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GEOTECHNICAL AND GEOENVIRONMENTAL PROPERTIES OF RECYCLED CONSTRUCTION AND DEMOLITION MATERIALS IN PAVEMENT SUBBASE APPLICATIONS

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Abstract

A comprehensive laboratory evaluation of the geotechnical and geoenvironmental properties of five predominant types of Construction and Demolition (C&D) waste materials was undertaken in this research study. The C&D materials tested were Recycled Concrete Aggregate (RCA), Crushed Brick (CB), Waste Rock (WR), Reclaimed Asphalt Pavement (RAP) and Fine Recycled Glass (FRG). The geotechnical assessment included particle size distribution, particle density, water absorption, compaction, Los Angeles abrasion, post-compaction sieve analysis, flakiness index, hydraulic conductivity and California Bearing Ratio (CBR) tests. Shear strength properties of the materials were studied through a series of triaxial tests. Consolidated drained triaxial tests undertaken on the recycled materials indicated that the recycled materials had a drained cohesion ranging from 41 kPa to 46 kPa and a drained friction angle ranging from 49° to 51°, with the exception of FRG and RAP. The response of the materials under repeated load was investigated using repeated load triaxial (RLT) tests. The RLT testing results indicated that RCA, WR and CB performed satisfactorily at 98% maximum dry density and at a target moisture content of 70% of the optimum moisture content under modified compaction. The geoenvironmental assessment included pH value, organic content, total and leachate concentration of the material for a range of contaminant constituents. In terms of usage in pavement subbases, RCA and WR were found to have geotechnical engineering properties equivalent or superior to that of typical quarry granular subbase materials. CB at the lower target moisture contents of 70% of the OMC was also found to meet the requirements of typical quarry granular subbase materials. The properties of CB, RAP and FRG however may be further enhanced with additives or mixed in blends with high quality aggregates to enable their usage in pavement subbases.

Keywords: geotechnical; pavement; subbase; recycled materials; waste; shear strength; resilient modulus.

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Introduction

Recycled solid waste materials are normally referred to as solid wastes which are collected near curbsides; or generated by Construction and Demolition (C&D) or Commercial and Industrial activities. C&D materials are the excess or waste materials associated with the construction and demolition of buildings and structures, including concrete, brick, reclaimed asphalt, steel, timber, plastics and other building materials and products (Sustainability Victoria 2010). The urgent need for recycling is of global concern and is driven mainly by environmental considerations, due to the increasing scarcity of natural resources and the growing disposal cost into the landfills in many countries (Landris 2007; Aatheesan et al. 2010; Disfani et al. 2011; Hoyos et al. 2011;). It is widely accepted that recycling and subsequent reuse of C&D materials will reduce the demand for scarce virgin natural resources and simultaneously reduce the quantity of this waste material destined for landfills (Arulrajah et al. 2011; Disfani et al. 2011; Hoyos et al. 2011). This will ultimately lower carbon footprints compared to using traditional quarried materials which can lead to a more sustainable environment (Disfani et al. 2012). The usage of C&D materials in pavement applications is a sustainable option to minimise the C&D waste while reducing the demand for scarce virgin quarried materials (Poon and Chan 2006; Tam and Tam 2007; Hoyos et al. 2011; Puppala et al. 2011; Arulrajah et al. 2012a).

In Australia, approximately 8.7 million tons of demolition concrete, 1.3 million tons of demolition brick, 3.3 million tons of waste excavation rock, 1.0 million tons of waste glass and 1.2 million tons of reclaimed asphalt pavement are stockpiled annually and these stockpiles are growing. These figures are the authors estimate obtained by applying the figures for the state of Victoria (Sustainability Victoria 2010) to the entire nation based on the ratio of Victoria's population to that of Australia. A similar trend exists around the world in all developed and developing countries. This seems to further support the fact that recycling and subsequent reuse of C&D materials would clearly provide substantial benefits in terms of reduced material supply

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and waste disposal cost, increased sustainability, and reduced environmental impact (Sivakumar et al. 2004). These figures also indicate that removing the obstacles for the reuse of C&D materials in road work and pavement applications through research will have a profound impact in moving toward a more sustainable global environment. Ultimately only through research such as this, can a framework for using new and different categories of waste materials in civil engineering applications be established.

In this research the geotechnical characteristics of five major categories of C&D materials have been characterized through an extensive series of geotechnical and geoenvironmental laboratory tests to address their usage in unbound pavement subbase applications. The properties of the C&D materials were tested and compared with typical road authority specified requirements for usage as a subbase material. The suite of geotechnical and geoenvironmental tests undertaken in this research is extensive and covers all requirements for the choice of a subbase material. The C&D materials studied in this research were RCA, CB, RAP, WR and FRG.

Concrete waste is a by-product of construction and demolition activities of concrete structures (Sustainability Victoria 2010). These concrete chunks are crushed into aggregates of variable sizes depending on the field of applications. Impurities such as dry mortar paste, gypsum yield degraded material quality compared to the natural aggregate.

Brick is a by-product of demolition activities of buildings and other structures. CB typically consists of 70% brick and 30% other materials such as asphalt, concrete and rock, which were not removed (Arulrajah et al. 2011).

WR used in this study originates from “basalt floaters” or surface excavation rock (basalt) which commonly occurs near the surface to the west and north of Melbourne, Australia. Traditionally this material, excavated during site preparation, would have been disposed as waste, often into landfill. This waste rock is often encountered in excavation for residential sub divisional development and in the excavation works for drainage lines as well as other subsurface infrastructure (Ali et al. 2011; Arulrajah et al. 2012b).

RAP is the name given to asphalt that has been recycled during removal from roadways which is done on a regular basis. RAP traditionally ends up in landfills without a sustainable method to reutilize it.

Municipal recycled glass comprises mostly of food and drink bottles which are usually collected at residential curbside, drop boxes or recycling stations (Landris 2007). The recovered waste glass in Australia comprises of mixed waste glass, glass containers and sheet glass as well as waste glass from demolition activities, and as such waste glass is often considered as a C&D material. Waste glass is a mixture of different colored glass particles and often comes with a wide range of debris such as paper, plastic, gravel, metals and food wastes (Wartman et al. 2004; Disfani et al. 2011). Recycled crushed glass is the by-product of crushing mixed color bottles and other glass products collected from both municipal and industrial waste streams (Landris 2007). While the glass recycling industry aims to process waste glass back into bottle making industry by sorting it into one of 3 color schemes, this is not always possible. This is because a large amount of waste glass delivered to the recycling industry is broken into small pieces during handling and collecting, or the glass pieces are covered with debris and labels or has other foreign material which makes it quite impossible to sort all the waste glass into different colors. FRG is the result of crushing the waste glass down to a maximum particle size of less than 4.75 mm and is the main by-product of the glass recycling industry in Australia. FRG mainly comprises of sand size particles with a small percentage of silt size particles (Disfani et al. 2011). The knowledge gap on geotechnical engineering characteristics of recycled crushed glass and the public concern on environmental risk associated with using this material in road works are the main obstacles in reusing it as an alternative to natural aggregate in road work applications (Disfani et al. 2012).

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Review of Past Studies

Several researchers have in recent years studied various types of C&D materials in an attempt to investigate the usage of various C&D materials in various civil and geotechnical engineering applications.

Recycled Concrete Aggregate (RCA)

Melbouci (2009) in an experimental study on compaction and shear behavior of recycled concrete aggregate suggested that the addition of 5% sand, 10% of cement and 6% of brick elements (smaller than 0.125 mm) can improve the mechanical resistance of the material although the final product was found weak compared to the requirements for aggregate used in roadways with high traffic (Melbouci 2009).

In an experimental research work performed by Chidirogou et al. (2008) on crushed concrete aggregate, the researchers emphasized that the findings of research on one demolition waste should not be applied to other recycled materials, as many different types are produced (Chidirogou at el. 2008).

Tam and Tam (2007) investigated the physical characteristics of variable grades of recycled aggregates and reported that the larger the size of the aggregate, the smaller the percentage of cement mortar attached to its surfaces and the better the aggregate quality will be. Tam and Tam (2007) concluded that recycled concrete aggregates have a larger amount of porosity and can potentially undergo a higher degree of deformation.

Poon and Chan (2006) conducted a study on use of crushed concrete in road subbase layers and concluded that recycled coarse and fine aggregates of different nominal sizes conform to the required grading limits specifications for pavements, embankments, roads and bridges (Poon and Chan 2006). Poon and Chan (2006) also studied the moisture-density curves for natural and

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recycled aggregates and concluded that materials with flat curves can tolerate a greater amount of variations in the moisture content without compromising much of the achieved density (Poon and Chan 2006). Results of their study suggested that a 4-day soaked period has a negligible effect on the CBR value of the recycled material while they exhibit a negligible swell percentage after the soaking period. Their results also suggested that the hydraulic conductivity of compacted fine recycled concrete aggregates is higher than that of natural aggregates (Poon and Chan 2006).

Sivakumar et al. (2004) in an experimental study found that recycled construction wastes have significant shear strength which makes these materials an alternative to natural aggregate in various geotechnical applications. The authors reported reductions in the frictional resistance of these materials caused by repeated loading (Sivakumar et al. 2004). McKelvey et al. (2002) studied the shear strength behavior of recycled construction materials for projected use in vibro-ground improvement applications. It is found that for both dry and wet material, the drained internal angle of friction is approximately 39°, which reduces to 32° when the recycled concrete was mixed with clay slurry (McKelvey at al. 2002).

An important parameter in investigating the application of recycled aggregate in pavement construction is permanent deformation. Papp et al. (1998) and Bennert et al. (2000) studied the permanent deformation characteristics of RCA, RAP and a dense-graded aggregate by conducting cyclic load triaxial tests and reported that RCA accumulated the least amount of permanent strain out of the three materials (Bennert et al. 2000; Papp et al. 1998). Gabr and Cameron (2012) studied the resilient modulus and permanent deformation of RCA and reported that the material was suitable for unbound basecourses. However, the performance of RCA compared to other C&D materials and the environmental implications for their use has not been previously reported.

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Crushed Brick (CB)

While there are several research works focusing on using CB in concrete mixture (Chang et al. 2011; Zheng et al. 2011), in concrete tiles and blocks (Jankovic et al. 2012; Li et al. 2012; Gayarre et al. 2011) or in new bricks (Liu et al. 2012), limited work has been conducted on using crushed brick in geotechnical applications.

Chidirogou at al. (2008) conducted an experimental study on particle size distribution, water absorption, flakiness index, particle density, compaction characteristics, aggregate impact and aggregate crushing value of CB concluding that crushed brick had significantly different engineering properties to crushed concrete. Poon and Chan (2006) investigated the possibility of using CB aggregates in unbound subbase layers in Hong Kong and noticed the inferior shear performance of crushed brick in CBR tests compared to RCA. A study on recycling and reuse of brick in United Kingdom was undertaken by Gregory et al. (2004). Their study discussed UK's current brick recycling strength and proposed new brick recycling technology to achieve higher economic and environmental performance. Arulrajah et al (2011, 2012a) and Aatheesan et al. (2010) have reported on the geotechnical properties of CB in pavement subbase applications. However, the performance of CB compared to other C&D materials and the environmental implications for their use has not been previously reported.

Waste Rock (WR)

Rodgers et al. (2009) studied the behavior of sandstone and shale aggregates under cyclic loading for the purpose of using them in unbound forest roads. Test results suggested that sandstone had very good resistance to deformation and rutting while shale had poor resistance (Rodgers et al. 2009). Jitsangiam and Nikraz (2009) studied the mechanical behaviour of treated crushed rock used in road base layers through a range of static and repeated load triaxial tests. Akbulut and Gürer (2007) conducted a research on using marble and andesite quarry wastes in

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asphalt pavements. Test results implied that physical properties of these waste aggregates are within specified limits and consequently they can potentially be used as aggregates in light to medium trafficked asphalt pavement binder layers (Akbulut and Gürer 2007).

McKelvey et al. (2002) examined the shear behavior of 40 mm uniform crushed recycled rock (quarry waste) in a study of their use in ground improvement works in the UK. Test results suggested that the presence of slurry has adverse effects on shear strength and settlement potential of quarry waste aggregates (McKelvey et al. 2002). Nunes et al. (1996) carried out a research use of secondary materials for pavement construction in the UK and undertook a range of tests including repeated load triaxial test on mine-rockwaste and slate waste. Arulrajah et al (2012b) and Ali et al. (2011) have reported on the geotechnical properties of WR in pavement subbase applications. However, the performance of WR compared to other C&D materials and environmental implications for their use has not been previously reported.

Reclaimed Asphalt Pavement (RAP)

While RAP application in road works including base and subbase layers has been limited, due to lack of laboratory and field performance data (Taha et al. 2002), there have been several studies in this field with cement stabilized RAP. Taha et al. (2002) conducted a laboratory evaluation of cement stabilized RAP and RAP-virgin aggregate blends as an alternative for base layers. Test results suggested that optimum moisture content, maximum dry density and strength of RAP by and large increases with the addition of virgin aggregate and cement (Taha et al. 2002). Test results suggested that pure RAP aggregate can be utilized as a conventional base material only if stabilized with cement (Taha et al. 2002). The ability of RAP aggregate to function as a structural component in road pavements is more pronounced when it is stabilized with cement rather than when blending with virgin aggregate (Taha et al. 2002).

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Hoyos et al. (2011) carried out tests on RAP materials treated with different percentages of Portland cement and with alkali-resistant glass fibers (Hoyos et al. 2011). Test results confirmed the potential of cement-fiber-treated RAP material as an environmentally and structurally sound alternative to non-bonded materials in base and subbase layers of road pavements (Hoyos et al. 2011). Puppala et al. (2011) conducted a series of repeated load triaxial tests in a research study to evaluate the effectiveness of adding cement in enhancing resilient characteristics of RAP aggregates. However, the performance of RAP compared to other C&D materials and environmental implications for their use has not been previously reported.

Fine Recycled Glass (FRG)

There are several research publications available on using recycled crushed glass in concrete mixtures (Meyer 2001; Taha and Nounu 2008) and also in asphalt aggregate as a replacement to sand and gravel material (FHWA 1998; Halstead 1993; Landris 2007; Meyer 2001). Recycled glass has been also suggested in applications such as backfill material (Wartman et al. 2004), embankment fills (Halstead 1993) and in pavements (Landris 2007; Pratt 1993; Senadheera et al. 2005). However, the lack of knowledge on the geotechnical characteristics of recycled glass and its possible environmental risks are the main barriers in its sustainable usage in road work applications (Disfani et al. 2011).

Current Research

Although all the above-mentioned studies have sought to investigate the sustainable usage of C&D aggregates in geotechnical and pavement applications, there is little known work undertaken to date on the complete range of important parameters for road applications from a geotechnical perspective. More importantly there is limited work reported that address the critical aspect of environmental concerns and risks attributed to using C&D material in road applications. The majority of research studies to date has solely focused on just one type of C&D

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material and there has been no known study to date that encompasses the geotechnical and geoenvironmental properties of these predominant C&D materials that exists in all developed and developing countries. A comparison of the properties of the predominant C&D materials is also required as this will be of importance to consultants, contractors, designers, local councils, state road authorities, operators and end-users alike in their potential usage in civil engineering applications. This paper presents a wide range of geotechnical and geoenvironmental laboratory experimentation on five predominant types of C&D material and also addresses the environmental risks through contamination level and leachate analysis.

Laboratory Experimental Works

Samples of recycled C&D aggregates were obtained from several recycling sites in the state of Victoria, Australia. The recycled CB, RCA, WR and RAP used in this research had a maximum particle size of 20 mm. FRG has a maximum particle size of 4.75 mm and comprises of sand size and a small percentage of silt size particles (Disfani et al. 2011). During sampling; ASTM practice for sampling aggregates was carefully practiced and all necessary precautions were taken to capture a sample containing representative particle sizes and all contaminants (ASTM 2009).

Laboratory tests were subsequently undertaken on these recycled C&D aggregates. The laboratory investigation included basic characterization tests such as particle size distribution, particle density (coarse and fine fraction) and water absorption (coarse and fine fraction), organic content, pH, hydraulic conductivity, flakiness index, Los Angeles (LA) abrasion, modified Proctor compaction and CBR tests. Shear strength tests were subsequently undertaken with static triaxial tests. RLT tests were undertaken to determine the permanent deformation and resilient modulus characteristics of the C&D materials. The room temperature was maintained at 20±1°C for the triaxial and RLT tests.

Using sieve analysis results, Unified Soil Classification System (ASTM 2010) was implemented to classify the recycled materials. Organic content of all the recycled material sources in this research was determined following "Standard test methods for moisture, ash, and organic matter of peat and other organic soils" (ASTM 2007a). pH values of the recycled materials were determined following the Australian standard for "Soil chemical tests-determination of the pH value of a soil electrometric method" (Standards Australia 1997a).

The test specimens for hydraulic conductivity tests were compacted with modified Proctor compaction effort, at optimum moisture content (OMC) to reach at least 98% of maximum dry density (MDD). The falling head test method was chosen for all recycled aggregate with the exception of FRG which was tested by the constant head method.

The flakiness index tests were carried out following "British Standard for testing aggregates-part 105: methods for determination of particle shape, section 105.1 flakiness index" (British Standard 1989). Oven dry samples that passed 63.0 mm and retained on the 6.30 mm were selected for testing.

CBR test specimens were prepared by applying modified compaction efforts to recycled aggregates mixed at the OMC obtained in compaction tests. A surcharge mass of 4.5 kg was placed on the surface of the compacted specimens and then the samples were soaked in water for a period of four days. This is to simulate the confining effect of overlying pavement layers and also the likely worst case in-service scenario for a pavement (VicRoads 1998).

The static triaxial tests were performed in an automated triaxial testing system with specimen dimensions of 100 by 200 mm (diameter by height) for all recycled material types except FRG which was tested with the dimensions of 50 by 100 mm. The test specimens were compacted to 98% of MDD from modified compaction test in a split mold in eight layers. The compaction was done by mechanical compactor with around 15 blows of modified compactive effort of 2700 kN-

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m/m^3 for each of the eight layers. It has also been recommended that the confining stress applied to the specimens in triaxial shear tests better encompass the maximum stress likely to occur in the ground (Head 1994). As such, the confining stress range of 50–200 kPa, which corresponds to shallow to moderate overburden pressure (Wartman et al. 2004), was applied to the samples. Triaxial compression (shearing) was executed on the saturated and consolidated specimens. The samples were compressed at the given consolidated confining pressures under drained conditions (CD test). The shearing was performed under strain – controlled condition at the selected strain rate of 0.01 mm/min. Replicate samples were tested for the triaxial tests at the various stress levels.

RLT tests were conducted to determine the resilient modulus and permanent deformation of the recycled materials. In this investigation, the RLT test was performed according to Austroads Repeated Load Triaxial Test Method AG: PT/T053 (AustRoads 2000). The RLT testing consists of two phases of testing, permanent strain testing and then resilient modulus testing. Permanent strain testing consists of three or four stages, each undertaken at different deviator stresses and a constant confining stress. The resilient modulus testing consists of sixty six (66) loading stages with 200 repetitions. In this test, the specimens were compacted to 98% MDD based on modified compaction effort and tested at three target moisture contents of 70%, 80% and 90% of the OMC based on modified compaction effort, so as to simulate the dry-back process in the field. Replicate samples were tested for the RLT tests at each of the various moisture levels.

Total Concentration (TC) and leachate analysis were carried out for a range of heavy metals on samples of C&D material. Before 1997, the US EPA specified Toxicity Characteristic Leaching Procedure (TCLP) was the accepted method for leaching tests in Australia. In 1997 an Australian Standard Leaching Procedure (ASLP) was developed and released and then opened its way to substitute TCLP in Australia (EPA Victoria 2007). Consequently, in preparation of leachate, the

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method described in Australian Standard "Wastes, sediments and contaminated soils: Part 3: preparation of leachates-bottle leaching procedure" (AS 4439.3-1997) was followed and slightly acidic leaching fluid (pH = 5) and alkaline leaching fluid (pH = 9.2) were used as leaching buffers (Standards Australia 1997b).

Results and Discussion

Table 1 presents the geotechnical properties of the various recycled C&D materials and discussions on the results are presented in this section.

Classification, index and geotechnical properties

The particle size distributions of the five recycled materials as-received to the laboratory (before compaction) and after modified compaction are shown in Figure 1. For reference purposes, the grading ranges (i.e., the upper and lower limits) of the standard specifications for type 1 gradation C material recommended in ASTM specification for materials for soil-aggregate subbase, base, and surface courses (ASTM 2007b) are also shown in Figure 1. The "after compaction" grading curves show that some breakdown has occurred during compaction especially for CB and RAP material. However, all the recycled C&D materials, except for FRG, satisfied the guidelines for type 1 gradation C road base material according to ASTM D1241-07, except for slight deviations in the finer side for some materials. The grain size distribution parameters including D_{10}, D_{30}, D_{50}, D_{60}, C_u, C_c, percentage of gravel, sand and fine particles, USCS symbol and description are summarized in Table 1. RCA, CB, WR, and RAP have approximately equal amount of sand and gravel sized fractions, enabling them to be classified as well-graded gravelly sand or sandy gravel.

The fine fractions used for Atterberg limit tests (i.e. particles smaller than 0.425 mm) are low and are mainly sand or silt by nature, so the plastic limit and liquid limit could not be obtained for any of C&D material studied in this research. As the clay content is low some difficulties

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may occur with the workability of the recycled materials as cohesion of particles and a tight prepared surface is usually a sought after characteristic. The blending of these recycled materials with other aggregates or addition of small quantities of clayey sand or crushed fines may overcome this potential issue.

Particle density and water absorption tests were performed on both coarse (retained on 4.75 mm sieve) and fine (passing 4.75 mm sieve) fractions of C&D materials. It can be noted from Table 1 that the particle densities of coarse aggregates are slightly higher than those of the fine aggregates for all the materials tested. The WR showed the highest particle density for coarse and fine materials among the five materials tested. The water absorptions of coarse aggregates are lower than those of the fine aggregates for all recycled materials as the fine particles, with larger specific surface, absorb more water than the coarse ones. Among the five recycled C&D materials, FRG showed the lowest values for water absorption. Generally, pure glass has zero water absorption. However, the FRG used in this investigation had little amount of soil and other particles and was not 100% pure glass, and accordingly recorded a small value for water absorption. It is found that the water absorption values of recycled materials range from 1% to 9.8% while for a natural aggregate the value does not exceed 3% (Poon and Chan 2006).

Figure 2 shows the modified compaction curves of C&D materials which possess characteristic convex shaped curves similar to natural aggregates (Wartman et al. 2004). The modified compaction test results indicated that WR had the highest MDD while FRG had the lowest value. The fact that FRG indicated the lowest MDD is consistent with the finer gradation curve of FRG and its lower particle density for both fine and coarse fractions. The flatter compaction curve of FRG suggests its low sensitivity to water content changes in comparison to natural aggregate which gives FRG stable compaction behavior and good workability over a wide range of water contents in geotechnical engineering applications (Disfani et al. 2011; Wartman et al. 2004). The

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OMC of the C&D materials indicated that RAP had the lowest OMC of 8.0% while CB had the highest of 11.25%.

Organic contents were found to be low for the recycled materials and high for the RAP. This could be due to the presence of bitumen in RAP that is rich in carbon. The pH values of all blends are above 7 and this indicates that the blends are alkaline by nature. Hydraulic conductivity of the recycled materials ranges from 1.75×10^{-5} to 4.50×10^{-9} m/s. These values can be described as low permeability for RCA and CB and high permeability for WR, RAP and FRG. It is believed that as RCA and CB had higher fine particles from cement mortar and clay, the materials showed lower values for hydraulic conductivity. The hydraulic conductivity values of RCA and CB are lower and WR, RAP and FRG are higher than that of 6.59×10^{-8} m/s of reported for natural aggregate with similar classification (Poon and Chan 2006).

Flakiness index is relevant for aggregates used in bituminous mixtures. The flakiness index values for the recycled materials varied from 11 to 23. This is however still within the requirements of typical state road authorities for usage as a base material, which specifies a maximum value of 35. Tam and Tam (2007) also suggested 40 as the flakiness index upper limit for aggregates to be used in pavement applications. Flakiness index values are not relevant for the FRG as flakiness index is not applicable to material passing 6.30 mm sieve.

Particles crushing and degradation is considered as a significant issue in certain geotechnical applications and accordingly any attempt to utilize recycled materials in geotechnical engineering applications should examine this issue carefully (Sivakumar et al. 2004). An LA abrasion maximum value of 40 is normally adopted by state road authority specifications for pavement subbase materials (VicRoads 1998). RCA, WR and FRG meet this maximum criteria, CB is just above the limits while RAP with a value of 42 is above the limits. This indicates that RCA, WR and FRG are more durable in abrasion than CB and RAP. This further substantiates

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that the gradation curves of CB and RAP showed the highest change after modified compaction tests. This further suggests that RAP may have to be blended with other aggregates to enable its usage in pavement subbase applications. The abrasion loss value obtained for RCA in this study is very close to the value of 25 for a recycled concrete investigated by Courard et al. (2010).

Shear strength properties

A CBR value of at least 80% is typically required by state road authorities for a subbase material (Aatheesan et al. 2010). Results presented in Table 1 suggest that RCA, CB and WR meet the CBR requirements for usage as a subbase material. However, FRG and RAP would need to be blended with other aggregates to improve their CBR performances to be used in road subbase layers. These two recycled materials are however suitable for usage as a fill material in embankments, which need far lower CBR requirements.

Figure 3 shows a typical deviator stress-strain plot for RAP from a triaxial CD test. CD triaxial tests undertaken on the recycled materials indicated that RCA, CB, WR had a drained cohesion ranging from 41 kPa to 46 kPa and a drained friction angle ranging from 49° to 51° as reported in Table 1. This indicates the shear strength parameters for these recycled materials are in the range of coarse aggregates. FRG had a drained cohesion of 0 kPa which indicate the properties of FRG are similar to coarse sand with little to no cohesion. RAP and FRG had similar low drained friction angles of 37°, similar to that of a loose sand.

WR in this study originates from basalt floaters or basalt surface excavation rock which is commonly found during subdivision and excavation works. When these waste materials are excavated and disposed, they are disposed together with excavated fine materials which contribute to high cohesion values for the WR material presented in Table 1. Furthermore, the addition of water to the WR during the compaction to the OMC could result in the fines present forming a paste which subsequently contributes toward a higher cohesion value. Recycled

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Concrete Aggregate (RCA) comprises of a high amount of cement dust and fines. Cementing and bonding could result when water is added to the crushed concrete when the samples are compacted to the OMC and MDD. Unreacted cement in the crushed concrete would react with water to provide cohesion and this would result in the high cohesion noted from the crushed concrete in the triaxial shear tests.

The RLT test provides resilient modulus–permanent deformation parameters that uniquely describe the material response to traffic loading under prevailing physical conditions. These parameters are used as input to the design and analysis of pavement structures (AustRoads 2004). The test results are used to establish a material selection criterion based on its ability to perform effectively in terms of permanent deformation sustained. Table 2 presents the range of permanent strain and resilient modulus from permanent strain testing for the various C&D materials compared with that of traditional virgin quarried aggregate. Results of permanent strain testing (variations of permanent strain and resilient modulus against number of load cycles) for the various C&D materials are plotted in Figure 4 and Figure 5. Results of resilient modulus testing for these materials are plotted in Figure 6.

The RLT test results indicated that RCA, CB and WR performed satisfactorily at 98% MDD and at a target moisture content of 70% of the OMC. RCA, CB and WR materials showed sensitivity to moisture and produced higher limits of permanent strain and lower limits of resilient modulus, particularly at higher target moisture contents in the range of 80%-90% of the OMC. The performance of RCA, CB and WR were found to be affected by increasing the target moisture contents and the density level. This is apparent particularly for CB which failed at the higher target moisture contents of 80%-90%. The results of permanent strain and resilient modulus for RAP and FRG could not be reported as these two materials possess very low cohesion values and their samples failed within a few cycles at a target moisture content of 60% of the OMC.

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Consequently, the tests for higher target moisture contents were not attempted for RAP and FRG.

Results of permanent strain and resilient modulus for typical natural granular subbases were extracted from a database of typical granular subbases in the state of Victoria, Australia and are provided for comparison in Table 2. The results in Table 2 indicate that, RCA and WR have much smaller permanent strain and much higher modulus than natural granular subbases, which indicate their performance as superior or equivalent to typical quarry subbase materials. High level of the modulus values achieved for the RCA suggests that "residual cementing action" is occurring in these samples. While this action may result in shrinkage cracks and possibly some reflective cracking, it is unlikely that this can significantly affect the performance of the pavement layer over time.

Total concentration and leachate tests

Using the method described previously, ASLP tests with two buffer solutions (acidic and alkaline) were conducted on representative samples of C&D materials and the results of TC and ASLP are presented in Table 3.

Fill material consists of soil (being clay, silt and/or sand), gravel and rock of naturally occurring materials and is often referred to as clean fill by industry, and may be suitable for site filling or leveling depending on an assessment of contaminant levels and intended use (EPA Victoria 2010). Soil and aggregates may be classified as fill, when an assessment demonstrates that the material is not contaminated or the contamination levels in form of TC are not higher than the values specified in Table 4 as maximum TC for fill material (EPA Victoria 2010).

TC values of C&D samples presented in Table 3 were compared with EPA Victoria (Australia) requirements for fill material presented in Table 4. The comparison implies that for all the

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contaminant constituents with the exception of chromium, TC values of C&D samples are far below the threshold. The chromium metal is found in a few oxidation states such as hexavalent chromium (chromium VI) and trivalent chromium (chromium III). The values reported for C&D samples are the total chromium (chromium III + chromium VI) while the EPA Victoria requirement presented in Table 4 is on hexavalent chromium (chromium VI). As such, C&D materials will go beyond the chromium boundary only and only if all the chromium found in the test is of type chromium VI which does not seem to be the case here (Disfani et al. 2012).

According to the US EPA, a material is designated as a hazardous waste if any detected metal occurs at concentrations larger than 100 times the drinking water standard (Wartman et al. 2004). Table 4 shows the acceptable concentrations for drinking water according to U.S. EPA. ASLP values of C&D materials shown in Table 3 can be compared with the 100 times of the values presented in Table 4. The ASLP values are again far below the threshold of hazardous waste proving that they will not be categorized as hazardous waste according to U.S. EPA.

Conclusions

A detailed laboratory investigation was undertaken to characterize five recycled C&D materials in terms of their basic properties, shear strength parameters, resilient modulus and permanent deformation characteristics. The density results indicate the existence of high quality aggregates in the recycled C&D materials, which contributes to higher density for the coarse aggregates. Among the five recycled materials FRG showed the least values for the water absorption. Organic contents were found to be low for the recycled materials and high for the RAP. The pH values of all blends are above 7 and this indicates that the blends are alkaline by nature. Hydraulic conductivity of the recycled materials can be described as low for RCA and CB and high for WR, RAP and FRG.

The LA abrasion test indicates that RCA, WR and FRG are more durable in abrasion than CB and RAP. RCA, CB and WR meet the CBR requirements for usage as a subbase material while FRG and RAP would need to be blended with other higher quality aggregates to improve their CBR performances for usage as a subbase material. The modified compaction test results indicated that WR had the highest MDD while FRG had the lowest. CD triaxial tests indicated that most of the recycled materials had a drained cohesion ranging from 41 kPa to 46 kPa and a drained friction angle ranging from 49° to 51°. FRG and RAP however had a drained cohesion of 0 kPa and 53 kPa respectively and a drained friction angle of 37°.

The RLT results indicated that RCA, CB and WR performed satisfactorily at 98% MDD and at a target moisture content of 70% of the OMC. RCA, CB and WR materials showed sensitivity to moisture and produced higher limits of permanent strain and lower limits of resilient modulus, particularly at higher target moisture contents in the range of 80% to 90% of the OMC. The performance of RCA, CB and WR were found to be affected by increasing the target moisture contents and the density level, particularly for CB which failed at the higher target moisture contents of 80%-90%. RCA, WR was found to have much smaller permanent strain and much higher modulus than natural granular subbases, which indicate their performance as superior or equivalent to typical quarry subbase materials. The results of permanent strain and resilient modulus for RAP and FRG could not be reported as these two materials possess very low cohesion values and their samples failed within a few cycles at a low target moisture content level.

In terms of usage in pavement subbases, RCA and WR were found to have geotechnical properties equivalent or superior to that of typical quarry subbase materials. CB at the lower target moisture contents of 70% of the OMC was also found to meet the requirements of typical quarry granular subbase materials. RAP and FRG on the other hand were unable to meet the RLT and CBR requirements. The properties of CB, RAP and FRG however may be enhanced with additives or mixed in blends with high quality aggregates to enable their usage in pavement

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subbases. TC and leachate test results for a range of heavy metals indicated that these C&D materials can be safely used in pavement subbases.

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Table 1: Geotechnical properties of recycled C&D materials

Geotechnical Parameters	RCA	CB	WR	RAP	FRG	Typical Quarry Material
D_{10} (mm)	0.24	0.18	0.075	0.24	0.16	-
D_{30} (mm)	1.3	1.7	1.5	1.9	0.45	-
D_{50} (mm)	5.0	5.6	3.9	4.5	0.85	-
D_{60} (mm)	7.5	8.0	5.6	5.9	1.2	-
C_u	31.2	44.4	74.7	25.6	7.5	-
C_c	0.9	2.0	5.4	2.5	1.5	-
Gravel content (%)	50.7	53.6	44.7	48.0	0.0	-
Sand content (%)	45.7	39.8	45.1	46.0	94.6	-
Fines content (%)	3.6	6.6	10.2	6.0	5.4	<10
USCS classification	GW	GW	SW	GW	SW	-
Particle density - Coarse fraction (kN/m^3)	27.1	26.2	28.1	23.5	24.4	>19.62
Particle density - Fine fraction (kN/m^3)	26.0	25.8	28.0	23.4	24.3	>19.62
Water absorption - Coarse fraction (%)	4.7	6.2	3.3	2.2	1.0	<10
Water absorption - Fine fraction (%)	9.8	6.9	4.7	2.4	1.8	<10
MDD (kN/m^3) - modified compaction	19.13	19.73	21.71	19.98	17.40	>17.5
OMC (%) - modified compaction	11.0	11.25	9.25	8.0	10.5	8-15
Organic content (%)	2.3	2.5	1.0	5.1	1.3	<5
pH	11.5	9.1	10.9	7.6	9.9	7-12
Hydraulic conductivity (m/s)	3.3×10^{-8}	4.5×10^{-9}	2.7×10^{-7}	3.5×10^{-7}	1.7×10^{-5}	$>1x10^{-9}$
Flakiness Index	11	14	19	23	-	<35
LA abrasion loss (%)	28	36	21	42	25	<40
CBR (%)	118-160	123-138	121-204	30-35	42-46	>80
Triaxial Test (CD): Apparent Cohesion (kPa)	44	41	46	53	0	>35
Triaxial Test (CD): Friction angle (degree)	49	48	51	37	37	>35
Resilient Modulus: Target 90% of the OMC	239-357	301-319	121-218	-	-	125-300
Resilient Modulus: Target 80% of the OMC	487-729	303-361	202-274	-	-	150-300
Resilient Modulus: Target 70% of the OMC	575-769	280-519	127-233	-	-	175-400

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Table 2: Range of permanent strain and resilient modulus from RLT tests for C&D materials at the end of each loading

Material	Permanent Strain Testing	Target Moisture Content (% of the OMC)	Achieved Moisture Content (% of the OMC)	Achieved Dry Density: 98% of MDD (kN/m^3)	Stage1: confining stress = 50 kPa deviator stress = 150 kPa	Stage2: confining stress = 50 kPa deviator stress = 250 kPa	Stage3: confining stress = 50 kPa deviator stress = 350 kPa	Stage4: confining stress = 50 kPa deviator stress = 450 kPa
RCA	Permanent strain (micro-strain)	90	83	18.85		4471	5669	7304
		80	71	18.85	-	2426	2956	3512
		70	60	18.85	1585	2079	2532	2995
	Resilient modulus (MPa)	90	83	18.85	-	342	357	346
		80	71	18.85	-	660	697	729
		70	60	18.85	695	713	716	769
CB	Permanent strain (micro strain)	90	84	19.42	882	failed	failed	-
		80	80	19.42	3720	7598	failed	-
		70	65	19.42	2703	4434	6445	-
	Resilient modulus (MPa)	90	84	19.42	319	failed	failed	-
		80	80	19.42	327	361	failed	-
		70	65	19.42	390	467	519	-
WR	Permanent strain (micro strain)	90	84	21.44	6629	11715	17835	-
		80	71	21.44	-	6366	9234	-
		70	67	21.44	7939	10620	14653	-
	Resilient modulus (MPa)	90	84	21.44	148	181	218	-
		80	71	21.44	-	240	274	-
		70	67	21.44	193	213	233	-
Typical Quarry Material	Permanent strain (micro strain)	90	90	>17.66	7000-15000	10000-20000	10000->20000	-
		80	80	>17.66	5000-10000	7000-15000	10000->20000	-
		70	70	>17.66	3000-10000	4000-15000	5000-20000	-
	Resilient modulus (MPa)	90	90	>17.66	125-300	150-300	175-300	-
		80	80	>17.66	150-300	175-300	200-300	-
		70	70	>17.66	175-350	200-400	225-400	-

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Table 3: TC and ASLP values obtained for C&D material

Contaminant	**RCA**			**WR**			**CB**			**RAP**			**FRG**		
	TC[a]	ASLP[b] (Acet)	ASLP[b] (Borate)	TC[a]	ASLP[b] (Acet)	ASLP[b] (Borate)	TC[a]	ASLP[b] (Acet)	ASLP[b] (Borate)	TC[a]	ASLP[b] (Acet)	ASLP[b] (Borate)	TC[a]	ASLP[b] (Acet)	ASLP[b] (Borate)
Arsenic	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1	6	0.01	< 0.1	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1
Barium	88	0.34	< 0.1	340	1.3	1.1	140	0.27	< 0.1	64	0.17	< 0.1	6	0.1	< 0.1
Cadmium	< 0.2	< 0.002	< 0.02	< 0.1	< 0.002	< 0.02	2.9	0.006	< 0.02	< 0.1	< 0.002	< 0.02	0.5	0.004	< 0.02
Chromium	15	0.05	< 0.1	19	< 0.01	< 0.1	17	0.01	< 0.1	18	< 0.01	< 0.1	< 5	< 0.01	< 0.1
Lead	11	< 0.01	< 0.1	< 5	< 0.01	< 0.1	67	< 0.01	< 0.1	15	0.02	< 0.1	12	0.19	< 0.1
Mercury	< 0.05	< 0.001	< 0.01	< 0.05	< 0.001	< 0.01	0.13	< 0.001	< 0.01	0.08	< 0.001	< 0.01	< 0.05	< 0.001	< 0.01
Selenium	< 3	< 0.01	< 0.1	5	< 0.01	< 0.1	< 3	< 0.01	< 0.1	< 3	< 0.01	< 0.1	< 5	< 0.01	< 0.1
Silver	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1	< 5	< 0.01	< 0.1

[a] mg/kg of dry weight

[b] mg/L

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Table 4: EPA Victoria and U.S. EPA requirements

Contaminant	Maximum TC allowed for fill material (mg/kg) [a]	U.S. EPA drinking water standard (mg/L) [b]
Arsenic	20	0.05
Barium	-	2.0
Cadmium	3	0.005
Chromium	1 (Chromium VI)	0.1
Lead	300	0.015
Mercury	1	0.002
Selenium	10	0.05
Silver	10	0.05

[a] EPA Victoria 2010

[b] U.S. EPA 1999

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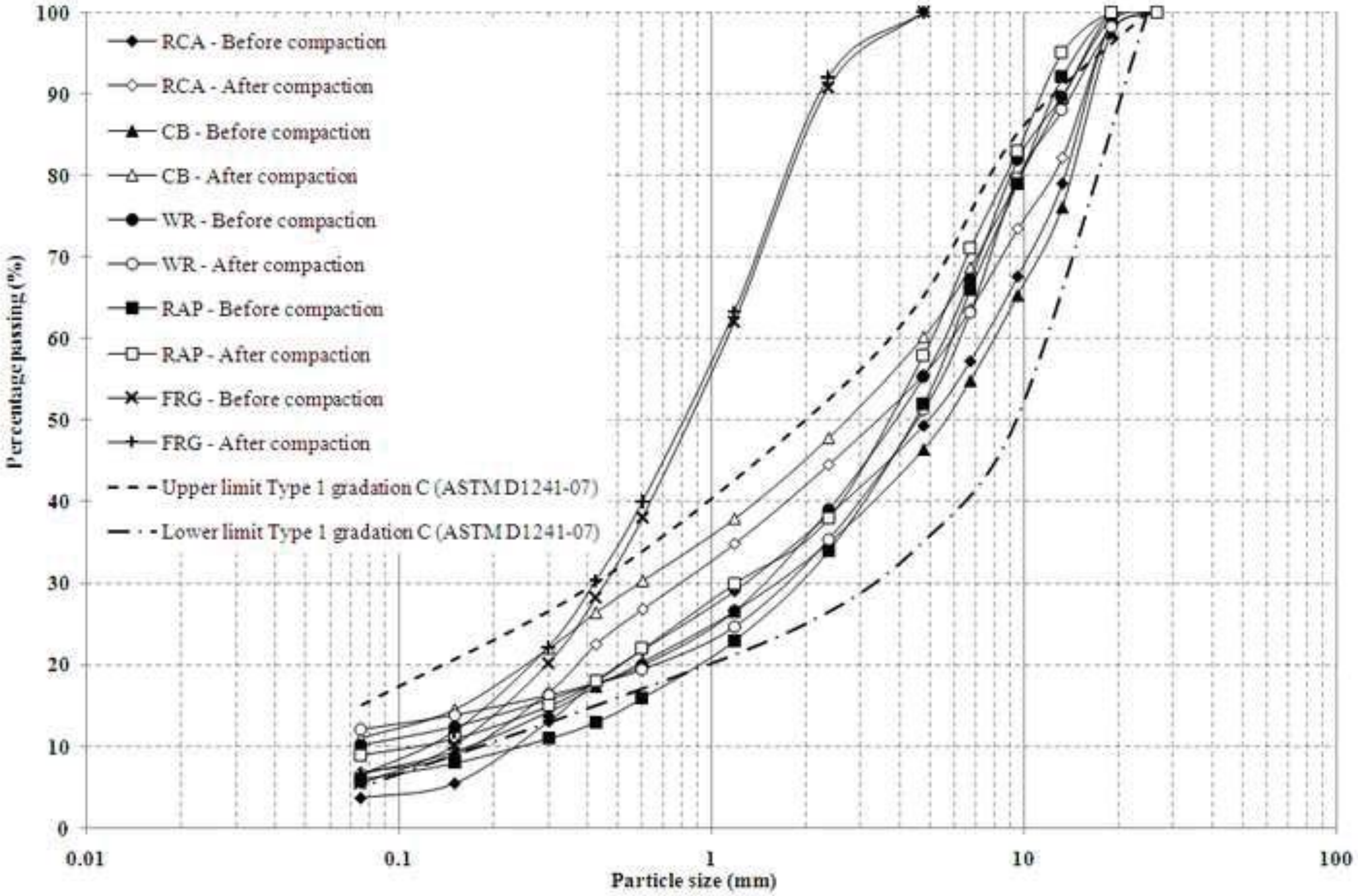

Figure 2

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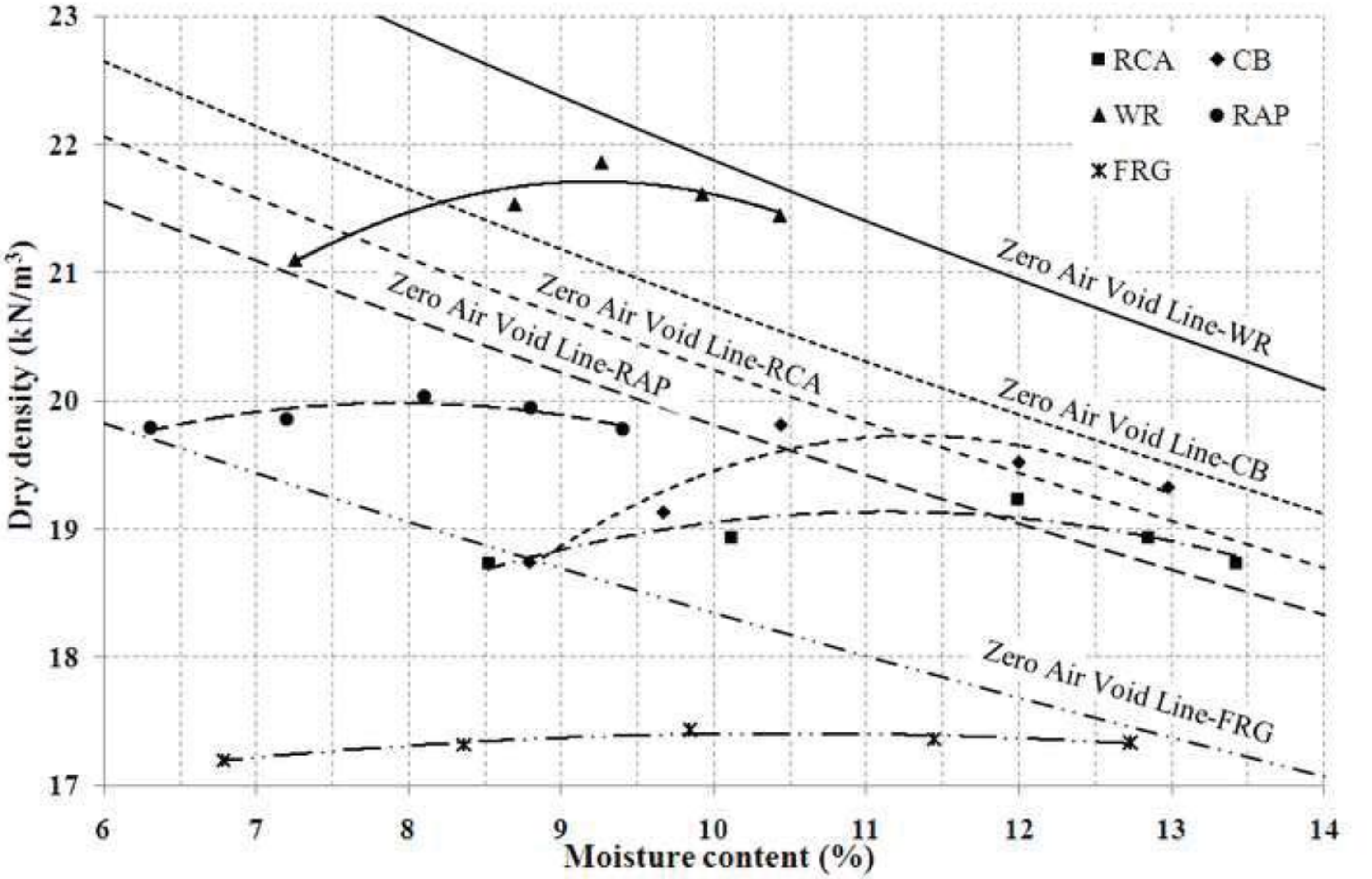

Figure 3

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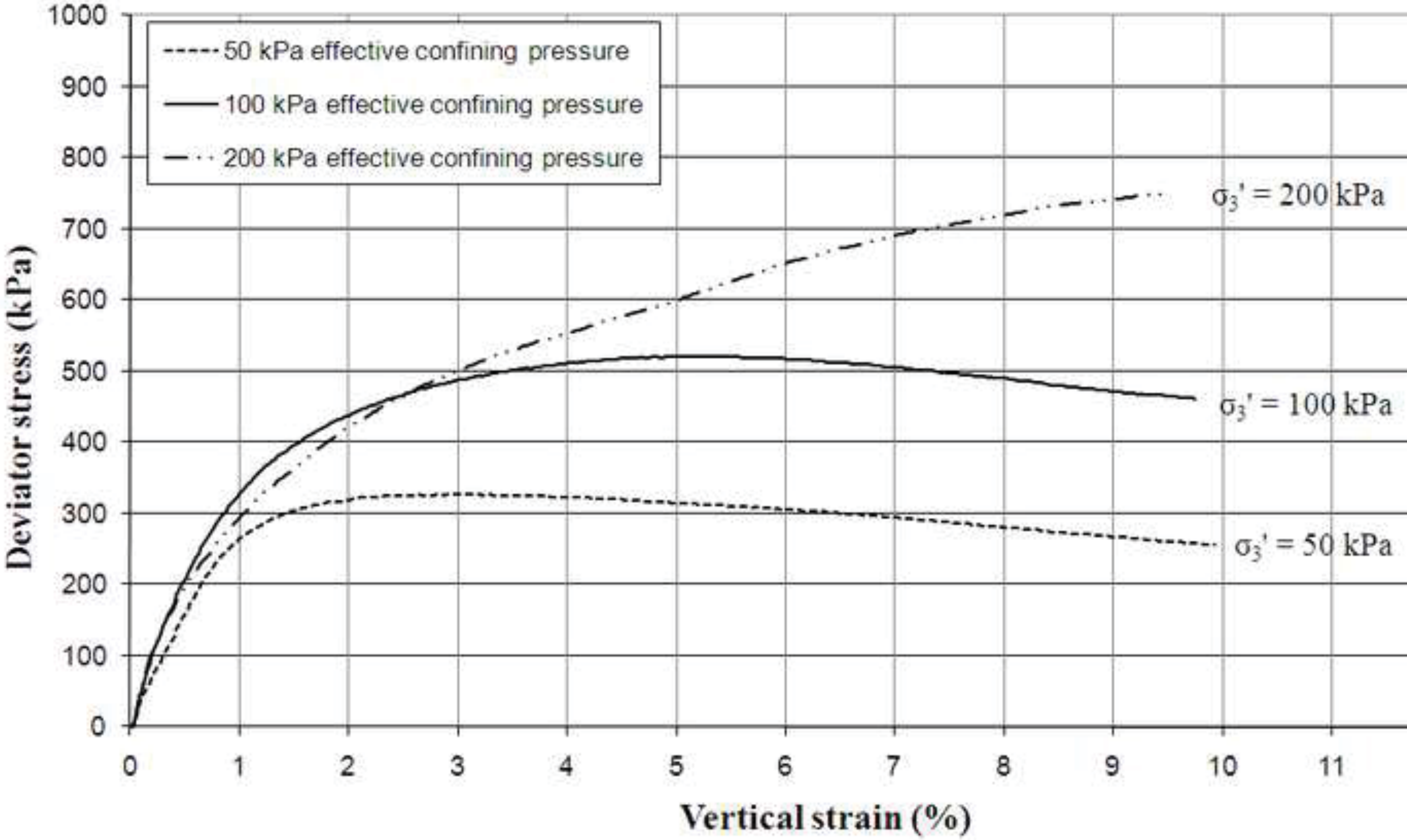

Figure 4

Journal of Materials in Civil Engineering. Submitted March 21, 2012; accepted August 13, 2012;
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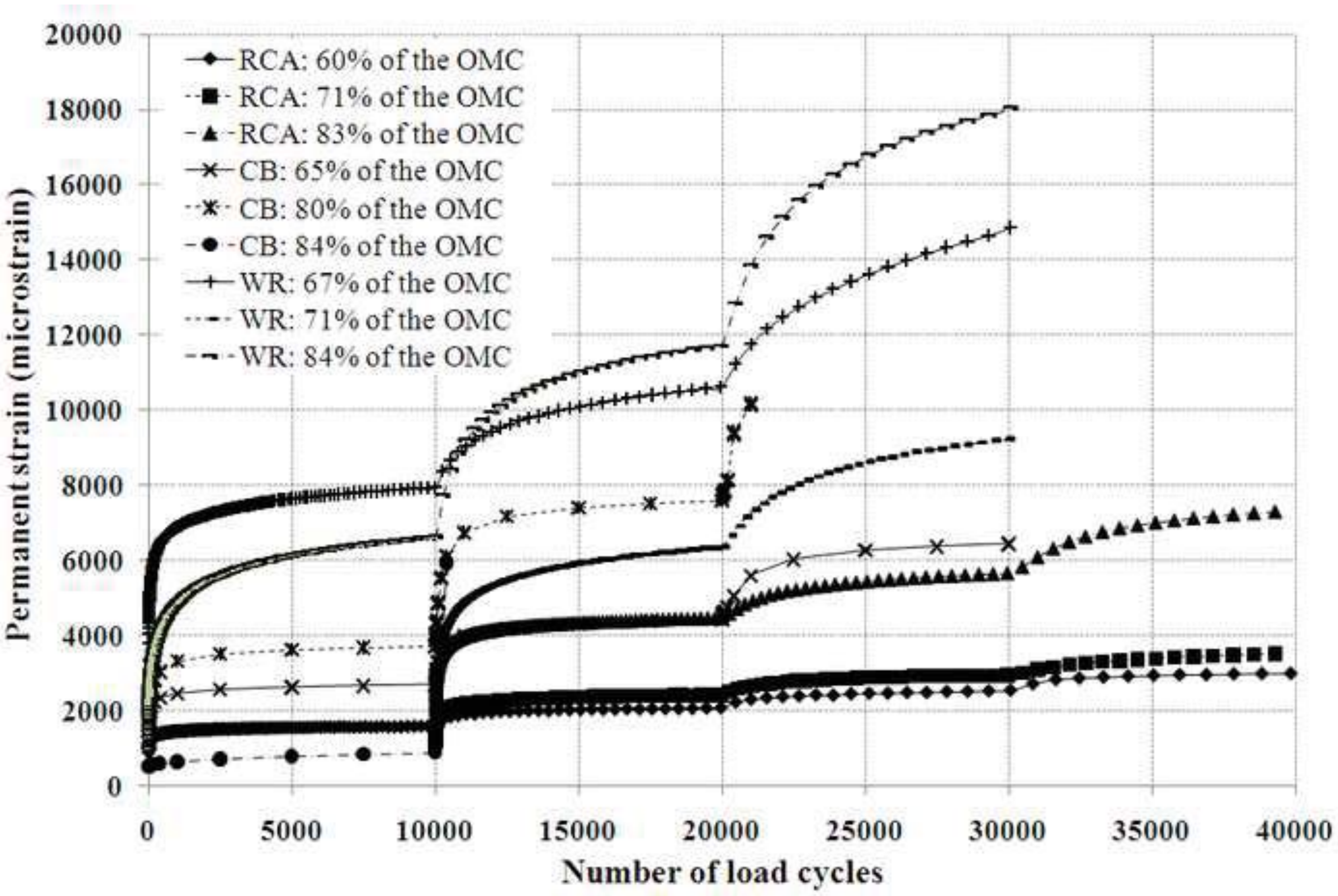

Figure 5

Journal of Materials in Civil Engineering. Submitted March 21, 2012; accepted August 13, 2012;
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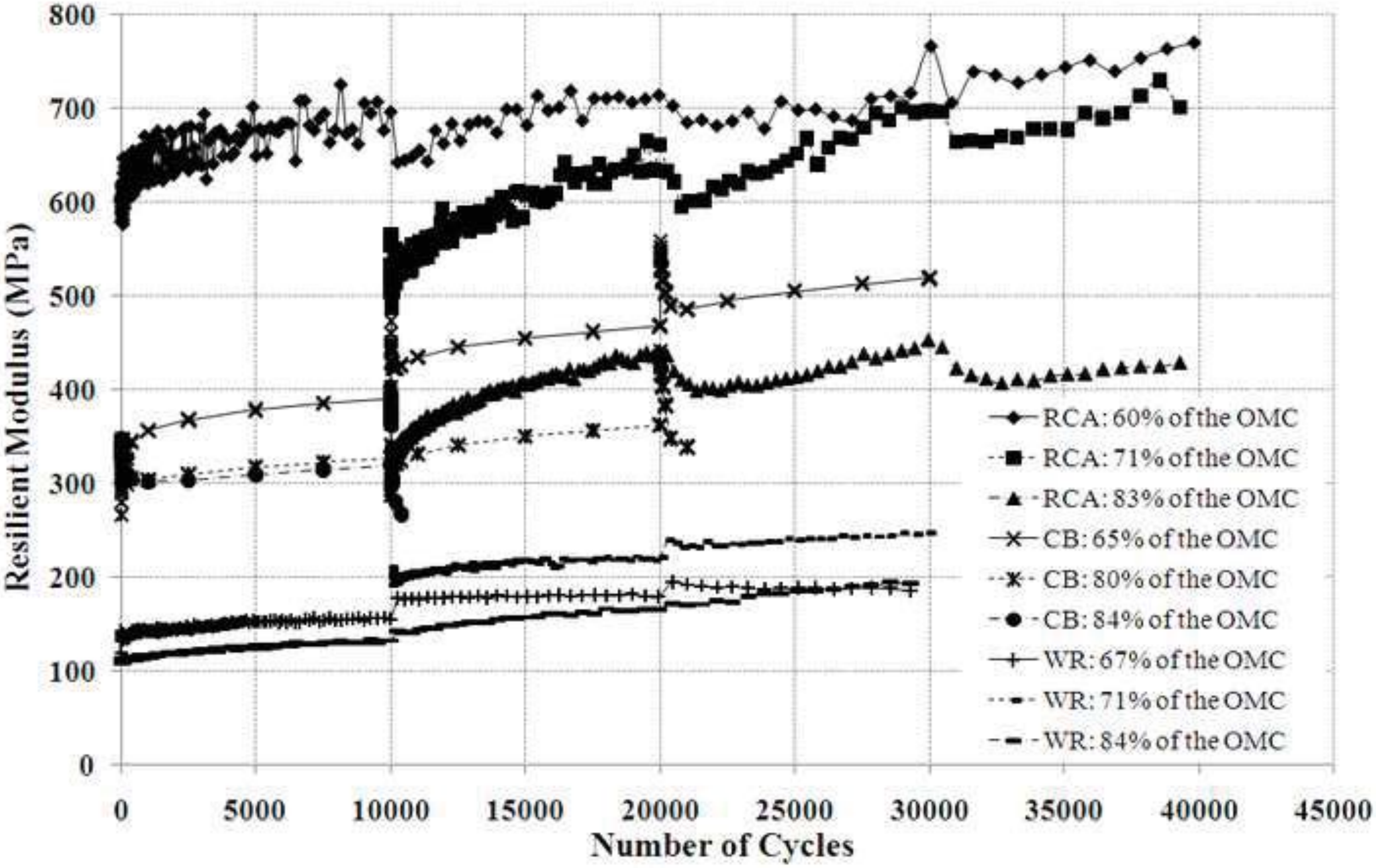

Figure 6

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