

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

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Editors

Hoang-Hung Tran-Nguyen
University of Technology
Ho Chi Minh City
Vietnam

Frederic Ragueneau
University of Paris-Saclay
Cachan Cedex
France

Henry Wong
University of Lyon
Vaulx-en-Velin
France

Cuong Ha-Minh
University of Paris-Saclay
Cachan Cedex
France

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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
Henry Wong
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Contents

Keynote Lectures

A Review of Recycled Aggregates (RAP and RCA) as Unbound Base Course Material for Sustainable Highway Construction	3
Tuncer B. Edil	
Effective Slab Width for Evaluating Ultimate Seismic Capacities of Reinforced Concrete Buildings	15
Toshimi Kabeyasawa and Toshikazu Kabeyasawa	
From 3-D to 1-D Generalised and Cosserat Continua for Structural Dynamics - Energy-Momentum Methods	30
Carlo Sansour, Tien Long Nguyen, and Mohammed Hjiiaj	
Recent Developments in Design for Structural Stability	41
Gregory J. Hancock	
Advanced Modelling of Structures (AMS)	
A Numerical Modeling of RC Beam-Column Joints Compared to Experimental Results	59
Q.-B. Bui, B. Sentosa, and T.-H. Duong	
Application of a Newly Puzzel Shaped Crestbond Rib Shear Connector in Composite Beam Using Opposite T Steel Girder: An Experimental Study	68
Duy Kien Dao, Duc Vinh Bui, Thi Hai Vinh Chu, and Van Phuoc Nhan Le	
Application of the THIN-WALL-2 V2.0 Program for Analysis of Thin-Walled Sections Under Localised Loading	78
Van Vinh Nguyen, Gregory J. Hancock, and Cao Hung Pham	

Bending Resistance of Steel-Bar Reinforced Concrete Beam with Extreme Compression Zones Using High-Performance Composite	89
Duy-Liem Nguyen and Duy-Ngo Tong	
Bolt-Loosening Detection in Steel Column Connections Using Impedance Responses	100
Duc-Duy Ho, Trung-Hieu Nguyen, and Quang-Huy Le	
Crack Propagation Analysis in Concrete Dams Based on the eXtended Finite Element Method	111
Giang Vo Thi Tuyet and Trong Nguyen Vo	
Experimental Study of Hybrid Walls with Several Fully Encased Steel Sections	120
Van Toan Tran and Quang Huy Nguyen	
Failure Analysis of a Cold-Rolled Steel Tensile Specimen Using a Damage-Plasticity Model	131
Bac V. Mai, Giang D. Nguyen, Cao Hung Pham and Gregory J. Hancock	
Finite Strain Plasticity Formulations for Dynamic Beams With and Without Rotational Degrees of Freedom	142
Tien Long Nguyen, Carlo Sansour, and Mohammed Hjjaj	
Fuzzy Linear Elastic Dynamic Analysis of 2-Dimensional Semi-rigid Steel Frame with Fuzzy Fixity Factors	152
Thanh Viet Tran, Quoc Anh Vu, and Xuan Huynh Le	
Incorporation of Measured Geometric Imperfections into Finite Element Models for Cold-Rolled Aluminium Sections	161
Ngoc Hieu Pham, Cao Hung Pham, and Kim J.R. Rasmussen	
Micromechanical Model for Describing Intergranular Fatigue Cracking in an Innovative Solder Alloy	172
Van-Nhat Le, Lahouari Benabou, and Quang-Bang Tao	
Modelling the Static Interaction Between a Shallow Foundation and Soil Base Using Contact Conditions	181
H.T. Tai Nguyen, T. Hang Nguyen, and N. Hung Nguyen	
Numerical Analysis of Hybrid Walls Using FEM	191
Van Toan Tran	
Numerical Simulations of Cold-Rolled Aluminium Alloy 5052 Channel Sections in Stub Column Tests	202
Le Anh Thi Huynh, Cao Hung Pham, and Kim J.R. Rasmussen	

Numerical Studies of Composite Steel-Concrete Columns Under Fire Conditions Including Cooling Phase 213
 Thi Binh Chu and Quang Vinh Truong

On the Finite Element Modeling of the Screwed Connections of Cold-Formed Steel 224
 Minh Toan Huynh, Cao Hung Pham, and Gregory J. Hancock

Redistribution of Moment at Beam-Column Joints in RC Structures: Comparison Between an Experimental Study and Eurocode 2 233
 B. Sentosa, Q.-B. Bui, J.-P. Plassiard, O. Plé, P. Perrotin, and H. Purnomo

Shear Resistance Behaviors of a Newly Puzzle Shape of Crestbond Rib Shear Connector: An Experimental Study 243
 Thi Hai Vinh Chu, Van Phuoc Nhan Le, Duy Kien Dao, Thanh Hai Nguyen, and Duc Vinh Bui

Simulation of Reinforced Concrete Short Shear Walls Subjected to Seismic Loading 254
 Khuong Le Nguyen, Ba Tam Truong, and Minh Quyen Cao

Strength Capacity of Steel Piles Filled with Concrete at Pile Top 263
 Moeko Matoba, Mutsuki Sato, Toshiharu Hirose and Yoshihiro Kimura

Systematic Analysis of the Concept of Equivalent Linear Behavior in Seismic Engineering 273
 Thuong Anh Nguyen, Pierre Labbé, Jean-François Semblat, and Guillaume Hervé

Tensioning Process Update for Cable Stayed Bridges 283
 Jose Antonio Lozano-Galant, Dong Xu, and Jose Turmo

The Roles and Effects of Friction in Cohesive Zone Modelling: A Thermodynamics-Based Formulation 288
 Giang D. Nguyen and Ha H. Bui

Materials For Construction (MFC)

A Review on Immobilisation of Toxic Wastes Using Geopolymer Technique 299
 Tran Huyen Vu and Mien Van Tran

Additional Carbon Dependent Electrical Resistivity Behaviors of High Performance Fiber-Reinforced Cementitious Composites 310
 Duy-Liem Nguyen, Thi-Ngoc-Han Vuong, and Tri-Thong Nguyen

An Experimental Study on Earthen Materials Stabilized by Geopolymer 319
 Q.-B. Bui, E. Prud'homme, A.-C. Grillet, and N. Prime

Analysis Behavior of Reinforcement in a Reinforced Concrete Beam Using Steel Slag Replacing Crushed-Stone Aggregate 329
 Anh-Thang Le, Trong-Quang Hoang, and Tat-Thanh Nguyen

Application of Empirical Models to Optimizing Concrete Pumpability 338
 Tien-Tung Ngo, Chanh-Trung Mai, El-Hadj Kadri, and Abdelhak Kaci

Behavior of Concrete-Filled Hybrid Large Rupture Strain FRP Tubes Under Cyclic Axial Compression 346
 Monika Nain, Mohanad M. Abdulazeez, and Mohamed A. ElGawady

Chemical Shrinkage Characteristics of Binder Pastes in Ultra High Performance Concrete Made from Different Types of Cement 354
 Quoc Si Bach

Chloride Binding Ability and Anti-corrosion Properties of Supersulfated Cement in Seawater/Sand Mixing Concrete 367
 Khanh Son Nguyen, Anh Toan Nguyen-Phung, Hong Thai Le, Thanh Tri Ho, Tri Huynh Nguyen-Ngoc, Soon Poh Yap, Nobuhiro Chijiwa, and Nobuaki Otsuki

Correlation Between Resilient Modulus and Permanent Deformation During a Large Scale Model Experiment of Unbound Base Course 377
 Makhaly Ba

Correlations Between DCP Penetration Index and Properties of Pavement Layer Materials 385
 Suppakorn Wachiraporn, Auckpath Sawangsuriya and Wilailak Sramoon

Crumb Rubber as a Sustainable Aggregate in Chip Seal Pavement 392
 Ahmed A. Ghenni and Mohamed A. ElGawady

Development of Geopolymer-Based Materials from Coal Bottom Ash and Rice Husk Ash with Sodium Silicate Solutions 402
 Hoc Thang Nguyen, Trung Kien Pham, and Michael A.B. Promentilla

Development of New Type of Screwed Pile with Large Bearing Capacity and Ecological Driving Method "Tsubasa PileTM" 411
 Marina Kawai, Kazuomi Ichikawa, and Kenji Kono

Durability of Polyester-Based GFRP Subjected to Hybrid Environmental and Mechanical Loads 426
 Song Wang and Mohamed ElGawady

Effect of Manufacturing Process on Material Properties at the Corners of G450 Cold-Formed Steel Channel Sections 434
 Huu Nam Trinh, Gwénaëlle Proust, and Cao Hung Pham

Effect of Pre-compressive Stress on Chloride Permeability of Concrete Used Anti-permeable Admixture 442
 The Truyen Tran, Xuan Tung Nguyen, and Xuan Ba Ho

Effect of Thermal-Humid Media on Durability of CFRP-Wrapped Reinforced Concrete Columns 448
 Van Mien Tran and Dong Viet Phuong Tran

Effective Design of Flexible Pavement on Treated Expansive Soil 459
 Raju Sarkar, Ankur Mudgal, Ritesh Kurar, and Varun Gupta

Experimental Approach to Identify the Thermomechanical Behaviour of a Textile Reinforced Concrete (TRC) Subjected to High Temperature and Mechanical Loading 471
 Tala Tlajji, Xuan Hong Vu, Emmanuel Ferrier, and Amir Si Larbi

Experimental Study on the Thermo-Mechanical Behavior of Hand-Made Carbon Fiber Reinforced Polymer (H-CFRP) Simultaneously Subjected to Elevated Temperature and Mechanical Loading 484
 Phi Long Nguyen, Xuan Hong Vu, and Emmanuel Ferrier

Fresh Properties and Early Compressive Strength of Alkali-Activated High Calcium Fly Ash Paste 497
 Eslam Gomaa, Simon Sargon, Cedric Kashosi and Mohamed ElGawady

Hygric and Thermal Insulation Properties of Building Materials Based on Bamboo Fibers 508
 Dang Mao Nguyen, Anne-Cécile Grillet, Thi My Hanh Diep, Thi Vi Vi Do, Chi Nhan Ha Thuc, and Monika Woloszyn

Investigation on the Blended Cement Mixture of Sintered Clinker of Calcium Sulfoaluminate Cement and Granulated Blast Furnace Slag 523
 Khanh Son Nguyen, Tuan Nghia Le, Anh Quyen Nguyen-Thi, Anh Toan Nguyen-Phung, Tri Huynh Nguyen-Ngoc, and Quang Minh Do

Numerical Tool for the Evaluation of the Hygrothermal Performance of a Hemp-Lime Concrete 533
 S. Moissette, M. Bart, Y. Aït Oumeziane, C. Lanos, F. Collet and S. Prétot

Seismic Performance of Hollow-Core Composite Columns Under Cyclic Loading 544
Mohanad M. Abdulazeez and Mohamed A. ElGawady

Semi-flexible Material: The Sustainable Alternative for the Use of Conventional Road Materials in Heavy-Duty Pavement. 552
T. Nhan Tran, H.T. Tai Nguyen, K. Son Nguyen, and N.T. Huynh Nguyen

Shear Behavior of High Performance Concrete Beams Using Digital Image Correlation Technique 560
Touhami Tahenni, Mohamed Chemrouk, and Thibaut Lecompte

Study on Effect of Cornsilk Fiber in Cemented Soil Stabilization 571
Khiem Quang Tran, Tomoaki Satomi, and Hiroshi Takahashi

Study on Strength of Modified Sludge Produced By Fiber-Cement Stabilized Soil Method Using Several Kinds of Fiber Materials 580
Thanh Nga Duong, Tomoaki Satomi, and Hiroshi Takahashi

Synergic Effects of Activation Routes of Ground Granulated Blast-Furnace Slag (GGBS) Used in the Precast Industry 588
Martin Cyr and Ludovic Andre

The Flow Response of Reinforced Earth Structures Utilized Fine-Grained Poorly Draining Materials as Backfill. 598
D. Bui Van, A. Chinkulkijniwat, S. Horpibulsuk, S. Yubonchit, A. Udomchai, I. Limrat, A. Le Tuan, H. Pham Tien, and O. Kennedy

Using a Spray Test to Study the Surface Erosion of Geomaterials Application on Construction Material of Soil-Cement Mixtures in Le Havre, France 610
Van-Nghia Nguyen and Said Taibi

Using Wastes from Thermal Power Plants for Manufacturing of Low Strength Construction Materials 617
Quoc-Bao Bui, Minh-Tung Tran, and Duc-Hien Le

Geotechnics for Environment and Energy (GEE)

3D Electrical Resistivity Tomography of Karstified Formations Using Cross-Line Measurements 627
Maurits Van Horde, Thomas Hermans, Gael Dumont, and Frédéric Nguyen

A Case Study of a Long-Duration Thermal Response Test in Borehole Heat Exchangers 637
Georgia Radioti, Benjamin Cerfontaine, Robert Charlier, and Frederic Nguyen

An Elastoplastic Model for Soils Exhibiting Particle Breakage 644
 Vu P.Q. Nguyen and Mamoru Kikumoto

Application of a Cyclic Accumulation Model UDCAM to FE Analyses of Offshore Foundations 656
 Huynh Dat Vu Khoa and Hans Petter Jostad

Assessment of Multiple Geophysical Techniques for the Characterization of Municipal Waste Deposit Sites 668
 Gael Dumont, Tanguy Robert, Nicolas Mark, and Frédéric Nguyen

Seismic Cone Testing Using Seafloor Drill Technology 677
 D.H. Doan, P. Looijen, and A.G. Cooper

Conductive Heat Transfer Analysis of Energy Pile 685
 Tri Van Nguyen, Anh Minh Tang, and Jean-Michel Pereira

Effect of Site Parameters on Dynamic Impedance of Bridge Piles Subjected to Seismic Loading 694
 Muhammad Tariq A. Chaudhary

Effects of Operating Parameters of the NSV System on Field Soilcrete Characteristics in the Mekong Delta, Vietnam 704
 Hoang-Hung Tran-Nguyen, Chau Dac Truong, and Khang Thien Truong

Effects of Pore-Water Chemistry on the Behaviour of Unsaturated Clays 716
 X. Lei, H. Wong, A. Fabbri, A. Limam, and Y.M. Cheng

Influence of Microcracking of Host Rock on the Hydromechanical Responses of Underground Structures: Constitutive Modeling and Numerical Simulations 726
 T.A. Bui, H. Wong, and F. Deleruyelle

Jet Grouting Mitigating Settlement of Bridge Approaching Embankments of Tam Bang and Vam Dinh Bridges 736
 Hoang-Hung Tran-Nguyen and Chuong Hong Quach

Laboratory Study of Local Clay-Pile Friction Evolution for Large Numbers of Cycles 746
 Rawaz Dlawar Muhammed, Jean Canou, Jean-Claude Dupla, and Alain Tabbagh

Numerical Modelling of Desiccation Cracking of Clayey Soil by Using Cohesive Fracture Method 756
 Thi Dong Vo, Amade Pouya, Sahar Hemmati, and Anh Minh Tang

Pneumatic Flow Mixing Method for Beneficial Use of Dredged Soil . . . 765
 M. Kitazume

Rigid Retaining Walls Interacting with Unsaturated Soils in Axial Symmetry 775
 Thanh Vo and Adrian Russell

Sanding Onset for Offshore Depleted Using Critical Drawdown Pressure: A Case Study for Well X Cuulong Basin in Vietnam 786
 Tu An Bui, Van Hung Nguyen, Tien Trung Duong, Hai Linh Duong, Huu Truong Nguyen, and Minh Hoang Truong

Soil Stabilization by Using Alkaline-Activated Ground Bottom Ash Coupled with Red Mud 800
 My Quoc Dang, Young-sang Kim, and Tan Manh Do

Thermal Conductivity of Controlled Low Strength Material (CLSM) Made with Excavated Soil and Coal Ash 808
 Tan Manh Do, Young-sang Kim, My Quoc Dang, and Ngan Thi Tuyet Vu

Undrained Behavior of Macau Marine Clay with Various Strain Rates and Different Stress Histories 816
 Shengshen Wu, Thomas Lok, and Annan Zhou

Innovative Design and Methods (IDM)

A New Formula for the Shear Strength of Exterior RC Beam-Column Joints Using Headed Bars 829
 Minh Tung Tran, Minh Tien Nguyen, and Quoc Bao Bui

A Probabilistic Explicit Cracking Model for Steel Fibres Reinforced Concretes (SFRC) 840
 Pierre Rossi and Jean-Louis Tailhan

Achieving Robustness of Structures Is Key to Resilience 850
 Paul Smith

BATIPACK®: An Innovative and Ecologic Building Process 860
 N. Matiere and Q.H. Ung

Experimental Investigation of Bond-Dependent Coefficient of Glass Fiber Reinforced Polymer Bars 868
 Thuy Duong Tran, Manh Hung Nguyen, and Trung Hieu Nguyen

Experimental Research on Flexural Strengthening of Two-Way Reinforced Concrete Slabs Using Carbon Fiber Reinforced Polymer Sheets 878
 Manh Hung Nguyen, Thuy Duong Tran, and Trung Hieu Nguyen

Image Processing in the Characterization of Crack Propagation in Cold-Formed Steel Samples 885
 Daniel Dias-da-Costa, Cao Hung Pham, and Gregory J. Hancock

Impact of Measurement Errors in Inverse Analysis 894
 Jun Lei, Jose-Antonio Lozano-Galant, Maria Nogal, Dong Xu,
 and Jose Turmo

**Improving the Understanding of Tunnel Excavation Under Pressure
 Using a Small-Scale EPBS Model** 905
 N. Berthoz, D. Branque, and D. Subrin

**Influence of Boundary Conditions on the Behavior
 of Infilled Frames** 914
 Quoc Khanh Le Dinh and Thanh Cong Bui

**In-Plane Behavior of Seismically Damaged Clay Masonry Walls
 Repaired with External TRC** 925
 Thi-Loan Bui, Xuan-Huy Nguyen, and A. Si Larbi

Potential of Periodic Networks for Seismic Isolation of Sites 935
 Ali Bougressi, Nouredine Bourahla, and Mohamed Anis Doufene

**Quantitatively Analysing Holistic Risk and Testing the Accident
 Coping Strategies** 945
 Paul Smith

**Review of Direct Strength Method of Design for Cold-Formed Steel
 Structures with Holes with a Focus on Shear** 954
 Song Hong Pham, Cao Hung Pham, and Gregory J. Hancock

**The Need for a Holistic Approach to Address Future
 Emerging Risks** 964
 Paul Smith

**Transmissibility Based Operational Modal Analysis in Presence
 of Harmonics** 972
 Van-Dong Do, Thien-Phu Le, and Alexis Beakou

Unibridge®: A New Concept in Prefabricated Modular Bridge 981
 N. Matiere, Q.H. Ung, and P.A. Nicolaudie

Water Treatment and Environment (WTE)

**A Modified Model for the Prediction of Bioclogging in Saturated
 Porous Media** 991
 Hoang Lam Pham, Philippe Sechet, and Zhujun Huang

**Modelling of Pollutant Diffusion in Unsaturated Double-Porosity
 Medium by a Multiscale Method** 1000
 T.D. Tran Ngoc, Q. Pham Minh, H. Ly Minh, T. Tran Van,
 and Thong Nguyen

On the Use of Foam for the in Situ Remediation of Polluted Heterogeneous Soils	1009
H. Bertin, E. Del Campo Estrada, and O. Atteia	
Optimization of Decolorization and COD Removal from Textile Wastewater Using Electro Fenton Process	1017
Duc Dat Duc Nguyen, Thi Thuy Nguyen, and Tan Phong Nguyen	
Parameter Study on Remediating Cr(VI) in Water Using Activated Charcoal	1027
Alfa-Sika Mande Seyf-Laye, Tchakala Ibrahim, Djaneye-Boundjou Gbandi, and Chen Honghan	
Processes Causing Strong Acidic Groundwaters in and Around the Mekong Delta Area	1037
Quang-Khai Ha, Seunghyun Choi, and Kangjoo Kim	
Removal of Cd(II) from Aqueous Solutions Using Red Mud/Graphene Composite	1044
Xuan Linh Ha, Ngan Hanh Hoang, Thi Trang Nhung Nguyen, Thi Thuy Nguyen, Thanh Hai Nguyen, Van Thanh Dang, and Nhat Huy Nguyen	
Studies on the Photocatalytic Activity of Metal Oxide and Their Composite for Dye Degradation Application	1053
Tchakala Ibrahim, Kodom Tomkouani, M. Vedhanayagam, Alfa-Sika Mande Seyf-Laye, K.J. Sreeram, Bawa L. Moctar, and Djaneye-Boundjou Gbandi	
Treatment of Domestic Wastewater from Small Cities on Vertical Flow Constructed Wetlands (VFCWs)	1066
R. Gourdon, M. Kania, M. Gautier, B. Kim, and P. Michel	
Treatment of Slaughterhouse Wastewater by Intermittent Cycle Extended Aeration System (ICEAS)	1074
Duc Tiep Nguyen and Tan Phong Nguyen	
Urban Stormwater Management by Green Infrastructure: Design and Comparison of Three Scenarios	1084
Jean-Luc Bertrand-Krajewski and Pauline Herrero	
Case Studies (CS)	
Behavior of Prestressed Concrete Self-stabilizing Floating Fuel Storage Tanks	1097
D. Jiang, K.H. Tan, K.C.G. Ong, S. Heng, J. Dai, B.K. Lim and K.K. Ang	

Current Concerns on Durability of Concrete Used in Nuclear Power Plants and Radioactive Waste Repositories 1107
Quoc Tri Phung, Norbert Maes, and Diederik Jacques

Innovating a New Kind of Modular Reactor Power Station Design 1122
Paul Smith

Nuclear Civil Engineering Towards the Simplification and Digitalisation 1134
Nguyen-Hoang Bui, Pascal Charles, and Hervé Blicek

Soil-Structure Interaction Under Multiple Static Loads Using a Flexibility Matrix of Soil: Case Study of a Nuclear Power Plant 1142
V.-N. Nguyen, P.-L. Regazzoni, D. Pham Thi Anh, S. Erlicher, S. Reynaud, and D. Allagnat

Tunnel Muck Recycling for Road Construction – A Case Study in Vietnam 1153
Thu-Hang Tran and Minh-Long Le

Author Index. 1165

Keynote Lectures

A Review of Recycled Aggregates (RAP and RCA) as Unbound Base Course Material for Sustainable Highway Construction

Tuncer B. Edil^(✉)

University of Wisconsin-Madison, Madison, WI, USA
tbedil@wisc.edu

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

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 from 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)

Sieve sizes (mm)	Design range (percentage passing by mass)		Tolerances (percentage passing by mass)	
	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/m³ for RAP at optimum moisture contents (OMC) of 5.2 to 8.8% and 19.4 to 20.9 kN/m³ 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

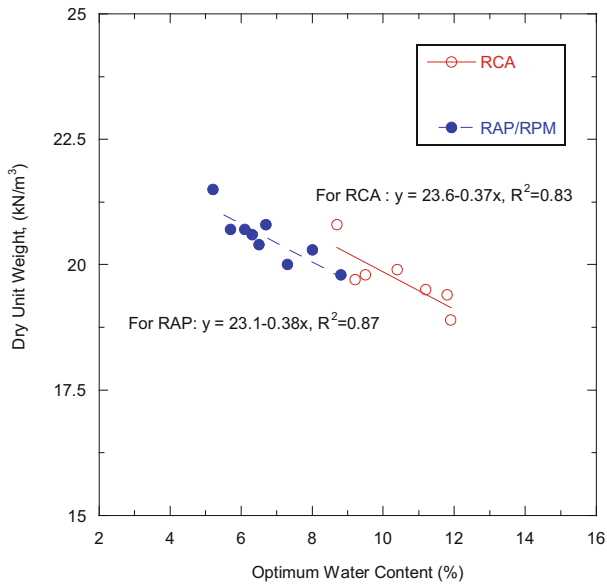


Fig. 2. Maximum dry unit weight versus optimum moisture content

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 * 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 * 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}	$_{-}2268.783 - (285.884 * \text{Fines } \%) + (628.742 * \text{AC } \%) + (201.107 * D_{60}) - (483.158 * G_s) - (58.243 * \text{Absorption } \%)$	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