The Use of Recycled Aggregates in Unbound Road Pavements

L'utilisation d'Agrégats Recyclés en Revêtements de Chaussée sans Liant

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ABSTRACT: This paper argues for the acceptability for use in unbound granular pavements of recycled concrete aggregates (RCA) and recycled clay masonry (RCM) derived from demolition. Specifications from road authorities both within and outside Australia are considered, and results of tests carried out on specimens of RCA and RCM are compared with these specifications. The tests included conventional classification tests for soils and aggregates, Los Angeles abrasion value, Micro-Deval, falling head permeability, drying shrinkage, undrained triaxial tests and repeated loading triaxial testing for resilient modulus and permanent strain rate. The influence of matric suction on resilient modulus of the granular pavement materials is presented. Both RCA and RCA blended with RCM (20% by mass maximum) were found to meet existing specifications and therefore can be incorporated in road pavements. RCA was found to be suitable for use as a base course. In the case of RCA blended with RCM, as the proportion of RCM increases, the permanent strain rate increases and resilient modulus decreases, thereby compromising use of the blends as base material. However, RCA with up to 20% RCM is suitable for use as sub-base of a road pavement.

RÉSUMÉ : Ce document plaide pour l'acceptabilité, pour les revêtement de chaussée granulaires sans liant, des agrégats de bétons recyclés (ABR) et de la maçonnerie recyclée d'argile (MRA) provenant de la démolition. Les spécifications des autorités routières d'Australie et d'ailleurs sont considérées, et des résultats d'essais effectués sur des spécimens de ABR et de MRA sont comparés à ces spécifications. Les essais comprennent des essais conventionnels de classification pour sols et agrégats (valeur d'abrasion Los Angeles, Micro-Deval , perméabilité à charge variable, séchage et rétraction, essais triaxiaux non drainé et essais triaxiaux répétés pour le module résilient et la vitesse de déformation constante. L'influence de la succion matricielle sur le module résilient des matériaux granulaires de revêtement de chaussée est présentée. l'ABR et l'ABR mélangé avec le MRA (20% maximum en masse) se sont avérés satisfaire les spécifications existantes et peuvent donc être incorporés en revêtement de chaussée. l'ABR s'est avéré approprié pour l'usage comme couche de base. Dans le cas de l'ABR mélangé avec le MRA, à mesure que la proportion de MRA augmente, le taux de déformation permanente augmente et le module résilient diminue, compromettant de ce fait l'utilisation des mélanges en tant que matériau de couche de base. Cependant, l'ABR avec jusqu'à 20% RCM convient pour l'usage comme sous-couche de chaussée routière.

KEYWORDS: recycled aggregate, C&D waste, resilient modulus, permanent strain, matric suction, prediction

1 INTRODUCTION

Recycling of construction and demolition wastes can produce acceptable aggregates for civil engineering applications such as unbound granular pavements. Australian practice is well behind countries such as Japan, the United Kingdom, France, Germany and the Netherlands, but the recycling aggregate industry, which has emerged over the last decade, is growing. Quarry industries seem to feel challenged by recycling but should realise that even in Europe with its long history of recycling, recycled aggregate supply is unlikely to exceed 10 to 15% of total demand (Meininger and Stokowski 2011). Much of the research in Australia to date has focussed on Recycled Concrete Aggregates (RCA), Recycled Clay Masonry (RCM), recycled glass and waste rock. Much can be learned from the European experience, but this experience cannot be simply adopted as it is based on the range of climates, pavement construction practices and geology throughout Europe. Furthermore, the great majority of pavements in Australia are thinly surfaced, resulting in higher stresses being applied to the aggregates by passes of traffic.

Much of the work to date has been limited to the laboratory (e.g. Nataatmadja and Tan 2001, Aatheesan et al. 2009, 2010, Arulrajah et al. 2011, 2012a, 2012b and 2012c, Gabr et al. 2012, Gabr and Cameron 2012a, Azam and Cameron 2012, Azam et al. 2012, Jitsangiam et al. 2009, Leek and Siripun 2010). Gabr 2012 developed an empirical model for predicting permanent strain from testing of South Australian RCA, which he incorporated into Finite Element Analysis (FEA) to predict pavement life, similar to the approach of Huvstig et al. 2008. However the validation of this approach has not been made. Nevertheless a few field trials of roads constructed with C&D waste have been conducted (Ecocycle 1997 and Bowman & Associates 2009a and 2009b). The combination of laboratory and field data with FEA has much potential to improve pavement design generally.

This paper summarizes the work undertaken at the University of South Australia (UniSA) to evaluate aggregate produced from two local producers of recycled C&D waste, which consisted of either crushed concrete or RCA blended with fired clay masonry (RCM). All products were nominally 20 mm sized maximum aggregate. Variations in moulding moisture levels have been investigated, leading to some interesting findings relating soil suction to resilient modulus.

The South Australian Department for Transport, Energy and Infrastructure (DPTI, formerly DTEI) stipulates a range of material properties (DPTI, 2011), but includes minimum resilient modulus and maximum rate of permanent strain for Class 1 bases, based on a simplified, single stress stage Repeated Load Triaxial Test (RLTT). These performance based specifications are unique in Australia if not worldwide. In parts of Scandinavia, specifications require back-calculated resilient modulus from a falling weight deflectometer or Young's modulus from a plate bearing test (Gabr and Cameron 2011).

2 MATERIALS AND RANGE OF TESTS

Two RCA basecourse products, A and B, were tested, along with a comparable product (A20) of RCA with 20% by mass of RCM. Further materials were made at UniSA by blending product B with RCM to 10%, 20% and 30% (B10, B20 and B30). DPTI permit up to 20% by mass in RCA of "foreign material" consisting of clay brick tile, crushed rock and masonry for base course and subbase applications. Finally a virgin quartzite aggregate (Q) was evaluated, which is commonly used in Adelaide for construction of Class 1 bases.

The particle size distributions of the materials fell within DPTI specifications for Class 1 base. All the materials were well-graded gravel and sand mixtures with silty gravel; GW-GM according to the Unified Soil Classification System (USCS). Material A lay close to the coarse specification limit, while Material B20 crossed between the limits and had a fairly high proportion of fine sand-sized particles. The fines content of the two RCA products, A and B were just 5% and 7% respectively, while the quartzite base material (Q) had 11%.

Tests were conducted in line with the requirements of current Australian specifications. These included plasticity of fines, aggregate strength tests, Los Angeles abrasion, CBR tests on 4 day soaked samples and RLTT to the DTEI 2008 protocol. In addition, falling head permeability tests and shrinkage tests were conducted. Some concern has been expressed relating to the propensity of RCA to exhibit some cementation upon wetting and compaction. This self-cementation of RCA materials can produce increase of strength with time, but also the possibility of reduced permeability (AASHTO 2002) and shrinkage. Therefore shrinkage was investigated.

3 MATERIAL PREPARATION

All materials were compacted to a target Dry Density Ratio (DDR) of 98% of maximum dry density under Modified Proctor compactive effort. Static compaction, which is advocated by DTEI for unbound granular material, was used for compaction, largely because of the consistency of preparation. Moulding moisture variations are indicated for particular tests as follows. In South Australia, materials are commonly compacted at 80% of OMC and are allowed to dry back to 60% of OMC.

3.1 Falling Head Permeability

For the falling head permeability tests, the moulding moisture contents were 100 and 80% of OMC. Blended materials were tested; A20, B10, B20 and B30.

3.2 Drying Shrinkage

Samples were 200mm high by 100 mm diameter. Triplicate samples of materials A and B, and duplicate samples of A20 and B20, were prepared OMC. The target moisture content was reduced to 90% OMC if the material was found to be too fragile upon extrusion (e.g. samples B & B20). After compaction, the samples were extruded from the mould and sealed in plastic bags to cure for 7 days; the samples were then stored in a curing room (temperature 23±2°C and relative humidity 55±5%).

3.3 Undrained Triaxial and RLTT Testing

Duplicate samples were prepared.The resilient modulus and permanent deformation behaviour of RCA mixtures were investigated at different levels of moulding moisture contents, as was the undrained shear strength. Generally just one day of curing occurred before de-moulding and testing.

4 RLTT TEST METHODS

In Australia, there are two standard approaches to Repeated Load Triaxial Testing (RLTT); multi-stage stress testing and single-stage stress testing, e.g. the DTEI approach. DTEI 2008 specified application of a constant confining stress of 196 kPa and a vertical deviator stress of 460 kPa, pulsed over 50,000 loading cycles. AUSTROADS established a multi-stage stress RLTT under drained conditions to determine the permanent deformation and resilient modulus properties. Both these test protocols ahave been applied. In the RLTT program, deformations were measured with two pairs of inductance coils ("Emu" coils) mounted on the sample (Gabr et al. 2012).

5 INDEX VALUES AND OTHER PROPERTIES

The plasticity of fines of the various materials is indicated in table 1. The DPTI (2011) specifications call for a maximum Liquid Limit of 25% for Class 1 and 28% Class 2, and so A20 falls into Class 2, while all other materials would be acceptable for Class 1 applications.

Los Angeles Abrasion Value (LAA) and Micro Deval help to evaluate the abrasion resistance/toughness under traffic loading. The LAA values of the South Australian RCA examples ranged between 37% and 39%, which failed to meet the maximum of 30% proposed by DPTI. The Ile de France specifications (2003) for LAA allowed 35% for roads with the greatest traffic (GR4), increasing to 40% for GR3 and 45% for GR2. The values for RCM blends were in the range of 40 to 45%. The French Micro Deval limit of 30% for GR4 was met by both RCA products as the Micro-Deval values were 30% and 28% for products A and B, respectively. There is however a further requirement that the sum of LAA and Micro Deval must not exceed 55 for GR4 and 65 for GR3. Product B was on the limit for GR3, while product A, exceeded it (69). GR3 corresponds to a road with daily annual traffic of 85.

Average shrinkage curves with time are provided in Figure 1 for the four materials that were tested. Interestingly, shrinkage strains were similar for the RCA products, as they were for the blends (20% RCM); however, the addition of crushed masonry resulted in an appreciable drop in shrinkage. In the case of product B, a reduction of almost 60% was observed.

The permeability of blended recycled material when prepared at OMC was approximately 2 x 10-8 m/sec for blends based on RCA product B, but it was observed that A20 was ten times more permeable. Compaction to the same density but at just 80% OMC increased the permeability of all materials generally by a factor of approximately three.

Table 1. Selected properties of the recycled aggregate blends

Material	*A*	*A20*	*B*	*B10*	*B20*	*B30*
Liquid Limit (%)	26	27	23	24	23	23
Plastic Index (%)	2	2	1	3	3	2
LAA (%)	39	42	37	42	43	45
Micro Deval (%)	30	-	28	-	-	-

All materials met the specification of a minimum CBR of 80%, despite masonry content reducing the CBR significantly. Similarly the requirement of a maximum unconfined compression strength of 1 MPa after curing was met.

A study was undertaken of the matric suction–moisture content relationship, or soil water characteristic curve (SWCC) of the materials to enable estimation of matric suctions of RLTT samples from measured moisture contents. Initial matric suction was determined by the hanging column method for low suctions and the contact filter paper method (refer Azam and Cameron

2012 for details of the filter paper method) for suctions greater than 20 kPa. The SWCC plots of gravimetric moisture content against matric suction are provided in Figure 2 for the 2 blends with 20% RCM. Air entry values (u_{ae}) were the same for these two samples but the residual suction (u_r) differed (15 and 30 kPa). The air entry values were within the range reported for RCA by Rahardjo et al. 2010.

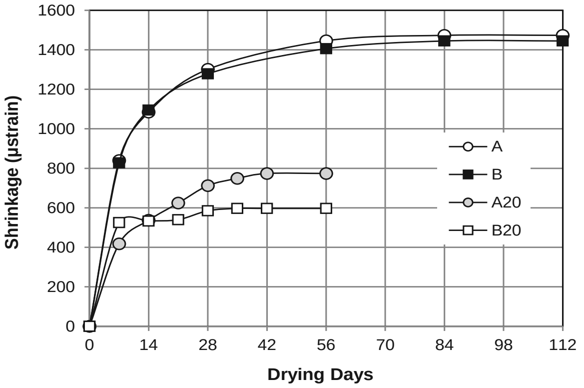

Figure 1. Shrinkage curves for the recycled materials

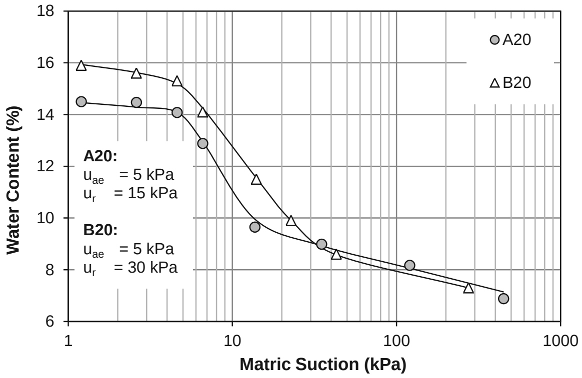

Figure 2. SWCC for materials A20 and B20

6 STATIC AND REPEATED LOADING RESULTS

Undrained shear strength data are indicated in Table 2 for material prepared at a target of relative moisture content of 80% OMC. The last row contains nominal shear strength values based on the shear strength parameters and a normal stress of 100 kPa. The nominal shear strength decreased generally with masonry content for the B samples, but the A samples seemed unaffected.

Shear strength increased with matric suction or decrease of relative moisture content. Between target moisture contents of 90 and 60% OMC, on average the nominal shear strength of the recycled materials increased by 13%, while the quartzite strength was improved by 9%.

The resilient modulus of the RCA products (materials A and B) varied between 500 and 950 MPa, clearly surpassing the DPTI 2011 requirement of 300 MPa. Generally resilient modulus decreased with moisture content although product A had a fairly constant modulus of approximately 600 MPa. The materials blended with crushed masonry performed well also. Even material B30 had a minimum modulus greater than 400 MPa. A relationship between initial matric suction and resilient modulus from the single stress stage of the DTEI test protocol, was developed and is illustrated in Figure 3. A simple power model fit the data for all materials adequately. The power function is consistent with the findings of Gupta et al. 2007. Further work is underway on predicting the resilient modulius from multi-stage triaxial stress testing (stress dependent model).

The DPTI specification for Class 1 material requires a minimum rate of permanent strain over the last 30,000 load cycles of $-1x10^{-8}$% per cycle. RCA performance was generally acceptable for Class 1 (refer Figure 4) although the blends with RCM were more appropriate for Class 2 applications. The quartzite material, Q, failed to make the DPTI Class 1 limit when prepared at 80% OMC or wetter.

Table 2. Undrained shear strength (80% OMC)

Material	*A*	*A20*	*B*	*B10*	*B20*	*B30*
Cohesion (kPa)	163	134	41	9	46	0
Friction angle (°)	48	55	60	53	44	53
Nom. strength (kPa)	277	274	214	142	143	133

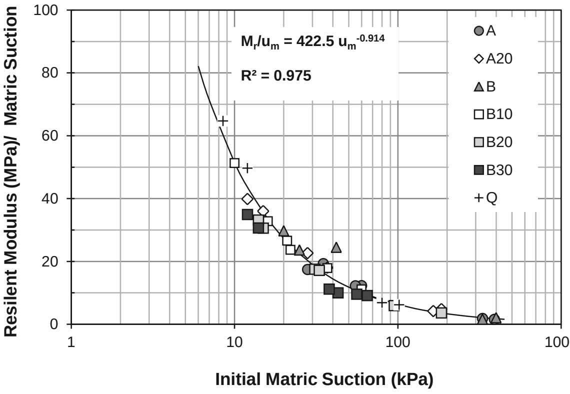

Figure 3. Resilient modulus as a function of initial matric suction

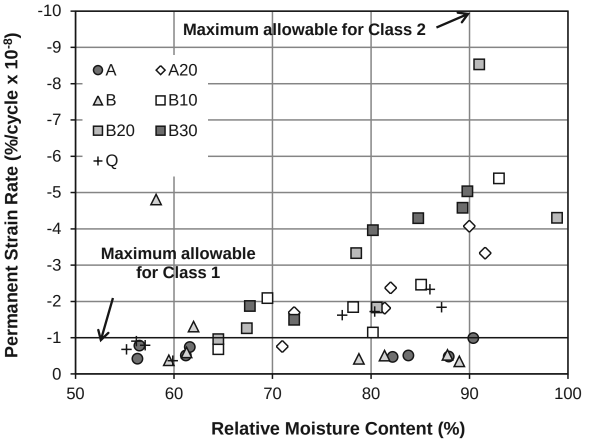

Figure 4. Permanent strain rate as a function of initial moisture content

7 PERMANENT STRAIN MODELLING

Gabr and Cameron 2012b proposed a predictive model for permanent strain from multi stage RLLT data on RCA materials A and B, and virgin aggregate, Q. Permanent strain increased with increase in either mean stress ratio (current stress to failure stress) or moisture content. The proposed model required mean normal stress, shear stress ratio, number of cycles, moulding moisture content, dry density and weighted plasticity index.

The model was found to fit very well the permanent strain for each material. An example is given in Figure 5. It was acknowledged by Gabr 2012 that the model attempeted to predict permanent strain over all material shakedown ranges, and so required further validation before confident application to prediction of rutting in pavements.Nonethless Gabr used finite element analysis of the impact of a single wheel load on a thin unsealed pavement, 320 mm thick, over a sand subgrade, to generate stresses for application of the permanent strain model and therefore predict pavement life. The life of a pavement constructed with material B was predicetd to improve 100 fold when the moulding moisture content was 60%, not 90% OMC.

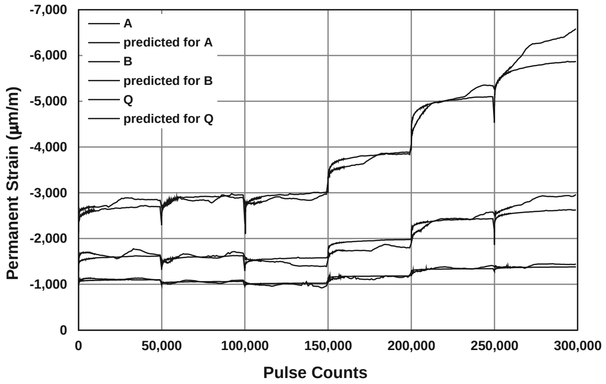

Figure 5. Permanent strain modeling of the materials at 80% OMC

8 CONCLUSION

From the evidence presented from RLTT data, the RCA products could be used as Class 1 base, while the blended products are more suited to Class 2 applications, or subbase. Other specification systems dependent on basic engineering properties, such as Los Angeles Abrasion and Liquid Limit may restrict the application of recycled materials to lesser applications. This paper has highlighted current research on recycled aggregates in South Australia, including the development of models for predicting both resliient modulus and permanent strain. Improvements to the models are being sought; for example matric suction should replace moisture content in the permanent strain model.

9 ACKNOWLEDGEMENTS

This research has been supported by industry partners ResourceCo and Adelaide Resource Recovery, as well as ZeroWaste and the Australian Road Research Board.

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