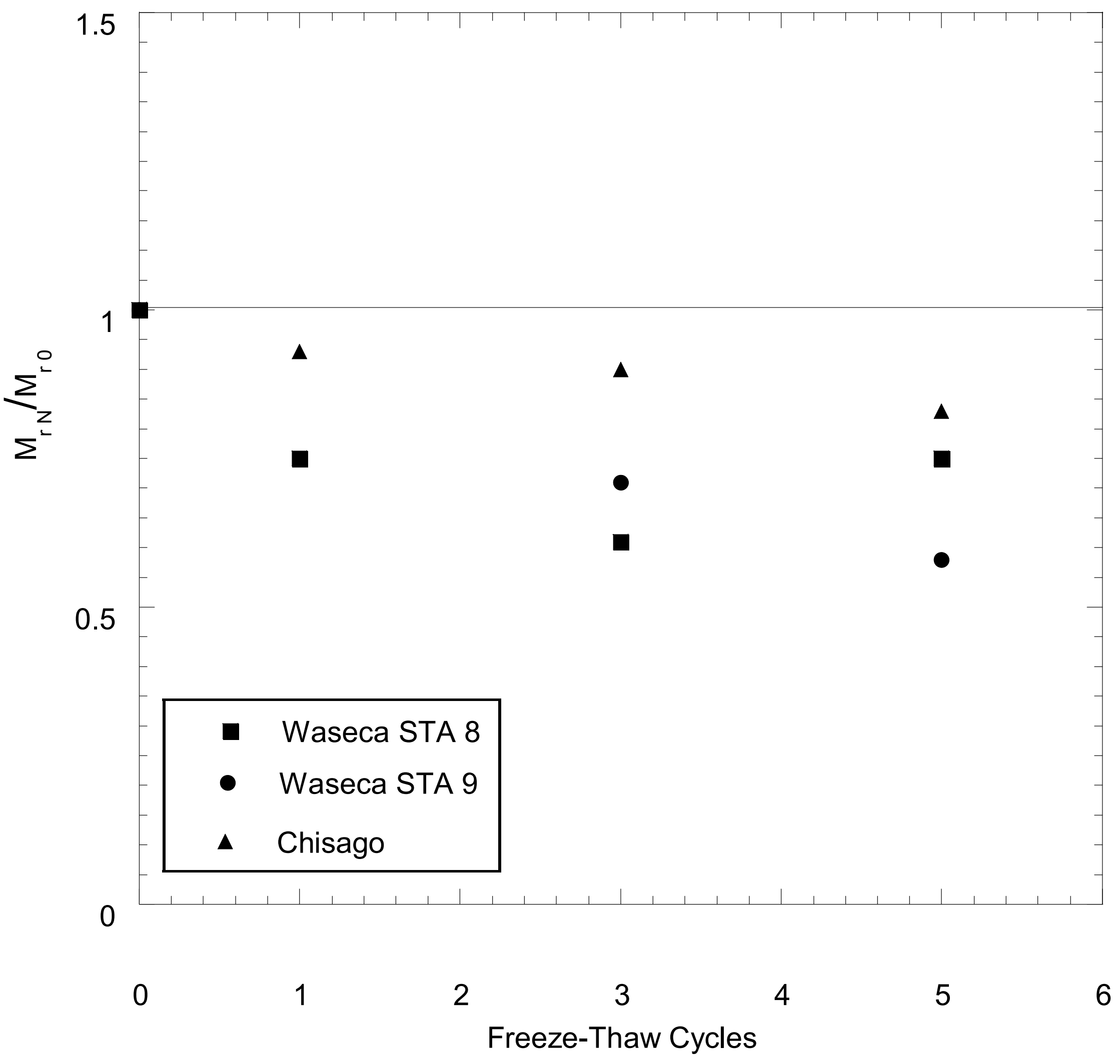

Fig. 7 Normalized resilient modulus vs. freeze-thaw cycles for fly ash-stabilized materials at Waseca and Chisago

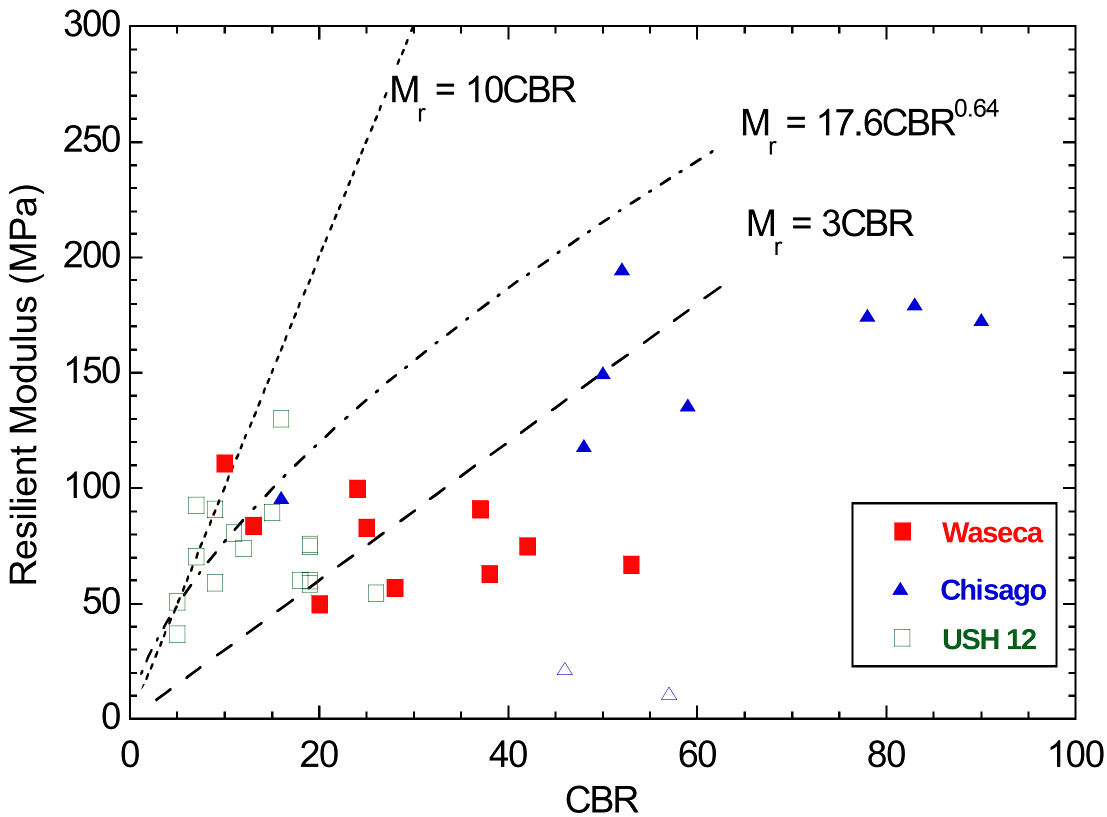

Fig. 8 Resilient Modulus versus CBR for fly ash-stabilized materials

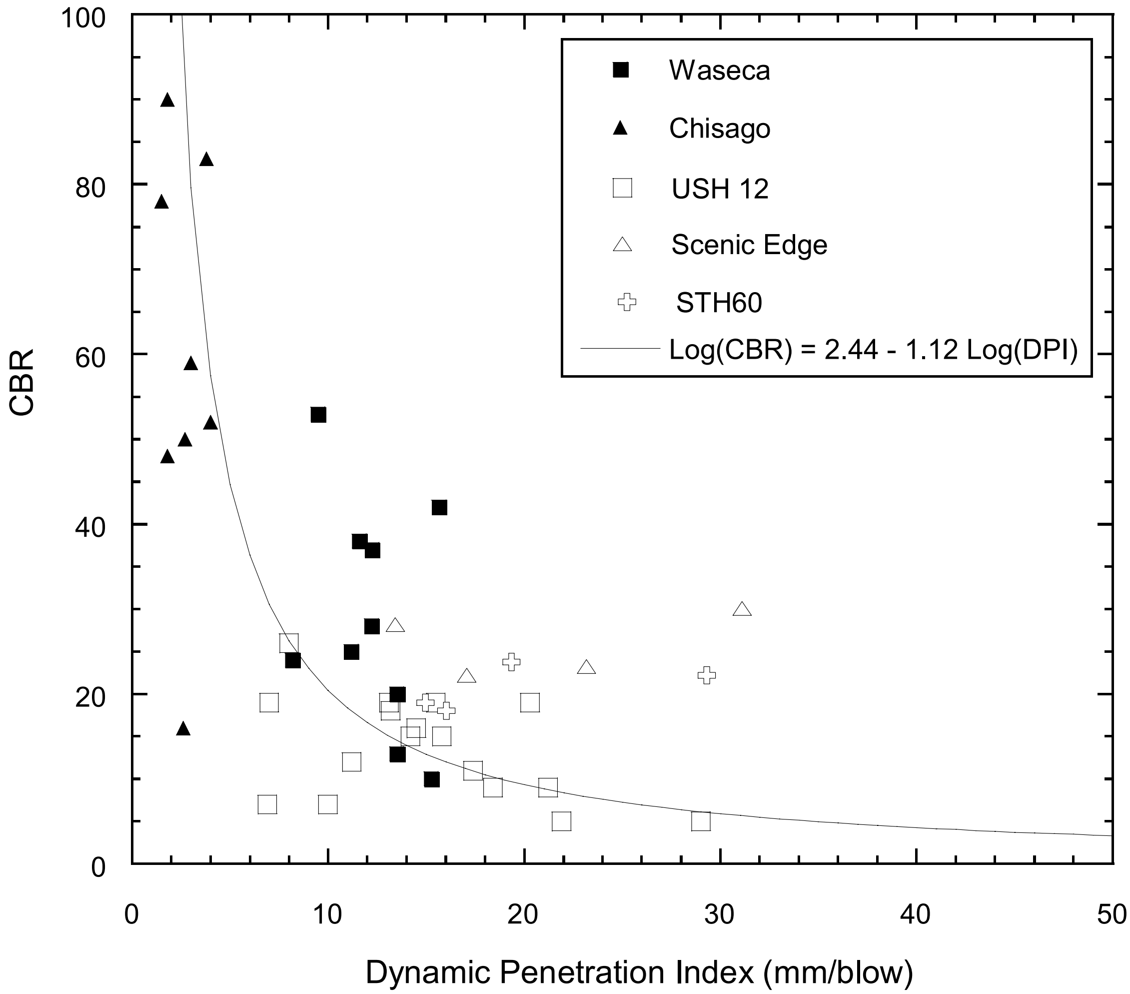

Fig. 9 CBR versus DPI for fly ash-stabilized materials

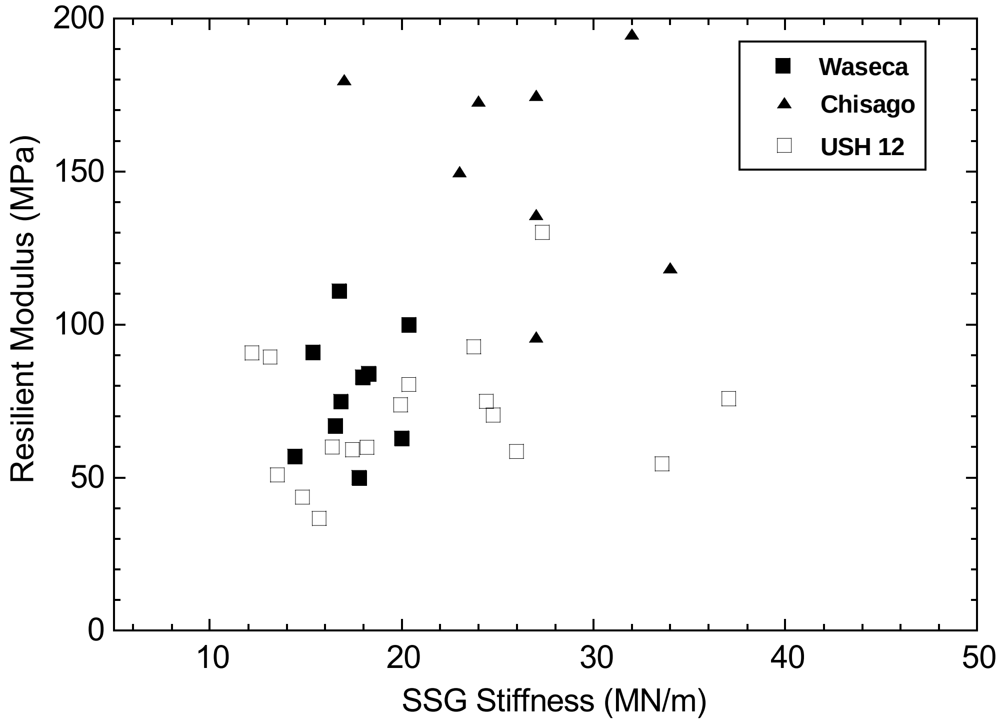

Fig. 10 Resilient modulus versus SSG stiffness for fly ash-stabilized materials

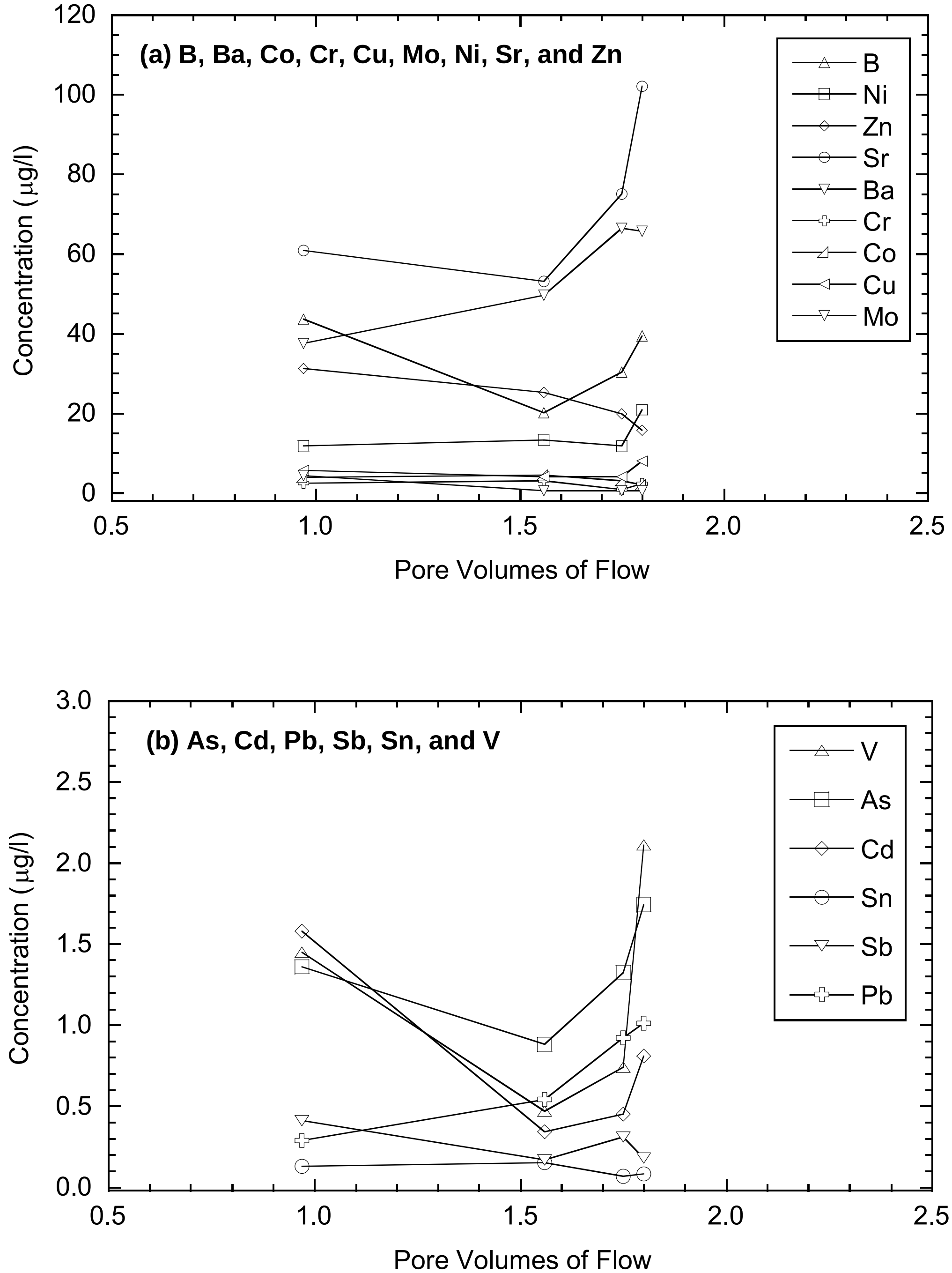

Fig. 11 Concentrations of trace elements in leachate collected in lysimeter in Waseca: (a) elements with peak concentrations between 3 and 102 μg/L and (b) elements with peak concentrations less than 2.5 μg/L.

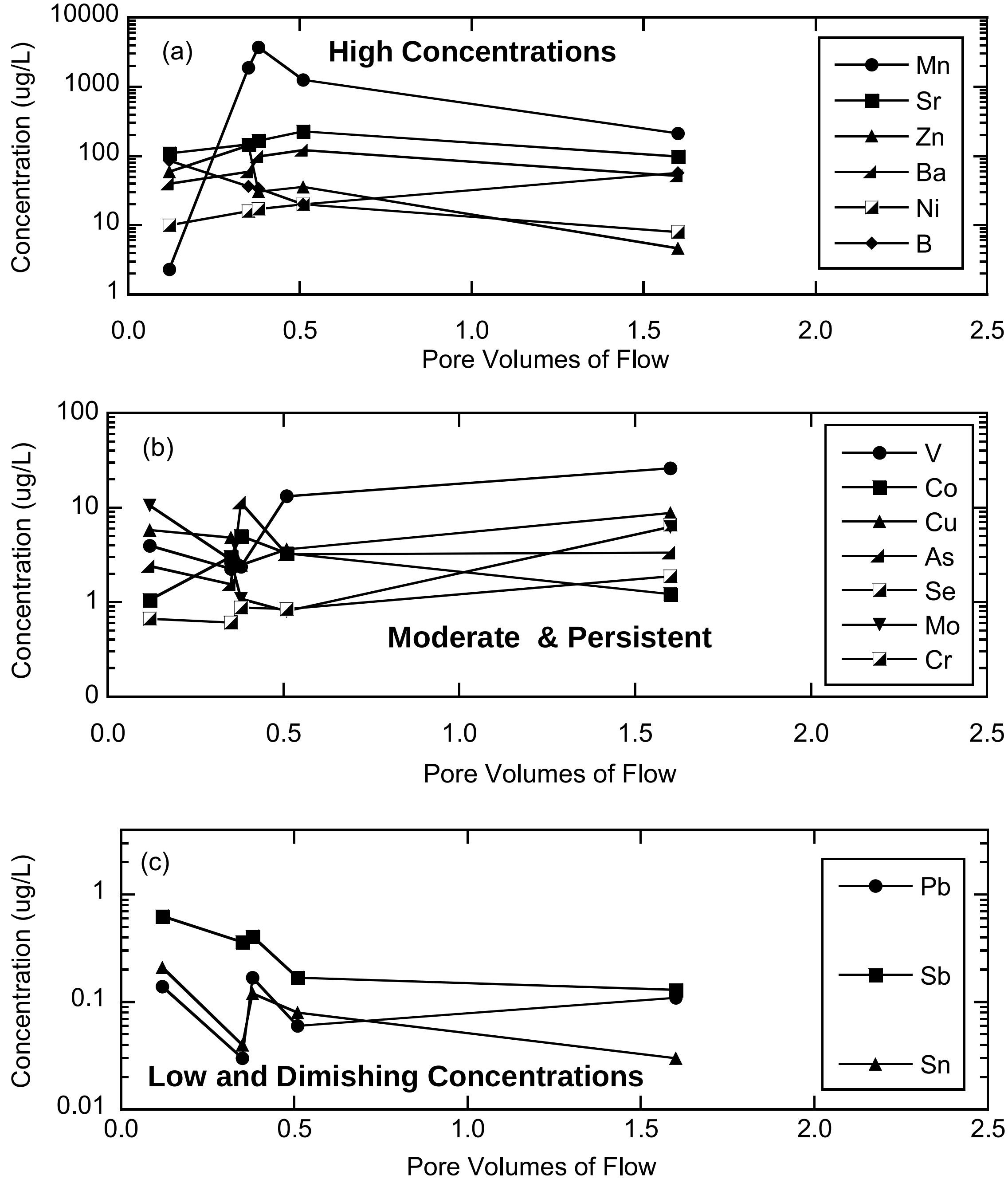

Fig. 12 Concentrations of trace elements in leachate collected in Chisago lysimeter: (a) elements with high concentrations, (b) elements with moderate and persistent concentrations and (c) elements with low and diminishing concentrations.

ATTACHMENT 1

WASECA PROJECT

ATTACHMENT 2

CHISAGO PROJECT