Literature Search and Report On Recycled Asphalt Pavement and Recycled Concrete Aggregate

TPF-5 (129) Recycled Unbound Materials

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Introduction

The production of demolition and construction waste has been increasing at a gradual rate in recent years.(1) The amount of landfill available to contain this material has been decreasing, and the need to find appropriate disposal locations has been of increasing concern.(2) Recycling programs offer a viable solution. The use of these materials as recycled base course in new roadway construction has become more common in the last twenty years, with some municipalities reporting as much as 400,000 tons of recycled materials used in this manner. (3, 4)

Recycled roadway materials are typically generated and reused at the same construction site, providing increased savings in both money and time.(3) It has been speculated that in some municipalities recycled materials costs less to use than conventional crushed-stone base material by as much as 30%.(5) Despite the increased acceptance of recycled base materials, research concerning the mechanical properties and durability of such materials has been lacking. (3, 6)

The most widely used recycled materials are recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA). RAP is produced by removing and reprocessing existing asphalt pavement (6,7), and RCA is the product of the demolition of concrete structures such as buildings, roads and runways.(2) The production of RAP and RCA results in an aggregate that is well graded and of high quality.(7) The aggregates in RAP are coated with asphalt cement that reduces the water absorption qualities of the material.(6) In contrast, the aggregates in RCA are coated with a cementitious paste that increases the water absorption qualities of the material.(1)

Production

There is some ambiguity regarding the nomenclature involved in the production of RAP. Based on the experience of the Geo Engineering Program at the University of Wisconsin-Madison, the following classification is recommended to remove ambiguity in nomenclature: RAP refers to the removal and reuse of the hot mix asphalt (HMA) layer of an existing roadway(7); full depth reclamation (FDR) refers to the removal and reuse of the HMA and the entire base course layer; and recycled pavement material (RPM) refers to the removal and reuse of either the HMA and part of the base course layer or the HMA, the entire base course layer and part of the underlying subgrade implying a mixture of pavement layer materials.(6) Unless specified, these three distinct recycled asphalt materials will be collectively referred to as RAP.

RAP is typically produced through milling operations, which involves the grinding and collection of the existing HMA(7), and FDR and RPM are typically excavated using full-size reclaimers or portable asphalt recycling machines. (6) RAP can be stockpiled, but is most frequently reused immediately after processing at the site. Typical aggregate gradations of RAP are achieved through pulverization of the material, which is typically performed with a rubber tired grinder.(8)

The production of RCA involves crushing the material to a gradation comparable to that of typical roadway base aggregate. Fresh RCA typically contains a high amount of debris and reinforcing steel, and the RCA must be processed to remove this debris prior to placement. The material is first crushed in a jaw crusher that breaks the steel from the material and provides an initial crushing of the concrete.(7) The material is sent down a picking belt where the steel is removed from the material.(2) The remaining concrete material is further crushed and screened to a predetermined gradation.(7)

Material Properties

The gradation of RAP can be compared to that of a crushed natural aggregate, although with a higher content of fines. The high fine content is the result of degradation of the material during milling and crushing operations. In RPM the inclusion of subgrade materials in the recycled material also contributes to a higher instance of fines. Finer gradations of RAP are produced through milling operations compared to crushing operations.(7) Table 1 provides a breakdown of typical physical and mechanical properties of RAP.

RCA is processed exclusively through crushing operations, and is very angular in shape.(7) Depending on the crushing methods, the particle size distribution of an RCA can have a wide variability, with a lower particle density and greater angularity than would normally be found in more traditional virgin base course aggregates. Residual mortar and cement paste are typically found on the surface of the RCA, as well as contaminants associated with construction and demolition debris.(2) The presence of this mortar contributes to a rougher surface texture, lower specific gravity, and higher water absorption than typical aggregates.(7)

The self-cementing capabilities of RCA are an interesting secondary property. The crushed material exposes un-hydrated concrete that can react with water, potentially increasing the materials strength and durability when used as unbound base course for new roadway construction. It follows that service life could also be extended as a result of these properties. Although widely acknowledged, not much actual documentation has been published regarding this secondary hydration.(5) Although the cause of self-cementing properties has been studied, the actual effect of such parameters as age, grade, and mix-proportions of the RCA on the overall cementitious effect has yet to be determined.(1) This effect is outside the scope of this literature review. Table 2 provides a breakdown of typical physical and mechanical properties of RCA.

Table 1: Typical Physical Properties of RAP (7)

Physical Properties	
Unit Weight	1940 - 2300 kg/m^3 (120 - 140 pcf)
Moisture Content	Normal: Up to 5% Maximum: 7 - 8%
Asphalt Content	Normal: 4.5 – 6%
Asphalt Penetration	Normal: 10 – 80% at 25°C (77°F)
Absolute Viscosity or Recovered Asphalt Cement	Normal: 4000 – 25000 poises at 60°C (140°F)
Mechanical Properties	
Compacted Unit Weight	1600 – 2000 kg/m^3 (100 – 125 pcf)
California Bearing Ratio (CBR)	100% RAP: 20 – 25% 40% RAP and 60% Natural Aggregate: 150% or Higher

Objective

The purpose of this literature review is to summarize the current state of knowledge regarding the mechanical behavior of RCA, RAP and blends of these recycled materials with traditional aggregate material. Laboratory and field investigations were considered in the scope of this review, and long-term performance issues were noted. Of particular interest was the effect the recycled material had on resilient modulus values, stress state sensitivity, and overall material degradation.

Table 2: Typical Physical Properties of RCA (7)

Physical Properties	
Specific Gravity	2.2 to 2.5 (Coarse Particles) 2.0 to 2.3 (Fine Particles)
Absorption	2 to 6 (Coarse Particles) 4 to 8 (Fine Particles)
Mechanical Properties	
LA Abrasion Loss	20 – 45 (Coarse Particles)
Magnesium Sulfate Soundness Loss	4 or Less (Coarse Particles) Less than 9 (Fine Particles)
California Bearing Ratio (CBR)	94 – 148%

Methods for Specification

When considering a recycled material for use as an unbound base course, the two most commonly used specifications are the gradation and the moisture-density relationship of the material. The gradation of a material can provide an indication of what the permeability, frost susceptibility, and shear strength of the material might be, and is determined through the use of material screening tests.(9) Screening tests are typically conducted through sieve analysis according to ASTM Standards C 117 and C 136, and AASHTO Standards T-27 and T-11. Some highway agencies and DOTs utilize their own screening test methods, such as Florida DOT FM1 T-027. Classification of soils is performed using the Unified Soil and AASHTO methods according to ASTM D 2487 and AASHTO M 145, respectively.

The determination of moisture-density relationships can help define the ideal density conditions that a material can achieve through compaction. Moisture-density relationships are established through compaction tests conducted according to the following standards: AASHTO T 99 Method C, AASHTO T-180 or ASTM D698, ASTM D 1557. Depending on the compaction effort to be used in the field, compaction tests can be performed in standard or modified variations. The information is used to determine the optimum moisture content (OMC) and the maximum dry density (MDD) of a material. Through testing of specimens prepared based on this data, material properties such as strength, stiffness and moisture susceptibility can be determined.(6)

Other aggregate classification methods involve the determination of the specific gravity, absorption and Atterberg limits of the soils. The specific gravity and absorption characteristics of a given recycled aggregate are determined using ASTM D 854, and Atterberg limits of recycled aggregates are assessed using ASTM D 4318, AASHTO T 89 and T 90. (5, 6)

Summary of Material Gradation

Tables 3 thru 5 represent the available estimated gradations of the RAP, RCA and RPM encountered in this literature review:

Table 3: Gradations of RAP *

Material	% Passing											
	#200	#100	#50	#30	#16	#8	#4	3/8"	1/2"	3/4"	1	1.5
Bejarano Pulverized(8)	2	3	7	12	20	31	46	68	---	100	---	---
Guthrie R1(6)	8	11	15	23	35	45	58	82	---	99	---	---
Guthrie R2(6)	1	3	8	12	21	39	59	82	---	97	---	---
Bennert RAP(3)	1	2	3	5	10	20	39	68	---	90	---	---
Saeed RAP-LS-MS(9)	3	5	9	12	19	27	38	62	75	95	95	100
Saeed RAP-GR-CO(9)	1	2	5	12	18	25	39	63	75	92	97	100
Saeed RAP-GV-LA(9)	0	2	6	11	17	23	33	61	76	92	98	100
Average Value	2.3	4.0	7.6	12.4	20.0	30.0	44.6	69.4	75.3	95.0	96.7	100
Standard Deviation	2.7	3.3	3.8	5.3	7.5	9.0	10.2	9.0	0.6	3.8	1.5	0.0
Coefficient of Variance	1.2	0.8	0.5	0.4	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0

*Gradations estimated from existing gradation curves in literature. Actual percent passing values are within ±1%

Table 4: Gradations of RPM *

Material	% Passing																		
	#200	#100	#60	#50	#40	#30	#20	#16	#10	#8	#4	1/4“	3/8”	1/2"	3/4"	7/8”	1”	1.5”	2”
Li RPM-1(10)	16	19	24	---	33	---	50	---	66	---	85	---	---	---	---	---	---	---	---
Li RPM-2(10)	12	15	18	---	24	---	35	---	49	---	66	---	---	---	---	---	---	---	---
Li RPM-3(10)	3	5	7	---	13	---	26	---	41	---	59	---	---	---	---	---	---	---	---
Li RPM-4(10)	9	9	13	---	20	---	33	---	50	---	67	---	---	---	---	---	---	---	---
Li RPM-5(10)	11	12	17	---	25	---	40	---	57	---	76	---	---	---	---	---	---	---	---
Li RPM-6(10)	6	8	10	---	16	---	27	---	41	---	59	---	---	---	---	---	---	---	---
Li RPM-7(10)	5	7	9	---	14	---	25	---	38	---	53	---	---	---	---	---	---	---	---
Li RPM-8(10)	7	9	12	---	20	---	34	---	52	---	70	---	---	---	---	---	---	---	---
Li RPM-9(10)	9	11	14	---	24	---	39	---	52	---	65	---	---	---	---	---	---	---	---
Li RPM-10(10)	10	12	16	---	25	---	41	---	55	---	70	---	---	---	---	---	---	---	---
Carmargo (11)	11	13	18	---	22	---	28	---	38	---	54	61	70	78	93	---	100	---	---
Wen & Edil(12)	6	6	---	9	---	16	---	26	39	38	60	---	69	77	96	---	99	---	100
Wen et al(13)	4	5	---	8	---	14	---	22	31	34	51	---	72	82	---	98	99	100	---
Wen et al(13)	3	5	7	---	13	---	22	---	35	---	55	62	74	84	95	97	99	---	100
Average Value	8.0	9.7	13.8	8.5	20.8	15	33.3	43.3	44.8	60.1	63.3	68.0	75.8	86.4	95.8	98.7	99.4	100	100
Standard Deviation	3.8	4.2	5.1	0.7	6.0	1.4	8.2	2.8	9.9	2.8	9.6	0.7	2.2	3.3	1.5	0.7	0.5	0	0
Coefficient of Variance	0.4	0.4	0.4	0.08	0.3	0.1	0.2	0.1	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Gradations estimated from existing gradation curves in literature. Actual percent passing values are within ±1%

Tables 3 thru 5 show that the coefficient of variance of gradation for the RAP, RPM and RCA remains approximately 40% or lower for materials retained on the #8 sieve and larger. This trend continues for the RPM and RCA retained in the remaining finer sieves. However, it can be seen that for RAP aggregates finer than the #8 sieve, the coefficient of variance for the data noticeably increases. This is more than likely due to the large gradation values found in the sample Guthrie R1. (6)

Table 5: Gradations of RCA *

Material	% Passing												
	#200	#100	#50	#30	#16	#10	#8	#4	3/8"	1/2"	3/4"	1	2"
Bennert RCA(3)	7	10	15	24	28	---	32	42	56	---	76	---	---
Blankenagel Demolition(5)	3	6	9	12	15	---	20	31	60	---	---	---	---
Blankenagel Haul-Back(5)	8	10	13	23	37	---	46	60	72	---	---	---	---
Saeed RCP-LS-IL(9)	4	8	15	26	36	---	48	60	89	---	99	100	---
Saeed RCP-GV-LA(9)	8	11	16	26	32	---	48	64	74	---	89	96	---
Saeed RCP-GR-SC(9)	3	5	9	13	19	---	27	38	62	76	95	98	---
Kuo District 1(2)	4	---	12	---	---	30	---	45	52	---	76	99	100
Kuo District 2(2)	5	---	17	---	---	30	---	40	53	---	76	99	100
Kuo District 4(2)	5	---	11	---	---	28	---	40	56	---	81	99	100
Kuo District 5(2)	4	---	18	---	---	45	---	56	80	---	100	100	100
Kuo District 6(2)	5	---	20	---	---	30	---	33	37	---	50	86	99
Kuo District 7(2)	5	---	20	---	---	40	---	50	63	---	82	99	100
Average Value	5.1	8.3	14.6	20.7	27.8	33.8	36.8	46.6	62.8	76.0	82.4	97.3	99.8
Standard Deviation	1.7	2.4	3.8	6.4	9.1	6.9	12.1	11.2	14.1	---	14.8	4.4	0.4
Coefficient of Variance	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.2	0.2	---	0.2	0.0	0.0

*Gradations estimated from existing gradation curves in literature. Actual percent passing values are within ±1%.

If the data for this sample is removed, the resulting variances fall within the same variance. The sample Guthrie R1 was a composite taken at different locations with different equipment, and therefore the actual source for the erratic gradation of the material could not be determined. (6) Gradation requirements for recycled materials vary from agency to agency. Unless indicated, the recycled materials referenced in this report passed the gradation requirements specified by the respective agencies.

Blankenagel et al (5) performed gradations on material taken from demolition sources as well as from relatively new materials sampled from batch-plant overruns and haul-back material sources. Batch plant overruns refer to excess concrete produced at a batch plant but never delivered to a job site, and haul-back material refers to excess concrete delivered to a job site but returned to the batch plant. The haul-back material was found to have more medium and fine materials than the demolition material. Although Blankenagel recognizes the source of the gradation differences could be due to crushing operations, the most likely reason is probably related to the mechanical breakdown tendencies of the materials. The haul-back material would have a higher porosity and lower strength due to being more properly consolidated and cured, resulting in a greater degree of pulverization regardless of crushing techniques.

In the study conducted by Kuo(2), gradations of the RCA met Florida DOT specifications. However, for specifications regarding average gradation for each sieve, the standard deviations of the 3/4", 3/8”, #4 and #10 sieves were all excessively high and each fell out of specification. The test would indicate that for recycled materials, these sieves might be considered more critical than the others.

Summary of Moisture-Density Characteristics

Table 6 and 7 represent the available moisture-density relationships for the RAP, RPM and RCA encountered in this literature review. For various blends of RAP with pure aggregate, some trends were noted regarding the effect of RAP content on the MDD and OMC of a material. Guthrie et al found that an increase in RAP content led to a decrease in MDD and OMC values.(6) The aggregates particles in the RAP were partially encased in asphalt, which decreased the specific gravity. It was further assumed that the partial asphalt coating reduced the aggregate water absorption potential and inter-particle friction, leading to a reduction in the required water to achieve MDD.

Table 6: Maximum Dry Density and Optimum Moisture Content of RAP and RPM

Material	Proctor Effort	Maximum Dry Density, kg/m3	Optimum Moisture Content, %
Bejarano: Pulverized (8)	Caltrans CTM 216	2332	5.5
Bennert RAP(3)	Standard	1872	5
Guthrie R1(6)	Modified	2083	5.6
Guthrie R2(6)	Modified	1842	5.8
Saeed RAP-LS-MS(9)	Standard	1988	6.3
Saeed RAP-GR-CO(9)	Standard	2015	10.3
Saeed RAP-GV-LA(9)	Standard	1978	5.4
Carmargo RPM(11)	Standard	2161	7.5
Wen et al(13)	Modified	2162	6.5

Table 7: Dry Density and Optimum Moisture Content of RCA

Material	Proctor Effort	Maximum Dry Density, kg/m3	Optimum Moisture Content, %
Bennert RCA(3)	Standard	1984	7.5
Blankenagel Demolition(5)	Modified	1830	9.7
Blankenagel Haul Back(5)	Modified	2020	10.6
Saeed RCP-LS-IL(9)	Standard	1971	11
Saeed RCP-GV-LA(9)	Standard	1950	9
Saeed RCP-GR-SC(9)	Standard	1990	9.5
Kuo UCF(2)	Modified	1823	11.2
Kuo FDOT(2)	Modified	1839	12.1

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An interesting variation in the study by Kim et al(14) was the use of a gyratory compaction test (GCT) instead of a proctor compaction test (PCT) to prepare RAP specimens. Comparisons with field density measurements indicated that MDD and OMC calculations determined from GCT methods were a better correlation than those determined by PCT testing. When compared to PCT results, GCT results showed a large change in MDD values and a small change in OMC values. Kim noted the effect of RAP content on the MDD and OMC of aggregate/RAP blends. As the RAP content of the material increased, the OMC of the material decreased for both the GCT and PCT prepared specimens. As with the study by Guthrie, the increase in asphalt content most likely reduced the absorption of the material, leading to the decrease in OMC. As the RAP content of the material increased, the MDD decreased for the PCT-prepared specimens and remained the same for GCT-prepared specimens.

Bennert et al (3) investigated the effect of recycled content on the MDD and OMC of samples containing both RAP and RCA. The study found that as the RAP and RCA content of a material increased, the MDD of the material decreased. As was found in the Guthrie(6) and Kim(14) studies, the OMC of the material decreased with increasing RAP content. However, as the RCA content of the material increased, the OMC also increased.

In the study conducted by Saeed et al (9), it was found that in general virgin aggregates had a higher MDD than pure (100%) RAP and RCA samples. In agreement with the study by Kim(14), the MDD of the material decreased as the RAP and RCA content of recycled material/aggregate mixtures increased.

Blankenagel et al (5) noted the effect of material source on the MDD and OMC of RCA. The demolition material used in his study had an OMC of 9.7% and a MDD of 1830 kg/m3, whereas the haul-back material had an OMC of 10.6% and a MDD of 2,020 kg/m3. The haul-back material had a higher fines content, which resulted in higher MDD and OMC values than those found in the demolition material. Pore spaces are more readily filled by the increased fines, resulting in a tighter aggregate matrix.

Investigations(11,13) on two RPM at the University of Wisconsin-Madison indicated an OMC of 6.5 to 7.5% and a MDD of 2162 kg/m^3.

Methods for Design and Performance Tests

The two most common tests used to determine strength parameters for unbound recycled materials are the Static Triaxial Test and the California Bearing Ratio test. The Static Triaxial Test is typically performed in accordance with ASTM D 2850 and AASHTO T 296, although some state DOTs have been known to use their own standards such as CalTRAN (8). The California Bearing Ratio test is typically performed in accordance with ASTM D 1883 or AASHTO T 193. Kuo(2) uses the Limerock Bearing Ratio test which is indigenous to the Florida DOT, and is documented as standard FM5-515. T

The two most common tests used to determine the stiffness for unbound recycled materials are the resilient modulus test and the free-free resonant column test. The resilient modulus test is typically performed in accordance with AASHTO TP46-94, Strategic Highway Research Program Test Protocol P-46 (SHRP P-46), or National Cooperative Highway Research Program Protocol 1-28A (NCHRP 1-28A). The free-free resonant column test is typically performed according to ASTM D 4015. Permanent deflection is typically performed by use of a cyclic triaxial test. Moisture susceptibility is typically determined by use of the Tube Suction Test. There is no current standard for the use of the test; however Guthrie and Blankenagel use methods as outlined by Scullion and Saarenketo in 1997. (5, 6, 16)

Two typical tests used to assess the durability of a material are the LA abrasion test and the freeze-thaw cycling test. The LA abrasion test is typically performed in accordance with ASTM C 131, although other methods are sometimes used by different agencies, such as Australian test method AS 1141.23. The freeze-thaw cycling test is typically performed in accordance with ASTM D 560.

A method that follows ASTM D 6035 for specimen conditioning is used at the University of Wisconsin-Madison(11,13) for frost susceptibility. ASTM D 6035 describes a method to determine the freeze-thaw effects on hydraulic conductivity; in the UW procedure, resilient modulus tests are performed to determine the freeze-thaw effects instead of hydraulic conductivity. Test specimens are compacted in molds at the specified moisture content and density. Preliminary testing on specimens instrumented with a thermocouple showed that complete freezing occurred within 1 d at -19°C. Thus, all specimens are retained in their mold and wrapped with plastic sheet in the freezer for at least 1 d. After freezing, the height and weight are measured and the specimen is allowed to thaw at room temperature. This process is repeated as many freeze-thaw cycles as desired but typically 5 cycles is used. After the last cycle, specimens are extruded frozen and thawed inside the resilient modulus cell prior to resilient modulus testing.

Summary of Strength and Stiffness Tests

Bejarano et al(8) conducted static triaxial tests on one RAP and two different aggregate materials. Individual RAP and aggregate specimens were compacted at OMC and 95% and 100% of maximum wet density (MWD) according to CalTRANS specification CTM 216. Static triaxial tests were conducted at confining pressures of 0, 35, 70 and 105 kPa. After comparing the shear strengths of the RAP and aggregate, it was determined that the shear strength calculated for the RAP was comparable in magnitude to shear strengths calculated for the representative aggregate materials. This shear strength correlation was valid at both 95% and 100% MWD and each of the four confining pressures. Bejarano(8) also conducted stiffness tests for the three material according to SHRP test protocol P-46. Of the three tested materials, the RAP had a higher resilient modulus than the two aggregate materials tested at 95% and 100% MWD. When the compaction level was increased from 95% to 100%, the resilient modulus of the RAP and one of the aggregate materials increased. This change in compaction level had no affect on the resilient modulus of the second aggregate material. Lime stabilized RAP specimens cured for 7 days had a higher resilient modulus than the non-stabilized material in all cases.

Bennert et al (3) conducted a similar test in which the shear strength of pure (100%) RAP and RCA were evaluated against the shear strength of a dense graded aggregate base course (DGABC) typical of the area the recycled materials would be used. Static triaxial test results for the pure samples indicate that the aggregate alone had higher shear strength than either RAP or RCA alone. Stiffness tests were also conducted on blends of the materials used in the study. Specimens were prepared combining the aggregate with RAP and RCA percentages of 100%, 75%, 50%, 25% and 0% (100% aggregate). Contraray to the strength behavior, it was found that as the amount of recycled material in the blend increased, the resilient modulus of the blended material also increased. Pure (100%) specimens of RAP and RCA had higher resilient modulus values than pure specimens of the virgin aggregate.

Guthrie et al(6) evaluated the effects of RAP content on the shear strength of base course materials using the California Bearing Ratio test. Two RAP and two aggregate materials (one recycled and one virgin) were acquired for the test. Specimens were prepared at RAP percentages of 100%, 75%, 50%, 25% and 0% (100% aggregate) for each of the permutations of RAP and aggregate samples. The tests found that the shear strength decreased with an increase in RAP content supporting Bennert et al.'s results..

Blankenagel et al(5) conducted a study documenting the difference between RCA samples obtained from demolition projects with relatively new RCA samples obtained through batch-plant overruns and haul-backs. The strength of the material was determined immediately after compaction using the California Bearing Ratio test. The demolition RCA and the haul-back RCA had CBR test results of 22% and 55% respectively. Unconfined compressive strength tests conducted on the material were used to determine strength gain over time due to the residual hydration in the RCA. The strength of the demolition material increased 130% and 180% at 3 and 7 days after compaction, respectively. The strength of the haul back material increased 150% to 190% at 3 and 7 days after compaction, respectively. Higher strength gain in the haul back material is most likely due to a greater amount of unreacted cement in the material as well as a finer material gradation. The average 7-day strengths for the demolition and haul-back material were 1260 kPa and 1820 kPa, respectively.

Kuo et al(2) incorporated the use of the Limerock Bearing Ratio (LBR) in Florida to determine the strength of RCA to be used as potential base course. The overall LBR values for the materials tested were 181.71%, which is higher than the required minimum value of 100%.

Kim et al(14) studied the effect of RAP content on the resilient modulus of blended aggregate base course. An in-situ blend of FDR was taken during the reconstruction of an existing road along with pure samples of RAP and aggregate materials. The FDR and several blends of the pure RAP and aggregate base material were tested for material stiffness using the resilient modulus test in accordance with NCHRP 1-28A protocol. Blended mixtures of the pure materials were prepared at RAP to aggregate ratios (%/%) of 0/100, 25/75, 50/50 and 75/25. The study found that for an increase in RAP content, the resilient modulus of the blended material increased.(10) The effects of increased RAP content were more defined when the blends were exposed to higher confining pressures, however specimens also experienced higher permanent deformation at higher confining pressures. Specimens tested at 65% optimum moisture content had higher resilient modulus values when compared to specimens prepared at 100% OMC. This trend was consistent for all confining pressures. At low confining pressures (~20kPa), specimens with RAP to aggregate ratios of 50% to 50% and specimens consisting of 100% aggregate had resilient modulus values that were approximately equivalent. As the confining pressures increased, the 50/50 and pure RAP blends became stiffer. The 50/50, 100% RAP and in-situ material tested at the corresponding site had similar resilient modulus values.

Nataatmadja et al(4) evaluated the resilient modulus of four RCAs. One commercial and three laboratory-produced RCAs were used in the study. The commercial RCA had an estimated compressive strength of 15 MPa, and the three laboratory manufactured RCAs had compressive strengths of 18.5, 49, and 75 MPa. The materials were tested individually and were not blended with any other material, although each material was prepared and mixed as to produce a particle size distribution comparable to typical road aggregate blends. The study found that the resilient modulus of each of the RCAs tested was comparable or better (higher) than the typical aggregates used for roadway base course; the resilient modulus seemed to increase with an increase in the compressive strength of the material. An increase in elongated particles also led to a decrease in resilient modulus, as these particles were more prone to degradation after extensive loading. Nataatmadja suggests that RCA with very high compressive strengths are more prone to break into elongated particles during crushing, resulting in a lower resilient modulus than would otherwise be expected. One exception in the test is that the specimen with a high flakiness index produced a lower strength value than would be expected.

Guthrie et al(6) used the free-free resonant column test to determine the stiffness of RAP and aggregate blends. At OMC, the stiffness of the material decreased with the addition of 25% RAP, and then increased with the addition of 50%, 75%, and 100% RAP. When the material was dried for 72 hours, the trend reversed: the stiffness of the material increased with the addition of 25% RAP and then decreased with the addition of 50%, 75% and 100% RAP. This decrease in stiffness can be attributed to the softening of the asphalt in the RAP during the drying process. Each specimen was then soaked for 24 hours prior to being tested for stiffness a third time. As with the oven-dried specimens, the soaked specimens displayed an increase in stiffness with the addition of 25% RAP followed by a decrease with increased RAP content. However, the soaked materials displayed a 40% to 90% decrease in stiffness when compared to the oven-dried materials.

Blankenagel et al(5) also used the resonant column test on RCA samples procured from demolition and haul-back sources. During the first 12 hours in 100% relative humidity, the modulus increased 390% for the demolition material and 940% for the haul-back material. Again, a greater amount of unreacted cement in the haul-back material accounts for the larger stiffness. Average 7-days stiffness measurements for the demolition and haul-back materials were 100 MPa and 150 MPa, respectively.

The tests performed at the University of Wisconsin-Madison(11,13, 15) on two RPMs indicated results in general support of the investigations summarized above. The unsoaked CBR values of RPM varied from 9 to 38 and, as an indicator of strength, were lower than the CBR of aggregates with similar gradation. However, higher resilient moduli(11) (257-309 MPa) were measured consistently for RPM compared to different crushed aggregates qualified as base course material.

Addition of fly ash increased the modulus of RPM (at least a factor of 6, which is less than for a similarly stabilized natural aggregate), and the modulus increased as the fly ash content was increased (11). Modulus also increased with curing time, with the rate of increase being largest between 7 and 28 d of curing. The moduli of RPM stabilized with fly ash were independent of bulk stress and could be described by a constant modulus.

Summary of Moisture Susceptibility Tests

In the tube suction test, a specimen is oven dried for 72 hours before being allowed to soak in a shallow water bath for 10 days. Over the course of the soaking period, unbound water within the material rises through the aggregate matrix and collects at the surface. The dielectric value at the surface of the material increases with an increase in the amount of unbound water permeating the specimen, and thereby provides an estimate of the materials susceptibility to moisture permeation.

Guthrie et al(6) used the tube suction test to determine the effect of RAP content on the moisture susceptibility of RAP/aggregate blends. It was found that the moisture susceptibility of the material increased as RAP was added to the mixture. However, tests were only conducted with the addition of 25% and 50% RAP. Materials with RAP contents above 75% were classified as non-moisture-susceptible and were not tested. Overall, the dry density of the blended material decreased as RAP content increased.

Blankenagel et al(5) used the tube suction test on demolition and haul-back RCA to help determine the moisture susceptibility characteristics of the material. The moisture susceptibility of the demolition material was classified as “good”, with a dialectic value of 6.4 and a gravimetric water content of 10.6%. The moisture susceptibility of the haul back material was classified as “marginal”, with a dialectic value of 15.0 and a gravimetric water content of 2.0%.

Summary of Durability Tests

Blankenagel et al(5) incorporated the LA Abrasion and freeze-thaw cycling test into his study comparing demolition and haul-back materials. Results of the LA Abrasion tests indicated that the demolition and haul-back materials experienced average material losses of 31% and 18%, respectively. The primary cause of the degradation was thought to be the stripping of cement paste from the aggregate. This degradation caused an increase in fines that affected each of the two RCAs differently. The demolition material was initially low in fines content, and an increase in degradation fines would lead to an increase in MDD. The haul-back material was initially high in fines content, and the addition of degradation fines would decrease the structural stability and increase the moisture susceptibility of the material.

Nataatmadja et al(4) attempted to use the LA abrasion test to determine the relative hardness of the four RCAs. Commercial RCA had a lower hardness than laboratory manufactured RCAs, even though commercial RCA had the lowest (estimated) compressive strength. The relative hardness between the laboratory manufactured RCAs could not be differentiated by the LA Abrasion Test method, most likely due to test severity.

Blankenagel et al(5) used freeze-thaw cycling to measure the durability of the demolition and haul-back RCMs. Freeze thaw testing was performed after 7 days of curing. Specimens were submerged for 4 hours, frozen (-29 deg C) for 24 hours and thawed (+20 deg C) for 24 hours. Stiffness was measured after each freezing period and after each thawing period. The demolition RCM experienced a 30% stiffness loss within the first two cycles and thereafter stabilized at a stiffness of 70 MPa. The haul-back RCM experience a 90% stiffness loss over the first 9 cycles and thereafter stabilized at a stiffness of 30 MPa. Unconfined compressive strength tests for the materials after freeze-thaw testing indicated strength losses of 52% and 28% for the demolition and haul-back material, respectively.

Freeze-thaw cycling tests performed at the University of Wisconsin-Madison showed that there was a small effect on resilient modulus (less than 15%) for RPM and also for natural aggregate with or without fly ash, with no consistent effect for materials stabilized with fly ash.

Summary of Permanent Deflection Tests

Bennert et al(3) studied the effect of recycled material content on the permanent deflection experienced by base course materials. Specimens were created from blends of aggregate with either RAP or RCA. For cyclic loads of 100,000 cycles, specimens blended with RCA were found to have the lowest amount of permanent deformation, and specimens blended with RAP had the highest amount of permanent deformation.

RPMs tested at the University of Wisconsin-Madison (11) exhibited smaller plastic strains during resilient modulus testing than base course aggregate, i.e., the opposite of the resilient modulus trend. However, other data show 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 stabilized with fly ash were smaller than the plastic strains of the RPM alone.

Conclusions

Several important findings were noted in the course of this literature review. Kim et al(14) compared the compaction properties of specimens prepared by typical proctor methods with specimens prepared with a gyratory compactor and found that the OMC and MDD of the specimens compacted via gyratory compactor were found to more closely correlate with field density measurements. Kim also found that at low confining pressures, pure aggregate and 50%/50% blends of RAP and aggregate had an equivalent stiffness, but at high confining pressures the 50%/50% blends had a higher stiffness than the pure aggregate. Bennert et al(3) found that pure specimens of RAP and

RCA had higher resilient moduli than pure virgin aggregate specimens. Bennert also found that specimens of pure aggregate had higher shear strength than pure RAP or RCA specimens. This trend is supported in a study by Guthrie et al(6) in which RAP/aggregate blends showed a decrease in shear strength as RAP content increased. In general, RPM seems to show a better response than natural aggregate for similar gradation and compaction in tests that induce relatively smaller strains such as resilient modulus tests than tests that induce large strains such as triaxial compression or CBR tests.

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