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Strength and stiffness of recycled materials stabilised with fly ash: a laboratory study

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Properties of a recycled pavement material (RPM) and a road surface gravel (RSG) stabilised with a Class C fly ash are compared with the properties of a conventional base material (Minnesota Class 5 base). California-bearing ratio (CBR), resilient modulus (M_r), and unconfined compressive strength (UCS tests were conducted to evaluate the effects of adding fly ash to the RPM and RSG to enhance their mechanical properties. Freeze–thaw durability was evaluated in terms of M_r and UCS. CBR, M_r, and UCS for RPM and RSG increased with fly ash content. M_r and UCS for RPM and RSG increased with curing time, with significant gains occurring after 7 and 28 days of curing. Addition of fly ash reduced plastic strains of the recycled materials during resilient modulus testing. Freeze–thaw cycling had a small effect on the M_r and UCS of the recycled materials. A strong relationship was found between summary resilient modulus (SRM) and UCS of recycled materials blended with fly ash, suggesting that the SRM can be estimated from a UCS test.

Keywords: strength; stiffness; recycled materials; fly ash; RPM; RSG

1. Introduction

There is a growing interest in reducing construction costs and increasing sustainability when reconstructing paved roads and upgrading unpaved roads to paved roads. One approach is to use recycled materials in place of conventional materials. For example, road surface gravel (RSG) from a gravel road undergoing rehabilitation may be reused as the base layer for newly paved roads (Hatipoglu, Edil, & Benson, 2008). Alternatively, recycled pavement material (RPM) (a mixture of pulverised asphalt, base, and possibly subgrade from the existing road) may be used as base course for a new pavement (Wen, Tharaniyil, Ramme, & Krebs, 2004). In some cases, the strength and stiffness of these recycled materials are enhanced by blending them with a cementitious material (Dutta, 2008), such as fly ash from coal-fired electric power plants (Hatipoglu et al., 2008; Li, Benson, Edil, & Hatipoglu, 2007).

An impediment to more common use of recycled materials in roadway reconstruction is lack of information on their engineering properties. In addition, pavement engineers need to know how to design pavements using recycled materials that will yield equal or better performance than pavements constructed with conventional materials. This laboratory study was conducted to characterise the engineering properties of a typical RPM and RSG blended with Class C fly ash (ASTM C618, 2005) and to compare these properties to those of a conventional base material (Minnesota Class 5 base course) (MnDOT, 2005). Two fly ash contents (10% and 15%), corresponding to typical application ranges used in practice, were used and three curing times

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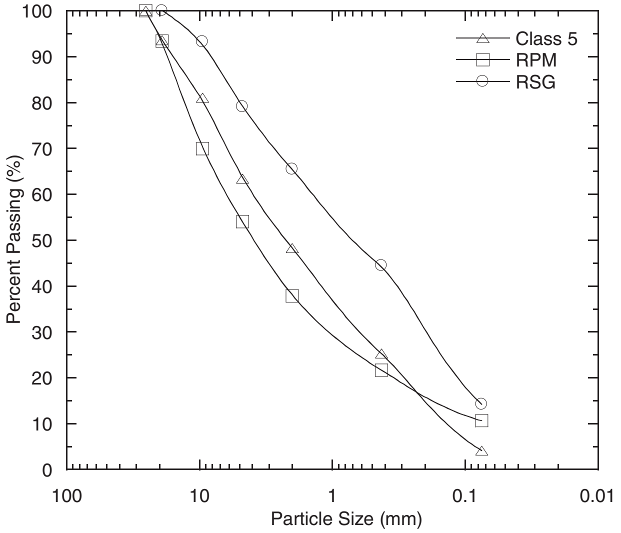

Figure 1. Particle size distributions for Class 5 base, RPM, and RSG.

were evaluated (7, 28, and 56 days). California-bearing ratio (CBR), resilient modulus (M_r), and unconfined compressive strength (UCS) tests were conducted to evaluate the engineering properties of the recycled materials with and without fly ash. Freeze–thaw durability was evaluated in terms of resilient modulus and UCS.

2. Materials

2.1. *Conventional base material*

Material meeting the Class 5 specifications for base course in Minnesota (MnDOT, 2005) was created by blending pit run gravel obtained from Wimme Sand and Gravel (Plover, Wisconsin) with crushed pea gravel obtained from Midwest Decorative Stone and Landscape Supply (Madison, Wisconsin). The pit run gravel was sieved past the 25 mm sieve prior to blending with the pea gravel. The Class 5 base classifies as poorly graded sand with gravel (SP) according to the Unified Soil Classification System (USCS) (ASTM D2487, 2000).

2.2. *Recycled materials*

The RPM was obtained from a roadway reconstruction project in southwestern Madison, Wisconsin, near the intersection of Muir Field Road and Carnwood Road. The RPM is a blend of pulverised asphalt and limestone base layer (approximately equal parts) created by removing and pulverising the existing pavement. The RPM has an asphalt content of 4.6%, as determined by the ignition method (ASTM D6307, 2005), and classifies as well-graded gravel or silty gravel (GW–GM) according to USCS. The RPM was screened with a 25-mm sieve prior to use.

A RSG was created by blending Class 5 base with washed limestone fines obtained from Rosenbaum Crushing and Excavating (Stoughton, Wisconsin). The Class 5 base was screened past the 19-mm sieve prior to blending with the limestone fines. The RSG meets the AASHTO gradation requirements for surface course materials, as outlined in AASHTO M 147 (AASHTO, 2001), and classifies as silty sand (SM) according to USCS. Particle size distribution curves for the Class 5 base, RPM and RSG are shown in Figure 1.

2.3. *Fly ash*

Fly ash was obtained from Columbia Power Plant Unit No. 2 in Portage, Wisconsin, where sub-bituminous coal is burned in pulverised boilers. The fly ash is collected using electrostatic precipitators. Columbia fly ash classifies as Class C (ASTM C618, 2005) and has cementitious properties. The 'CaO/SiO_2' and '$CaO/(SiO_2+Al_2O_3)$' ratios for Columbia fly ash, which are indicators of cementing potential (Janz & Johasson, 2002; Tastan, 2005), are 0.8 and 0.4, respectively.

3. Methods

3.1. *Compaction/CBR*

Specimens for compaction and CBR tests were prepared following Method C in ASTM D698 (2001). However, polyvinyl chloride moulds were used in lieu of metal ones. Material passing the 25-mm sieve was compacted in three lifts of equal mass and thickness. Samples containing fly ash were compacted 1 h after adding water to simulate typical field construction. CBR tests were performed on specimens without fly ash immediately after compaction, whereas specimens with fly ash were tested after 7 days of curing in a 100% relative humidity room at 24°C. All CBR tests were conducted following the methods in ASTM D1883 (2005). To simulate conditions shortly after construction, the CBR specimens were not soaked prior to testing (Bin-Shafique, Edil, Benson, & Senol, 2004).

The CBR tests were carried out in the unsoaked condition because soaking the specimens has a negative effect on unbound materials due to negative pore water pressure in an unsaturated compacted soil and may have a positive effect on materials stabilised with fly ash due to the pozzolanic strength gain as a result of a compete chemical process of hydration of the small amount of lime in the fly ash (Little, 1999). Thus, CBR tests were carried out on unsoaked specimens for consistency. The main objective of the CBR tests was to show whether or not fly ash effectively cements these materials, and if the cement controls their strength and stiffness.

3.2. *Resilient modulus*

Resilient modulus testing was performed in accordance with the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol (NCHRP, 2004). All materials were tested under Procedure Ia, which applies to base and subbase materials. Internal linear variable displacement transducers (LVDTs) were mounted at the quarter points of specimens using clamps meeting NCHRP 1-28A specifications.

Specimens were compacted in six lifts of equal mass and thickness using a split mould 152 mm in diameter and 305 mm in height. All materials were compacted within 1% of maximum dry density and within 0.5% of optimum water content (standard Proctor) (NCHRP, 2004). Similar methods were employed for base and recycled materials whether prepared with or without fly ash.

Resilient moduli (M_r) from the last five cycles of each test sequence were averaged to obtain the resilient modulus for each load sequence. The resilient modulus data were fit to the power function proposed by Moosazedh and Witczak (1981)

$$M_r = k_1 \theta^{k_2}, \tag{1}$$

where θ is bulk stress and k_1 and k_2 are fitting parameters. For a given material, k_2 was not expected to vary appreciably. Hence, k_2 obtained from replicate or triplicate tests were averaged and fixed for that material. A second fit was then performed using the average k_2 and fitting k_1 to all tests. A summary resilient modulus (SRM) was also computed, as suggested in Section

10.3.3.9 of NCHRP 1-28A. For base materials, SRM corresponds to the resilient modulus at a bulk stress of 208 kPa.

3.3. *Unconfined compression strength*

Unconfined compression tests were not conducted on Class 5 base, RPM, and RSG alone because they are granular materials with relatively low fines content (<15%) and therefore little cohesion. Unconfined compression tests were conducted on the specimens stabilised with fly ash after resilient modulus testing. ASTM D5102 (2004) was followed for the unconfined compressing testing. Resilient modulus specimens were reused for unconfined compression because stresses applied during resilient modulus testing are low enough that specimens with fly ash do not deform significantly. Although axial deformation rates ranging from 0.5% to 2.0% per minute are suggested in ASTM D5102 (2004), slower rates are optional for stiffer materials. All specimens were tested unsoaked and loaded continuously to produce an axial deformation rate of 0.21% per minute (Acosta, 2002).

3.4. *Freeze–thaw durability*

Tests were conducted to determine the effects of freeze–thaw cycling on the engineering properties of each of the materials. Freeze–thaw cycling for stabilised materials was evaluated for specimens with a fly content of 10% only. Rosa (2006) reports the effects of freeze and thawing on resilient modulus and unconfined compression generally occur within five cycles. Therefore, test specimens were subjected to five freeze–thaw cycles and then their resilient modulus and unconfined compression strength were measured.

Specimens for freeze–thaw testing were prepared in the same manner as other resilient modulus specimens (i.e. moisture content and dry unit weight). Preliminary testing on specimens instrumented with a thermocouple showed that complete freezing occurred within 1 day at −19°C. Thus, all specimens were retained in the freezer for at least 1 day. After freezing, the height and weight were measured and the specimen was allowed to thaw at room temperature. This process was repeated until five freeze–thaw cycles were completed. After the last cycle, specimens were extruded frozen and thawed inside the resilient modulus cell.

4. Results and analysis

4.1. *Compaction*

Optimum water contents and maximum dry unit weights for Class 5 base, RPM and RSG with and without fly ash are summarised in Table 1. Increasing fly ash content resulted in an increase in optimum water content and a decrease in maximum dry unit weight. The shift in compaction curves with increasing fly ash content was more pronounced for RPM. The lower dry unit weights for the materials mixed with fly ash are attributed to the energy loss incurred when cement bonds are broken during compaction. Wen, Warner, and Edil (2008) also report that adding fly ash to RPM causes a shift in the compaction curve, and that the type of shift (up or down) can depend on the type of fly ash.

4.2. *California-bearing ratio*

The maximum CBR and corresponding water content for Class 5 base, RPM, and RSG (with and without fly ash) are given in Table 1. The water content resulting in the maximum CBR for the materials mixed with fly ash is 1% lower than optimum water content for dry unit weight.

Table 1. Compaction characteristics and CBR of Class 5 base, RPM, and RSG with and without fly ash.

Material	Fly ash content (%)	Optimum water content (%)	Max. dry unit weight (kN/m^3)	Water content at max. CBR (%)	Max. CBR (%)
Class 5 base	0	5.0	20.9	5.0	10
RPM	0	7.5	21.2	7.0	22
	10	8.5	20.4	7.5	67
	15	9.5	20.1	8.5	134
RSG	0	6.0	21.4	6.0	31
	10	7.0	21.4	6.0	183
	15	7.5	21.2	6.5	334

The CBR for Class 5 base was 10%, whereas RPM and RSG had CBRs of 22% and 31%, respectively. The CBR for Class 5 base was significantly lower than the expected CBR (<50%) given this is a base material. However, a second CBR test confirmed the initial results. The low CBR of the Class 5 base is attributed to its large sand fraction (59%), and the rounded to subrounded characteristics of the gravel fraction. CBR decreases with increasing particle roundness because of the decrease in inter-particle friction particles.

The CBRs obtained for RPM and RSG were higher than expected for these types of material when compared with the results found in the literature. Baugh (2008) reports an average CBR of 13 for RPM, whereas Li et al. (2007) report CBRs ranging from 3% to 17%. Similarly, Baugh (2008) reports an average CBR of 21% for RSG, whereas Hatipoglu et al. (2008) report a CBR of 24%.

4.2.1. *Effect of fly ash content*

The variation of CBR and normalised CBR (ratio of CBR of base material with fly ash to the CBR of base alone) with fly ash content for RPM and RSG are shown in Figure 2.

CBR increases with increasing fly ash content for both recycled materials up to 15% fly ash. The CBR and normalised CBR of RPM increased from 22% and 1 to 134% and 6, respectively. Similarly, the CBR and normalised CBR of RSG increased from 31% and 1 to 334% and 11, respectively. The increase in CBR is attributed to cementation of the particles by the fly ash. Wen et al. (2008) also report an increase in CBR with increasing fly ash for RPM blended with high carbon fly ash. The CBR of RPM increased with increasing fly ash content up to 18% fly ash (from 38% to 212%).

RPM shows a three-fold increase in CBR when stabilised with 10% fly ash, whereas RSG shows a six-fold increase. Addition of 15% fly ash yields further gains in CBR for both recycled materials. Hatipoglu et al. (2008) and Li et al. (2007) report similar increases in CBR for RPM and RSG stabilised with 10% fly ash. Both RPM and RSG had CBR higher than the CBR typically desired for base materials (CBR $\geq$ 50%) (Hunt, 1986) when stabilised with at least 10% fly ash (67% for RPM and 183% for RSG).

4.3. ***Unconfined compressive strength***

Unconfined compressive strengths (UCS) for RPM and RSG blended with fly ash are summarised in Table 2 along with the resilient modulus test results and shown in Figure 3. For both RPM and RSG, the UCS increases with increasing fly ash content and, for the same fly ash content, RSG has higher UCS than RPM. The UCS of RPM and RSG stabilised with fly ash also increased with curing time (Figure 1), with significant increases occurring even after 28 days. The UCS in

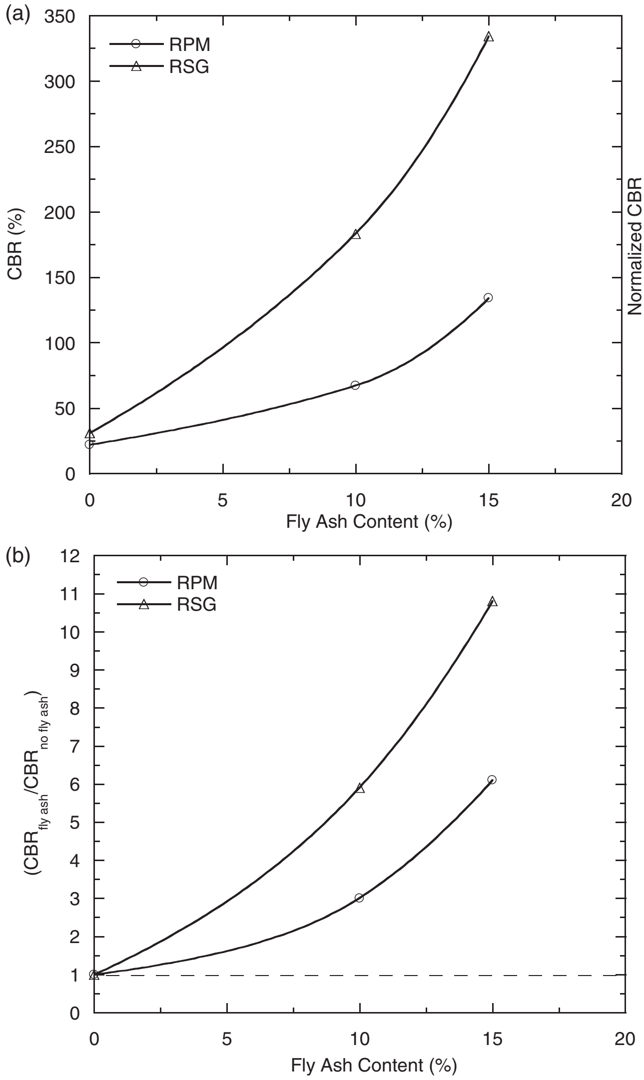

Figure 2. CBR (a) and normalised CBR (b) with fly ash content for RSG and RPM.

Table 2 are similar to those reported by Wen et al. (2008) (1300–2040 kPa for RPM stabilised with up to 14% high carbon self-cementing fly ash and curing times up to 14 days).

The AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG) suggests a minimum UCS (28 days cure) of 5200 kPa for a chemically stabilised base layer and 1700 kPa for a chemically stabilised subbase layer (ARA, 2004). The highest UCS observed in this study was 3600 kPa (RSG with 15% fly ash). Thus, the UCS of RPM and RSG blended with fly ash fall below the minimum suggested UCS for chemically stabilised base layers (>5200 kPa). The UCS requirement for a subbase layer (>1700 kPa) was met for all but one mixture of RSG and fly ash, and for only one mixture prepared with RPM (15% fly ash and 28 day cure). Even though the UCS criteria are not satisfied for most cases of RPM, field experience (Hatipoglu et al., 2008; Li et al., 2007; Wen et al., 2004) has shown that RPM and RSG blended with 10–15% fly ash have

Table 2. SRM and power model fitting parameters k_1 and k_2 (Eq. 1) for base materials with and without fly ash.

Material	Fly ash content (%)	Curing Time (d)	k_1	k_2	SRM (MPa)	Plastic strain (%)	UCS (kPa)
Class 5 base	0	–	13.6	0.534	236	3.35	–
RPM	0	–	49.2	0.344	309	1.94	–
	10	7	1753	0	1753	0.89	780
		28	2702	0	2702	0.80	1000
		56	2947	0	2947	0.77	1100
	15	7	4477	0	4477	0.50	1500
		28	6816	0	6816	1.22	2300
RSG	0	–	17.0	0.473	212	3.33	–
	10	7	5785	0	5785	2.18	1400
		28	7219	0	7219	0.70	1800
		56	8183	0	8183	0.71	2500
	15	7	10118	0	10118	1.08	3300
		28	12189	0	12189	0.62	3600

Note: Bulk stress (θ) in terms of kPa in Equation (1) for determining k_1 and k_2.

more than adequate strength to support construction and traffic loads commonly applied to base and subbase layers.

4.4. *Resilient modulus*

The SRM for the Class 5 base, RPM, and RSG are summarised in Table 2, along with the parameters k_1 and k_2 for the resilient modulus power function model (Equation (1)) for varying fly ash contents (0–15%) and varying curing times (7–56 days). The specimens with 10% fly ash were used to in order to evaluate the effects of curing up to 56 days.

RPM has the highest SRM (309 MPa) of the three base materials, RSG has the lowest SRM (212 MPa), and Class 5 base has an intermediate SRM of 236 MPa.The high resilient modulus for RPM is attributed to its recycled asphalt pavement (RAP) content (50%). Similar findings have been reported by Kim, Labuz, and Dai (2007). They conducted resilient modulus tests on an aggregate base blended with 0–75% of RAP. All blends of aggregate base and RAP had resilient moduli higher than the aggregate base alone, and the resilient modulus increased with the RAP content.

Plastic strains were calculated for the resilient modulus test on each specimen (Table 2) using data from the internal LVDTs. The total plastic strain ($\varepsilon_{\text{plastic}}$) for a resilient modulus test was calculated as the sum of the plastic strains for each loading sequence, excluding the plastic strains in the conditioning phase (Sequence 0). The total plastic strains in Table 2 are the average of replicate specimens for each material. Class 5 base and RSG showed plastic strains of 3.35% and 3.33%, respectively, whereas RPM showed a plastic strain of only 1.94%. The trend in the results is different from those in Wen et al. (2008) and Kim et al. (2007), who report larger plastic strains for RPM relative to typical aggregate base materials.

The plastic strains for RPM may be higher or lower than those of conventional base aggregates, depending on the type of aggregate used. For example, plastic strains and physical properties for an additional RPM and a crushed granite from the MnROAD research facility (Camargo, Wen, Edil, & Patton, 2008) are given in Table 3 along with those for the Class 5 base and RPM evaluated in this study. The plastic strain of both RPMs (2.77% for MnROAD RPM and 1.94% for WI RPM) is lower than that of Class 5 base (3.35%), but is significantly higher than the plastic strain of

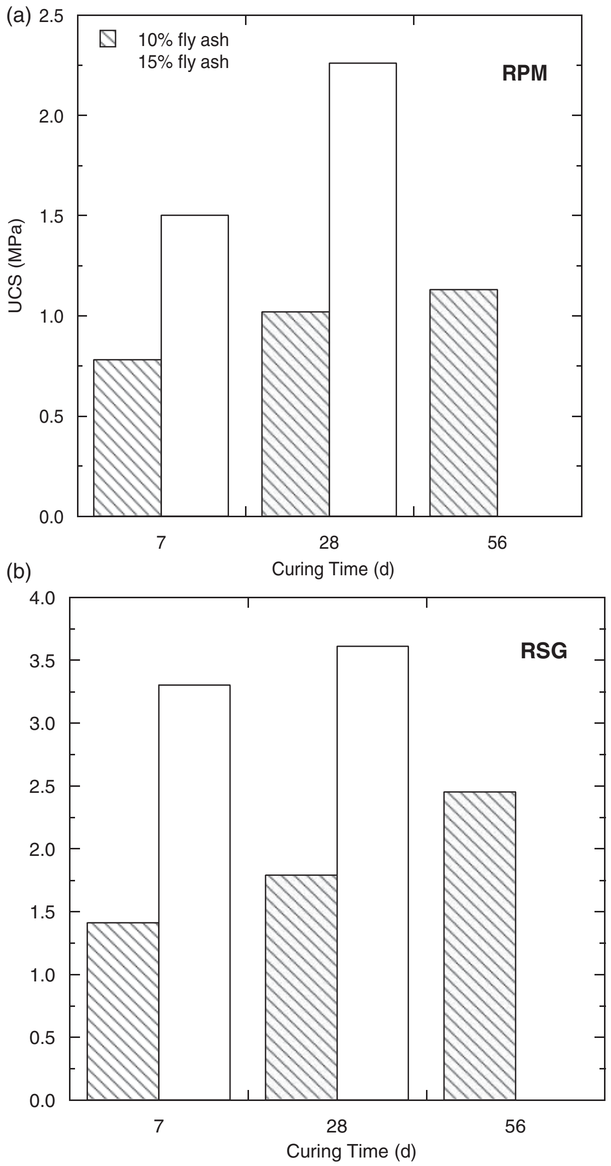

Figure 3. Unconfined compression strength for RPM (a) and RSG (b) blended with fly ash.

Table 3. Plastic strains, along with other material properties, for two RPMs and two conventional base aggregates.

Material	Gravel (%)	Sand (%)	Fines (%)	Dry unit weight (kN/m^3)	Relative density (%)	SRM (MPa)	$\varepsilon_{\text{plastic}}$ (%)
Class 5 base – this study	37	59	4	20.9	100	236	3.35
Crushed granite	68	30	2	21.2	97.5[a]	238	0.71
MnROAD RPM	40	56	4	19.6	97.5[a]	287	2.77
RPM – this study	46	43	11	21.2	100	309	1.94

[a] Modified Proctor.

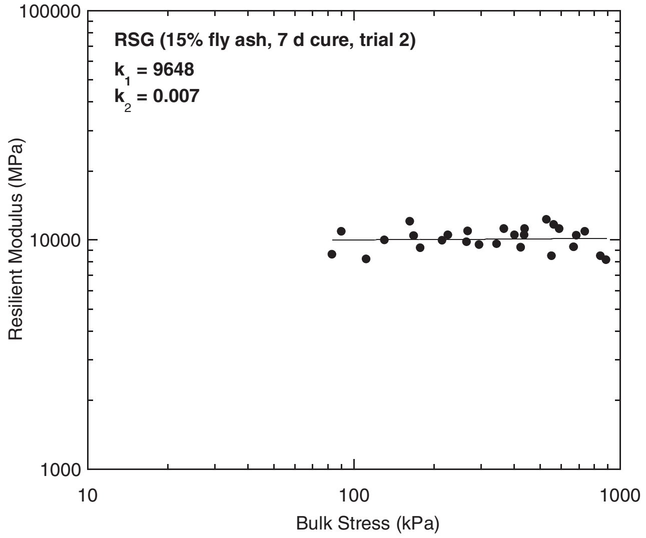

Figure 4. Resilient modulus test showing no trend in resilient modulus with bulk stress (RSG with 15% fly ash, 7 day cure, trial 2).

crushed granite (0.71%). The high plastic strain for Class 5 base is attributed to its large sand fraction (59%).

4.4.1. *Effect of fly ash content and curing time*

The SRMs for RPM and RSG blended with fly ash are summarised in Table 2, along with the parameters k_1 and k_2 for the resilient modulus power function model (Equation (1)). The resilient modulus of specimens blended with fly ash showed no apparent dependency on bulk stress (*i.e.* k_2 in Equation (1) was close to zero). An example of a resilient modulus test showing no trend is shown in Figure 4.

A linear regression analysis was performed on resilient modulus data for each specimen containing fly ash to determine if a statistically significant relationship existed between resilient modulus and bulk stress. Two-thirds of the tests showed no stress dependency for $\alpha = 0.05$, the significance level commonly used in hypothesis testing (Berthouex & Brown, 2002). In those cases where k_2 was not found to be statistically insignificant, the p-value was only slightly smaller than α, suggesting only a slight dependency on bulk stress. Furthermore, the analysis was based on all bulk stresses employed in the resilient modulus test protocol, with some significantly higher than that would be encountered in a pavement structure.

Thus, the resilient moduli of the materials blended with fly ash are described herein with a single modulus. This approach is consistent with MEPDG, which recommends a constant modulus for chemically stabilised materials (ARA, 2004).

As in the CBR test, addition of fly ash resulted in a significant increase in SRM for both materials, with the RSG exhibiting higher SRM than RPM. Specimens cured for 28 days were used because MEPDG specifies properties at 28 days cure for other chemically stabilised materials. The SRM for RPM and RSG blended with fly ash are shown in Figure 5(a) as a function of fly ash content. The SRM increases with increasing fly ash content. This finding is consistent with Wen et al. (2008). They report an increase in resilient modulus of RPM as the fly ash content was increased from 10% to 18%. Increasing the fly ash content causes more cementation of the

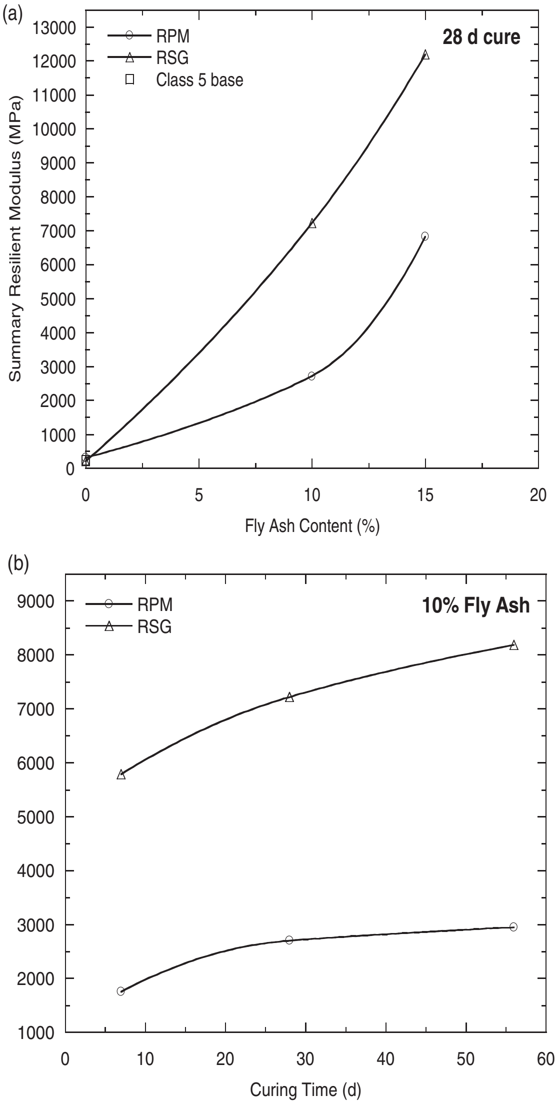

Figure 5. SRM with fly ash content (a) and curing time (b) for recycled materials with 10% fly ash.

particles, yielding specimens with higher stiffness. Diminishing returns are likely to be realised at fly ash contents higher than those described here, and additional testing is needed to assess the fly ash content beyond which stiffness no longer increases.

The effect of curing time on the SRM of RPM and RSG with fly ash is shown in Figure 5(b). The data in Figure 5(b) are from specimens blended with 10% fly ash that were cured for 7, 28, and 56 days. SRM increased with curing time for both RPM and RSG, with the increase rate being larger between 7 and 28 days. SRM for RPM increases an additional 250 MPa for 56 days of curing, whereas a more pronounced increase is observed for RSG (1000 MPa increase) for 56 days of curing. Wen et al. (2008) also report an increase in resilient modulus with curing time for RPM stabilised with fly ash.

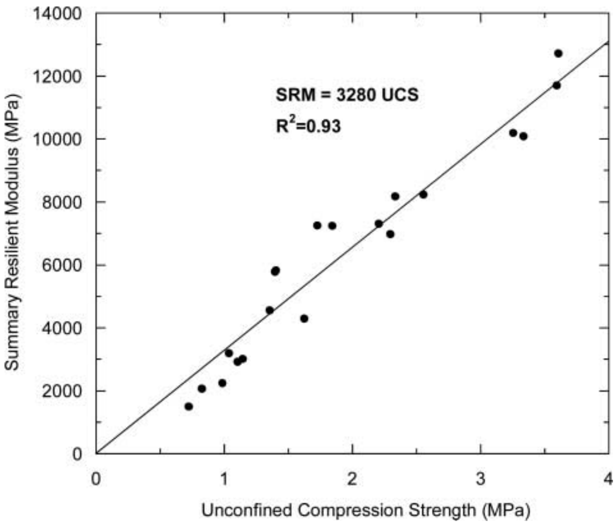

Figure 6. SRM as a function of UCS for all recycled material specimens blended with fly ash used in this study.

Resilient moduli based on internal LVDT measurements, as specified in NCHRP 1-28A test protocol (NCHRP, 2004), for materials blended with fly ash were not found in the literature. However, a range of resilient moduli for chemically stabilised soils is reported by MEPDG (ARA, 2004). The range of SRM for both materials blended with fly ash is similar to the ranges for materials stabilised with other chemicals. For example, resilient moduli for materials stabilised with lime–cement–fly ash range from 3500 to 13800 MPa, whereas resilient moduli of soil–cement mixtures from 350 to 6900 MPa.

Addition of fly ash also resulted in relatively smaller plastic strains for both recycled materials (Table 2). Plastic strains ranged from 0.5% to 1.22% for RPM with fly ash, whereas plastic strains ranged from 0.62 to 2.18% for RSG with fly ash. Wen et al. (2008) also report a decrease in plastic strains for an RPM specimen blended with fly ash.

4.4.2. *Relationship between SRM and UCS*

The relationship between the SRM and UCS for RPM and RSG blended with fly ash is shown in Figure 6 for all test results (7, 28, and 56 days cure as well as for 10% and 15% fly ash). A strong relationship exists between SRM and UCS, which suggests that the SRM of RPM and RSG blended with fly ash could be estimated from a UCS test for these materials. In particular, SRM can be estimated by ($R^2 = 0.93$)

$$\mathrm{SRM} = 3280 * \mathrm{UCS}, \tag{2}$$

where SRM and UCS are in terms of MPa.

4.5. *Freeze–thaw durability*

The change in SRM and UCS of base materials with and without fly ash incurred due to five freeze–thaw cycles us given in Table 4. The UCS of RSG increased 18% after five freeze–thaw cycles and the UCS of RPM increased by 5%. Zaman and Naji (2003) report similar findings for

Table 4. Change in SRM and UCS due to freeze–thaw cycling.

			Change	
Material	Fly ash content (%)	Volume change (%)	SRM (%)	UCS (%)
Class 5 base	0	0	−7.0	–
RPM	0	0	14	–
RSG	0	0.5	1.0	–
RPM	10	0	−15	5.0
RSG	10	0	−5.0	18

the UCS of an aggregate base blended with 10% Class C fly ash (28 days cure). They found that the UCS increased with increasing freeze–thaw cycles (up to 30 cycles).

Freeze–thaw cycling has a small effect on SRM of Class 5 base (7% decrease), RPM (15% decrease), or RSG (5% decrease) with or without fly ash. There is no consistent effect of freeze–thaw cycling on materials without fly ash; the SRM of Class 5 base decreased slightly (7%), whereas RPM and RSG increased slightly (14% and 1%). Rosa (2006) suggests a reduction of 20–66% for various coarse and fine grained materials. Freeze–thaw data on RPM alone were not found in the literature. RPM and RSG stabilised with fly ash decreased modestly (15% and 5%). The decrease in SRM is smaller than the decreases reported by Rosa for RPM and RSG stabilised with fly ash (7–42%).

The small effect of freeze–thaw cycling on the SRM is consistent with the small volume changes recorded during freezing and thawing (Simonsen, Janoo, & Isacsson, 2002). No net changes in volume were measured for Class 5 base and RPM or RSG and RPM blended with fly ash, and the volume change for RSG alone was only 0.4–0.6%. Thus, the small decrease in SRM for RPM and RSG with fly ash is probably due to the breaking of cement bonds during freezing.

5. Conclusions

Based on the results of this laboratory investigation, the following conclusions are warranted.

RSG and RPM have CBRs greater than that of Class 5 base, but the CBR of all three materials is less than typically desired for base course material (CBR $\geq$ 50%).

- Addition of fly ash to RSG or RPM significantly increases the unsoaked CBR (at least three times for RSG and 6 times for RPM), and the unsoaked CBR increased with increasing fly ash content for both materials. Moreover, addition of fly ash (10% and 15%) to RPM and RSG results in unsoaked CBRs greater than the CBR typically desired for base course ($\geq$50%).
- The UCS of RPM and RSG stabilised with fly ash increased with increasing fly ash content and curing time, with significant increases occurring even after 28 days. RPM and RSG stabilised with fly ash have UCS lower than the minimum suggested UCS for a chemically stabilised base layer (5200 kPa), but field experience reported by others has shown RPM and RSG stabilised with fly ash have more than adequate strength to support construction traffic and other loads commonly applied to base and subbase layers. In addition, the UCS is maintained even when the RPM and RSG are exposed to freezing. After five freeze–thaw cycles, the UCS of RPM and RSG stabilised with fly ash was higher (5% and 18%) than the UCS not subjected to freeze–thaw cycling.
- RPM had a higher SRM than Class 5 base, whereas the SRM for RSG was slightly lower than that of Class 5 base. The SRM for RPM and RSG stabilised with fly ash were independent

of bulk stress and were described by a constant modulus. Addition of fly ash increased the SRM of RPM and RSG (at least a factor of 6 and 29, respectively), and the SRM increased as the fly ash content was increased for both materials. SRM also increased with curing time, with the rate of increase being largest between 7 and 28 days of curing.

- RPM exhibited relatively smaller plastic strains during M_r testing than Class 5 base, whereas RSG showed similar plastic strains to Class 5 base. However, additional data shows that plastic strains for RPM may be higher or lower than those of conventional base aggregates, depending on the type of aggregate used. Plastic strains for RPM and RSG with fly ash were smaller than the plastic strains of the recycled materials alone.
- Freeze–thaw cycling had a small effect on SRM of Class 5 base (7% decrease), RPM (15% decrease), or RSG (5% decrease) with or without fly ash, with no consistent effect for materials stabilised with fly ash.
- A strong relationship ($R^2 = 0.93$) was found for SRM and UCS of RPM and RSG stabilised with fly ash, suggesting that the resilient moduli of these materials can be estimated from a UCS test. SRM (in MPa) can be estimated by multiplying UCS by 3280.

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