Thermal Preloading to Improve Geotechnical Properties of Recycled Asphalt Pavements

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ABSTRACT: A procedure to induce thermal preloading was introduced to improve geotechnical properties of recycled asphalt pavements (RAP) including resilient modulus, compressibility, shear strength and creep response. RAP specimens were compacted at different temperatures. Temperature-controlled resilient modulus, one-dimensional and triaxial compression test cells were developed. Results show that compaction temperature affects geotechnical properties of RAP. Increasing compaction temperature induced thermal preloading to RAP specimens and increased resilient modulus and reduced plastic strains under cyclic loading. Thermal preloading also increased the shear strength, reduced compressibility and susceptibility of the compacted RAP to creep failure. To improve performance of structural fills containing RAP, construction is recommended during warm seasons to induce thermal preloading.

KEYWORDS: thermal preloading, recycled asphalt pavement, resilient modulus, compressibility.
Introduction

Use of recycled materials in large volumes promotes sustainability in geotechnical construction by reducing consumption of energy and emission of greenhouse gases associated with mining and production of natural aggregates. Recycled material, because of their composition and the nature of their particulate characteristics, often manifests mechanical behavior that is distinct from that of natural aggregate. One such material is recycled asphalt pavement (RAP). RAP is produced by removing and reprocessing existing asphalt pavement (Guthrie et al. 2007; FHWA 2008). More than 73 million tons of RAP are processed each year in the US (Viyanant 2006).

RAP has been considered for use in geotechnical applications such as base course in pavement system (Guthrie et al. 2007; FHWA 2008; Edil et al. 2012) and backfill (Viyanant 2006) in mechanically stabilized earth walls. When using unbound aggregates as base course, two primary properties evaluated for design include resilient modulus (material stiffness under cyclic loading) and permanent deformation. RAP has competent resilient modulus as base course in pavement system compared to natural aggregates (Guthrie et al. 2007; FHWA 2008; Locander 2009; Wen et al. 2010; Shedivy 2012). Although RAP has suitable resilient modulus, it exhibits higher plastic strain and rutting potential than virgin aggregates under cyclic loads (Kim et al. 2007; Wen et al. 2010; Edil et al. 2012). Resilient modulus and rutting of unbound materials are used as input in the Mechanistic-Empirical Pavement Design Guide (MEPDG) for pavement design (ARA 2004).

RAP also has appropriate shear strength for use as backfill. However, asphalt binder coating on the particles makes the compacted RAP susceptible to excessive deformation over time and creep rupture under constant deviator stresses present in embankment fills or backfills (Viyanant et al. 2007). Creep is the accumulation of time-dependent shear strain under a
sustained shear stress that is controlled by the viscosity of soil structure (Mitchell 1993; Mitchell and Soga 2005). Evaluation of creep behavior is important in design of a structural fill to assess long term deformations and potential failure of the material.

Since viscosity of asphalt binder is temperature dependent (Robert et al. 1996; ASTM 2009), temperature change may affect mechanical properties of the compacted RAP. Therefore, thermal preloading may be potentially used to reduce plastic deformation and compressibility of RAP. Thermal preloading has been shown effective in reducing compressibility of other materials such as seafloor sediments (Houston et al. 1985), peat (Edil and Fox 1994; Hanson 1996), and recycled asphalt shingle mixtures (Soleimanbeigi et al. 2013, 2014). This paper describes the effect of thermal preloading on geotechnical properties of RAP. Effect of thermal preloading on resilient modulus, plastic strain, compressibility, shear strength and creep response of RAP was evaluated. Test procedures and thermo-mechanical systems were developed to induce thermal preloading to RAP specimens.

**Materials**

A bulk sample of RAP was obtained from Payne and Dolan Inc. in Fitchburg, Wisconsin. The asphalt binder contents of the RAP sample measured per ASTM D6307 was 4.3%. The majority of the RAP particles were coated with asphalt binder. Grain-size distribution tests were conducted following ASTM D422. RAP particles used in this research are classified as poorly-graded sand (SP) according to the Unified Soil Classification System (USCS). The specific gravity of RAP measured in accordance with ASTM D854 (Method B) is 2.39 which is lower than the typical specific gravity of natural granular materials (2.65-2.70). Relatively low specific gravity is attributed to asphalt binder coating. Fig. 1 shows the compaction curves of the RAP
sample obtained from standard and modified Proctor compaction efforts following ASTM D698 and ASTM D1557 respectively. From standard Proctor test, the optimum water content ($w_{opt}$) is 5.0% and maximum dry unit weight ($\gamma_{dmax}$) is 18.6 kN/m$^3$. Modified Proctor test renders $w_{opt}$ of 4.0% and $\gamma_{dmax}$ of 20.4 kN/m$^3$.

**Methods**

*Resilient Modulus Test*

NCHRP 1-28A Procedure IA was followed for laboratory resilient modulus testing. Specimens of 152-mm diameter and 305-mm height were prepared at $w_{opt}$ and 95% of $\gamma_{dmax}$ obtained from the modified Proctor testing. Each specimen was compacted in five layers inside the compaction mold. The number of tamps on each layer using a standard Proctor hammer was determined by trial to achieve the target density. To verify sensitivity of plastic strain and resilient modulus of the compacted RAP to temperature change, the resilient modulus tests were conducted at a range of typical field temperatures (i.e. 5 °C, 22 °C, 35 °C, or 50 °C) on specimens that were compacted at room temperature. A temperature-controlled resilient modulus test cell was developed. The cell consisted of a conventional cell equipped with a heating and cooling system designed to induce different temperatures to the specimens. Fig. 2 shows a schematic of the system. To uniformly induce a target temperature to each specimen, copper tubing (with 6-mm-outside diameter) was wound around the specimen to circulate heated or cooled water. There was a 3.0-cm distance between the copper coil and the specimen to avoid contact during the tests. Water was heated inside a heating bath and circulated using a water circulating pump. Temperatures in the bath ($T_b$), in the cell chamber ($T_c$), and inside the specimen ($T_s$) were measured using three K-type thermocouples. Target temperature (with a tolerance of ±1 °C) was
controlled by regulating the electrical power to the heater. The cooling bath was a 75-L plastic container filled with water and placed in a freezer. Temperature below room temperature was induced to the specimen by circulating cooled water through the copper coil. The required time to bring the $T_\text{s}$ from room temperature to the target temperature (i.e., $5 \, ^\circ\text{C}$ or $50 \, ^\circ\text{C}$) was approximately 15 h.

To evaluate the effect of thermal preloading on plastic strain and resilient modulus, the RAP sample, water, and the compaction equipment were placed in an environmental chamber for 24 h at each target temperature (i.e. $5 \, ^\circ\text{C}$, $22 \, ^\circ\text{C}$, $35 \, ^\circ\text{C}$, or $50 \, ^\circ\text{C}$). The target temperature of RAP sample was also verified by a thermometer placed in the sample. At each target temperature, the RAP sample was compacted inside the compaction mold at $w_{opt}$ and 95% of $\gamma_{d\text{max}}$ immediately after removing from the environmental chamber. The sample temperature was also monitored during the specimen preparation using a thermometer. The sample temperature remained within $\pm 1 \, ^\circ\text{C}$ of the target temperature. The same compaction energy (same number of blows per layer) was applied to each specimen to ensure that the compaction temperature is the only changing parameter. After compaction of each specimen at a target temperature, the split mold was removed and the resilient modulus test cell was assembled. The specimen temperature was allowed to reach to the room temperature ($22 \, ^\circ\text{C}$) for 24 h. All the resilient modulus tests on the specimens compacted at different temperatures were conducted at room temperature.

Deformation of each specimen under cyclic loads was measured by internal (mounted on the specimen) and external linear variable displacement transducers (LVDT). Design agencies are moving to adopt MEPDG, which requires use of modulus based on internal deflection measurements. Additionally, using internal LVDTs eliminates the error resulting from machine compliance and end effects (NCHRP 2004, Camargo et al. 2012). Therefore, resilient modulus
obtained from deformations measured by the internal LVDTs was considered in this study. An MTS servo-hydraulic system was used for loading the specimens. The resilient modulus was calculated as follows:

\[
M_R = \frac{\sigma_{dN}}{\varepsilon_r}
\]

(1)

where \(\sigma_{dN}\) is the dynamic deviator stress of the \(N^{th}\) load cycle and \(\varepsilon_r\) is the resilient strain from \(\sigma_{dN}\). Resilient moduli from the last five cycles of each test sequence were averaged to obtain the \(M_R\) for each load sequence. The resilient modulus data were fitted with the NCHRP model defined as:

\[
M_R = k_1 \cdot p_a \cdot \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + k_7\right)^{k_3}
\]

(2)

where \(k_1, k_2, k_3, k_6,\) and \(k_7\) are constants, \(p_a\) is atmospheric pressure, \(\tau_{oct}\) is octahedral shear stress, and \(\theta\) is bulk stress. For base-course, the summary resilient modulus (SRM) corresponds to the \(M_R\) at \(\theta = 208\) kPa and \(\tau_{oct} = 48.6\) kPa, as suggested by the NCHRP 1-28A procedure.

**One-dimensional (1D) Compression Test**

Settlement of a wide highway embankment can be considered one-dimensional and therefore the compressibility properties can be obtained from the results of 1D compression tests. The specimens for 1D compression tests were prepared by compaction of RAP sample at \(w_{opt}\) and 95% of \(\gamma_{dmax}\) obtained from the standard Proctor testing. The compaction was conducted by a manual hammer inside a 101-mm-diameter oedometer ring in three layers. The number of tamps
on each layer was determined by trial to achieve the target density. To evaluate the effect of temperature on compressibility, temperature-controlled 1D compression tests on the compacted RAP were conducted in a 101-mm-diameter oedometer ring equipped with a heating system that maintained constant temperature of 35 °C. The schematic of the system is shown in Fig. 3. A coil of copper tubing (6-mm-outside diameter) was wound around the oedometer ring (with 10-mm separation) to circulate heated water. The stainless steel ring was placed inside a PVC cylinder filled with water to conduct heat from the copper coil to the specimen. The elevated target temperature was achieved by circulating heated water in the coil using a pump placed outside of a heating water bath. Tygon tubing was used to connect the pump to the coil to minimize temperature loss during water circulation. Temperatures in the bath (T_b), in the PVC cylinder (T_c), and inside the specimen (T_s) were measured using three type-K thermocouples. A LabView program was used to control the temperatures so that the specimen temperature could be maintained within ±1 °C of the target temperature. Since insertion of the thermocouples inside the specimens disturbs them, after the initial calibration tests, a correlation between the T_s and T_c was obtained to estimate the T_s from T_c. The required time to bring the T_s to the target temperature was approximately 100 min.

To evaluate the effect of thermal preloading on the 1D compressibility, the same procedure as in the resilient modulus test was employed to heat the RAP sample, water, the oedometer ring, and a manual hammer inside an environmental chamber. At 35 °C, the RAP sample was compacted at \( w_{opt} \) and 95% of \( \gamma_{dmax} \) inside the oedometer ring immediately after removing from the environmental chamber. The sample temperature was monitored during the specimen preparation using a thermometer. The sample temperature remained within ±1 °C of the target temperature. During compaction at 35 °C, the same compaction energy (same number
of blows) as in the compaction of a replicate sample at room temperature was applied to the specimen. The compacted RAP specimen inside the 1D compression ring was incrementally loaded with load increment duration (LID) of 24 h and load increment ratio (LIR) of 1.0 from $\sigma'_v = 12.5$ kPa to 100 kPa at 35 °C. After loading for 24 h at $\sigma'_v = 100$ kPa and $T = 35$ °C, the specimen temperature was reduced to room temperature and the compression test was continued for three weeks. Selection of $\sigma'_v = 100$ kPa was based on overburden pressure in typical highway embankment of 5-m height in the US (Wright 1996).

**Triaxial Compression Test**

A temperature-controlled triaxial compression cell was developed to evaluate the effect of thermal preloading on shear strength of the compacted RAP. The cell is a conventional triaxial cell equipped with a heating system. The heating system is similar to the one used for the temperature-controlled resilient modulus test cell. The triaxial specimens were prepared at room temperature and at elevated temperature of 35 °C. The procedure for specimen preparation at elevated temperature is similar to that of the resilient modulus test specimens that were compacted at elevated temperatures. Each specimen was compacted in three layers in a split mold with 74-mm inside diameter and 148-mm height at $w_{opt}$ and 95% of $\gamma_{dmax}$ obtained from standard Proctor test. The number of tamps per layer using a standard Proctor hammer was determined by trial to achieve the target density. The same compaction energy (blows per layer) was applied to the replicate specimens compacted at 22 °C and 35 °C. After assembling the temperature-controlled triaxial compression cell, to measure the specimen volume change, each specimen was backpressure-saturated according to ASTM D4767 so that a B-value greater than 95% was attained. The specimen compacted at 35 °C was consolidated inside the cell at $\sigma'_3 = 70$
kPa for 48 h at the same temperature while the volume change was measured from the water elevation in the backpressure burette. The specimen temperature was thereafter reduced to room temperature while the consolidation continued for another 24 h (total of 72 h for consolidation). The selected $\sigma'_3$ were calculated based on a consideration of typical heights of highway embankments (2-5 m) (Wright 1996) and the unit weight of the compacted RAP. The time required to reduce the specimen temperature from 35 °C to 22 °C was 100 min as obtain from calibration of the temperature-controlled triaxial cell. Consolidation of a specimen compacted at room temperature was also continued for 72 h. Shearing of each specimen was started thereafter at an axial strain rate of 3.0%/h, which is considered to provide drained conditions. The volume change of each specimen during shearing was recorded from the water elevation in the graduated backpressure burette.

**Creep Test**

The creep tests were conducted using the temperature-controlled triaxial cell. Two replicate specimens were prepared; one compacted at room temperature and the other one at 35 °C. The procedures for specimen preparation and consolidation are the same as those employed for triaxial compression tests. After consolidation of each specimen for 72 h, the deviator stress ($\sigma_d$) was gradually increased at a loading rate of 0.2 mm/min until the target stress level was attained. The stress level ($\bar{D}$) is defined as the ratio of the applied $\sigma_d$ to deviator stress at failure ($\sigma_{df}$) as obtained from triaxial compression test. The applied $\bar{D}$-value to the RAP specimen was 0.90 to make sure the specimen fails. At the target stress level, the creep started immediately by measuring the axial displacement of the specimen until the specimen failed.
Results

Plastic Strain and Resilient Modulus

Fig. 4(a) shows the cumulative plastic strain versus loading sequence of RAP specimens at different temperatures. At any given loading sequence, plastic strain of RAP specimens consistently increases with increasing temperature. The sensitivity of plastic strain of RAP with respect to temperature is attributed to presence of asphalt binder coating on RAP particles. The viscosity of asphalt binder decreases with increasing temperature (Roberts et al. 1996; ASTM 2009). At decreased viscosity, the shear strain at the particle contact surfaces thus plastic strain of the RAP specimen increases. As shown in Fig. 4(a), the plastic strains of the RAP specimens increase with increasing temperature. Therefore, a RAP sample compacted at an elevated temperature and cooled down to room temperature is expected to have lower void space thus higher stiffness compared to a RAP specimen compacted and tested at room temperature throughout the test. Fig. 4(b) compares the plastic strain-loading sequence curves of RAP specimens compacted at different temperatures. Increasing compaction temperature significantly reduces the plastic strain at different loading sequences. Compaction at an elevated temperature induced thermal preloading to the RAP specimens. The average plastic strains of the specimens compacted at 35 °C and 50 °C are respectively 60% and 24% of the average plastic strain of the specimen compacted at room temperature. As shown in Fig. 4(b), reducing the compaction temperature to 5 °C increased the plastic strain of the specimen.

Fig. 5 shows the variation of SRM of RAP specimens with and without thermal preloading. The SRM of the replicate specimens compacted at room temperature is consistently reduced with increasing temperature. The most significant reduction of SRM occurs within temperature range of 22 °C-35 °C where SRM is reduced by 70% from 380 MPa to 272 MPa.
Similar observation was reported by Shedivy (2012). Reduction of temperature from 22 °C to 5 °C increased the SRM by ~10% from 380 MPa to 420 MPa. Thermal preloading of the specimens however increased the SRM as shown in Fig. 5. Increasing the compaction temperature from 5 °C to 50 °C consistently increased the SRM of the RAP specimen by 55% from 308 MPa to 480 MPa. The practical implication of this behavior is that RAP compacted at warm temperatures (i.e., during summer), will exhibit higher modulus and lower permanent deformations thus lower rutting potential later during mild and cold seasons and therefore construction of base course with RAP is recommended during warm seasons to induce thermal preloading. Additionally, when the embankment is constructed and the road is paved, surface pavement will act as a thermal insulator and during the second summer, the temperature in the embankment containing RAS can be expected to be lower (i.e., 25 °C-27 °C) than the temperature in the first summer when the RAS mixture is directly exposed to warm weather during construction (Rababah 2007).

One-dimensional Compression

Fig. 6 shows the results of 1D compression tests on three replicate specimens as the variation of axial strain ($\varepsilon$) with logarithm of time. Specimen 1 was loaded at room temperature throughout the test. Specimen 2 was loaded at room temperature until $\sigma_v'=100$ kPa for 24 h and then was induced an elevated temperature of 35 °C for three weeks at $\sigma_v'=100$ kPa. Specimen 3 was incrementally loaded at 35 °C until $\sigma_v'=100$ kPa for 24 h when the specimen temperature was reduced to room temperature thereafter with the compression test being continued for another three weeks.
Specimen 2 exhibited higher $\varepsilon_p$ compared to Specimen 1. The sensitivity of $\varepsilon_p - t$ curves (or compressibility) to temperature change is attributed to presence of asphalt binder in RAP particles. Since the applied stress is sustained by friction between the particles, presence of viscous asphalt binder at the particle contact surfaces is postulated to make the compressibility of RAP specimens sensitive to temperature. Reduced viscosity increases the micro-shear strains between the RAP particle contacts. Increasing temperature generally corresponds to significant reduction of stiffness and increase of permanent deformation for bituminous mixtures due to reduction of asphalt binder viscosity (Tayebali et al. 1994; Sondag et al. 2002; Palit et al. 2004; Fu and Harvey 2007; Cao et al. 2009). The increased compressibility with increasing temperature was also observed in peat and clay (Campanella and Mitchell 1968; Plum and Esrig 1969; Fox and Edil 1996; Hanson 1996; Delage et al. 2000) but with different mechanisms than those assumed in the compacted RAP and other bituminous materials.

Secondary compression ratio ($C_{ae} = d\varepsilon/d \log t$) is used as an index for compressibility. The average secant values of $C_{ae}$ over 5000-min period after 24 h of $\sigma'_v$=100 kPa, were determined from the $\varepsilon_p - \log t$ curves. This $C_{ae}$ was chosen as an index of the temperature effects. Increasing temperature to 35 °C, rapidly increased the $C_{ae}$ for the compacted RAP from 0.0066 (Specimen 1) to 0.0899 (Specimen 2) reflecting a ~14-time increase. Temperature rise increased compressive strain of the compacted RAP specimens in 1D compression test. The higher compressive strain results in a lower void space in the specimen. Therefore, when the specimen temperature is reduced back to room temperature, the specimen that was compressed at an elevated temperature is expected to have higher stiffness thus lower compressibility compared to the replicate specimen compressed at room temperature throughout the test. This was confirmed by conducting compression tests on replicate Specimen 3 for RAP. As shown in Fig.
6, under each incremental $\sigma'_v$, Specimen 3 exhibits higher vertical strain compared to Specimen 1. Therefore, at the target $\sigma'_v$ ($\sigma'_v=100$ kPa), Specimen 3 has lower void space compared to Specimen 1. The measured $C_{ae}$ for Specimen 3 is 0.0015; which is ~20% of the corresponding $C_{ae}=0.0066$ for Specimen 1. This indicates that the elevated temperature induces thermal preloading to the compacted RAP during incremental loading to the target $\sigma'_v$ and significantly reduced the $C_{ae}$ to as low as that for low compressible granular materials (see Table 1). As a result, construction of embankments containing RAP is recommended during warm seasons. At higher temperature, viscosity of asphalt binder is reduced which reduces the void space of the fill at a higher rate. Therefore, the majority of compression occurs during construction and soon after thus the potential for settlement during the following seasons is significantly reduced.

**Triaxial Compression**

Fig. 7(a) compares the volumetric change of two replicate RAP specimens compressed at 22 °C and 35 °C. The specimen that was isotropically compressed at 35 °C exhibits more compressive volumetric strain than the specimen compressed at 22 °C. Therefore, a RAP specimen compacted and compressed at 35 °C is expected to have lower void ratio thus higher stiffness and shear strength when the temperature is reduced to room temperature compared to a specimen compacted and compressed at 22 °C throughout the test. Fig. 7(b) verifies that the reduction in void ratio resulted in increased stiffness and strength ($\sigma_{df}$) of the specimen compared to those of the specimen compressed at constant room temperature. Thermal preloading technique also increased the shear strength of clay (Burghignoli et al. 2000), seafloor sediments (Houston et al. 1985), and recycled asphalt shingle mixtures (Soleimanbeigi et al. 2013). The practical implication of this behavior is that the embankment fill containing RAP, compacted and brought
to equilibrium with the operating stresses at warm temperatures (i.e., during summer), will exhibit higher shear strength and stiffness later during mild and cold seasons.

**Creep**

Fig. 8(a) shows the results of creep tests on RAP specimens as the variation of axial strain ($\varepsilon$) with logarithm of time. The axial strain increases with time, which indicates creep susceptibility of the compacted RAP. The axial strain of the RAP specimen compacted at room temperature increases more rapidly compared to the RAP specimen compacted at 35 °C. Creep strain of the compacted RAP is mainly attributed to shear strain between the particles due to presence of asphalt binder at the contact surfaces between individual RAP particles. The axial strain data in Fig. 8(a) were differentiated with respect to time to obtain the axial strain rate ($\dot{\varepsilon}$). Fig. 8(b) is a plot of the calculated $\dot{\varepsilon}$ against elapsed time on a log-log plot. The strain rates decrease with elapsed time and also with increasing the compaction temperature. Each log $\dot{\varepsilon} – \log t$ curve exhibits a minimum point where the $\dot{\varepsilon}$ starts to increase. Once the $\dot{\varepsilon}$ increased, the specimen was observed to fail (creep rupture) during the tests. Therefore, the initiation of creep rupture in Fig. 8(b) is identified when $\dot{\varepsilon}$ starts to increase with time. This is similar to failure criterion considered by Singh and Mitchell (1968), Campanella and Vaid (1974), Ting (1983), Viyanant et al. (2007) and many others.

The time to initiation of creep rupture ($t_r$) corresponds to minimum strain rate ($\dot{\varepsilon}_{\text{min}}$) on the log $\dot{\varepsilon} – \log t$ curves. The $t_r$ increases with increasing compaction temperature. Increasing the compaction temperature from 22 °C to 35 °C increased the $t_r$ from 20 min to 322 min at a relatively high stress level of 0.90 and therefore reduced the susceptibility of creep rupture. Compaction and compression at 35 °C increased the volumetric compressive strain therefore
reducing the void space [Fig 7(a)]. Reducing the specimen void space increases the particle contact surfaces thus friction between the RAP particles. Viyanant et al. (2007) reported that compacted RAP used as backfill is susceptible to creep rupture and suggested that strength of the compacted RAP be reduced by 40% to alleviate the problems related to creep. The results of this research introduce thermal preloading as a promising way to reduce creep susceptibility of compacted RAP. The results suggest that if the RAP fill is constructed during warm seasons, the majority of compression occurs during construction and the strain rates and creep susceptibility are expected to decrease significantly during subsequent seasons.

**Summary and Conclusions**

In this study the effect of thermal preloading on engineering properties of RAP including resilient modulus, shear strength, compressibility and creep was investigated. Temperature-controlled triaxial and one-dimensional compression cells were developed to induce elevated temperatures to the RAP specimens. The following conclusions are made from the test results:

- Increasing temperature consistently increased plastic strain and reduced summary resilient modulus of RAP. Compaction temperature significantly affects the plastic strain and the modulus. Increasing compaction temperature induced thermal preloading to the specimens which significantly reduced plastic strains and increased the summary resilient modulus.
- Thermal preloading reduced the compressibility of the compacted RAP in a one-dimensional compression test. Compaction and loading at elevated temperature
compresses the compacted RAP thus the compressibility is reduced when temperature of the compacted RAP is brought to equilibrium at room temperature.

• The stiffness and shear strength also increased when thermal preloading was induced to the compacted RAP. Thermal preloading also reduced the strain rate and creep susceptibility of the compacted RAP under constant deviator stress.

• Construction of structural fill containing RAP is recommended during summer to induce thermal preloading and to reduce rutting potential and deformation of the fill.

The RAP sample used in this research is a processed industrial material. Therefore, it is expected that its behavior will vary in a relatively narrow range. Although only one source is used as the test materials, the observations are expected to be quite representative. While the overall behavior is not likely to vary significantly, the quantitative values of the various parameters may be different if materials from other sources are used and therefore should be evaluated for design. Recycled asphalt pavements can be used in construction of highway embankment fills taking into account their intrinsic characteristics such as compressibility and temperature sensitivity during design and construction.

Acknowledgments

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TABLE 1–Secondary compression ratio of different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_{cc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berthierville Clay (Mesri and Castro 1987)</td>
<td>0.0185</td>
</tr>
<tr>
<td>California Tar Sand (Mesri and Castro 1987)</td>
<td>0.0014</td>
</tr>
<tr>
<td>Micaceous Antelope Valley Sand (Lade and Liu 1998)</td>
<td>0.0011</td>
</tr>
<tr>
<td>Lake Michigan Beach Sand (Mesri et al. 1990)</td>
<td>0.0004</td>
</tr>
<tr>
<td>Wisconsin Outwash Sand (Soleimanbeigi et al. 2013)</td>
<td>0.0003</td>
</tr>
<tr>
<td>RAP (This study)</td>
<td>0.0066</td>
</tr>
<tr>
<td>Preloaded RAP (This study)</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

FIG.1–Standard and modified Proctor compaction curves
FIG. 2—Schematic of temperature-controlled resilient modulus cell
FIG. 3–Temperature-controlled 1D compression cell

FIG. 4–(a) Plastic strains versus loading sequence at different temperatures (b) Effect of compaction temperature on plastic strain
FIG. 5–Effect of thermal preloading on summary resilient modulus

FIG. 6–Effect of temperature on compressibility of the compacted RAP
FIG. 7–Effect of thermal preloading on (a) volumetric change and (b) stress-strain behavior of compacted RAP
FIG. 8—(a) Axial strain (b) and axial strain rate versus time for RAP specimen at $\sigma'_3=70$ kPa.