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Comparison of Specifications for Recycled Concrete Aggregate for Pavement Construction*

ABSTRACT: This paper reviews existing specifications, specifically for the application of crushed concrete or recycled concrete aggregate (RCA) as pavement material for unbound subbases and basecourses. While the use of recycled crushed concrete is not new internationally, its application in Australia is unique as it is being commonly used as a granular basecourse/subbase supporting thin bituminous seals (asphalt or spray seal/chip seal). Commonality of specifications is explored and differences that exist are questioned. In light of practice outside of Australia, limitations by Australian authorities placed on recycled material inclusions other than crushed concrete are raised. In this paper, two South Australian-based RCA products, which were designed for use as pavement bases, are compared with current engineering specifications. The RCA products performed well in terms of resilient modulus and permanent deformation. However, properties such as abrasion resistance and wet/dry strength may restrict the application of the material if current specifications are justifiable.

KEYWORDS: recycled concrete, road base, resilient modulus, specification

Introduction

In the last several decades, the supply of natural materials for aggregates available for construction has been declining. There have been increases in transport costs to haul aggregates to job sites, leading to a substantial increase in the cost of pavement construction and this fact has led to recycling [1]. Governments and many private organizations have looked to using recycled materials to conserve natural resources, preserve the environment, and decrease construction costs and stockpiles of waste.

There has been a considerable history of recycling construction waste in Europe. For example, from 1945 to 2000, about 600×10^6 m^3 of masonry debris was used in the rebuilding of Germany after World War II [2]. More recently in Finland in 1998, approximately 350 000 tonnes of crushed concrete was used in the construction of bases and subbases for roads.

The European Alternative Materials (ALT-MAT) project was established in Europe in 1998 to encourage the use of alternative materials in road construction and develop methods of evaluation for these materials. Data were obtained from nine research organisations in seven countries to close the gap between laboratory evaluation of materials and field experience. It was confirmed that crushed concrete was a suitable alternative material for unbound road base [3].

In the United States, over 130×10^6 tonnes of construction and demolition (C&D) waste is produced each year [4]. In Australia, more than 14×10^6 tonnes of C&D waste was generated in 2004/2005 [4]. Only about 50 % of this C&D waste was recycled. Table 1 provides information regarding C&D waste for the five mainland states. It can be seen in Table 1 that South Australia (SA), the home state of the senior authors, was the most successful state in recycling. Currently, in SA, there are two Adelaide based companies (D A C, R A, P W M), ResourceCo and Adelaide Resource Recovery, producing over 500 000 tonnes of aggregate each year, mostly from building demolition waste sourced from the Adelaide region.

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The recycling sequence for recovering aggregate from concrete building waste consists of removing, stockpiling, and grading aggregate products. First, the concrete demolition elements are delivered to the central processing plant. Then, the concrete is crushed into pieces with a pavement breaker or by jack hammering, followed by removal of the steel reinforcement from the concrete. These pieces are then crushed further, sized, screened, and graded as indicated in Fig. 1. The recycled concrete aggregate from the crushed concrete (referred to RCA hereafter) is then stockpiled and cleaned as far as practical from any foreign materials such as glass, wood, or other impurities according to specification requirements [1,6]. RCA products may be allowed to have small inclusions of other materials, such as crushed clay masonry or glass.

It is essential to manage the selection of waste for recycling to ensure that the waste materials are clean from significant contamination and from chemical substances, as evidenced by alkali–silica reaction and rust stains on concrete [7].

Specifications do exist for the applications of RCA and other C&D waste. However, these specifications have been based largely on existing specifications for virgin aggregate, with varying levels of concessions, in part depending upon the geological nature of the aggregates in the experience of the road authority [4,8]. With more experience with RCA, it is expected that specifications will be developed further.

Current Specifications

It is difficult to directly compare specifications as applicable classes of pavement; therefore, traffic over the design life may differ between road authorities. There are now in existence many national and international standard specifications for recycled concrete materials and in the following sections these specifications are briefly reviewed and, where feasible, compared.

Australian Specifications

The Australian specifications include those from VicRoads—Victoria, the Department for Transport, Energy and Infrastructure (DTEI)—South Australia, Institute of Public Works Engineering Australia (IPWEA)—New South Wales (NSW), Roads and Traffic Authority (RTA)—NSW, and Main Roads Western Australia (MRWA). The specifications for RCA for road construction for each state will be discussed in the following sections.

Victoria—In 1993, VicRoads published standard specifications for using RCA as subbase and base layer based on traffic design. An update to the specifications was published in March 2009. The specification divided RCA applications into three categories: light duty base, and heavy duty upper and lower subbase [9]. Heavy duty traffic is greater than 5×10^6 equivalent standard axle (ESA), while the light duty traffic is less than 5×10^5 ESA. Table 2 presents the summary of the specification for 20 mm nominal size RCA material. However, higher percentages of crushed brick (not indicated in Table 2) are permitted in subbases as part of a "registered crushed concrete mix design." Maximum crushed brick contents of 15 % and 50 % are possible for class 3 and class 4 subbases, respectively.

New South Wales—Many road authorities and local government bodies have developed their own specification and have successfully used RCA in local roads in NSW. Authorities such as RTA, Southern Sydney Region of Councils, and IPWEA have been involved in using RCA.

TABLE 1—*The amounts of C&D waste generated around Australia in 2004/2005 [4].*

	Inert Landfill Levy (Metropolitan)		Construction and Demolition Waste 2004/2005		
State	Current	In 2005	Waste Diverted for Recovery, Million Tonnes	Total Waste Generated, Million Tonnes	% Diverted
South Australia	$24.20/tonne	$10.50/tonne	1.103	1.595	69.2
Victoria	$15.00/tonne	$11.00/tonne	2.423	4.817	50.3
New South Wales	$46.70/tonne	$21.20/tonne	3.139	5.118	61.3
Queensland	0	0	0.128	1.409	9.1
Western Australia	\$3.00/m^3	\$1.00/m^3	0.452	2.078	21.8

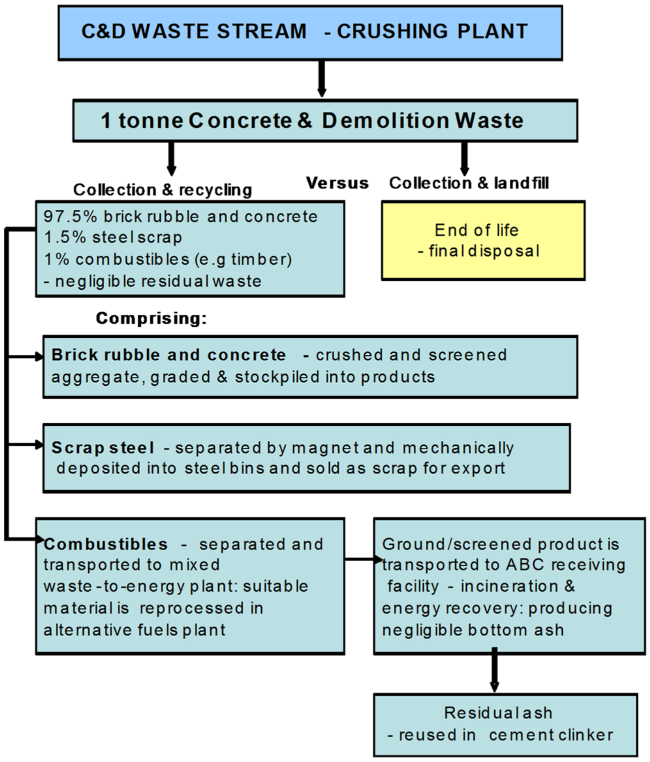

FIG. 1—*Recycling process at a crushing plant [5]—ABC is Adelaide Brighton Cement.*

Specification RTA 3051 was introduced by RTA in 1991 and was recently updated [10]. It covers construction of unbound and modified base and subbase materials for surfaced road pavements. Table 3 summarizes some properties required of 20 mm nominal size unbound materials for base and subbase construction. The specification is based on particle size distribution and other properties such as plasticity and strength for dense graded materials. The percentage of "foreign" material allowed in a basecourse depends upon the design traffic, which is defined in Table 4.

TABLE 2—*Summary of VicRoads specification for 20mm RCA [9].*

Particle size distribution	Light duty base class 2	Heavy duty upper subbase class 3	Heavy duty lower subbase class 4
Sieve size, mm	Grading limits, %	Grading limits, %	Grading limits, %
26.5	100	100	100
19	95–100	95–100	. . .
13.2	78–92	75–95	. . .
9.5	63–83	60–90	. . .
4.75	44–64	42–76	42–76
2.36	30–48	28–60	. . .
0.425	13–21	10–28	10–28
0.075	5–9	2–10	2–14
Atterberg and strength and LAA limits	Base (class 2)	Upper subbase (class 3)	Lower subbase (class 4)
Liquid limit, % (max)	35	35	40
Plasticity index, % (max)	6	10	20
CBR 4 days soaked, % (min)	100	80	20
Los Angeles Abrasion, % (max)	35	40	45
Foreign material limits			
High density materials such as metal, glass and brick, % (max)	2	3	5
Low density materials such as plastic, rubber, and Plaster, % (max)	0.5	1	3
Wood and other vegetable matter, % (max)	0.1	0.2	0.5

TABLE 3—*Summary of RTA specification for 20 mm unbound materials [10].*

Particle size distribution		DGB[a]		DGS[b]
Sieve size, mm		Grading limits, %		Grading limits, %
26.5		100		100
19		95–100		95–100
13.2		78–92		70–90
9.5		63–83		58–80
4.75		44–64		43–65
2.36		35–49		30–55
0.425		14–23		10–30
0.075		7–14		4–17
0.0135		2–7		2–10
Atterberg limit		DGB		DGS
Liquid limit, % (max)				
For natural or manufactured materials for all traffic categories		23		23
For recycled materials		27		27
Plasticity index, % (max)				
For traffic category A		...		10
For traffic category B and C		2–6		10
For traffic category D		8		12
Strength limits		DGB		DGS
MDCS[c] MPa (min)		...		1.0
For traffic category B and C and D		1.7		...
UCS[d]—accelerated 7 days curing at 65°, MPa (max)		1.0		...
Wet strength, kN (min)				
For base materials—traffic category B and C and D		70		...
For subbase materials—traffic category A and B		...		70
Wet/dry variation, % (max) for all traffic		35		35
California bearing ratio (CBR) 4 days soaked, % (min) for C and D		...		40
Acid soluble sulfate content, % (max)		0.6		0.6
Foreign material limits for		Base		Subbase
Traffic category	A	B	C and D	All traffic
Metal, glass and ceramics, % (max)	0	3	5	5
Plaster, clay lumps and other friable material, % (max)	0	0.2	0.5	1.0
Rubber, plastic, tar, paper, cloth, paint, wood and other vegetable matter, % (max)	0	0.1	0.2	0.2

[a]Dense graded base.
[b]Dense graded subbase.
[c]Maximum dry compressive strength.
[d]Unconfined compressive strength.

IPWEA released a specification for RCA in 2001 for base and subbase material in urban roads with light to medium traffic. IPWEA classified the materials into two types, R1 with a medium traffic loading of greater than 10^6 ESA and R2 for light traffic of less than 10^6 ESA, for either base or subbase according to the traffic loading [11]. Class R1 material is similar to the dense graded base characteristics in RTA 3051 specification, while class R2 is similar to the dense graded subbase characteristics in RTA 3051.

South Australia—DTEI, South Australia, released the first revision of the specification in 1997 as an adjunct to its general specification for supply and delivery of pavement materials. This was revised in 2001 with recycled materials classified into three classes of quality and the option of manufacture to either a specific set of intrinsic parameters or parameters associated with performance and manufacturing capability. These specifications formed part of the Master Road Specification for construction of road infrastructure [12]. Table 5 provides a summary of all DTEI specifications for 20 mm nominal size RCA material. The strength limits presented in Table 5 are based on triaxial shear testing properties rather than the California bearing ratio (CBR). Stiffness requirements are based on repeated loading triaxial testing (RLTT) to a DTEI protocol.

TABLE 4—*Traffic categories based on design equivalent standard axles loads (DESAs) [10].*

Traffic Category	Traffic Classification	Design Traffic for 20 Year Design Life (DESAs)
A	Very heavy	$N \geq 10^7$
B	Heavy	$10^7 > N \geq 4 \times 10^6$
C	Medium	$4 \times 10^6 > N > 10^6$
D	Light	$N \geq 10^6$

Repeated Load Triaxial Test

DTEI, South Australia, has adopted a single-stage, constant stress state test; a constant confining pressure of 196 kPa is applied and the deviator stress pulses between 25 and 460 kPa over 50 000 cycles. A "characteristic value" of resilient modulus is determined and the rate of permanent deformation over the last 30 000 cycles is recorded [13].

More sophisticated RLTT protocols are used around the world to determine the permanent deformation and resilient modulus properties of the granular material, e.g., AASHTO T307 [14], AUSTROADS [15], and Transit New Zealand TNZ T/15 [16]. However, DTEI adopted the simpler RLTT protocol to provide an indication of material performance under a high stress state, applicable to bases under a thinly surfaced pavement.

Western Australia—In 2006, MRWA completed a revision of Specification 501—Pavements for recycled concrete road base materials. The specification was based on experience gained from construction of a field trial and subsequent performance of the pavement case study conducted during the construction of Gilmore Road in 2004 [4,8]. The latest revision to the specifications was in April 2009 [17] and the specification was eased with respect to the strength of base material and the permissible percentage of high density foreign materials. Maximum design traffic was limited to 5×10^6 ESA over a 20 year design life. A summary of the specifications are given in Table 6.

TABLE 5—*Summary of DTEI Specification for 20 mm RCA materials [12].*

Particle size distribution	Class 1	Class 2	Class 3
Sieve size, mm	Grading limits, %	Grading limits, %	Grading limits, %
26.5	100	100	100
19	95–100	90–100	90–100
13.2	77–93	74–96	...
9.5	63–83	61–85	...
4.75	44–64	42–66	40–65
2.36	29–49	28–50	...
0.425	13–23	11–27	...
0.075	5–11	4–14	5–15
Atterberg limits and LAA limits	Class 1	Class 2	Class 3
Liquid limit, % (max)	25	28	35
Plasticity index, % (max)	1–6	1–8	15
Linear shrinkage, % (max)	3	4	8
Los Angeles Abrasion, % (max)	30	45	45
Stiffness and strength limits	Class 1	Class 2	Class 3
Resilient modulus, MPa (min)[a]	300	250	NA
Permanent deformation rate/load cycle (max)[a]	10^{-8}	10^{-7}	NA
Cohesion (c), kPa (max)[b]	150	250	NA
Friction angle (φ), ° (min)[b]	45	40	NA
Foreign material limits	Class 1	Class 2	Class 3
Clay brick tile, crushed rock, masonry, % (max)	20	20	20
Plaster, clay lumps, and other friable material, % (max)	1.0	1.0	1.0
Rubber, plastic, tar, paper, cloth, wood and other vegetable matter exclude bitumen, % (max)	0.5	0.5	0.5
Bitumen, % (max)	1.0	1.0	1.0

[a] Single stage, stress state testing according to TSA-MAT-TP 183, DTEI.
[b] Undrained triaxial compression testing according to TSA-MAT-TP 184, DTEI.

European Specifications

Several European countries have accepted RCA for use in the construction of base and subbase, e.g., Finland, Sweden, Denmark, The Netherlands, and Portugal. Most of the specifications have been based on experience gained from construction of field trials and case studies conducted in a number of European countries [2]. The following gives a brief review of some of the specifications around Europe. The information is limited by the access to English translations of relevant documentation. Furthermore, freeze–thaw related specifications of interest in the northern hemisphere have not been reproduced in this paper.

The Netherlands—Molenaar [18] referred to a summary of specification in his lectures at Delft University for using RCA as basecourse in The Netherlands. The specification was based on the gradation and the purity of the material. Table 7 presents a summary of some key properties of 20 mm RCA according to the Dutch specifications. There is little difference in sieve sizes and passing percentages to that required by Australian specifications.

Finland—Finland has used RCA since 1994 under the tradename Betoroc crush. Betoroc crush was classified into four grades based on the raw materials and technical properties for base and subbase layers. The specific applications of the different grades were not made clear. Either a plate load test or falling weight deflectometer was used to determine "the design bearing capacity" of RCA, which is presented in terms of stiffness [19]. Table 8 presents key properties of the RCA materials.

Portugal—In 2006, the National Portuguese Laboratory for Civil Engineering (LNEC) developed specifications for using RCA in base and subbase pavement layers. The specification is based on the requirements that are covered in the European Standards EN 13242 [20]and 13285 [21]. Recycled products are classed into either B or C according to the constituents of the product (refer Table 9 which is based partly on EN 933-11 [22]). For instance, class B may be comprised of 85 % crushed concrete, 10 % clay masonry, and 5 % recycled asphalt.

Thereafter, the product specification is designed to fit the end use, i.e., traffic, as defined by Daily Average Traffic (DAT) (refer to Table 10). The RCA materials are categorized into AGER1, 2, and 3.

TABLE 6—*Summary of MRWA specification for RCA materials (after [8,17]).*

Particle size distribution	Base	Subbase
Sieve size, mm	Grading limits, %	Grading limits, %
37.5	...	100
26.5	100	...
19	95–100	71–100
9.5	59–80	...
4.75	41–60	36–65
2.36	29–45	...
1.18	20–35	...
0.60	13–27	...
0.425	10–23	...
0.30	8–20	...
0.15	5–14	...
0.075	3–11	2–14
Atterberg and strength and LAA limits	Base	Subbase
Liquid limit, % (max)	35	45
Linear shrinkage, % (max)	3	4
CBR 4 days soaked, % (min)	100	50
Los Angeles Abrasion, % (max)	40	45
UCS—accelerated 7 days curing at 65°, MPa (max)	0–1.0	1.0
MDCS, MPa (min)	0.8	...
Foreign material limits	Base	Subbase
High density materials such as metal, glass, and brick, % (max)	10	15
Low density materials such as plastic, rubber, and plaster, % (max)	2	3
Wood and other vegetable matter, % (max)	0.5	1

TABLE 7—*Summary of Dutch specification for 20 mm RCA materials (after [18]).*

Particle size distribution	Base (0–20)
Sieve size	Retained, %
C 31.5	0
C 22.4	0–10
C 16	. . .
C 8	15–45
C 4	. . .
2 mm	45–70
63 μm	92–100
CBR after preparing, % (min)	50
Crushing factor	0.65
Foreign material limits	
Crushed concrete content, % (min)	80
Asphalt, % (max)	5
Other broken crushed stone, dry density > 2.1 tonnes/cubic meter, % (max)	10
Other broken crushed stone, dry density > 1.6 tonnes/cubic meter such as light concrete, glass, slag, etc., % (max)	10
Organic materials such as wood, rope, paper, etc., % (max)	0.1
Gypsum, metals and plastics, % max	1.0

AGER3 is for relatively heavy traffic (DAT = 300) and for this category only class B material is deemed satisfactory. Accordingly, abrasion resistance requirements can be more stringent.

Sweden—The RCA materials were seen to be classified into four classes, 1, 2, 3, and 4, according to their material properties [24]. Class 1 or class 2 can be used as either base or subbase under light traffic loading, under pedestrian and bicycle lanes. However, class 3 can be used as capping layers and class 4 as fill material. Interestingly, the quality of each class was based on the properties of the concrete prior to being crushed; compressive strength, F'_c, according to EN 12390-3 [25], and abrasion from LAA or Micro-Deval test to EN 1097-1 [26]. The minimum requirements of F'_c for class 1 and class 2 were 30 and 20 MPa, respectively. Table 11 provides a summary of some key properties of RCA materials for class 1 and class 2. It should be noted that the base rock in Sweden is often granite [3].

Denmark—In 2002, the Danish Road Institute established national specifications for using RCA as a road base. Three classes were created, A, B, and C (refer Table 12), which were based on the backcalculated modulus, *E*, the abrasion resistance determined by Los Angeles Abrasion testing, and the purity of the material. Class A and class B can be used as base in all types of roads; however, class C has limited

TABLE 8—*Summary of Finland specification for RCA materials (after[19]).*

Property	I	II	III	IV	In general
Grain size, mm	0–50	0–50	0–50	Varies	. . .
Optimum moisture content, %	8–10	8–12	. . .	. . .	8–12
Maximum dry density, kN/m^3	18–20	17.5–20.5	. . .	. . .	. . .
Specific gravity	. . .	. . .	. . .	. . .	2.55–2.65
UCS at 7 days, MPa	1.2–1.3	0.3–1.1	. . .	. . .	. . .
UCS at 28 days, MPa	2.0–2.1	0.6–1.3	. . .	. . .	. . .
CBR	. . .	. . .	. . .	. . .	90–140
Design E-modulus, MPa	700	500	280	200	. . .
Los Angeles Abrasion, %	23	28	. . .	. . .	. . .
Friction angle (φ), °	. . .	. . .	. . .	. . .	40
Permeability, m/s	$(1–7) \times 10^{-5}$	. . .	. . .	. . .	. . .
*p*H	12.7–12.9	. . .	. . .	. . .	≥ 11
Capillarity, m	0.25	0.2	. . .	. . .	. . .
Foreign material limits					
Brick content, % (max)	0	10	10	30	. . .
Other materials such as wood, plastics, etc., % (max)	0.5	1.0	1.0	1	. . .

TABLE 9—*Classification of RCA in accordance with the nature of the constituents of coarse fraction (after [23]).*

Class	Constituents According to EN 13242				
	R_C [a] + R_U [b] + R_G [c]	R_B [d]	R_A [e]	FL_S [f] + FL_{NS} [g]	X [h]
B	$\geq 90\,\%$	$\leq 10\,\%$	$\leq 5\,\%$	$\leq 1\,\%$	$\leq 0.2\,\%$
C	$\geq 50\,\%$	$\leq 50\,\%$	$\leq 30\,\%$	$\leq 1\,\%$	$\leq 0.2\,\%$

[a]Concrete products, concrete, and mortar.
[b]Unbound aggregates, natural stone, aggregates treated with hydraulic binders, and non-aerated floating.
[c]Glass.
[d]Masonry units of clay materials (brick, tiles, etc.), masonry units of calcium silicates.
[e]Bituminous materials.
[f]Floating stone material[g] Stony material does not float
[h]Undesirable materials: cohesive materials (e.g., clay soils), plastics, rubber, and metals (ferrous and non ferrous).

use. To fulfill the requirements of the particle size distribution for all classes as shown in Fig. 2, the grading limits can be determined as follows: the particle size distribution for class A and class B should intersect two of the dashed lines and have a maximum of 5 % and 7 %, respectively, passing through a 0.063 mm sieve. However, class C should intersect three dashed lines and can have 9 % passing the 0.063 mm sieve [27]. For nominal 20 mm basecourse material, the specifications are similar to that required by the Australian road authorities.

France—Ile de France [28] completed the first revision of the technical guide for using RCA in 2002 under the direction of MA DESTOMBES Regional Laboratory of the West of Paris. Ile de France has produced 3×10^6 tonnes of recycled materials each year. Ile de France categorized the recycled materials into five classes according to the particle size and the abrasion resistance as indicated in Table 13. GR0 and GR1 are not suitable for road bases. GR2, GR3, and GR4 can be used as base material, depending on the traffic classes, with GR4 able to take the greatest traffic (DAT of 150). Treatment with hydraulic binder may increase allowable traffic levels for GR3 and GR4 as shown in Table 13.

Comparison of Specifications

Road authorities have specified the application of various classes of RCA to the construction of roads for various levels of traffic. As far as practical, specifications for similar applications have been compared in the following sections. It should be noted, however, that unlike the European applications, Australian applications are usually for thin surfacing and therefore relatively high stresses. Some values pertinent to well-compacted South Australian RCA basecourse product (class 1, 20 mm) from supplier 1 and supplier 2 are given in this discussion. The RCA products had insignificant volume of inclusions.

Particle Size Distributions

Figures 3 and 4 present the average target particle size distributions of all the specifications around Australia for 20 mm RCA for base and subbase materials, respectively. The target grading specifications from The Netherlands and France for basecourse are provided in Fig. 3. Figure 5 presents the particle size distributions of the two Adelaide-based products for 20 mm RCA for base.

TABLE 10—*Summary of some properties of RCA materials (after [23]).*

Category	AGER1		AGER2		AGER3
Class	B	C	B	C	B
Description	0/31.5	0/31.5	0/31.5	0/31.5	0/31.5
Los Angeles Abrasion, % (max)	45	45	40	40	40
Micro-Deval (max)	45	45	35	35	35
Los Angeles + Micro-Deval (max)	80	80	65	65	65
DAT for base (max)	150	NR[a]	150	150	300
DAT for subbase (max)	150	50	300	150	300

[a]Not recommended.

TABLE 11—*Summary of Swedish specification for RCA materials (after [24]).*

RCA property	Class 1	Class 2
E-modulus, MPa	450	450
Optimum moisture content, %	6	6
Maximum dry density, kN/m^3	18	18
Porosity	0.32	0.32
Water saturation ratio	0.34	0.34
Micro-Deval max	25	35
Foreign material limits		
Crushed concrete content, % (min)	100	95
High density brick > 1.6 Mg/m^3, % (max)	0	5
Low density concrete < 1.6 Mg/m^3, % (max)	0	1.0
Other materials such as wood, plastics, etc., % (max)	0	0.5

There is little difference generally in the grading for basecourses; the Dutch specification is noticeably different and specifies the least fines. Differences in requirements for grading across the Australian states are more significant for subbase materials, as is evident in Fig. 4.

Plasticity of Fines

According to the RTA specification, acceptable fines for a basecourse material can be ML or OL, CL-ML, and CL, according to the traffic category. However, a subbase can have fines classified as CL for all traffic categories. When compared to other road authorities, RTA appears to be rather stringent with its requirement for liquid limit, being just 27 % for both base and subbase. All other authorities in this review accept liquid limits ranging between 35 % and 45 % for subbase applications. The liquid limit (LL) and plastic index (PI) values of the two South Australian RCA basecourse products were found to range from 23 % to 26 % and from 1 % to 2 %, respectively, with both ranges meeting all specifications.

Aggregate Properties

Acceptable Inclusions (Exclude Hazardous Waste, Defined by EPA, 2010)—Most of the specifications in this paper state the acceptable limits of non-concrete inclusions in RCA material. These inclusions may be wood, plaster, masonry (or other hard inclusions), bitumen, paper, metal, glass, and rubber. Most of these inclusions are assumed to be deleterious, although glass and fried clay masonry have been used in pavement materials in Europe. The overall percentage of non-concrete inclusions excluding fried clay brick is less than 10 % for all authorities. Denmark and Finland allow 30 % and 20 % of brick or masonry content for subbases. However; South Australia permits up to 20 % fried clay masonry for both bases and subbases, which exceeds the European standards for bases (< 10 %).

The maximum permissible percentage of bitumen is 5 % as specified by Portugal and The Netherlands. DTEI, South Australia permits a maximum of 1 % bitumen content for either a base or subbase.

Fines—Moisture sensitivity depends upon the fines content and soil plasticity. As the fines content increases, an increase in moisture content can result in more significant reduction of the strength of RCA

TABLE 12—*Summary of Danish specification for RCA materials (after[27]).*

Engineering property	A	B	C
E-modulus, MPa	400	300	200
Los Angeles Abrasion, % (max)	35	40	...
Foreign material limits			
Crushed concrete content, % (min)	98	95	80
Asphalt, % (max)	2	2	2
Low density concrete, % (max)	2	5	20
Glass, china, hard plastic, iron and other hard material, % (max)	2	5	20
Wood, soft plastics, paper, ash and insulating material % (max)	5	1	2
Light insulating material such as polyurethane, % (max)	0.02	0.02	0.02

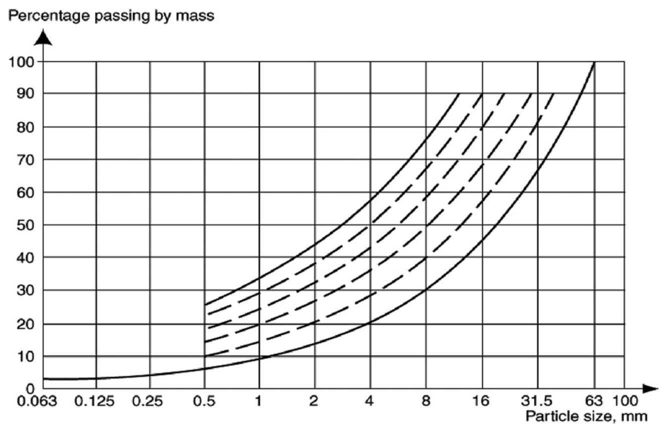

FIG. 2—*Particle size distribution limits for three classes of RCA materials in Danish specification (after [27]).*

[29]. RTA specifies a maximum fines content of approximately 15 % for both base and subbase. However, as previously stated, RTA is stringent in specifying the plasticity of the soil, thereby diminishing the potential negative impact of high fines content on RCA strength. The fines content of the two South Australian RCA products was just 5 %–7 %.

Strength—MRWA and RTA-NSW employ unconfined compressive strength (UCS) and MDCS (maximum dry compressive strength) to evaluate the strength of RCA. The UCS is conducted on a cured specimen (28 days, or 7 days of accelerated curing), which is soaked for 4 h prior to the test. The MDCS test is conducted on a cubic specimen of side length of 70 mm. Both RTA and MRWA allow a maximum UCS of 1.0 MPa for a base; MWRA stipulates the same requirement for a subbase. Finland permits a range of UCS of 0.6–1.3 MPa after 28 days of curing for a class II base. Although the range embraces the Australian maximum value, RCA with very little unconfined compression strength can be adopted in Australia. The minimum requirement of MDCS is 1.7 MPa for RTA, while 0.8 MPa is required by MRWA.

The local basecourse materials from South Australia when prepared to 98 % dry density ratio and moulded at OMC gave UCS values ranging from 0 to 0.9 MPa. The maximum dry compressive strength was found to vary between 2.0 and 2.4 MPa, comfortably higher than either the RTA or MRWA requirement.

RTA-NSW also specifies wet strength and wet-dry strength variation of RCA products. The two South Australian RCA basecourse products were found to meet the RTA requirements for the strength variation (22 %–23 %); however, the wet strength was lower than required (57–58 kN).

CBR testing, after 4 days of soaking, is also employed by a number of road authorities (VicRoads, MRWA, and RTA). The requirements do not seem to be particularly onerous and in the limited experience of the authors can be readily met by well compacted RCA products. Finland and The Netherlands have CBR requirements, but it is not clear in the Finnish specifications (CBR to range between 90 % and 140 %) if, and how long, samples are soaked prior to testing. The Dutch requirement is for a minimum of 50 % immediately after compaction of the specimen.

Stiffness—DTEI (South Australia) has issued specifications relating to RLTT in the form of resilient modulus and rate of development of permanent strain. The DTEI specifications are potentially of

TABLE 13—*Summary of some properties of recycled materials (after [28]).*

Category	GR2	GR3	GR4
Size 0/D, mm	0/31.5	0/20	0/20
Los Angeles Abrasion, % (max)	45	40	35
Micro-Deval (max)	45	35	30
Los Angeles + Micro-Deval (max)	80	65	55
DAT for base without treatment (max)	50	85	150
DAT for base with treatment (max)	50	50–150	150–300

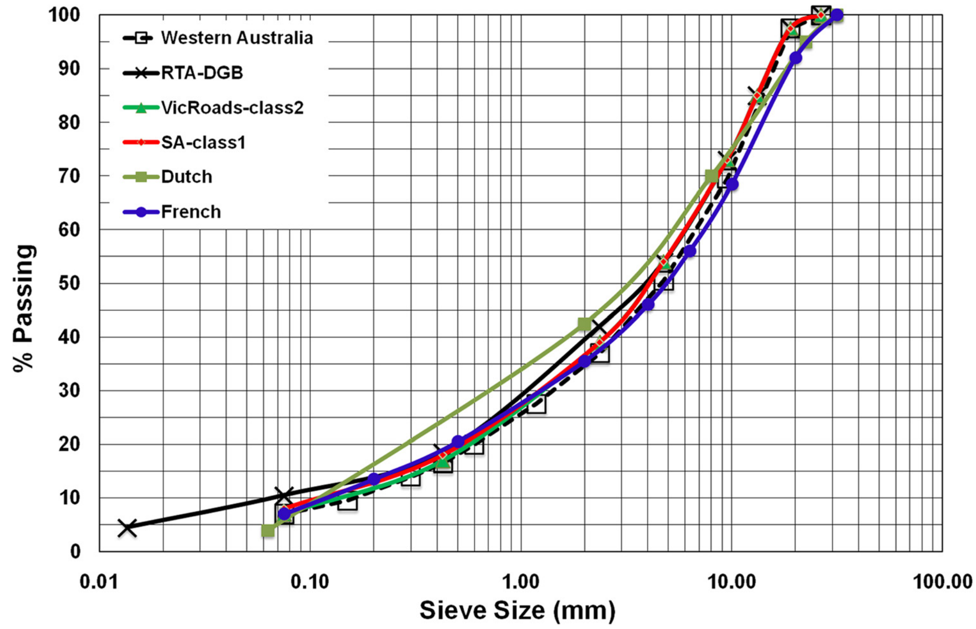

FIG. 3—*The target particle size distribution of 20 mm RCA for base material.*

considerably great value, given the importance of mechanistic pavement design to modern day pavement design. However, RLTT testing and its relevance to pavements is constantly under review.

The resilient modulus of South Australian RCA basecourse product, prepared to a dry density ratio of 98 % and over a range of moisture contents (60 %, 80 %, and 90 % OMC), was found to vary between 500 and 950 MPa, clearly surpassing the DTEI requirement of 300 MPa. The rate of permanent strain with load repetitions was generally acceptable; just one of the 16 test results did not meet the basecourse requirement over the last 30 000 load repetitions of the 50 000 cycles.

Abrasion Resistance/Toughness/Durability/Soundness—Abrasion Resistance/Toughness/Durability/ Soundness are used to characterize the aggregate quality. Los Angeles Abrasion Value (LAA or LAV), Micro-Deval, and crushing factor are used to evaluate the abrasion resistance/toughness under traffic loading. However, sulphate soundness and freezing and thawing soundness tests are used to determine

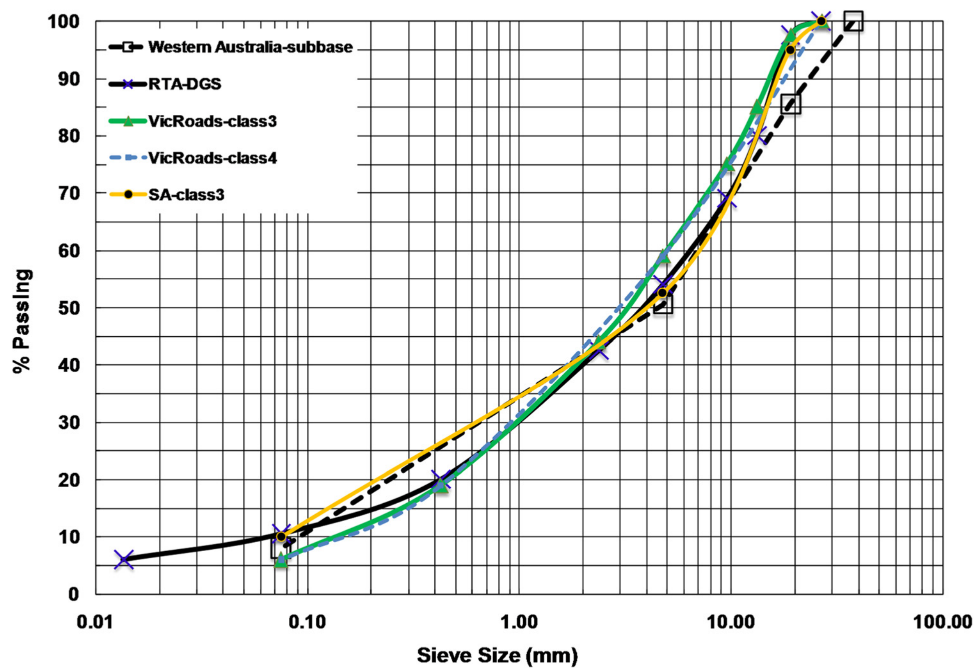

FIG. 4—*The target particle size distribution of 20 mm RCA for subbase material.*

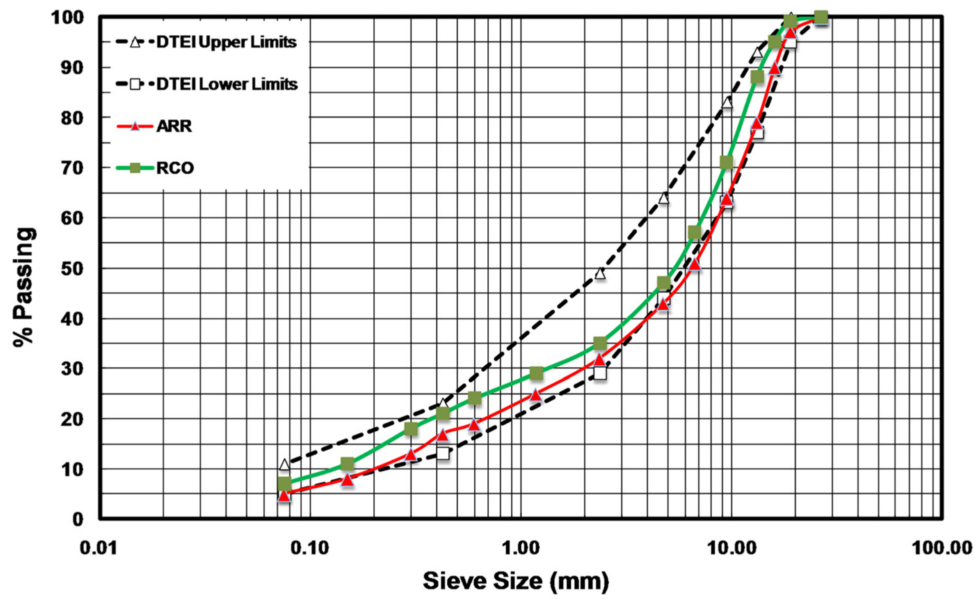

FIG. 5—*The particle size distribution of the two RCA products for base material.*

durability or soundness. It has been suggested that the Micro-Deval and sulphate soundness test are the best indicators of aggregate quality [30].

RTA (NSW) specifies a limiting value for sulphate soundness. The Netherlands specifies a crushing factor or toughness value for RCA determined by a Dutch standard. In Europe, the nations of France and Portugal employ Micro-Deval and LAA, however the Micro-Deval values that are required are almost the same as the LAA requirement.

Finland seems to be rather stringent with its abrasion resistance requirements, requiring LAA values of just 23 %–28 % for basecourse materials. Most authorities accept values for both LAA and Micro-Deval ranging between 30 % and 45 % for bases. The LAA values of the South Australian RCA examples ranged between 37 % and 39 %, which met the MRWA specifications, but failed to meet the maxima of 30 % and 35 % proposed by DTEI and VicRoads, respectively. The Micro-Deval values were just 28 %–30 %, which met the European requirements.

Inappropriate Applications

High alkalinity of RCA, particularly in the presence of water percolating through the particles, generates a corrosive solution with an increase in *p*H. Therefore, RCA materials should be kept away from shallow groundwater and should not be used in the presence of metal and aluminium [31,32]. Fortunately, in much of Australia, groundwater levels can be quite deep and so this is not too restrictive.

In addition, carbon dioxide in the air reacts with calcium hydroxide in RCA to form calcium carbonate that may block geotextiles and affect the permeability between particles [31,32].

The self cementation of RCA materials plays a significant role in influencing material performance; strength may be gained with time accompanied by loss of permeability [31]. It has been reported widely that shrinkage strain increases with time and reaches a constant value after a period of time (e.g., [33]). Shrinkage characteristics depend on the amount of residual cement and free water in the mix, and the water absorption of the material. Shrinkage may present a problem with reflective cracking of wearing courses.

Summary of Findings

Two RCA products have been evaluated in terms of compliance with all specifications in Australia. The recycled basecourse products that were investigated were found to meet the requirements of all authorities, generally. However, the RTA requirement for wet strength could not be met.

The resilient modulus of the 20 mm RCA was significantly greater than the minimum DTEI requirement of 300 MPa. The rate of permanent deformation with repeated loading was acceptable for 15 of the 16 test specimens.

Concluding Comments

It is evident that there are differences in approaches to specifying crushed concrete or RCA for unbound granular pavements. Undoubtedly, Australian State Road Authorities have been influenced by experiences with natural aggregates and the origin of the rocks used to produce the aggregates. Some authorities have experience with field trials of local RCA products, e.g., VicRoads [34] and MRWA [4,7]. These experiences are valuable, but it should be noted that since the resource recovery industry has made and continues to make improvements, old trials should be treated with some caution.

The European experience is longer and potentially of greater significance, but is based on the range of climates, pavement construction practices, and geology in those areas. It is interesting that just Sweden and Finland in Scandinavia stipulate stiffness in terms of a modulus associated with "bearing capacity." In the Swedish document reference is made to a resilient modulus backcalculated from a falling weight deflectometer on a field trial pavement, or Young's modulus from a plate loading test.

DTEI (South Australia) is the only authority specifying resilient modulus and permanent strain response to repeated loading in a triaxial chamber, albeit under a simple testing protocol. The persistence with CBR in other specifications is understandable given the long experience with the test and calibration with pavement performance, but in terms of mechanistic design it is theoretically unsupportable.

Further Work

Further work is being conducted by the authors into the engineering behavior of RCA sourced from South Australian operations. The research will concentrate on RLTT testing under different stress states and the development of permanent strains. The applicability of RLTT in general specifications will be evaluated through repetitive load testing of instrumented trial pavements, which may be either full scale (accelerated loading facility) or a modified loading system for laboratory testing (wheel tracking or pulsing loading). Finite element analysis of the pavement performance is likely to lead to insights into the granular material behaviour.

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