In-Situ Mixed Concrete with 93 % to 100% Recycled Content: We Energies "Eco-Pad" Pavement

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ABSTRACT: This paper presents research that identifies mixture proportions and methods for an in-situ mixed concrete pavement for a 3.5 acre (1.42 hectare) storage pad constructed in the fall of 2004 at We Energies' Pleasant Prairie Power Plant, located in Kenosha County, Wisconsin. The constituents to produce the concrete consisted of recycled concrete, bottom ash, Class C fly ash, and either portland cement for a 93% recycled content concrete or slag cement for a 100% recycled content in the concrete. The process to make the in-situ mixed concrete included vane spreaders for distributing the cementitious materials, mixing aggregates and binders with an asphalt pavement reclaimer/pulverizer, and then using conventional techniques for roller compacted concrete. Compressive strengths attained 3,100 psi (21 MPa) for the portland cement/Class C fly ash blend at an age of 1 year and 1,700–2,000 psi (12 – 14 MPa) for the slag cement/Class C fly ash blend.

KEYWORDS: fly ash, bottom ash, slag cement, coal combustion products, Eco-Pad, in-situ mixing, roller compacted concrete, recycled concrete, crushed concrete, blended cementitious material, portland cement

INTRODUCTION

The objective of this research project was to develop a mixture that had more than 90% recycled materials and industrial byproducts to produce durable concrete and to demonstrate the economic efficiency of in-situ mixing and roller compaction methods to construct a 3.5 acre (1.42 hectare) outdoor storage pad for stockpiling bottom ash and synthetic gypsum. Long-term performance will be evaluated. The name Eco-Pad refers to the economic and environmental benefits of the materials and construction process.

A literature search was conducted and rather than compiling an exhaustive review of roller compacted concrete and high volume concrete literature, some important publications were reviewed and are listed in the references. A conceptual design and economic analysis of alternatives determined that in-situ mixing could provide significant savings versus conventional concrete pavement, roller compacted concrete and asphalt pavement.

The class C fly ash and bottom ash used in this project were produced at We Energies' Pleasant Prairie Power Plant (P4) located in Kenosha County, Wisconsin, and is a byproduct of Wyoming Powder River Basin sub-bituminous coal combustion. The power plant is also equipped with We Energies patented ash fuel reburn systems where high carbon bituminous coal ash is introduced in direct proportion to the coal being consumed, thus producing a fly ash that meets ASTM C-618 class C specifications. The fly ash is captured by electrostatic precipitators from flue gas prior to discharge through a chimney. The plant uses an SCR (selective catalytic reduction) for reduction of NOx emissions. At the time of construction of the Eco-Pad, the plant was installing wet scrubbers for SOx emission reductions. The Eco-Pad was used as a staging area for that project as well as storage of bottom ash. Ultimately FGD gypsum from the wet scrubbers will also be stored on the Eco-Pad.

The bottom ash was collected from a wet bottom tangentially fired boiler and was used as the fine aggregate component in the concrete. The 1-1/2" topsize recycled concrete was supplied from a crushed and screened stockpile managed by an asphaltic concrete producer in Racine County, Wisconsin was used as the coarse aggregate component in the concrete. Type I /II cement was used on the western half of the site and slag cement was on the eastern half. The project scope was changed during construction where slag cement was substituted in place of the portland cement after the first day of paving due to a shortage of available portland cement and the progressively colder temperatures of the late Fall season. This field change provided the opportunity to demonstrate concrete with a 100% recycled content.

Most of the pavement area had been previously used as a bottom ash storage pad that consisted of a clay sub-base and a well graded crushed dolomitic limestone base. The area was re-graded using a 12 inch thick layer of compacted bottom ash for the base for the Eco-Pad. Structural analysis considered the maximum service load from a 6 cubic yard Caterpillar 980 front end loader and the result indicated an 8” concrete pavement thickness on a 12 inch base and a minimum 3000 psi compressive strength.

An in-situ mixing and construction process was used for construction of the pavement. The Eco-Pad pavement was constructed by placing a specified thickness of the recycled concrete and bottom ash, premixing the two aggregate materials with an asphalt reclaimer/pulverizer. A specified amount of the blended cementitous binder is then placed with a vane spreader, and then cementitious and aggregate materials are mixed with the pulverizer. Water content can be added through the pulverizer if needed for moisture conditioning. The mixture is then compacted to the specified level of compaction. The pavement was saw-cut on 20 foot grid within 24 hours and a curing compound was also applied. Saw cut joints were sealed with an elastomeric filler after at least one week of curing. A two foot layer of bottom ash was placed on the slab to facilitate curing and provide some freeze-thaw protection for the Eco-Pad during the first winter.

Owners, constructors, engineers and architects are demanding “green” materials that conserve natural resources, and construction alternatives that that have low life cycle costs. The Eco-Pad will be monitored for performance to determine if it is a viable long term solution for large storage areas such as manufacturing and commercial warehousing storage yards, terminals, dockyards, and other large pavements.

LABORATORY TESTING

An analysis laboratory mixes were performed to determine the mixture proportioning. Test data from high volume fly ash concrete mixes were reviewed to determine the effectiveness of various proportions of cementituous materials (portland cement and class C fly ash). Various proportions of coarse aggregate (recycled concrete) and fine aggregate (bottom ash) materials were assessed by evaluating the proposed materials’ grainsize distribution. The same blends were assessed for moisture-density relationship and moisture-compressive strength relationships.

The selected materials included 1 ½ inch (38 mm) top size crushed and screened recycled concrete from Racine County, Wisconsin; bottom ash and Class C fly ash from We Energies’ Pleasant Prairie Power Plant (P4); and Lafarge Alpena Type I/II portland cement. Laboratory testing of the samples included moisture content testing (ASTM D2216), grainsize analysis (ASTM D422), and moisture density relationship by Modified Proctor method (ASTM D1557). In order to simulate the conditions of roller compacted concrete, the compressive strength analysis used ASTM D1633 *Compressive Strength of Molded Soil-Cement Cylinders*. The moisture density relationship for each mixture was performed in general accordance with ASTM D1557, except that the 5 lifts requirement was replaced with 3 lifts. A 4 inch diameter split mold was used for compressive strength determination per ASTM D1633 to facilitate the removal of each specimen with minimal disturbance to the samples. Upon completion, the specimens were sealed in plastic bags and accelerated cure for seven days at 100ºF in accordance with ASTM C-593 to approximate conditions of 28-day cure periods. After curing, the samples were capped with a gypsum cap and the compressive strength was determined using a constant drive calibrated load frame. The tested specimens had a height to diameter ratio of 1.15:1, therefore the strengths obtained provide a relative measure of strength rather than the measure of compressive strength such as would be obtained for conventional concrete specimens having a height to diameter ratio of 2:1. In general 1.15:1 height to diameter ratio samples will produce a slightly higher strength than that achieved with a 2:1 height to diameter ratio.

The preliminary mixture proportioning testing was performed in two phases. Initially, samples of the proposed recycled concrete (coarse aggregate) and the bottom ash (fine aggregate) were tested to determine their optimum blend for grainsize distribution and density. The second phase consisted of mixing the selected aggregate blend with varying amounts of the blended cementituous binder material for determination of the mixture's optimum density and compressive strength characteristics.

LABORATORY TESTING RESULTS

Based on the grainsize analysis of the proposed recycled aggregate, the coarse aggregate is described as a poorly to well-graded crushed concrete with about 48-67% gravel, 31-45% sand, and 2.6-6.6% silt/clay sized particles. The initial sample of recycled concrete was somewhat more open graded with limited fines compared to the more densely graded samples supplied during the second phase of the laboratory and field test. This was also evident in the aggregate blends, moisture-density, and moisture-strength test results. The bottom ash fine aggregate is described as 4-6% gravel, 77-85% sand, and 13-17% silt/clay sized particles. Results of the unit weight tests on the coarse and fine aggregate indicated dry loose unit weights of 99 pcf to 105 pcf, and 65 pcf, respectively. Grain size analysis test results are shown on Table 1.

Results of the coarse/fine aggregate blends 50/50, 60/40, 70/30, and 80/20 generally indicate a poorly graded aggregate with about 35-54% gravel, 41-57% sand, and 5-8% silt/clay sized particles. The compacted unit weights of the blends ranged from 102.8 to 109.1 pcf with the 60/40 and 70/30 blends producing the higher densities. Based on the blended aggregate test results the 60/40 recycled concrete/bottom ash blend was selected for the moisture-density and moisture-strength relationship testing. Table 2 provides a summary of the aggregate trial blending tests.

Commercially available chemical and physical data representative of the cementitious materials used on this project are shown on Table 3. The class C fly ash was supplied from We Energies Pleasant Prairie Power Plant. The slag cement and Type I/II portland cement were both provided by Lafarge NA. The cementitious materials were pre-blended at Lafarge's terminal located in Milwaukee, Wisconsin. A blend of 50% portland cement and 50% class C fly ash blend (denoted as 50PC/50FA), by mass, was selected due a history of excellent results on numerous construction projects, and to reduce the number of variables on this demonstration project. The compression strength potential at three different cementitious material proportions mixed with the

60/40 aggregate blend was evaluated. Moisture-density and moisture-strength relationship testing by Modified Proctor method as previously described was also performed. Results of the compressive strength tests, moisture-density and moisture-strength test results are summarized in Table 4. The test results indicated that the 18% (approximately 540 #/cy) cementitious content exhibited the highest compressive strength. However, since the increase in strength from the 15% versus the 18% specimen was less than 5 psi, the 15% 50PC/50FA content (450 #/cy) was selected for economic and environmental benefits.

Additional tests were performed with varying aggregate blends when the second sample of recycled concrete showed a somewhat denser gradation. Therefore, aggregate blends of 50/50, 60/40 and 70/30 recycled concrete/bottom ash were mixed with a constant 15% content of 50PC/50FA to determine their moisture-density and moisture-strength relationship. Results of the tests are summarized in Tables 5 and 6.

Results of the moisture-density and moisture-strength tests indicate the 70/30 aggregate blend with 15% blended cementitious content exhibited the higher strength and density. This is likely due to the material's denser graded nature which allows for a more compact arrangement of particles which also produce a higher density. Higher density also generally produces higher strengths.

It was not practical to determine the mass of materials being placed in the field during construction therefore it was decided to place the materials volumetrically based on the dry loose densities of the materials. Construction of the pavement would consist of placing 3 inches of bottom ash and 5 inches of recycled concrete prior to mixing with the pulverizer. This ratio by volume was expected to be similar to the 70/30 ratio, by mass, performed in the preliminary lab testing phase and also reflected the practical level of precision in construction.

ECO-PAD CONSTRUCTION OVERVIEW

A 12 inch thick compacted bottom ash base grade was established for the Eco-Pad pavement of which 3 inches will later be incorporated into the concrete by in-situ mixing and 9 inches remains as the base. The in-situ mixing phase consisted of placing 5 inches of crushed recycled concrete across the proposed pavement area with dump trucks and using a road grader to create a uniform layer. The recycled concrete and bottom ash were then pre-mixed with a Wirtgen WR2500 asphalt reclaimer/pulverizer set at an 8 inch depth.

Lafarge pre-blended 50% portland cement and 50% class C fly ash, by mass, at their bulk terminal in Milwaukee, Wisconsin. The 50PC/50FA blend of cementitious material was delivered to the jobsite via bulk pneumatic tanker trucks. The cementitious material was pneumatically conveyed to the vane spreader. The dry cementitious materials were placed with a vane spreader over the previously mixed aggregates. The 50PC/50FA blend was spread at a rate of 110 pounds per square yard. This rate was based on a 15% dry unit weight basis of the maximum dry density of the laboratory blended mixture.

Moisture conditioning was not generally required on this project due to relatively wet site conditions due to a rainy period prior to mixing. After mixing from the second pass of the pulverizer, the aggregate and cementitious materials mixture was compacted with a large vibratory sheepsfoot compactor, graded, and final rolling was accomplished with a smooth drum roller in the static mode. A target mixture moisture content of 10.5% for optimum strength was recommended along with directions to minimize the delay period from mixing of the cementitious material to compaction. Compaction of the in-situ mixture was specified at 95 percent of the maximum dry density as determined by the Modified Proctor method. Saw cuts on a 20 foot grid followed the next day. A curing compound was applied following the saw cuts and finally an elastomeric joint filler was applied to seal the saw cut joints.

Weather conditions were challenging during construction. Due to a regional cement shortage, construction was delayed into late October and early November, when temperatures begin to get cold in Wisconsin. This was complicated by a rainy period that made attaining an optimum moisture content for compaction a challenge at the beginning of the project. The bottleneck in the construction operation was the rate at which the cementitious materials could be blended at the terminal, trucked 40 miles to the project and conveyed into the vane feeder. Delays could be avoided in the future by having two vane spreaders and pre-loading additional tanker trucks before the start of day's work. Additionally an operating issue at the cement terminal also threatened to further delay the project because cement could not be unloaded. However, ground granulated blast furnace slag cement was available at the terminal and substituted for the portland cement thus adding another interesting dimension to this research project. A call to the Slag Cement Association indicated that they were not aware of a prior use of a 50/50 fly ash/slag cement blend without portland cement on large construction project. Unfortunately there was no time to perform lab testing prior to its use on the project. The slag cement and class C fly ash binder pavement combined with the recycled aggregates provided a 100% recycled material content in approximately two thirds of the pavement area.

FIELD TESTING

Field testing of the materials used in the construction of the Eco-Pad test pavement was performed in three stages. The initial stage consisted of performing grainsize analysis on samples of the field blended aggregates. A laboratory mixture analysis of the field aggregate blend with 15% of the blended cementitious material was also performed to establish laboratory moisture-density and moisture-strength relationships.

The second stage of the testing was performed during the field mixing of the blended aggregate and cementitious materials. The field testing consisted of performing field density testing by nuclear gauge method (ASTM D2922) during the compaction phase to assess the in-situ moisture content and percent compaction achieved. In addition, samples of the in-situ mixed concrete were obtained and compacted in the field by the Modified Proctor method. The field molded specimens were delivered to the laboratory and cured for a period of 7 to 365 days to assess the compressive strength development of the mixture.

The final phase of the testing included obtaining in-situ core specimens after approximately one and two years to assess the in-place strength of the pavement. The cores were obtained with a rotary type drill with a diamond impregnated core barrel in general accordance with ASTM D42. Samples were subsequently air dried for 7 days, capped with a gypsum capping compound and compressive strengths were determined in accordance with ASTM C39.

RESULTS OF FIELD TESTING

Evaluation of the in-situ recycled concrete mixture constructed in the Eco-Pad pavement was based on the 5" recycled concrete and a 3" bottom ash aggregate blend and 15% blended cementitious materials (50PC/50FA) at the western side of the Eco-Pad or 15% blended 50% slag cement and 50% fly ash (50SA/50FA) at the eastern side of the Eco-Pad.

Results of the grainsize analysis of the individual bottom ash and recycled concrete samples used on-site indicated gradations similar to the results obtained in the laboratory testing phase. Results of the field blended aggregate samples also are similar to those obtained in the laboratory test phase. The 5" recycled concrete and 3" bottom ash volumetric field blend is very similar to the 70/30 blend, by mass, prepared for the laboratory mixture analysis. Results of the grainsize analysis of the lab and field aggregate blends are summarized in Table 7.

Results of the moisture density relationship testing indicated a higher maximum dry density at about the same optimum moisture content as in the preliminary laboratory mix proportioning phase. This is likely due to a well-graded sample resulting in a more densely compacted mixture. The higher result in the compressive strength may also be due to the higher density characteristics and lower optimum moisture contents. Subsequently, two (2) additional samples of the previously sampled and combined field blended aggregate were mixed in the lab, one (1) with 15% 50PC/50FA and the other with 15% 50SC/50FA cementitious blend to further assess the moisture-density and moisture-strength relationships. Results of the tests on the 50PC/50FA blend showed similar results to those of the 50PC/50FA blend of the first aggregate field blend mixture. Results of the 50SC/50FA blend also provided results that were similar to those of the first aggregate field blend mixture. Results of the 50SC/50FA cementitious blend resulted with similar moisture density relationships but with lower compressive strengths, 1600 psi vs. 2225 and 2700 psi. This is likely due to the fact that the slag cement contained less CaO and also generally develops its strength at a slower rate than portland cement.

The second phase of the field testing included performing field moisture and density testing during the placement and compaction phase of the construction. In summary, the field blended aggregate had moisture contents initially of 14 to 19 percent, which was above the recommended optimum target of 10.5 percent. However, during the mixing process the moisture contents were generally found to range from 10 to 16 percent based on the in-place field density testing. The field density testing also indicated an in-place compaction ranging from 92 to 99 percent with an average of 96.5 percent of the modified proctor.

Results of the field molded compressive strength specimens are summarized in Table 9. In summary, the field molded samples of the 50PC/50FA blend indicated compressive strengths (2440 psi at 28 days and 2525 psi at 56 days) are similar to those of the laboratory mixtures with the field blend aggregates (2225 psi and 2700 psi), and somewhat higher than these with the laboratory blended aggregates (1880 and 1920 psi). The field molded samples with the 50SC/50FA blend indicated compressive strengths on the order of 195 psi and 175 psi at 28 days which turned out to be much less than the laboratory mixture which yielded a compressive strength of 1600 psi using the accelerated core method. This is probably due to the much lower curing temperatures of the field samples, the high water content and the fact that slag cement generally develops strength at a slower rate at lower temperatures.   The 365 day test results indicated compressive strengths on the order of 4325 psi and 2565 psi for the 50PC/50FA and 50SC/50FA mixtures, respectively.

The final phase of the field testing included obtaining field core samples from the Eco-Pad pavement section after one and two years of field curing. Test results of field cores at 1 year of service indicated an average compressive strength of 3150 psi and 1852 psi for the 50PC/50FA and 50SC/50FA mixtures, respectively. In comparing these results to the molded field samples, it must be recognized that the molded specimens have a height to diameter ratio of 2. Therefore, the molded samples will yield a somewhat higher strength value. Correcting the shorter molded samples with a correction factor of 0.91 as suggested in ASTM C42, the molded samples would indicate strengths of 3930 psi and 2334 psi, respectively. Test results of cores of the Eco-Pad after 2 years of service indicated an average compressive strength of 2960 psi for the 50PC/50FA, and 1983 to 2550 psi 50SC/50FA mixtures. There was no significant strength development over the second year of service as would normally be expected for a cement and fly ash concrete. The test results for the field molded and cored samples are summarized in Table 9.

CONCLUSIONS

1.) Based on the results of this study, when 70% crushed recycled concrete and 30% bottom ash are blended and mixed with a 15% blended (50% Portland Cement/50% Class C Fly ash) cementitious material by mass, in-situ mixed with an asphalt reclaimer/pulverizer, moisture conditioned and compacted, a compressive strength on the order of 3100 psi in one year was attainable.

2.) When the aggregate blend is mixed using slag cement in lieu of portland cement in the cementitious material blend, a compressive strength on the order of 1700 to 2000 psi in one year, and 2000 to 2500 psi in 2 years was attainable.

3.) The field concrete moisture content (approximately 13% to 15%) during construction exceeded the optimum target (10.5%), consequently the actual water to cementitious ratios were approaching 1.0 in some areas and had significant influence on the lower compressive strengths. It is not practical to reduce the moisture during construction therefore it is better to stay on the drier side and add water if necessary to achieve the optimal moisture targets around 8%. The vane spreader facilitates quick adjustments to add more cementitious materials in wet areas.

4.) Future work should consider a minimum of 18% cementitious material content (approximately 540 #/cy) to attain higher compressive strengths. A higher cementitious content can offset variable moisture contents that exceed the optimal range.

5.) Some variability in the test data due to variations of the individual materials was observed and subsequently showed some variability in the results obtained. Therefore, a mixture analysis for the specific ingredients of each mixture should be undertaken for each project.

6.) After 2 years of service, the concrete is not showing any significant distress due to freeze thaw, except for some scaling near the storm water outlets that had excessive moisture contents during construction. There are no indications of structural failure despite high compressive loads from trucks, loaders and cranes that used the pad. Typically the Eco-Pad was covered with at least 2 feet of stockpiled bottom ash over the winter months, thus providing some freeze thaw protection. Saw cutting may not be necessary if random cracking can be tolerated.

7.) An environmentally beneficial and economical mix design and construction process for large outdoor storage area pavements has been developed with a 93 to 100% recycled content. An 8 inch in-situ mixed concrete Eco-Pad, excluding the base material, can be built for about $2.05/sf (2005 dollars) and was approximately 15% less expensive than roller compacted concrete for this project. Long term performance and maintenance will be evaluated to determine life-cycle costs.

8.) Future research and demonstrations should explore in-situ mixed permeable concrete using only coarse recycled crushed concrete and no fine aggregate.

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Appendix

Figure 1. Eco-Pad Construction at Pleasant Prairie Power Plant, Kenosha County, Wisconsin

Table 1. Summary of Grainsize Analysis Tests Recycled Aggregates Eco-Pad Pavement MES Project No. 7-45151

Sample No.	Bottom Ash		Recycled Concrete		
Grainsize Analysis, mm [in. or sieve #]	BA1	BA2	RC1	RC2	RC3 (field)
38.1 [1½]	-	-	100	-	-
25.4 [1]	-	-	95.7	100	100
19.05 [¾]	100	100	85.0	93.4	94.2
12.7 [½]	99.0	98.5	65.2	75.5	79.1
9.5 [3/8]	98.1	96.7	54.6	66.1	69.4
4.76 [#4]	95.6	94.0	33.5	48.4	51.8
2.0 [#10]	92.3	91.2	20.3	37.1	35.8
0.84 [#20]	83.5	83.8	12.1	27.9	24.2
0.42 [#40]	67.0	70.1	7.5	20.6	17.1
0.147 [#100]	26.7	36.1	3.5	9.4	8.7

0.074 [#200]	12.6	16.7	2.6	6.6	6.6

Table 2. Summary of Aggregate Trial Blending Tests

Grainsize Analysis, mm [in or sieve #]	BA1	RC1	50/50	60/40	70/30	80/20
38.1 [1½]	-	100	100	100	100	100
25.4 [1]	-	95.7	97.6	97.4	97.0	96.6
19.05 [¾]	100	85.0	92.5	91.0	89.5	88.0
12.7 [½]	99.0	65.2	82.1	78.7	75.3	72.0
9.5 [3/8]	98.1	54.6	76.4	72.0	67.7	63.3
4.76 [#4]	95.6	33.5	64.6	58.3	52.1	45.9
2.0 [#10]	92.3	20.3	56.3	49.1	41.9	74.7
0.84 [#20]	83.5	12.1	47.8	40.7	33.5	26.4
0.42 [#40]	67.0	7.5	37.3	31.3	25.4	19.4
0.147 [#100]	26.7	3.5	15.1	12.8	10.5	8.1
0.074 [#200]	12.6	2.6	7.6	6.6	5.6	4.6
USCS	SM	GW	SP-SM	SP-SM	GP-GM	GP
Unit Weight (Loose), kg/m3 [pcf]	1041.3 [65]	1586 [99]	-	-	-	-
Unit Weight (Compacted), kg/m3 [pcf]	-	-	1646.9 [102.8]	1744.6 [108.9]	1747.8 [109.1]	1733.4 [108.2]

Notes:

- Compacted unit weight is based on modified proctor method (ASTM D1557) at moisture content of 15%
- Loose unit weight is based on as received moisture content
- Aggregate blends are based on initial bottom ash and recycled concrete samples submitted

Appendix

Table 3. Selected Chemicals and Physical Composition of Cementitious Materials

Chemical Data	Class C Fly Ash	Slag Cement	Portland Cement
SiO_2 %	40.35	35.68	20.7
Al_2O_3 %	18.94	10.00	4.8
Fe_2O_3 %	5.18	0.58	2.7
SiO_{2+} Al_2O_{3+} Fe_2O_3%	64.47	46.26	28.2
CaO %	21.65	38.62	65.4
MgO %	3.81	11.2	2.5
SO_3 %	1.93	2.41	2.4
LOI %	0.45	-	1.61
Na_2O %	1.78	0.35	-
K_2O %	1.25	0.42	-
Available Alkalis (as equivalent Na_2O%)	1.3	-	0.53
Physical Data	**Class C Fly Ash**	**Slag Cement**	**Portland Cement**
Fineness, retained on #325 sieve%	13.6	1.0	5.3
Specific Gravity	2.52	2.95	3.15
Strength Activity Index 7 day (%)	106	103	

Table 4. Summary of Density/Strength Tests of 60/40 RC/BA Aggregate Blend with Varying Cement Contents

Mixture ID	Moisture-Density Relationship		Moisture-Strength Relationship	
	Optimum Moisture %	Maximum Dry Density, kg/m3 [pcf]	Optimum Moisture %	Maximum Strength, MPa [psi]
60/40 RC1/BA1 @12% 50PC/50FA	15.5	1762.2 [110.0]	16.6	11.3 [1640]
60/40 RC1/BA1 @15% 50PC/50FA	16.5	1762.2 [110.0]	16.6	12.5 [1820]

60/40 RC1/BA1 @18% 50PC/50FA	14.5	1778.2 [111.0]	14.2	12.6 [1825]

Table 5. Summary of Aggregate Trial Blending Tests

Grainsize, mm [in. or sieve #]	BA2	RC2	50/50	60/40	70/30
38.1 [1½]	-	-	-	-	-
25.4 [1]	-	100	100	100	100
19.05 [¾]	100	94.2	96.7	96.0	95.4
12.7 [½]	98.5	79.1	87.0	84.7	82.4
9.5 [3/8]	96.7	69.4	81.4	78.3	75.3
4.76 [#4]	94.0	51.8	71.2	66.6	62.1
2.0 [#10]	91.2	35.8	64.2	58.7	53.3
0.84 [#20]	83.8	24.2	55.9	50.3	44.7
0.42 [#40]	70.1	17.1	45.4	40.4	35.5
0.147 [#100]	36.1	8.7	22.8	20.1	17.4
0.074 [#200]	16.7	6.6	11.7	10.6	9.6
USCS	SM	6P-6M	SP-SM	SP-SM	SP-SM
Unit Weight (Loose), kg/m3 [pcf]	1041.3 [65]	1682.1 [105]	-	-	-

Notes:

- Loose unit weight is based on as received moisture content
- Aggregate blends are based on second set of Bottom Ash and Recycled Concrete samples submitted

Table 6. Summary of Moisture Density and Moisture/Strength Tests with Varying Aggregate blends

Mixture Identification	Moisture-Density Relationship Optimum Moisture %	Moisture-Density Relationship Maximum Dry Density, kg/m3 [pcf]	Moisture-Strength Relationship Optimum Moisture %	Moisture-Strength Relationship Maximum Strength, MPa [psi]
50/50 RC2/BA2 @15% 50PC/50FA	13.5	1770 [110.5]	12.6	10.1 [1460]

60/40 RC2/BA2 @15% 50PC/50FA	12.5	1842 [115.0]	12.4	13.0 [1880]
70/30 RC2/BA2 @15% 50PC/50FA	10.5	1922 [120.0]	11.2	13.2 [1920]

Table 7. Comparison of Aggregate Blend Gradations

Aggregate Blend RC/BA Grainsize Analysis, mm [in. or sieve#]	60/40 Blend Sample 1 60/40-1	 Sample 2 60/40-2	70/30 Blend Sample 1 70/30-1	 Sample 2 70/30-2	Field Blend Sample 1 5" RC 3" BA	 Sample 2 5" RC 3" BA
38.1 [1½]	100	100	-	-	-	-
25.4 [1]	97.4	97	100	100	100	100
19.05 [¾]	91.0	89.5	96	95.4	95.1	95.1
12.7 [½]	78.7	75.3	84.7	82.4	84.2	84.0
9.5 [3/8]	72.0	67.7	78.3	75.3	77.6	79.1
4.76 [#4]	58.3	52.1	66.6	62.1	63.6	65.0
2.0 [#10]	49.1	41.9	58.7	53.3	51.8	53.0
0.84 [#20]	40.7	33.5	50.3	44.7	40.7	39.1
0.42 [#40]	31.3	25.4	40.4	35.5	30.4	26.8
0.147 [#100]	12.8	10.5	20.1	17.4	14.2	13.0
0.074 [#200]	6.6	5.6	10.6	9.6	9.7	8.9

Table 8. Summary of Density/Strength Tests Based on Field Blended Aggregate Samples

Mixture Identification	Moisture-Density Relationship Optimum Moisture %	 Maximum Dry Density, kg/m3 [pcf]	Moisture-Strength Relationship Optimum Moisture %	 Maximum Strength, MPa [psi]
Field Sample 1 @ 15% 50PC/50FA	10.5	1986.5 [124.0]	10.3	18.6 [2700]
Field Sample 2 @ 15% 50PC/50FA	10.0	1986.5 [124.0]	10.6	15.3 [2225]

Field Sample 2 @ 15% 50SC/50FA	11.0	1954.4 [122.0]	10.3	13.2 [1600]

Appendix

Table 9. Summary of Field Molded and Core Specimens Compressive Strength Test Results

Sample No.	FS-1	FS-2	FS-3
Sample Date	11-04-04	11-05-04	11-08-04
Cementitious Blend	PC/FA	SC/FA	SC/FA
Moisture Content, %	13.6	14.9	13.1
Dry Density, kg/m3 [pcf]	1941 to 1956 [121.2-122.1]	1919 to 1948 [119.8-121.6]	1933 to 1954 [120.7-122]
Compaction, %	99-100	96-98	97-98
Compressive Strength, MPa [psi]			
7 day (air)	11.1 [1620]	1.3 [185]	1.0 [145]
28 day (air)	16.8 [2440]	1.3 [195]	1.2 [175]
56 day (air)	17.4 [2525]	1.8 [265]	1.7 [240]
180 day (air)	22.6 [3280]	6.8 [985]	6.2 [900]
365 day (air)	29.9 [4325]	18.4 [2675]	16.9 [2455]
365 day (corrected)[1]	27.1 [3930]	16.8 [2435]	15.4 [2235]
Field core specimens			
1 year (air)	21.7 [3150]	13.6 [1970]	12.0 [1735]
2 year (air)	20.4 [2960]	13.7 [1983]	17.6 [2550]

Note:

1.) The molded field samples have a height to diameter ratio of 1.15:1 compared to the length to diameter ratio of 2:1 for the field core samples. The 1.15 H/D samples therefore result in a somewhat higher strength than would be achieved with the 2 H/D core samples. A correction factor of 0.91 was therefore applied to obtain a corrected strength value on the molded 365 day sample for comparison purposes.

Appendix

Figure 3: Eco-Pad Compressive Strength of Field Molded Specimens

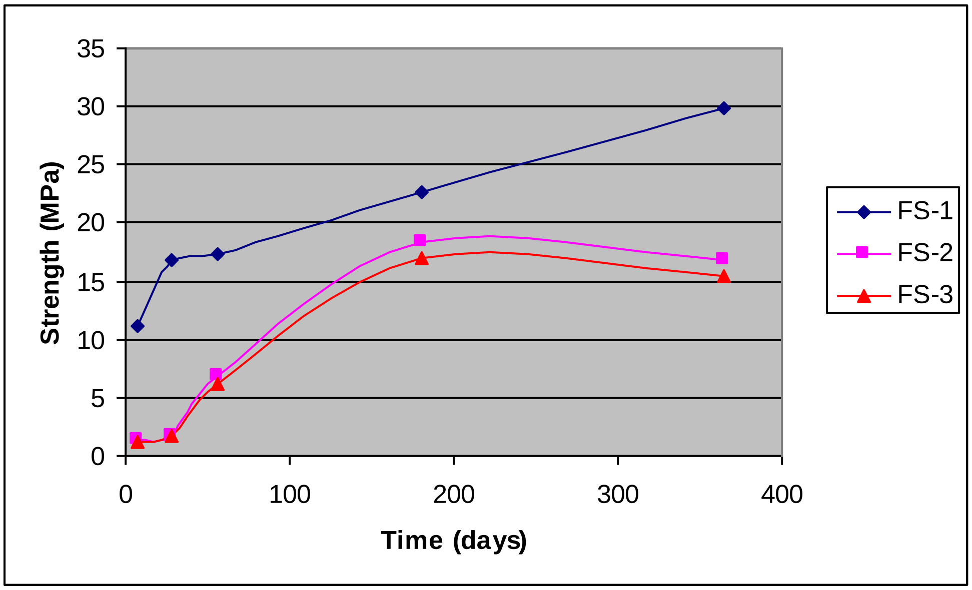

Figure 4: In-situ mixing of recycled material to make Eco-Pad pavement

Appendix