AN EVALUATION OF RESEARCHE UNDERTAKEN ON RECYCLED CONCRETE AGGREGATES IN ROAD CONSTRUCTION

NAZANIN ARDALAN[1], DOUGLAS J. WILSON[2], THOMAS J. LARKIN[3]

[1]*MS(Civil), PhD Candidate*
Department of Civil and Environmental Engineering, The University of Auckland
E-mail: nard561@aucklanduni.ac.nz

[2]*PhD, Senior Lecturer*
Department of Civil and Environmental Engineering, The University of Auckland
E-mail: dj.wilson@auckland.ac.nz

[3]*PhD, Senior Lecturer,*
Department of Civil and Environmental Engineering, The University of Auckland
E-mail: t.larkin@auckland.ac.nz

ABSTRACT

Cities and regions that have a rapidly growing population and rising standards of living, have resulted in greater demands on infrastructure and the need for increased construction activity to meet increasing demand. This demand leads to a significant increase in extraction and consumption of virgin aggregates and imposing significant pressures on the environment.
Therefore, there is an urgent need to investigate the resource and environmental cost of virgin aggregate extraction and production to mitigate adverse environmental effects. One proven strategy is to replace the use of natural virgin aggregates extracted from exhaustible resources with recycled aggregates from waste materials.

Different researchers have evaluated the sustainability of C&D waste materials in various civil engineering applications but it is required to understand the characteristics of Recycled aggregate thoroughly in the New Zealand context to enable their usage in these engineering applications (Arulrajah, Disfani et al. 2014). This paper studies the application of Recycled Concrete Aggregate (RCAg) in unbound layers of road construction by overviewing various literature conducted in this area. A review shows that RCAg properties are relatively consistent and can meet criteria determined by researchers and quality specifications and can therefore be a suitable alternative for premium pavement layer products in high stress roads.

INTRODUCTION

The rapid growth of the world's population has led to a considerable increase in the use of non-renewable resources. Extraction of natural virgin aggregates from the ground and riverbeds to produce core materials for infrastructure can have, if not properly managed, environmental consequences such as; destroying the natural habitat of species, deforestation, top-soil erosion, and loss of water storage capacity of the ground. Mining, processing and transportation of virgin aggregates significantly contribute to greenhouse gas emissions. Increasing transportation costs of a bulk infrastructure material commodity (i.e. Aggregate) increases the final price of construction, which leads to dissatisfaction in extracting and shipping of natural aggregate to job sites (Gabr, Cameron et al. 2012). Moreover, the increased generation of non-decaying waste materials and the lack of landfill sites for waste disposal, especially in urban areas, has become a global concern. Governments and industries have looked to reduce the demand of natural virgin aggregates extracted from quarries by considering the use of Construction and Demolition (C&D) waste materials. The use of Recycled Concrete Aggregates (RCAg) as a replacement for natural aggregates in road construction is motivated by this demand. (Gabr, Cameron 2012)

1.1. RCAg Manufacturing Process

Each type of recycled aggregate has its unique waste streams operation. The C&D waste materials, obtained from old concrete structures, delivered to the manufacturing plant are reviewed by visual inspection to ensure that received materials don't contain hazardous materials or contaminants with incompatible impacts on RCAg quality. The large fragments of waste concrete is crushed to smaller size by impact and compression crushers, followed by steel being removed from crushed concrete by an overhead electro magnet which is installed over the crushing machine and conveyor. Crushed concrete pieces are then sized and screened based on the final product grading. Crushed concrete chunks with lager size than required product specifications are crushed further and stockpiled. Cleaning processes are then used to remove impurities to meet various specification requirements. Due to the generation of RCAg from old concrete structures, it usually contains small percentages of other foreign materials such as crushed masonry, glass, wood, steel and asphalt. 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 (GVR April 2015).

1.2. RCAg in Road Construction

Research into new uses of recycled materials is continually advancing. Many road authorities and private industries have conducted studies into the possibility of using recycled products in road construction (Schaertl, Edil 2009). In the last few decades, recycled concrete aggregate (RCAg) has become more common to use in road application especially in pavement granular layers such as base and subbase, shoulder pavement and drainage (Chini, Kuo et al. 2001).

A pavement is a multi-layered structure comprising various layers such as the surface, base, subbase, and subgrade. The pavement bases and sub-bases are designed to provide uniform support for pavement surface layers (Huang 1993). Conventionally, natural materials such as crushed rocks, selected gravels and stabilized materials which meet requirements, are used in road base and subbase. So, in order to provide a viable option for use of C&D waste, there is a need to investigate the possibility of using RCAg as an unbound granular material in road base or subbase courses (Kim, Ceylan et al. 2011).

1.3. History of RCAg

In the 1990s, the necessity of preserving natural resources and increasing landfill space, inclined Australian authorities to start the technology of using RCAg in lightly trafficked road construction. In

2004 and 2005, South Australia was generating around 1.5 million tons of C&D waste which just 70% of this waste was recovered. In recent years, over 500 million kg of RCAg are produced annually in South Australia mostly from building demolition waste, and a significant proportion of this is used in pavement construction (Gabr, Cameron 2012). In Europe, from 1945 to 2000, around 600×10^6 m^3 of waste masonry was used in the rebuilding of Germany after World War II. In 1998 about 350,000 tonnes of crushed concrete was used in base and subbase layers of Finland's road construction (Gabr, Cameron et al. 2012). The Federal Highway Administration (FHWA) agency within the U.S. Department of Transportation, released a memorandum in 2002 that has accentuated the interest of FHWA in using recycled material products in the national highway system (Kim, Ceylan et al. 2011). Thereafter, in United States, over 130×10^6 tonnes of construction and demolition (C&D) waste is produced each year which around 70% of RCAg produced is used in pavement construction and particularly as a granular material in base and subbase layers (Gabr, Cameron et al. 2012).

1.4. Specifications & Tests

In recent years, considerable effort has been undertaken to conduct and support research studies with the purpose of managing and characterising C&D waste and implementing them in order to achieve more sustainable outcomes. Parts of these studies have also led to the compiling of guidelines and specifications for the application of Recycled Aggregates (RAg) and RCAg particularly in unbound pavement layers. There are many national and international specifications for RCAg that exist in the world which are applicable to different classes of pavement based on the traffic loads. Table 1 shows the most important RCAg base layers specifications and their publishers in New Zealand, Australia and United States of America. Although existing specifications are largely based on the natural aggregates' specifications, it is expected that they will be improved by further studies and experiences along the way (Gabr, Cameron et al. 2012).

County	Organisation	Specifications	Description
New Zealand	New Zealand Transport Agency	NZTA M4	Specification for Basecourse Aggregate
		NZTA M3	Specification for Subbase Aggregate
Australia	Roads Corporation of Victoria	VicRoads 820	Crushed Concrete for Pavement Subbase and Light Duty Base
	Department for Transport, Energy and Infrastructure,	DTEI TSA2428	Standard Specification for Supply and Delivery of Pavement Materials
	Institute of Public Works Engineering Australia	IPWEA	Specification for Supply of Recycled Material for Pavements, Earthworks & Drainage
	Roads and Traffic Authority NSW	RTA 3051	Granular Base and Subbase Materials for Surfaced Road Pavements
	Main Roads Western Australia	MRWA 501	Pavements
United States	United States Department of Transportation	DOT	Standard Specifications for Road Construction
	U.S Department of Transportation Federal Highway Administration	FHWA	Transportation Applications of Recycled Concrete Aggregate

Table 1- RCAg base layers specifications

In New Zealand, the appropriate specification for basecourse aggregate is NZTA M/4, which sets out requirements for basecourse aggregate for use on heavily trafficked roadways. For aggregates to perform in the subbase layer in New Zealand, the requirements of NZTA M/3 specification should be followed.

The role of the pavement foundation layers such as bases and subbases is to support the surfacing layer and provide adequate drainage. To satisfy these conditions, recycled aggregates used in unbound granular layers must meet specific engineering properties; particle size distribution, sufficient stiffness, acceptable durability, adequate permeability, and high resistance to permanent deformation (Kim, Ceylan et al. 2011). The most widespread laboratory tests which appropriately characterise the performance of unbound granular materials in base layers are shown in table 2.

Engineering Properties	Laboratory tests
Resistance to wear	Los Angeles Abrasion test
	Micro-Deval
Shear strength	California Bearing Ratio Test
Stiffness	Unconfined Compression Strength Test
	Repeated Load Triaxial
Durability	Unconfined Compression Strength Test
	Repeated Load Triaxial
Permanent deformation	Repeated Load Triaxial
Permeability	Repeated Load Triaxial

Table 2- Suggested test to evaluate the performance of RCAg in base layers

1.4.1. Los Angeles Abrasion test

The Los Angeles Abrasion test (LAA) is a specified test to appraise the resistance of aggregates to abrasion and impact forces. This test indicates the relative quality or competence of various sources of aggregate having similar mineral compositions, through measuring the breakdown of aggregates in a dry condition (American Society for Testing and Materials 2012). However, the National Cooperative Highway Research Program (NCHRP) (2008) in the United States have recently selected the Micro-Deval (MD) test (a water soaked test) instead of the dry Los Angeles Abrasion (LAA) to evaluate toughness, abrasion resistance and the water susceptibility of unbound recycled materials. It was considered that the MD test better provides a degradation indication of recycled aggregates (Gabr, Cameron 2012).

1.4.2. Compaction test

The compaction test is conducted to determine the relationship between dry density and moisture content which leads to finding the maximum dry unit weight and water range for effective compaction of granular materials (New Zealand Standards 1986). It is noted that according to Australian and ASTM standards, the sample is compacted in five layers with the application of 25 hammer blows per layer for the compaction testing, whereas in New Zealand the standard 27 hammer blows per layer was recommended.

1.4.3. California Bearing Ratio (CBR) test

The CBR test is a practical penetration type test for aggregates and construction materials. This test is applicable for various types of material ranging from heavy clay material to medium gravel size aggregates (although is more relevant to cohesive soils). The CBR test determines the indirect shear strength of materials which is highly dependent on moisture content and level of compaction (Standards Australia 1998). In the CBR test on pavement construction materials (aggregates), samples are usually soaked for 4 days prior to a test in order to simulate the worst case in-service scenario for a pavement (Arulrajah, Disfani et al. 2014).

1.4.4. Unconfined Compression Strength test

Unconfined Compression Strength (UCS) test is a common test to evaluate the stiffness of pavement material used in mechanistic pavement design methods. In the UCS test, the axial vertical load is applied to a sample through loading plates and the UCS number is determined by using strain-control or stress-control as the maximum unit stress obtained from load testing (Arulrajah, Disfani et al. 2014).

1.4.5. Repeated Load Triaxial test

Triaxial testing is a research tool with the aim to simulate as closely as possible the range of conditions that will be experienced in a field pavement. The Repeated Load Triaxial (RLT) apparatus applies repetitive loading on cylindrical materials for a range of specified stress conditions, the output is deformation versus number of load cycles for a particular set of stress conditions and resilient modulus which reflects the stress-dependent stiffness of materials (Arnold 2010).

Different RLT protocols are available based on different standard test methods which determine the permanent deformation and resilient modulus of granular material and they have been followed by various organisations and road controlling authorities; DTEI, AUSTROADS, NZTA T/15, AASHTO. DTEI, follows a simple single-stage RLT protocol with steady stress state which is applicable to the base of thin surfaced pavements. In this protocol, resilient modulus is determined by applying a constant confining pressure of 196 kPa to the sample and the deviator stress pulses between 25 and 460 kPa over 50,000 cycles. The permanent deformation of sample is recorded over the last 30,000 cycles (Gabr, Cameron 2012). Whereas DTEI has adopted single stage RLT, AUSTROADS and NZTA T/15 RLT protocols have endorsed multi stages methods to measure resilient modulus and deformation of base materials. Differences between multi stage RLT methods are due to the number of stages and cycles, which in the AUSTROADS RLT there is 3 stages of 10,000 cycles and in the NZTA T/15 specification there is 6 stages of 50,000 cycles per stage (Vuong, Arnold et al. 2006).

2. LITERATURE REVIEW

Attention to recycling materials and methods began in particular countries since the late 1970s and led to extensive research in this area. Among the earliest researches, Hansen and Angelo in 1986 found that fine aggregates of recycled concrete while mixing with the soils, could improve the engineering properties of clay soils for earthwork applications (Poon, Chan 2006). In 2001 Chini et al (2001) studied the influence of various ratios of RCAg and natural aggregate. The combined aggregates were chosen ranging from 0% to 100% by total aggregate mass. Nine sections were considered for the circular accelerated test, while four sections were flexible with maximum base thickness of 300 mm. A layer of Hot Mix Asphalt (HMA) with 90 mm thickness was placed at the top of each basecourse layer. The life expectancy analysis was conducted on the flexible sections and it was shown that with an average daily traffic (ADT) of 7,500 vehicles (4% heavy trucks) it could be expected that after 3.0 years, RCAg would perform at least equally to virgin aggregates.

Various research projects have been conducted to investigate the characteristics of RCAg and also the application of RCAg in unbound pavement layers. In 2002 Molenaar and Nierkerk from Netherlands measured different parameters such as gradation and composition of unbound base course materials using recycled concrete and masonry rubble. It was concluded that the compaction level has the highest impact on the properties of the base and is the key factor pertaining to the mechanical characteristics of unbound base courses made of recycled materials. Taha et al. in 2004, discussed various experimental studies on demolished concrete and showed that this material can be used for road bases and subbases (Herrador, Pérez et al. 2011). In another research in 2010 on Western Australia's RCAg, the characteristics of three types of RCAg materials were investigated in details by Leek and Siripun (Leek, Siripun 2010). Their work included the results of the most important laboratory tests on RCAg. Field trial results were conducted over two years and the results were compared to two natural aggregates. The research findings corroborated with previous studies and showed that RCAg is suitable for a premium basecourse product where high stress applications are required.

In 2006 Poon and Chan (2006) evaluated the possibility of mixing recycled and crushed clay brick as subbase materials. As a common benchmark they compared the results with the subbase materials produced with virgin aggregates. The results of their research indicated that the use of 100% recycled concrete aggregate increased the optimum moisture content and decreased the maximum dry density of the subbase materials compared to the use of aggregate composed of natural subbase materials. They found that if the characteristics of combined recycled concrete aggregates with crushed clay brick was comparable with natural aggregates, the mixture could be used as subbase materials and consequently it would significantly reduce the demand while increase the service life of the dumping facilities. Herrador et al. (2011) focused on verifying the possibility of exploiting construction waste as material for the subbase in road construction. A field study was conducted to assess the performance of a subbase of mixed recycled aggregate including concrete, asphalt mix, and ceramic material.

Several researchers have undertaken repeated load triaxial tests (RLTTs) in order to assess the resilient modulus and deformation characteristics of unbound granular materials. Nataatmadja and Tan in 2001 studied the resilient modulus of four different RCAs. As for the materials, they have chosen concrete beams with compressive strength variation of 15 to 75 MPa and crushed them into small pieces. The compressive strength was increased in the test specimens and the resilient modulus was monitored. It was concluded that higher compressive strength brings about higher resilient modulus. The results showed that the RCAg can compete with typical virgin road aggregates in terms of resilient modulus. Moreover, it was presented that the strength of concrete, the amount of softer material in the recycled aggregates, and the flakiness index of RCAg play an essential role in the resilient response of a subbase material and RCAg products can be utilised as subbase or basecourse while satisfying the standards criteria. In 2006, Vuong and Arnold (2006) compared evaluations of unbound granular pavement materials tested in the CAPTIF (Canterbury Accelerated Pavement Test Indoor Facility) wheel tracking facility in Christchurch, New Zealand to the AUSTROADS RLT approach. Although research results showed consistent field performance based on the AUSTROADS test, researchers recommended the AUSTROADS protocol to be used only in ranking the performance of granular bases, due to the different deformation observed by changing laboratory compaction methods. In Australia, Jitsangiam et al (2009) focused on local RCAg material which was gathered from Western Australia and carried out tests on this material as basecourse. The main point of their research was to obtain the resilient modulus and compare it with their benchmark material. To have a reference material they tested crushed rock base. RLT tests were conducted on the samples moulded at optimum moisture content (OMC). They measured the maximum dry density (MDD) of the specimens and compared it with the results of crushed rock samples. The results illustrated that the resilient modulus of RCAg could be compared to the modulus of crushed rock base, therefore, RCAg could be a viable alternative to the traditional aggregate.

3. SUMMARY DISCUSSION

The environmental restrictions of exploring natural aggregate on one side and the growing concern about the lack of waste disposal landfills on the other side, have led to increased interest of governments and industries to use recycled aggregate in engineered structures (De Farias Pinto, De Sérgio Ricardo Honório et al. 2014). The recycling of construction materials has high potential to conserve natural resources and to reduce the energy used in production. Therefore, replacement of natural aggregates by recycled aggregates, totally or partially, is the topic of many investigations in the world. The recycled aggregates and recycled concrete aggregate in particular, can be used in basecourse and subbases as unbound granular materials (Barbudo, Agrela et al. 2012).

Numerous studies have been conducted on RAg and significant research initiatives are currently under way to determine how technical characteristics, such as moisture content, the California Bearing Ratio (CBR), and degree of compaction, are affected when recycled construction and demolition waste (CDW) aggregate is included in pavement layers. This paper refers to relevant examples (Herrador, Pérez et al. 2011). The literature reflects that the use of recycled aggregates is a viable alternative to pavement construction and test results show that the RCAg can compete with typical virgin road aggregates in terms of resilient modulus. Moreover, it was presented that the strength of concrete, the amount of softer material in the recycled aggregates, and the flakiness index of RCAg play an essential role in the resilient response of a subbase material and RCAg products can be utilised as subbase or basecourse while satisfying the standards criteria (Poon, Chan 2006).

Regarding to RLT tests, researchers have measured the maximum dry density (MDD) of the specimens and compared it with the results of crushed rock samples. The results illustrated that the resilient modulus of RCAg could be compared to the modulus of crushed rock base, therefore, RCAg could be a viable alternative to the traditional aggregate. Studies shows that RCAg properties were consistent and met criteria determined by researchers. The life expectancy analysis also showed that with an average daily traffic, it could be expected that a pavement consisting of RCAg would have an acceptable life time. Therefore, RCAg is suitable for a premium basecourse product and/or other pavement locations where high stress applications are required. It should be mentioned that in the long-term condition, the rehydration of the cement within the RCAg material could be a real concern, so, the stiffness of the material could go beyond the required level and this could cause a change in the failure mechanism from compressive fatigue to a possible tensile failure (Leek, Siripun 2010).

Ongoing research at The University of Auckland sponsored by Auckland Council, Auckland Transport, Green Vision Recycling and New Zealand Transport Agency seeks to:

- Determine the quantity of available recycled aggregate in the Auckland region’s market and the types of usable materials.
- Investigate the characteristics and performance of existing recycled concrete (and other waste streams) aggregates in Auckland region.
- Evaluate ‘fit for purpose’ criteria be evaluating where these materials may economically be used in road construction.
- Evaluating the environmental impacts and carbon footprint

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