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Characterization of recycled materials for sustainable construction

Caractérisation des matériaux recyclés pour la Construction durable

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ABSTRACT: Recyclable materials and industrial byproducts provide an environmentally and economical alternative to natural earthen materials when used safely and wisely in geotechnical construction. In particular, the construction of various elements of transportation systems requires large quantities of materials and locally available recyclable materials can be used extensively enhancing sustainability of construction. This paper addresses the rapid characterization required for this new class of materials such as recycled asphalt pavement, concrete aggregate, and coal combustion residues (fly ash, bottom ash). Recycled materials and industrial byproducts require an assessment of their environmental suitability in terms of potential impacts on surface and ground water quality for their acceptance. Finally, their field behavior need to be evaluated and their contribution to sustainability to be assessed.

RÉSUMÉ : Les matériaux recyclables et les sous-produits industriels fournissent ambiant et l'alternative économique aux matériaux de terre naturels une fois utilisés sans risque et sagement dans la construction géotechnique. En particulier, la construction de divers éléments des systèmes de transport exige de grandes quantités de matériaux et localement des matériaux recyclables disponibles peuvent être employés intensivement augmentant la durabilité de la construction. Ce document adresse la caractérisation rapide exigée pour cette nouvelle classe des matériaux tels que le trottoir réutilisé d'asphalte, l'agrégat concret, et les résidus de combustion de charbon (cendres volantes, cendre inférieure). Étant les matériaux réutilisés ou les sous-produits industriels, leur acceptation exige une évaluation de l'aptitude environnementale en termes d'impacts potentiels sur la qualité extérieure et d'eaux souterraines. En conclusion, leur besoin de comportement de champ d'être évalué et leur contribution à la durabilité à évaluer.

KEYWORDS: recycled materials, sustainable construction, recycled asphalt pavement, recycled concrete aggregate, coal ash.

1 INTRODUCTION

Development and growth need to be sustainable, in other words, integrate environmental, economic, and social dimensions towards global stewardship and responsible management of resources. Strategies need to evolve for sustainable development..Large quantities of natural and processed materials are used in construction activities such as buildings, transportation facilities, infrastructure, and environmental applications. These materials use natural resources and consume large quantities of energy to extract or process with associated green house gas emissions. Transportation facilities, such as highways, in particular use large quantities of materials in initial reconstruction and also during periodic rehabilitation. Recycling industrial byproducts and construction materials in highway construction can generate “green highways” where use of virgin materials and large amounts of energy and generation of green house gas emissions are minimized.

The necessary steps for characterization of widely used recycled materials (i.e., recycled asphalt pavement and recycled concrete aggregate) and industrial byproducts (i.e., coal combustion products such as bottom ash and fly ash) in highway construction are presented and discussed. The approaches for determining their physical characteristics, geomechanical behavior (i.e., resilient modulus), durability (i.e., freeze-thaw cycling, temperature effects, wet-dry cycling), constructability (i.e., compaction), material control, and their environmental suitability (i.e., leaching characteristics) for alternative beneficial uses are presented. Life cycle assessment (LCA) of the environmental benefits and the life cycle cost analysis (LCCA) for use of these materials are also discussed.

2 CHARACTERIZATION

We have been characterizing natural earthen materials systematically for nearly a century. Widespread use of these recycled materials is relatively new and time window to characterize them is short because of economical and environmental drivers. Testing methods developed for soils and construction specifications for natural aggregates and soils can be adapted to this new class of recycled materials and the existing pavement design procedures can be followed.

Material control in terms of variability of composition, grain size characteristics, inclusion of impurities are issues that need to be assessed for recycled materials, as they are products of anthropogenic processes rather than geological processes. There may be differences arising from basic material characteristics that may impact constructability in terms of compaction control. Modern pavement design requires resilient or elastic modulus as the primary geomechanical property. On the basis of this property layer thicknesses in a pavement and service life of a pavement can be determined. Durability under climatic effects, i.e., freeze-thaw and wet-dry cycles, is a critical quality for pavement materials because the pavements are surficial and directly influenced by the climate. Some of these materials have sensitivity to temperature in ways we are unaccustomed dealing with soils. Finally, while we do not question the environmental suitability of traditional materials like crushed aggregate, concrete and asphalt used in highway construction, use of recycled materials and industrial byproducts requires evaluation of environmental suitability, i.e., the leaching characteristics.

3 MATERIALS, APPLICATIONS & CRITICAL CHARACTERISTICS

The outstanding characteristics of a range of recycled materials widely used in highway construction are described along with typical applications.

3.1 Recycled Asphalt Pavement (RAP)

RAP (Figure 1) is produced by removing and reprocessing the hot mix asphalt (HMA) layer of existing asphalt pavement (Guthrie et al., 2007; FHWA, 2008). 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 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.

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. Seven RAP and 2 RPM samples collected from geographically diverse 7 states in the U.S.A. indicated a range of 5-7% asphalt content. RAP and RPM are widely used as unbound base material and the most common test used for specification is Grain Size Analysis. The most distinguishing physical characteristics are the grain size with some samples coarser and others finer. D_{50} of the 9 samples ranged 1.6 to 5.8 mm and the fines content was less than 2%. These materials all classified as A-1-a or A-1-b according to the AASHTO soil classification system. These samples had an average impurity (geotextiles, pavement markings, etc.) content of 0.2% for RAP, indicating that recycling industry has developed sufficient controls.

The compaction characteristics using the modified Proctor test indicated that the maximum dry unit weight (MDU) varies within a narrow range (19.4 to 21.5 kN/m^3) for RAP and the optimum moisture contents (OMC) (5.2 to 8.8%). OMC correlates significantly with the uniformity coefficient and percent moisture absorption and MDU correlates with OMC for RAP (Bozyurt et al. 2012).

Summary resilient modulus (SRM calculated at a bulk stress of 208 kPA, typical of base course layer) of the 9 RAP and RPM samples measured at OMC and 95% modified Proctor MDU, indicated that RAP/RPM has higher SRM (168 to 266 MPA) than natural crushed aggregate (152 MPa) and is significantly correlated with grain size characteristics (percent fines, D_{60}), asphalt content, specific gravity, and percent absorption (Bozyurt et al. 2012).

Application of freeze-thaw cycles indicated that SRM decreased in a range of 28 to 53% up to 20 cycles. However, RAP still had a higher stiffness than natural crushed rock aggregate regardless of the number of freeze-thaw cycles (Edil et al. 2012). Because of its asphalt content RAP can be expected to be sensitive to temperature changes. A decrease of approximately 30% in SRM was observed in RAP between the 23 and 35 °C. These temperature effects were absent in control specimens containing no asphalt. Micro-Deval and particle size distribution tests conducted on RAP after 5, 10, and 30 wet/dry cycles showed no apparent particle degradation (Edil et al. 2012).

RAP has excellent drainage capacity due to the hydrophobic nature of the asphalt coating and does not retain moisture (Nokkaew et al. 2012). Field leachate samples collected indicated that the concentrations of As, Se and Sb for RAP were slightly higher than the corresponding USEPA groundwater maximum contaiminant level (MCL) but decreased rapidly after the first flush (Edil et al. 2012). Falling Weight Deflectometer (FWD) tests were conducted at a test facility (MNROAD) on pavement with base course material of RAP indicated relatively small variation in stiffness and resilient modulus seasonally and indicated no deterioration over 4 years.

The investigations undertaken on RAP indicate that it is a suitable material for unbound base course applications and shows equal or superior performance characteristics compared to natural aggregates in terms of stiffness, freeze-thaw and wet-dry durability, and toughness. Their compositional and mechanical properties vary in relatively small range. The relative differences of RAP from natural aggregate such as temperature sensitivity, plastic deformations, and water absorption and retention characteristics are also well established. To determine the various properties of RAP (e.g., compositional characteristics, grain size distribution, compaction, resilient modulus), existing standard test methods employed for natural crushed aggregate can be used with added consideration for temperature control. There are no established standards for freeze-thaw and wet-dry cycling but published research methods can be adopted (Edil et al. 2012).

3.2 Recycled Concrete Aggregate (RCA)

The production of RCA (Figure 1) 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. 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 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.

Seven RCA samples collected from geographically diverse 7 states in the U.S.A. indicated a range of 5-6.5% mortar content. The most distinguishing physical characteristics are the grain size with some samples coarser and others finer. D_{50} of the 7 samples ranged 1 to 13.3 mm and the fines content was less than 3-4% except two samples and higher than for RAPs. The mortar content was about 50% with small variation for these RCA samples. These materials classified mostly as A-1-a with some as A-1-b according to the AASHTO soil classification system. These samples had an average impurity (geotextiles, pavement markings, etc.) content of 1% for RCA, indicating that recycling industry has developed sufficient controls. The most predominant impurities for RCA were asphalt aggregate, aggregate with plastic fibers, brick, and wood chips. RCA derived from structures tend to have brick content. The effect of brick content up to 30% indicated no adverse effect on resilient modulus of RCA (Shedivy 2012).

The compaction characteristics using the modified Proctor test indicated that the maximum dry unit weight (MDU) varies within a narrow range (19.4 to 20.9 kN/m^3) for RCA and optimum moisture contents (OMC) (8.7 to 11.8%). OMC is greater than RAP's due the higher absorption capacity due to the porous nature of the mortar portion of RCA. OMC of RCA correlates significantly with the uniformity coefficient and percent moisture absorption and MDU correlates with OMC for RCA (Bozyurt et al. 2012)

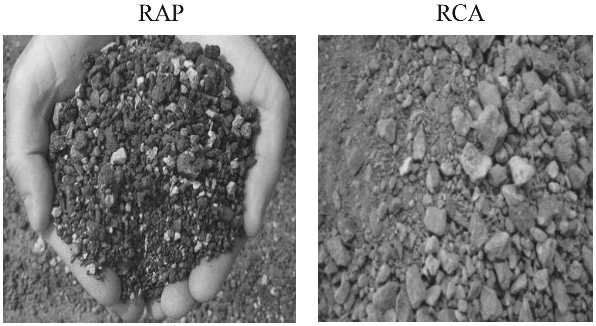

Figure 1. Recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA)

Summary resilient modulus (SRM calculated at a bulk stress of 208 kPA, typical of base course layer) of the 7 RCA samples measured at OMC and 95% modified Proctor MDU, indicated that RCA has higher SRM (163 to 208 MPA) than natural crushed aggregate (152 MPa) and lower than RAP/RPM. SRM is significantly correlated with D_{30} and OMC (Bozyurt et al. 2012).

Application of freeze-thaw cycles indicated that SRM decreased 10-18% during the first five freeze-thaw cycles, but then an increased 30-38% above the initial SRM after 20 freeze-thaw cycles. The self-cementing properties of RCA and fines content generation over time could explain why an increase in stiffness after five freeze-thaw cycles occurred. (Bozyurt et al. 2011). Micro-Deval and particle size distribution tests were conducted on RCA after 5, 10, and 30 wet/dry cycles and no apparent trend was found between particle degradation and wet/dry cycling of the material

RCA has high drainage capacity but retains moisture more than RAP and natural aggregate base because of its hydrophilic cement mortar (Nokkaew et al. 2012). Laboratory batch and column leach tests and field leachate samples collected indicated that RCA base course has high alkalinity (pH = 10.8 to 12.9). As, Cr, Pb, and Se exceeded the maximum contaminant levels (MCLs) for the USEPA drinking water standard both at the field sites and in the laboratory column leaching tests. The concentrations of As, Pb, and Se for RCA exceeded the corresponding MCL only once or twice and the leaching behaviors were similar to that of the control natural crushed aggregate base course. As and Cr appear to be mainly sourced from the cement mortar based on the acid digestion results (Edil et al. 2012). Falling Weight Deflectometer (FWD) tests that were conducted at the MnRoad test facility on pavement with base course material of RCA indicated relatively small seasonal variation in modulus and no deterioration over 4 years.

The investigation undertaken on RCA indicate that it is a suitable material for unbound base course applications and shows equal or superior performance characteristics compared to natural aggregates in terms of stiffness, freeze-thaw and wet-dry durability, and toughness. Their compositional and mechanical properties vary in relatively small range. The relative difference of RCA from RAP and natural aggregate is its water absorption and retention characteristics. RCA displays high alkalinity thus oxyanions (As, Se, and Cr) should be given more attention to as they demonstrate enhanced leaching in a highly alkaline environment.

To determine the various properties of RCA (e.g., compositional characteristics, grain size distribution, compaction, resilient modulus), existing standard test methods employed for natural crushed aggregate can be used. There are no established standards for freeze-thaw and wet-dry cycling but published research methods can be adopted (Edil et al. 2012).

3.3 Coal Combustion Products (CCP)

CCPs of interest to highway construction include fly ash and bottom ash. When pulverized coal is burned in a dry bottom boiler, about 80 percent of the unburned material or ash is entrained in the flue gas and is captured and recovered as fly ash (Figure 2). The remaining 20 percent of the unburned material is dry bottom ash, a porous, glassy, dark gray material with a grain size similar to that of sand or gravelly sand (Figure 3). Although similar to natural fine aggregate, bottom ash is lighter and more brittle and has a greater resemblance to cement clinker. Beneficial use of bottom ash in highway applications, which is less than 50% of the material produced in the U.S.A., include structural fill (nearly half of all use), road base material, working platform material for construction of pavements over soft subgrade, fine aggregate in wearing surface in pavements and flowable fills, and as snow and ice control products. Bottom ash is predominantly well-graded sand-sized, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve and 0 to 10 percent passing a 0.075 mm (No. 200) sieve (http://rmrc.wisc.edu).

Bottom ash has MDU of 11.8 to 15.7 kN/m^3 and OMC of 12-24%. Its internal friction angle varies from 32° to 45°. California bearing ratio (CBR) is typically 20 to 40. Summary resilient modulus (SRM calculated at a bulk stress of 208 kPA, typical of base course layer) for properly compacted bottom ash can be taken as 100 MPa. Bottom ash has similar drainage characteristic as sand with a hydraulic conductivity of $1x10^{-2}$ mm/s. All standard tests used to characterize natural granular materials like sand can be directly used for bottom ash.

The fly ash is a fine-grained, powdery particulate material that is carried off in the flue gas and usually collected by means of electrostatic precipitators, baghouses, or mechanical collection devices such as cyclones. Beneficial use of fly ash in highway applications, which is less than 50% of the material produced in the U.S.A., include cement replacement /additive in concrete (nearly half of all use), structural fill, stabilization agent for road subgrade and base material, working platform material for construction of pavements over soft subgrade, flow agent in flowable fills, and mineral filler in asphalt layers (http://rmrc.wisc.edu). Self-cementing coal fly ashes are suitable materials for the stabilization of subgrade soils, recycled pavement materials, and road surface gravel. Fly ash stabilization can result in improved properties, including increased stiffness, strength and freeze-thaw durability; reduced hydraulic conductivity, plasticity, and swelling; and increased control of soil compressibility and moisture. Fly ash stabilized materials may be used in roadway construction, such as working platforms during construction, stabilized subgrade, subbase, and base layers (Edil et al. 2006). Recently published ASTM standard practice provides guidance for testing and designing of stabilization of soil and soil-like materials with self-cementing fly (ASTM D7762 2011).

The possibility of groundwater contamination by trace elements that are commonly associated with coal combustion by-products is a concern. Areas with sandy soils possessing high hydraulic conductivities and areas near shallow groundwater should be given careful consideration especially

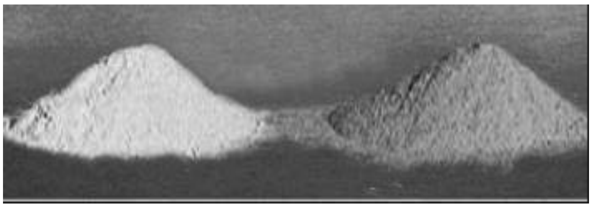

Figure 2. Fly Ash (different colors)

Figure 3. Bottom Ash

for large volume uses like structural fills. An evaluation of groundwater conditions, applicable state test procedures, water quality standards, and proper construction are all necessary considerations in ensuring a safe final product. There are several leaching tests and currently U.S. Environmental Protection Agency is nearing publication of new leaching standard appropriate for beneficial use application of CCPs and other similar materials (Kosson et al. 2002). U.S. EPA is currently reviewing its rules regarding beneficial use of CCPs.

4 ASSESSMENT OF SUSTAINABILITY

Assessment of sustainability involves the life cycle assessment (LCA) of the environmental benefits and the life cycle cost analysis (LCCA). LCA involves determining a variety of sustainability metrics (e.g., energy consumption, GHG emissions, water use, hazardous waste generation, etc.) associated with production of construction materials, their transportation to the construction site, and construction itself. These determinations can be made using available database programs such as the PaLATE model (Horvarth, 2004). LCCA evaluates life cycle cost of design alternatives including the initial construction and maintenance based on service life. A convenient computer code named RealCost can be used for this purpose (FHWA 2004). Service life is a crucial part of this analysis and materials with higher modulus typically result in a longer service life for the same thickness of pavement layers. Examples of LCA and LCCA are available (Lee et al. 2011).

A rating system for sustainable highway construction, named Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways, BE^{2}ST-in-Highways^{TM} was developed to provide a quantitative methodology for rating the benefits of sustainable highway construction (Lee et al. 2011). The methodology is grounded in quantitative and auditable metrics so that a transparent linkage exists between the project rating and the sustainable practices employed in construction. This rating system can be employed by the highway construction industry and agencies to quantitatively evaluate sustainable practices and to incorporate sustainable elements into projects.

The BE^{2}ST-in-Highways^{TM} system evaluates sustainability of a highway project in terms of a quantitative difference between a reference design and proposed alternative design(s). Thus, the reference highway design must be defined realistically. A conventional design approach in which sustainability concepts are not incorporated explicitly can be used as a reference design. The analysis assumes that the service life of conventional and alternative designs can be based on an international roughness index (IRI) prediction made with the Mechanistic Empirical Pavement Design Guide (M-EPDG) program (NCHRP) and that rehabilitation occurs at the end of the predicted service life.

5 CONCLUSIONS

1. It is imperative that industry-wide sustainable construction practices be adopted and recycled materials play a significant role in earthen construction where large quantities of materials are used such as in roadway construction.
2. Benefits of recycled materials include reduction in greenhouse gas emissions, energy, natural resources, and cost.
4. Wise use of recycled materials may create longer lasting structures and reduction in cost.
5. Conducting quantitative analyses using appropriate sustainability metrics to assess alternatives involving recycled materials is imperative.

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