Cementitious High-Carbon Fly Ash Used to Stabilize Recycled Pavement Materials as Base Course

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Because of the increasingly stringent environment policy stipulated by the U.S. Environmental Protection Agency, local authorities, or both, the power generation industry must take measures to reduce the emission of nitrogen oxides, sulfur oxide, and mercury. These measures increase the amount of residual unburned carbon in fly ash. The increase makes the fly ash unsuitable for concrete production and destines it to become landfill. During roadway construction, existing asphalt pavement is often removed. This paper presents the test results of using cementitious high-carbon fly ash to stabilize recycled asphalt pavement materials in situ as a new base course. A series of laboratory tests was performed, including moisture–unit weight relationship, California bearing ratio, unconfined compressive strength, and freeze–thaw durability. Two high-carbon fly ashes (high-calcium and low-calcium) were used in this study. The test results indicate that using high-calcium, high-carbon fly ash has the potential to be a cost-effective and environmentally friendly technology.

Most highways in the United States were constructed in the 1950s and 1960s, and the majority of them have asphalt pavement surfaces. Many of these highways have deteriorated significantly during their operation. The two most common techniques of recycling asphalt pavement are milling and full-depth removal (FDR) (*1*). In milling operations, the upper level of the existing roadway is removed and reused, and the resultant material is recycled asphalt pavement. In FDR operations, the entire existing asphalt layer is pulverized and mixed with the underlying base course. FDR is often used for low-volume-road rehabilitation or reconstruction. The FDR material can be stockpiled but is most frequently reused immediately after processing at the site. FDR is typically performed by using full-size reclaimers or portable asphalt recycling machines, and pulverization is typically performed to specified gradations with a rubber-tired grinder (*2*). Often, existing hot-mix asphalt (HMA) is pulverized and blended with some or the entire base course and possibly some soils to form a broadly graded material, which here is referred to as recycled pavement material (RPM). The RPM is typically compacted as the new base course and overlaid by a new layer of HMA. It can also be stockpiled for later use. One possible method to increase the stiffness and strength of RPM is to add self-cementing fly ash to the mix for high-volume-traffic roads during reconstruction.

Fly ash is a by-product of pulverized coal-fueled power plants. Ash is collected from exhaust gas, by either electrostatic or mechanical means. Collection from exhaust gas causes fly ash to form spherical particles with sizes ranging from 0.005 to 0.074 mm (*3*). Within-specification fly ash is classified as Class C or Class F, which has a loss on ignition (typically carbon) less than 6% in accordance with ASTM C618. Class C fly ash is self-cementing, while Class F ash is pozzolanic and requires an activator such as lime to form cementitious compounds. Off-specification fly ashes, such as high-carbon fly ash, may contain sufficient calcium oxide (CaO) to be self-cementing but are substandard for use in concrete.

In 2002, approximately 76.5 million tons of fly ash were produced in the United States by coal power plants, and about 49.8 million tons were landfilled (*4*). The Clean Air Act and the Clear Skies Initiative require power plants to reduce emissions of sulfur oxide (SO_x), nitrogen oxide (NO_x), and mercury. Technologies such as activated-carbon injection (ACI), wet scrubbers, and selective catalytic reduction may be used to reduce mercury emissions. In 1997, the U.S. Environmental Protection Agency (EPA) submitted its *Mercury Study Report to Congress,* in which it suggests that, in cost and technology, ACI is the most feasible mercury removal mechanism. However, ACI increases the carbon content of fly ashes (*5*).

NO_x emissions are reduced by altering the combustion characteristics in coal boilers. This reduction is typically done by limiting the oxygen available during combustion. One side effect of oxygen restriction is that some carbon remains unburned. Thus, the carbon content of the resulting fly ash is increased (*6*).

High-carbon fly ash is unsuitable for air-entrained concrete and some other commercial applications because the carbon absorbs the air-entraining admixtures. There are ways to make high-carbon ash more usable, such as reburning as fuel and carbon–ash separation, but the former requires a burner that produces marketable fly ash, and the latter requires energy. Finding a new application for high-carbon fly ash would prove beneficial for power plants and the environment by providing another alternative to landfilling.

Class C fly ashes have been shown effective in stabilizing soft, fine-grained subgrade soils (*7, 8*) and RPM as a base course (*9–11*). The increase in carbon content of fly ashes due to new regulations may make Class C fly ash more expensive because of reduced availability or the additional processing required to meet the Class C specifications.

The objective of this study was to determine if cementitious, high-carbon fly ashes are viable as stabilizers for RPM base material. Laboratory testing included California bearing ratio (CBR), unconfined compressive strength (UCS), and freeze–thaw durability. Test

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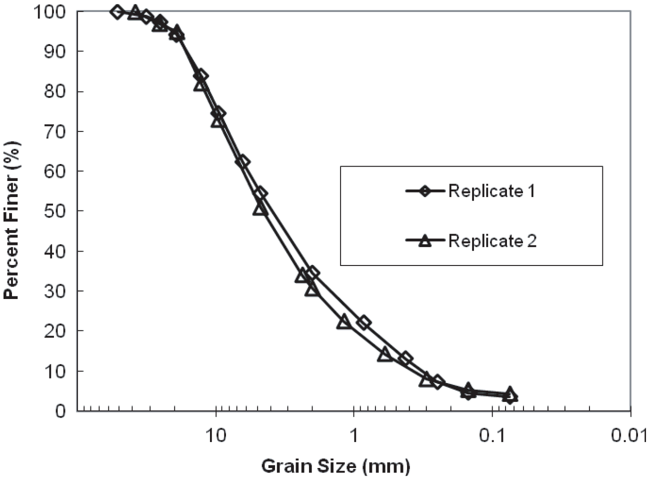

FIGURE 1 Grain size distribution curves for recycled pavement material (duplicate tests).

results were used to determine suitability of high-carbon fly ash for RPM stabilization.

MATERIALS

Recycled Pavement Material

The cold in-place asphaltic RPM was sampled from SH-144, West Bend, Wisconsin, in the summer of 2005 during a highway reconditioning project. The RPM consisted of the pulverized existing 100-mm asphalt pavement mixed with the top 25-mm base course material. The particle size gradations for the materials are shown in Figure 1. The RPM classifies as a well-graded sand with gravel under the Unified Soil Classification System and as A-1-a(0) under the AASHTO classification system.

Cementitious, High-Carbon Fly Ash

Two fly ashes, Dewey and King, were used in this study. Dewey fly ash came from the Nelson Dewey Power Plant operated by Alliant Energy in Cassville, Wisconsin. King fly ash came from the Alan S. King Power Plant operated by Xcel Energy in Bayport, Minnesota. Both plants burn subbituminous coal in cyclone boilers and collect fly ash electrostatically. The chemical components of the King and Dewey fly ashes along with the specifications for Classes C and F fly ashes are shown in Table 1. Loss on ignition (LOI) primarily measures carbon content. Dewey fly ash has an LOI of 49.3% while King fly ash has an LOI of 12.0%. Both are significantly higher than the maximum LOI, 6%, for Class C or F fly ash.

EXPERIMENTAL METHODS

Physical Properties of Untreated and Treated RPM

Particle gradations were determined in accordance with ASTM D442. Optimum moisture content and maximum dry unit weight were determined through the modified Proctor test in accordance with ASTM D1557, except that three layers were compacted instead of five on the basis of recommendations in ASTM C593. The three layers were compacted in a 152-mm mold with 56 blows per layer. About 5.7% of the RPM was retained on the 19-mm sieve. According to ASTM D1557, all the material should pass the 19-mm sieve, but both ASTM D1557 and ASTM D4718 state that the effects of a small percentage of material greater than 19 mm are insignificant. Inclusion of the larger particles was more representative of field conditions and was used in this study. The optimum moisture content and maximum dry unit weight were determined for untreated RPM and RPM stabilized with 6%, 10%, and 14% fly ash (by the dry weight of RPM).

CBR Tests

CBR tests were performed in accordance with ASTM D1883. Both untreated RPM and RPM–fly ash specimens were compacted at the optimum moisture contents and maximum dry unit weights. For the RPM–fly ash mixture, fly ash was first mixed with RPM, and then sufficient water was added to bring the material to the optimum moisture content. Untreated RPM samples were tested after soaking for 4 days under a 4.54-KN surcharge, which was also used during CBR testing. RPM–fly ash samples were cured for 7 days in a curing room with 100% relative humidity at room temperature, followed by 4 days of soaking and then the CBR tests. During the CBR tests, the piston intruded into the specimens at a rate of 1.27 mm/min in accordance with ASTM D1883.

Determination of UCS

UCS was determined in accordance with ASTM D1633 for RPM–fly ash specimens only. Untreated RPM, like crushed stone, has no

TABLE 1 Chemical Compositions of Dewey and King Fly Ash

Fly Ash	Strength Activity at 7 Days, Minimum (%)	LOI (%)	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)
Dewey	82.7	49.3	9.19	8.01	6.95	2.60
King	77.7	12.0	25.80	24.00	14.95	5.98
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, SiO_2 = silicon dioxide, AL_2O_3 = aluminum oxide, Fe_2O_3 = iron oxide.

significant UCS. Compression occurred at a strain rate of 0.21% per min until specimen fails.

Freeze–Thaw Durability

ASTM D6035 was used as a guide for this procedure. RPM–fly ash specimens were made to test the effects of freeze–thaw cycles on strength and stiffness. After extrusion from polyvinyl chloride molds, the specimens were soaked for 5 h. The specimens were then wrapped in plastic to prevent changes in moisture content during freeze–thaw cycling and placed in a freezer to begin cycling. The embedded thermocouples were used to confirm freezing. Thawing took place at room temperature. Specimens were subjected to 12 freeze–thaw cycles before UCS testing. Results were compared with specimens that were soaked for 5 h but not subjected to freeze–thaw cycles.

RESULTS

Compaction Characteristics

The compaction characteristics of untreated and RPM–fly ash mixtures are given in Table 2. The optimum moisture contents of Dewey fly ash mixtures are higher than those for untreated RPM, while the maximum dry unit weights of Dewey fly ash mixtures are less than those of untreated RPM. In contrast, the optimum moisture contents and maximum dry unit weights of King fly ash mixtures are about the same as those of the untreated RPM. The optimum moisture contents and maximum dry unit weights were used to prepare specimens for CBR and UCS.

CBR Characteristics

CBR tests on both untreated RPM and RPM–fly ash mixtures were performed at the optimum moisture content and maximum dry unit weight of the mixtures, following the same specimen preparation procedure as for the compaction test for both untreated RPM and RPM–fly ash mixtures. The test results at 5-mm penetration depth are shown in Table 2. The CBR values of RPM–fly ash mixtures are significantly higher than those of untreated RPM, which has an average CBR of 9.2. The CBR value of untreated RPM is fairly low compared with conventional base course materials, such as crushed aggregate, whose CBR values range from 50 to 80 (*12*). The CBR values of RPM in this study are comparable to the CBR values of RPM reported by Li et al (*11*).

TABLE 2 Compaction Characteristics and CBR

Material	Optimum Moisture Content (%)	Maximum Dry Density (kN/m^3)	CBR (%)
Untreated RPM	6.5	21.21	9.2
Dewey			
6 (%)	8.9	19.89	44
10 (%)	7.8	19.35	56
14 (%)	8.5	18.55	57
King			
6 (%)	6.4	21.18	94.5
10 (%)	5.8	21.24	134
14 (%)	5.7	21.07	160

NOTE: CBR = California bearing ratio.

The CBR values of RPM stabilized with Dewey fly ash were 44, 56, and 57 for 6, 10, and 14% fly ash, respectively. For King fly ash–stabilized RPM, the CBR values were 94.5, 134, and 160 for 6, 10, and 14% fly ash, respectively. Both King- and Dewey-stabilized RPM had significantly higher CBR values than the untreated RPM. In addition, King fly ash was more effective in increasing the CBR values than was Dewey fly ash. This is probably because King fly ash has higher CaO content and is more cementitious than Dewey fly ash.

The low CBR value of untreated RPM implies that untreated RPM is not suitable as a pavement base course material (*12*), especially for heavy loads. However, adding fly ash, especially the high calcium fly ash (King fly ash in this case), significantly increased the CBR values and thus the load capacity of pavement. The treated RPM can be used as base course material and provides strong support to the surface layer. However, there is limitation to apply CBR to pavement design, as discussed in the later section.

UCS Test

The UCS test is one of the most common ones for stabilized materials. UCS data are reported in Table 3. Untreated materials like crushed stone have no significant UCS. As Table 3 shows, after 7-day curing, the compressive strengths were 120, 410, and 640 kPa for, respectively, 6%, 10%, and 14% King fly ash mixtures. Increasing fly ash application rate and curing period increased the UCS. The results indicated that King fly ash was more effective in increasing the UCS of RPM than Dewey fly ash did, probably because of the high calcium content in King fly ash.

Freeze–Thaw Durability

The pavement base course is subject to increasing moisture content from either pavement surface or underground after construction. The stiffness and strength of stabilized materials with high water content, when subjected to freeze–thaw, typically is decreased. The UCS for the fly ash–stabilized RPM subjected to freeze–thaw cycles is given in Table 4. Specimens of Dewey fly ash mixtures were very

TABLE 3 UCS of RPM–Fly Ash Mixtures

	q_u (kPa) After Curing Duration (days)		
Material	7	28	56
Dewey			
6%	34	NT[a]	NT[a]
10%	81	140	150
14%	120	150	210
King			
6%	120	230	290
10%	410	520	660
14%	640	990	1,090

NOTE: q_u = unconfined compressive strength.

[a] NT = not tested.

TABLE 4 UCS of RPM–Fly Ash Mixtures Subjected to Freeze–Thaw Cycles

Fly Ash	Fly Ash Content (%)	q_u (kPa) After Freeze–Thaw Cycles: 0 Cycle	q_u (kPa) After Freeze–Thaw Cycles: 12 Cycles
Dewey	10	71	NT
	14	NT	68
King	10	540	320
	14	520	510

NOTE: q_u = unconfined compressive strength. NT = not tested, because these samples did not survive to be tested after soaking or freeze–thaw.

difficult to keep intact after 5 h of soaking or freeze–thaw cycles, and most of the specimens broke before testing. For King fly ash mixtures, the specimens with 14% fly ash had higher resistance to freeze–thaw than the ones with 10% fly ash. Only minimal reduction in UCS was observed after 12 freeze–thaw cycles. This result indicates that adding high calcium fly ash is beneficial to increasing the durability of stabilized RPM. This further indicates that RPM stabilized with high calcium fly ash could be used in pavements that are subject to freeze–thaw attacks.

SUMMARY AND CONCLUSION

In this study, the feasibility of using high-carbon fly ash to stabilize cold in-place recycled asphalt pavement as a base course material was investigated. It was found that untreated RPM had extremely low CBR values. Adding fly ash significantly increased the CBR values. Higher calcium content in fly ash, King fly ash in this case, led to higher CBR values than the low calcium fly ash (i.e., Dewey fly ash). The RPM treated with fly ash had comparable or higher CBR values than crushed aggregate. UCS allows identification of the suitable fly ash and optimum fly ash content (e.g., 10% King fly ash). The freeze–thaw durability results indicated that RPM stabilized with King fly ash is suitable for use in a pavement subjected to freeze–thaw attacks.

The laboratory tests demonstrated the feasibility of using the high-calcium, high-carbon, fly ash–stabilized, recycled pavement material as a base course material. Performance needs to be verified in a field application in which real traffic and climatic conditions are imposed. The long-term strength–modulus development and deterioration of stabilized recycled pavement material under traffic loading and weathering also need to be evaluated.

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