Lecture Notes in Civil Engineering

Hoang-Hung Tran-Nguyen
Henry Wong
Frederic Ragueneau
Cuong Ha-Minh *Editors*

Proceedings of the 4th Congrès International de Géotechnique – Ouvrages – Structures

CIGOS 2017, 26–27 October, Ho Chi Minh City, Vietnam

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Preface

Following the success of the CIGOS (Congrès International de Géotechnique - Ouvrages -Structures) conferences in 2010, 2013 and 2015, the Fourth international conference CIGOS Vietnam 2017 has expanded beyond the collaboration of scientists between France and Vietnam, to an international level. CIGOS Vietnam 2017 was held in Ho Chi Minh City University of Technology, which is one of the best universities in Vietnam. About 130 technical papers were reviewed carefully, and many outstanding professors from over 20 countries delivered keynote lectures during the conference. The proceedings of CIGOS Vietnam 2017 published by Springer issued the latest research achievement and exchanged ideas among worldwide researchers and professional engineers in the civil engineering arena.

The conference covered six topics which discussed recent findings in civil engineering as follows :

1 Advanced modelling of structure
2 Materials for construction
3 Geotechnics for environment and energy
4 Innovative design and methods
5 Water treatment and environment
6 Case studies (Tunnel, Nuclear Power Plant, etc.)

We acknowledge all the contributors for the high-quality papers, the international advisory members and the organizing committee for their dedicated work and a great collaboration, and the sponsors for their generous support. Finally, we would like to thank all the invited speakers and participants who made the CIGOS Vietnam 2017 a unique international event.

By the editors of the CIGOS Vietnam 2017

Hoang-Hung Tran-Nguyen
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A Review of Recycled Aggregates (RAP and RCA) as Unbound Base Course Material for Sustainable Highway Construction

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Abstract. This paper presents a review of unbound recycled materials, specifically recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA), as road base course for sustainable highway construction. A total of fifteen recycled materials were collected for characterization and testing from across the USA. Compaction characteristics and resilient moduli of these samples were determined and predictive equations were derived. Test sections were constructed using recycled materials in the granular base layers at the MnROAD test facility. Large-Scale Model Experiments (LSME) replicating field-scale conditions were also conducted and scalability of various scale modulus measurements was investigated. When compared to conventional base course, RAP and RCA experienced higher modulus. Discussion includes mechanical and durability characteristics, and leaching behavior. Sustainability evaluation of material alternatives in a project is described.

Keywords: Base course aggregate · Recycled asphalt pavement · Recycled concrete aggregate · Modulus · Durability · Leachate · Sustainability

1 Introduction

This paper presents a review of unbound recycled materials, specifically recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA), as road base course for sustainable highway construction based on a comprehensive research conducted on the subject (Edil et al. 2012). RAP and RCA are the two most common recycled construction materials used as base course (Fig. 1). RAP is produced by removing and reprocessing the hot mix asphalt layer of existing asphalt pavement (Guthrie et al. 2007; FHWA 2008). RAP particles are coated with asphalt and its most value added use is in production of hot mix asphalt (HMA) with the benefit of reducing the fresh asphalt content; however, its use as unbound recycled aggregate in base course is extensive. There is some ambiguity regarding the nomenclature involved in the production of RAP. 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 (Guthrie et al. 2007, Edil et al. 2012). Unless specified, these

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three distinct recycled asphalt materials are collectively referred to as RAP. RAP is typically produced through milling operations, which involves the grinding and collection of the existing HMA, and FDR and RPM are typically excavated using full-size reclaimers or portable asphalt recycling machines (FHWA 2008, Guthrie et al. 2007). 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.

Fig. 1. Recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA).

The production of RCA involves crushing structural or pavement concrete to a predetermined gradation. Fresh RCA typically contains a high amount of debris and reinforcing steel, and it must be processed to remove this debris prior to reuse (FHWA 2008). One of the value-added applications is use of RCA as a base course material although it can be used in constructing working platforms over soft subgrade and drainage medium as well as aggregate in concrete production. 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. 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 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.

A survey of the state departments of transportation was conducted in the USA to better define the state of practices involving the use, storage, and testing of materials used as granular base course in roadway applications (i.e. RAP and RCA) (Edil et al. 2012). RCA was the most commonly used material, followed by RAP and recycled pavement material, RPM. However, when RAP and RPM combined accounts for a higher frequency and quantity of use than RCA. RAP and RCA are more commonly stockpiled before use while RPM is more commonly used immediately. The most common test used for specification with recycled materials is Grain Size Analysis.

To evaluate aggregate quality, the most common tests were: the California Bearing Ratio test to evaluate aggregate strength, LA Abrasion for toughness, and the Sulfate Soundness test for durability. From the survey, it was apparent that there is limited data for structural properties of RAP and RCA (i.e. no resilient modulus tests are performed routinely). The literature implied that RAP and RCA have higher resilient moduli than natural aggregate; however, a lack of in-depth studies on characterizing RAP and RCA compositionally and mechanically was indicated.

2 Characteristics of RAP and RCA

To identify the characteristics of RAP and RCA typically available in different parts of the country, samples were obtained from eight states: California (CA), Colorado (CO), Michigan (MI), Minnesota (MN), New Jersey (NJ), Ohio (OH), Texas (TX), and Wisconsin (WI) covering a geographically diverse area. A conventional base course meeting the Class 5 gradation standard of the Minnesota Department of Transportation was used as a control and comparison material as well as a 50/50 RCA/Class 5 blend. These materials were characterized with respect to grain size distribution, fines content, asphalt content (RAPs), mortar content (RCAs), specific gravity, absorption, and impurities. The materials, although obtained form 8 different states, had reasonably consistent properties.

2.1 Physical Properties

Washed sieve analyses were performed according to ASTM D 422 and specific gravity (G_s) and absorption tests were conducted according to AASHTO T 85. Asphalt content was determined via ASTM 6307. Materials were classified according to the Unified Soil Classification System (USCS) (ASTM D 2487). The modified Proctor compaction test (ASTM D 1557) was performed to determine the optimum moisture content (w_{opt}) and maximum dry unit weight (γ_{dmax}). Physical properties of the recycled materials are summarized in Table 1.

Table 1. Physical properties of RCA and RAP/RPM

Properties	RCA Average (range)	RAP/RPM Average (range)
%Fines	5.05 (2.01–12.8)	0.92 (0.4–1.8)
%Gravel	46.19 (32–69)	38.38 (32–51)
Cu	24.60 (8–45)	9.80 (7–17)
Specific gravity	2.31 (2.2–2.4)	2.38 (2.34–2.57)
Absorption (%)	5.52 (5.5–6.9)	1.84 (0.6–3.0)
Asphalt content (%)	–	5.9 (4.7–7.1)
Mortar content (%)	50 (37–65)	
Classification	SP, GP, GW	SP, SW, GW
	A-1-a, A-1-b	A-1-a, A-1-b

Fines content was 3–4% for RCAs except two samples and lower for RAPs, i.e., 1–2%. The mortar content was about 50% with small variation for the RCA samples and the asphalt content was about 5% with small variations for the RAP samples. The most distinguishing physical characteristics were the grain size with some samples coarser and others finer. Most samples had grain size distributions within the bounds for RCA and RAP given in the literature. A new standard developed by ASTM (D 8038 Standard Practice for Reclamation of Recycled Aggregate Base (RAB) Material) provides guidance for processing RAP and RCA as a quality base aggregate. Table 2 gives the grading requirements for aggregate base including RCA and RAP according to ASTM D 8038.

Table 2. Aggregate grading requirements for RAB (ASTM D 8038)

	Design range (percentage passing by mass)		Tolerances (percentage passing by mass)	
Sieve sizes (mm)	Bases	Subbases	Bases	Subbases
50.0	100	100	−2	−3
37.5	95–100	90–100	±5	±5
19.0	70–92		±8	
9.5	50–70		±8	
4.75	35–55	30–60	±8	±10
0.60	12–25		±5	
0.075	0–8	0–12	±3	±5

2.2 Deleterious Materials

The amount of deleterious materials present in RCA and RAP varied amongst the source of the materials. The most predominant impurities for RCA were asphalt aggregate, aggregate with plastic fibers, brick, and wood chips. Geotextiles and pavement markings were the predominant type of impurity in RAP. The average impurity content was 1% for RCA and 0.2% for RAP, indicating that recycling industry has developed sufficient controls. The effect of brick content on the resilient modulus and compaction of RCA was investigated at 0, 10, 20, and 30% brick by mass (Edil et al. 2012). No apparent trends were observed between modulus and brick content of RCA, but a decrease in plastic strain was observed with increased brick content. An increase in optimum moisture content and decrease in dry unit weight was observed in RCA mixed with brick at 30% compared to 0% brick. This was attributed to brick having higher absorption and lower specific gravity and density than RCA. ASTM D8038 limits deleterious materials to be no more than 1% by mass in RAB, however, brick content is allowed up to 20% by weight in RCA.

3 Compaction Characteristics

The compaction characteristics were also determined using the modified Proctor test. Maximum dry unit weight (MDU) varies within a narrow range of 19.4 to 21.5 kN/m^3 for RAP at optimum moisture contents (OMC) of 5.2 to 8.8% and 19.4 to 20.9 kN/m^3 for RCA at OMC of 8.7 to 11.8%. Figure 2 shows the trend of MDU versus OMC for RAP and RCA samples. The OMC of RAP was lower than RCA since asphalt coatings reduce the amount of water required to achieve MDU by preventing the water from reaching the individual particles of the material. RCA has high absorption capacity due to the porous nature of the cement paste portion. Therefore, the amount of water required to achieve the MDU for RCA is higher than for natural aggregate and RAP. Stepwise regression was performed by using multiple linear regressions to

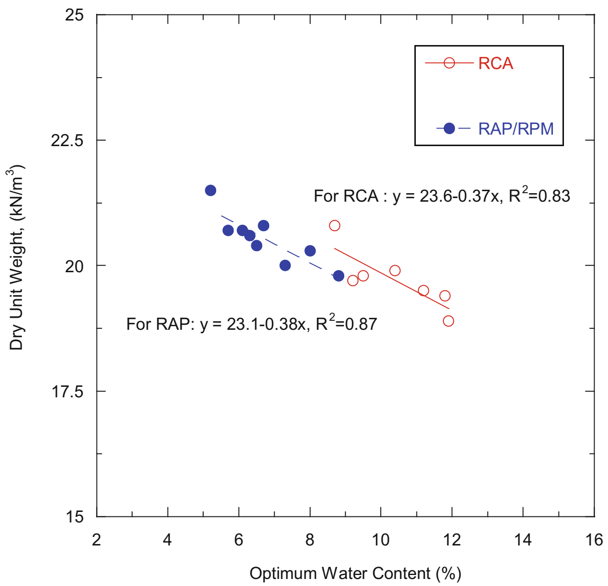

Fig. 2. Maximum dry unit weight versus optimum moisture content

Table 3. Correlations between compaction characteristics and index properties

Materials	Compaction characteristics	Correlation equations	R^2
RCA	w_{opt} (%)	$-0.064 * C_u + 0.763 * \text{Absorption} (\%) + 7.749$	0.65
	γ_{dmax} (kN/m^3)	$-0.373 * w_{opt} (\%) + 23.575$	0.67
RAP	w_{opt} (%)	$-0.0626 * C_u - 1.349 * \text{Absorption} (\%) + 9.844$	0.92
	γ_{dmax} (kN/m^3)	$-0.398 * w_{opt} (\%) + 23.264$	0.70

develop correlations (models) to predict the compaction characteristics (OMC and MDU) of RCA and RAP based on their gradation characteristics as shown in Table 3 (Bozyurt et al. 2012). OMC correlates significantly with the uniformity coefficient and percent moisture absorption and MDU correlates with OMC for both RAP and RCA.

4 Modulus

4.1 Laboratory Resilient Modulus

Resilient modulus of the samples was measured on specimens at OMC and 95% modified Proctor MDU in accordance with NCHRP 1-28a (2004). The MEPDG model with 5 parameters were fitted to the test data. A summary resilient modulus (SMR) was calculated from the fitted equations at a stress level representative of the base course layer. For base course, the summary resilient modulus (SRM) corresponds to the M_r at bulk stress of 208 kPa and octahedral shear stress of 48.6 kPa, as suggested in Section 10.3.3.9 of NCHRP 1-28a (2004). A comparison of SRM indicated that RAP/RPM has the highest SRM of the recycled materials evaluated. RCA has slightly lower SRM in comparison to RAP/RPM, while Class 5 aggregate has the lowest SRM. Stepwise regression was performed by using multiple linear regressions to develop correlations (models) to predict SRM of RCA and RAP based on their physical and moisture content as shown in Table 4 (Bozyurt et al. 2012). SRM is significantly correlated with D_{30} and moisture content, i.e., OMC for RCA. The correlation for RAP involved other variables such as grain size characteristics (percent fines, D_{60}), asphalt content, specific gravity and percent absorption. Blending recycled materials with natural aggregate result in intermediate modulus between the moduli of the two materials.

Table 4. Correlations between compaction characteristics and index properties

Materials	Resilient modulus (MPa)	Correlation equations	R^2
RCA	SMR_{INT}	$14683.478 - (36.764 * D_{30}) - (72.719 * w_{opt})$	0.89
RAP	SMR_{INT}	$\_2268.783 - (285.884 * Fines\ \%) + (628.742 * AC\ \%) + (201.107 * D_{60}) - (483.158 * G_s) - (58.243 * Absorption\ \%)$	0.99

Note: AC = Asphalt content

4.2 Scalability of Modulus from Laboratory to Field

To verify the scalability of laboratory modulus to field conditions both Large-Scale Model Experiment (LSME), a large prototype-scale test developed for simulating the performance of pavement sections in a laboratory setting (Edil et al. 2012), and field