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ORIGINAL PAPER

Laboratory Comparison of Crushed Aggregate and Recycled Pavement Material With and Without High Carbon Fly Ash

Haifang Wen · Justin Warner · Tuncer Edil · Gingan Wang

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Abstract In-place recycling of asphalt pavement materials is a sustainable rehabilitation method. Existing hot-mix asphalt (HMA) layer is pulverized and blended with some or the entire base course and possibly some subgrade to form a broadly graded material referred to as recycled pavement material (RPM). The RPM is then compacted as the new base course and overlaid by a new layer of HMA. In some occasions, additives are added to increase the strength of RPM base course, such as cement, emulsion, fly ash. It is plausible to utilize high calcium high carbon fly ash, as the high level of carbon prevents fly ash from being used in concrete. A series of laboratory tests were conducted to evaluate the performance of these materials, including crushed aggregate, untreated RPM, and treated RPM with high carbon fly ash. The tests included compaction, California Bearing Ratio, resilient modulus, and unconfined compressive strength for treated RPM. The engineering properties of these materials were compared.

H. Wen (✉) · G. Wang
Department of Civil and Environmental Engineering, Washington State University, PO Box 642910, Spokane Street, Sloan Hall 35, Pullman, WA 99164-2910, USA
e-mail: haifang_wen@wsu.edu

J. Warner
Department of Civil and Environmental Engineering, University of Wisconsin at Madison, 1221 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706-1691, USA
e-mail: jwarner@wisc.edu

T. Edil
Department of Civil and Environmental Engineering, University of Wisconsin at Madison, 2228 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706-1691, USA
e-mail: edil@engr.wisc.edu

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1 Introduction

In-place recycling of asphalt pavement materials is a sustainable rehabilitation method. Existing hot-mix asphalt (HMA) layer is pulverized and blended with some or the entire base course and possibly some subgrade to form a broadly graded material referred to as recycled pavement material (RPM). The RPM is then compacted as the new base course and overlaid by a new layer of hot mix asphalt (HMA). In some occasion, additives are added to increase the strength of RPM base course, such as cement, emulsion, fly ash. Wen et al. studied the field performance of Class C fly ash stabilized RPM in Wisconsin and concluded that it was a feasible technology (Wen et al. 2004). Edil et al. also studied the feasibility of this technology in Minnesota (Lin et al. 2007). Class C fly ash has a carbon content of less than 6 percent and could also be used in concrete as a cement substitute. However, with the increasingly stringent environmental policy to control the pollutant emission, fly ashes with carbon contents higher than 6 percent are produced. High carbon fly ash generally can not be used in concrete, as the carbon absorbs the air-entraining admixtures and causes a loss of durability of concrete (Ramme and Tharaniyil 2004). It is possible to utilize high calcium high carbon fly ash as a chemical stabilizer of soils and other granular materials such as RPM. However, there is a lack of performance evaluation of RPM with and without high carbon fly ash.

In addition, the mechanistic-empirical pavement design requires the input of engineering properties, such as resilient modulus (M_r), for base course materials (ARA 2004). To properly design a pavement with RPM as base course materials, it is imperative to test or estimate the above mentioned engineering properties. Unlike traditional base course materials, such as crushed aggregate, the engineering properties of RPM are not readily available. Kim et al. studied the resilient modulus of RPM (Kim et al. 2007). However, the stabilized RPM was not included in the study.

The objective of this study was to determine the effectiveness of high carbon fly ash to stabilize RPM and compare the performance of untreated and treated RPM to that of crushed aggregate as base course materials. Laboratory tests included California Bearing Ratio (CBR), resilient modulus, permanent deformation, and unconfined compressive strength (only on fly ash stabilized RPM).

2 Materials

2.1 Dense-graded Crushed Aggregate

Wisconsin Department of Transportation (WisDOT) Grade 2 gravel is a manufactured aggregate quarried from limestone and dolomite formations near Madison, WI. The Grade 2 gravel used in this study was collected from a section of State Trunk Highway (STH) 60 under re-construction. It has a top size of 25.00 mm. Grade 2 gravel used in this study is classified as well-graded gravel with some silt and sand by the Unified Soil Classification System (USCS), and is recognized as medium-sized aggregate by WisDOT specifications. Grade 2 gravel is most commonly used as base course in road construction in Wisconsin. The particle size gradation for Grade 2 gravel is shown in Fig. 1.

2.2 Recycled Pavement Material

The recycled pavement material (RPM) was sampled from roadways in Madison, WI in the summer of 2006 during a highway reconditioning project. The existing 100 mm-thick asphalt layer was pulverized and mixed with 100 mm base course materials to obtain the RPM. The particle size gradation for RPM is shown in Fig. 1. RPM is classified as well-graded sand (SW) with gravel under the Unified Soil Classification System (USCS). Atterberg limits were not performed. The RPM is classified as A-1-a(0) under the AASHTO classification system. The gradation of RPM is also shown in Fig. 1.

2.3 Cementitious High Carbon Fly Ash

Fly ash obtained from unit 8 of the Riverside Power Station of Xcel Energy in St. Paul, MN was used to stabilize the RPM. The physical and chemical properties of Riverside unit 8 fly ash, and typical class F and class C fly ashes are listed in Table 1. The calcium oxide (CaO) content of Riverside unit 8 fly ash is 22.37%, silicon dioxide (SiO_2) content is 18.96%, the CaO/SiO_2 ratio (an indicator of cementation potential) is 1.18 which indicates that the

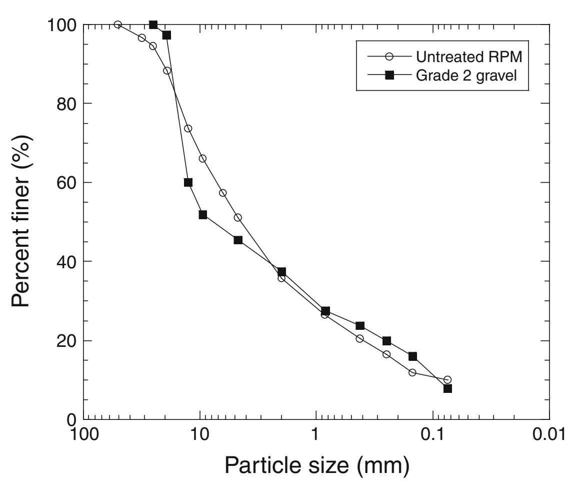

Fig. 1 Particle size distributions for RPM and grade 2 gravel

Table 1 Chemical compositions of riverside unit 8 fly ash

Fly ash	Strength activity @ 7 days, min (%)	LOI (%)	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)
Riverside 8	87	16.35	22.37	18.96	13.96	5.93
Class C	75	6.00 Max	–	$SiO_2 + Al_2O_3 + Fe_2O_3$ 50.0 min		
Class F	75	6.00 Max	–	$SiO_2 + Al_2O_3 + Fe_2O_3$ 70.0 min		

Note: *LOI* loss on ignition

cementation potential is medium. A material of strong cementation potential, e.g., cement, has a CaO/SiO_2 ratio of 2–4. An overly high cementation ratio (e.g., lime without SiO_2) or low (e.g., soil without CaO) is considered to be not cementitious. The loss on ignition or carbon content is 16.35. Therefore, Riverside unit 8 fly ash is a high calcium high carbon fly ash. The high carbon content in the Riverside unit 8 fly ash makes it not suitable for concrete production.

3 Experimental Methods

3.1 Physical Properties of Untreated and Treated RPM

Particle gradations were performed in accordance with ASTM D 442. Optimum moisture content (OMC) and maximum dry unit weight (MDUW) were determined using the modified proctor compaction test in accordance with ASTM D 1557. Samples were compacted in 5 lifts in a 152-mm mold using 56 blows per layer. Approximately 6–7% of the RPM is retained on the 19-mm sieve. ASTM D 1557 specifies that all material chosen for compaction must pass the 19-mm sieve, therefore; sample material retained on the 19-mm sieve was removed prior to compaction. OMC and MDUW were determined for untreated RPM and RPM-fly ash mixtures of 10, 14, and 18% fly ash (as percent of the dry weight of RPM). Reported MDUWs for RPM-fly ash mixes include RPM and fly ash weight. Reported OMCs are the ratio of the weight of water to the weight of RPM and fly ash.

3.2 California Bearing Ratio

California Bearing Ratio (CBR) tests were performed on all compacted specimens in accordance with ASTM D 1883. In doing so, the relationship between CBR and compaction moisture content could be determined. After compaction, untreated RPM and gravel samples were soaked for 4 days under a 4.54 kg surcharge. The 4.54 kg surcharge was also used during CBR testing. RPM-fly ash samples were cured for 7 days at room temperature and 100% humidity, followed by four-day soaking. During the CBR tests, the piston intruded into the specimens at a rate of 1.27 mm per minute as specified by ASTM D 1883.

3.3 Resilient Modulus

Resilient modulus tests were performed on Grade 2 gravel, untreated RPM, and RPM-fly ash mixtures. Resilient tests were conducted in accordance with the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol for base and subbase materials (*6*). Three replicates were used for each material. The materials were brought to OMC and compacted to MDUW in six layers into a split metal mold. The split metal mold had a diameter of 152 mm and a length 305 mm. For RPM-fly ash mixtures, RPM was mixed with fly ash and water was then added to OMC. Specimens were cured at room temperature and 100% humidity for 7 and 14 days prior to resilient modulus testing.

3.4 Unconfined Compressive Strength

Unconfined compressive strength was determined in accordance with ASTM D 1633 for RPM-fly ash specimens only. Untreated RPM and Grade 2 gravel were not tested, due to the non-cohesive nature of these granular materials. Two RPM-fly ash samples were prepared at each of the three fly ash contents (six total samples). These samples were cured for 7 and 14 days and tested for unconfined compression strength to determine the effect of curing length on

Table 2 Compaction characteristics of untreated RPM, grade 2 gravel and RPM-fly ash mixtures

Material	Fly ash content (%)	Maximum dry density (kN/m^3)	Optimum water content (%)
Grade 2 gravel	0	21.5	7.4
Untreated RPM	0	21.2	5.5
RPM w/fly ash	10	21.5	7.0
RPM w/fly ash	14	21.6	7.4
RPM w/fly ash	18	21.3	7.4

unconfined compression strength. Compression of RPM-fly ash specimens occurred at a strain rate of 0.21% per minute until specimen failure.

4 Results and Analysis

4.1 Compaction Characteristics

The compaction characteristics of untreated RPM, RPM-fly ash, and Grade 2 gravel are summarized in Table 2. The optimum water contents of RPM-fly ash and Grade 2 gravel are close to each other, ranging from 7.0 to 7.4%, while the untreated RPM had an optimum water content of only 5.5%. The maximum dry unit weight of Grade 2 gravel is comparable to those of RPM-fly ash mixtures and untreated RPM. The optimum water contents and maximum dry unit weights were used to prepare samples for resilient modulus and unconfined compression strength testing.

4.2 CBR Characteristics

CBR versus water content curves are shown in Fig. 2 for untreated RPM, Grade 2 gravel, and RPM-fly ash mixtures. The maximum CBR, corresponding compaction water contents and dry unit weights for untreated RPM, Grade 2 gravel, and RPM fly-ash mixtures are shown in Table 3. The optimum water contents for Grade 2 gravel, untreated and treated RPM were comparable to those for maximum dry density. The CBR value of crushed aggregate was 86, which is significantly higher than that of untreated RPM, 38. The addition of fly ash significantly increased the CBR values of RPM, 120 for 10% fly ash, 155 for 14% fly ash, and 212 for 18% fly ash.

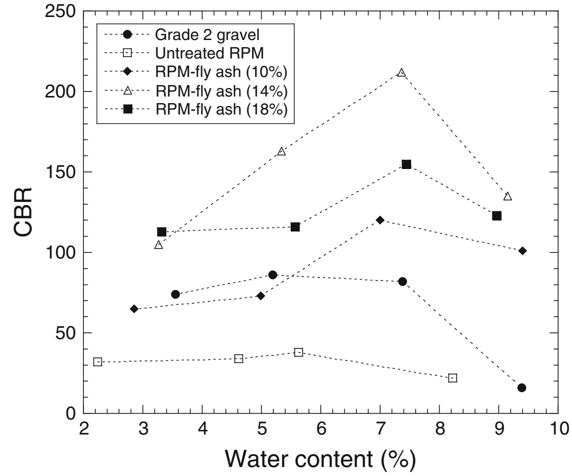

Fig. 2 CBR versus compaction water content for grade 2 gravel, untreated RPM, and RPM-fly ash mixtures

The RPM-fly mixtures had higher CBR values than those of both untreated RPM and crushed aggregate. Riverside 8 fly ash improved the bearing strength of RPM.

4.3 Resilient Modulus

Resilient modulus is reported as a relationship between bulk stress, octahedral shear stress, and several empirically derived constants as shown in Eq. 1 (Witczak et al. 2004).

$$M_r = k_1 \cdot p_a \left(\frac{\sigma_b - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + k_7\right)^{k_3} \quad (1)$$

where M_r is resilient modulus, k_1, k_2, k_3, k_6, and k_7 are empirical constants, p_a is the atmospheric pressure, τ_{oct} is the octahedral shear stress, and σ_b is the bulk stress. In this study the empirical constants are

Table 3 California bearing ratio of untreated RPM, grade 2 gravel and RPM-fly ash mixtures

Material	Maximum CBR	Fly ash content (%)	Dry density (kN/m^3)	Water content (%)
Grade 2 gravel	86	0	21.0	5.2
Untreated RPM	38	0	21.2	5.5
RPM w/fly ash	120	10	21.5	7.0
RPM w/fly ash	155	14	21.6	7.4
RPM w/fly ash	212	18	21.3	7.4

calculated such that bulk stress has units of kPa and resilient modulus has units of MPa. Bulk stress is calculated by

$$\sigma_b = \sigma_1 + \sigma_2 + \sigma_3 \quad (2)$$

where σ_b is the bulk stress and σ_1, σ_2, and σ_3 are the principal stresses acting on the specimen. Octahedral shear stress is calculated as

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \quad (3)$$

The resilient modulus test results for untreated RPM, Grade 2 gravel, and RPM-fly ash mixtures are summarized in Table 4, at a bulk stress of 83 kPa. Resilient modulus of untreated RPM, 79 MPa at a bulk stress of 83 kPa, is higher than that of Grade 2 gravel, 59 MPa. However, this result contrasts to the CBR test results. Recall the CBR value of Grade 2 gravel was much higher than that of untreated RPM. This phenomenon was also reported in a previous study (Wen et al. 2007). It is believed that this stems from the difference in the nature of these two tests: damage is induced during CBR test while the opposite is true for the Mr test. The resilient modulus for RPM-fly ash specimens increased with the increase fly ash content, from 135 MPa for 10% fly ash, 196 MPa for 14% fly ash, to 273 MPa for 18% fly ash, after 7-day curing. The resilient modulus also increased when the curing period increased from 7 to 14 days. The resilient modulus values of RPM-fly ash specimens are significantly higher than those of the untreated RPM and Grade 2 gravel.

Table 4 Resilient modulus of untreated RPM, grade 2 gravel and RPM-fly ash mixtures

Material	Fly ash content (%)	Curing period (days)	Modulus (MPa)
Grade 2 gravel	0	0	59
Untreated RPM	0	0	79
RPM w/fly ash	10	7	135
		14	259
RPM w/fly ash	14	7	196
		14	345
RPM w/fly ash	18	7	273
		14	488

Note: M_r, resilient modulus, resilient modulus was calculated using a bulk stress of 83 kPa and an octahedral shear stress of 19.3 kPa

The resilient modulus versus bulk stress and resilient modulus versus octahedral shear stress plots of the Grade 2 gravel, untreated RPM, and RPM-fly ash specimens are given in Figs. 3 and 4, respectively. A review of these plots suggests that bulk stress has a greater effect on resilient modulus than does octahedral shear stress. Resilient modulus

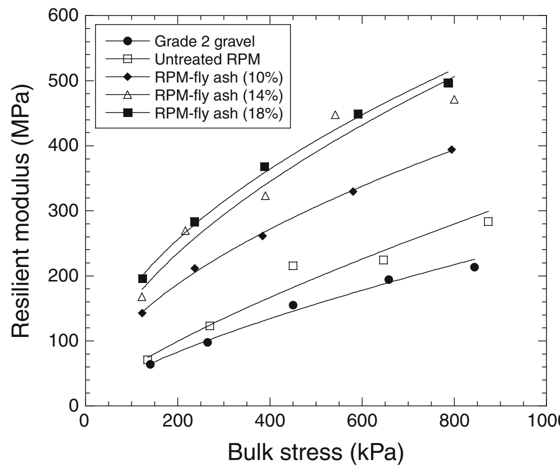

Fig. 3 Variation of resilient modulus with increasing bulk stress for grade 2 gravel, untreated RPM, and RPM-fly ash mixtures

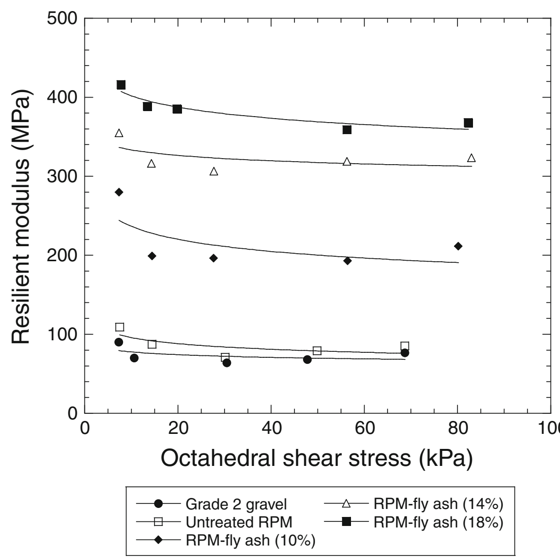

Fig. 4 Variation of resilient modulus with increasing octahedral shear stress for grade 2 gravel, untreated RPM, and RPM-fly ash mixtures

increases with increasing bulk stress, whereas increasing octahedral shear stress causes resilient modulus to decrease. However, at high octahedral shear stresses, resilient modulus appears to become constant.

4.4 Permanent Deformation

When a material is cyclically loaded and unloaded (such as in a resilient modulus test) it will exhibit hysteretic behavior i.e. as the applied stress is relieved, the material will begin to rebound (elastic or recoverable strain), but may not fully rebound to its original dimensions. Permanent deformation is non-recoverable, and accrues with each additional application of stress to the soil. In the field, this permanent deformation in base course could cause rutting on the surface of asphalt pavement. The total permanent deformations measured after resilient modulus tests for untreated RPM, Grade 2 gravel, and RPM-fly ash mixtures are shown in Fig. 5. All test specimens were approximately 304.8 mm in length.

Untreated RPM had the largest total permanent deformation, 2.84 mm, after the resilient modulus tests. Grade 2 gravel had a permanent deformation of 2.33 mm. RPM-fly ash specimens experienced significantly smaller permanent deformations: 1.02 mm for 10% fly ash, 0.73 mm for 14% fly ash, and 0.52 for 18% fly ash. Permanent deformation decreased with the increase of fly ash content. Therefore, the addition of fly ash increased the resistance of RPM to permanent deformation.

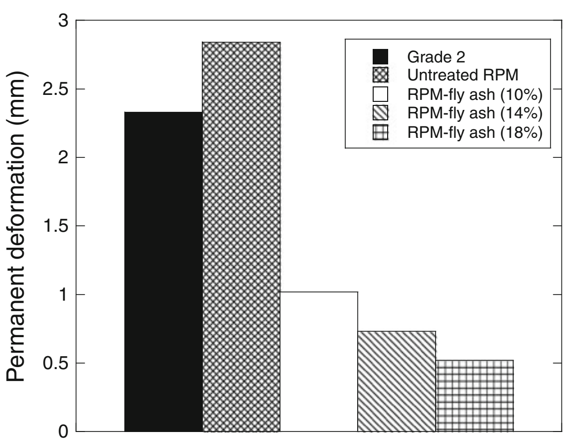

Fig. 5 Permanent deformation of grade 2 gravel, untreated RPM, and RPM-fly ash mixtures during resilient modulus testing

The permanent deformation of RPM was larger than that of Grade 2 gravel. However, the Mr of untreated RPM was also higher than that of Grade 2 gravel. This agrees with the findings by Kim et al. (2007). This indicates that resilient modulus test alone can not be used as the only source of performance evaluation, especially for the unconventional materials, such ash RPM.

4.5 Unconfined Compressive Strength

Unconfined compressive strength tests were performed on the fly ash treated RPM specimens and are shown in Table 5 and Fig. 6. Untreated granular materials such as crushed aggregate or RPM can not be tested, due to the non-cohesive nature of these two materials.

The unconfined compressive strength increased with the increase of the fly ash content: 1.30 MPa for 10% fly ash, 1.67 MPa for 14% fly ash, and 2.05 MPa for 18% fly ash, after 7-day curing. The unconfined compressive strength increased slightly from 7 to 14-day curing. When compared to cement, the fly ash stabilized materials gain strength relatively slower,

Table 5 Unconfined compressive strength of untreated RPM, grade 2 gravel and RPM-fly ash mixtures

Material	Fly ash content (%)	Q_u 7 days (MPa)	Q_u 14 days (MPa)
RPM w/fly ash	10	1.30	1.39
RPM w/fly ash	14	1.67	2.04
RPM w/fly ash	18	2.05	2.46

Note: Q_u, unconfined compressive strength

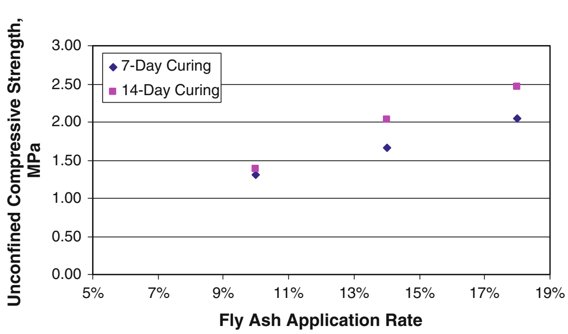

Fig. 6 Unconfined compressive strength results

but longer. This is because the pozzolanic reaction is more pronounced in fly ash than that in cement. It is anticipated that the long-term strength of fly ash treated RPM be significantly higher than that of RPM at 14-day curing. A test that better characterizes both the conventional and unconventional materials is warranted.

4.6 Observation

Based on the test results, it is clear that fly ash stabilized RPM has more desirable characteristics than untreated RPM and Grade 2 gravel, in terms of CBR, Mr, and permanent deformation. However, there are inconsistencies in the lab test results between untreated RPM and Grade 2 gravel. Field performance should be used to investigate the true performance of these materials, including durability, reflective cracking, if any, and life cycle cost analysis.

5 Summary and Conclusions

In this study, there materials were evaluated in the laboratory: untreated RPM, fly ash treated RPM, and Grade 2 gravel. The tests included compaction, California Bearing Ratio (CBR), resilient modulus (M_r), and unconfined compressive strength for treated RPM. When compared to crushed aggregate, RPM had lower CBR values, but higher resilient modulus values. RPM also exhibited higher permanent deformation than crushed aggregate, after being subjected to the same stress history. A test that can be used to characterize both the conventional and unconventional materials is warranted. Fly ash stabilized RPM has more desirable characteristics than untreated RPM and Grade 2 gravel, in terms of CBR, M_r, and permanent deformation. Increasing fly ash content also increased CBR, M_r, and unconfined compressive strength, but decreased the permanent deformation. Based on the lab results, fly ash treated RPM has the potential to increase the performance of pavement.

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