# Keynote Address

# Recent advances in the usage of recycled materials in transportation geotechnics

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## ABSTRACT

Priority waste materials currently generated in Australia include construction wastes, demolition wastes, glass fines, waste tyres, plastics, industrial wastes and organic wastes. The increase in generation of these wastes have led to significant research over the past decade on the reuse of recycled waste materials in geotechnical engineering applications. An estimated 7.9 Mt of wastes, which accounts for 36% of Australia's current annual landfilled waste, have the potential to be diverted into civil engineering applications, such as for the construction of roads, railways and land reclamation projects. Recycled materials have been evaluated in the laboratory and new specifications successfully developed, to incorporate their usage in pavement geotechnology and ground improvement applications. Recycled materials are increasingly being used in unbound and stabilised pavement applications. In addition, industrial wastes such as fly ash and slag have also been evaluated in recent years as alternative binders to cement in pavement and ground improvement applications. This paper discusses recent advances in the usage of recycled materials in transportation geotechnics, with reference to case studies of recycled materials usage in Australian projects. Ground improvement projects, comprising of the installation of ground inclusions in waste materials, in an international railway and an airport land reclamation project are also discussed.

*Keywords:* sustainable geotechnics; pavement base; ground improvement; railways; recycled materials; waste.

## 1 INTRODUCTION

An estimated 7.9 Mt of wastes, which accounts for 36% of Australia's current annual landfilled waste, have the potential to be diverted into geotechnical engineering applications, including roads, railways and land reclamation projects. The recycling and reuse of solid wastes for civil engineering projects has become significant in recent years, given the shortages of natural resources and the increasing cost of landfills.

Recycled aggregates, such as construction and demolition (C&D) wastes have in recent years become a mainstream pavement base/subbase material in road construction projects (Hoyos et al., 2011, Puppala et al., 2011, Arulrajah et al., 2018, Yaghoubi et al., 2018, Perera et al., 2019). The reuse of C&D materials in pavement geotechnics projects have reduced the demand for quarry materials and diverted traditional waste materials from landfills (Disfani et al., 2011, Hoyos et al., 2011, Vieira et al., 2020). In addition to C&D materials, other recycled aggregates such as steel slags have also made significant inroads into Australian road projects (Maghool et al., 2019).

Ground improvement projects are increasingly being undertaken on waste tailings and mining ponds. These project involve land reclamation and ground improvement works inclusive of prefabricated vertical drains (PVDs), stone columns and deep soil mixing. Dredging spoils have also been used as a sustainable land reclamation fill material.

This paper discusses some recent advances in the usage of recycled materials in transportation geotechnics projects in Australia and internationally. Case studies of geotechnical engineering projects in pavements, airport and railway construction where recycled materials have been implemented will also be discussed.

## 2 RECYCLED MATERIALS IN PAVEMENT BASES

### 2.1 Unbound recycled C&D aggregates

The main components of C&D materials include; Recycled Concrete Aggregate (RCA), Crushed Brick (CB), Reclaimed Asphalt Pavement (RAP), Waste Rock (WR) and Recycled Glass (RG). Recycled CB, RCA, WR and RAP used in pavement geotechnics projects in Australia have a maximum particle size of 20 mm. RG has a maximum particle size of 4.75 mm (Disfani et al., 2011).

For each recycled material or blend of recycled materials, a suite of extensive geotechnical tests are undertaken to ensure the properties of the recycled materials meet the requirement of road authorities. Characterisation tests undertaken include: particle size distribution, particle density, modified compaction, organic content, pH, hydraulic conductivity, flakiness index, Los Angeles abrasion loss, California bearing ratio and repeat load triaxial (RLT) tests. In addition to geotechnical testing, leachate analyses are undertaken on C&D materials, to ensure the materials are below the threshold required for hazardous waste. The particle size distributions of these C&D materials are shown in Figure 1.

The RLT test is a specialised testing method to determine the resilient modulus and permanent deformation of unbound recycled materials. The

RLT test consists of two phases, permanent strain testing followed by resilient modulus testing. Permanent strain testing phase consists of three or four stages, each undertaken at different deviator stresses and a constant confining stress. The resilient modulus testing phase consists of 66 loading stages with 200 repetitions. Figure 2 shows the permanent deformation results of C&D materials while Figure 3 shows the resilient modulus results.

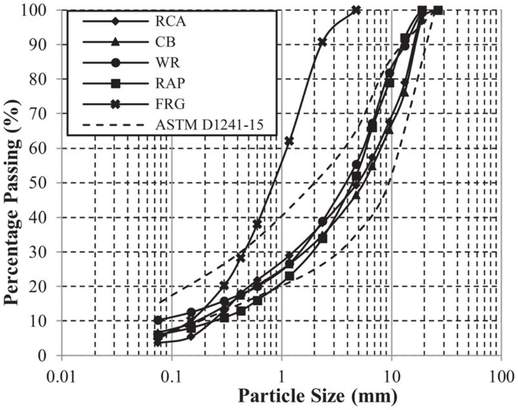


*Figure 1. PSD curves of C&D materials (Arulrajah et al., 2013a)*

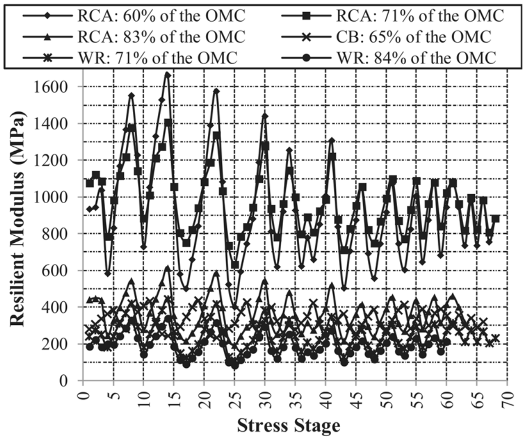


*Figure 2. Permanent strain test results for C&D materials (Arulrajah et al., 2013a)*

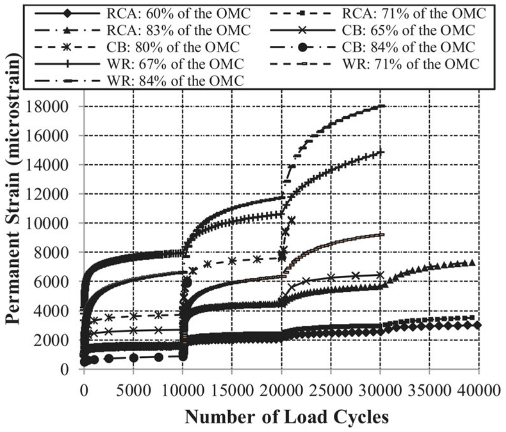


*Figure 3. Resilient modulus test results for C&D materials (Arulrajah et al., 2013a)*

## 2.2 Chemically stabilised wastes

Chemical stabilisation is a ground improvement method that is used to improve the strength of soils and aggregates in transportation geotechnics projects. Cement and lime are traditional binders used for the chemical stabilisation of soils and aggregates. In recent years, alternative binders comprising of waste by-products such as with alkali-activated geopolymers have been evaluated for the chemical stabilisation of geomaterials.

### 2.2.1 Cement stabilised wastes

Research has been undertaken to evaluate the performance of recycled materials in blends with other supplementary recycled products. Figure 4 shows the UCS values for RCA/RG blends, indicating the values met the local road authority minimum requirement of 3.5 MPa, for a minimum of 7 day curing. Further strength increase is evident after 28 days of curing, as compared to after 7 days of curing.

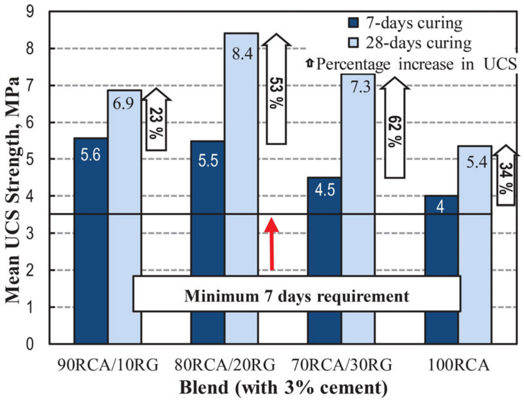


*Figure 4. UCS results of cement stabilised RCA/RG blends (Arulrajah et al., 2015a)*

RLT tests are often undertaken on cement stabilised materials to ascertain the performance under simulated traffic loading conditions. Figure 5 shows typical permanent deformation results for a cement stabilised RCA/RG blends.

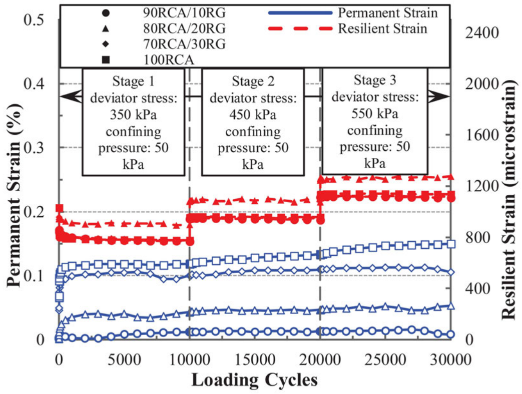


*Figure 5. Permanent deformation results of cement stabilised RCA/RG blends (Arulrajah et al., 2015a)*

Figure 6 shows typical resilient modulus results for an RCA/RG blend. The figures indicate that an increase in the RG content in RCA would result in lower resilient modulus and higher permanent strains.

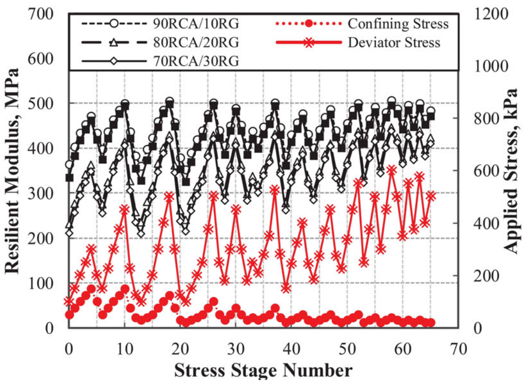


*Figure 6. Resilient modulus results of cement stabilized RCA/RG blends (Arulrajah et al., 2015a)*

Modulus of rupture and fatigue life for recycled products are determined using flexural beam tests. Figure 7 shows the modulus of rupture and flexural modulus for a cement-stabilised RCA/RG blends, indicating these blends are suitable for stabilised pavement bases/subbases. Evidently, the higher the RG content, the lower the modulus of rupture, flexural modulus and corresponding design modulus. The results of the flexural beam tests were compared to that of cement stabilised quarry crushed rock products, to ensure compliance with road authority specifications. Research on cement stabilised recycled products has indicated that the water/cement ratio needs to be maintained at 3.5 to ensure consistent testing outcomes.

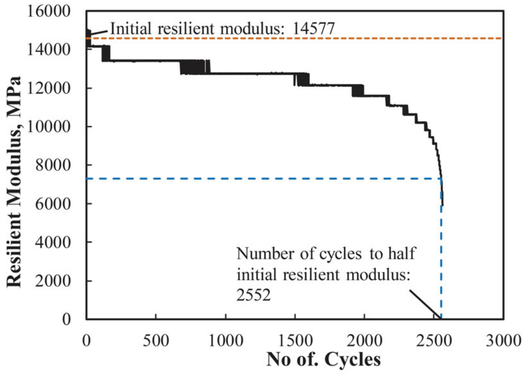


*Figure 7. Fatigue test results of cement stabilised 70RCA/30RG blend (Arulrajah et al., 2015a)*

### 2.2.2 Geopolymer stabilised wastes

Geopolymers have been researched as an alternative binder for ground improvement and pavement stabilisation works. Significant research has been undertaken on geopolymers from a laboratory testing and physical modelling perspective.

Geopolymers comprise of two prime components, being a precursor and an alkali activator. The precursor typically comprises of a material that is in the amorphous phase, such as fly ash (FA) or ground granulated blast furnace slag (S). The multi-compound activator on the other hand typically comprises of a sodium hydroxide and sodium silicate solution.

Other forms of precursors that have been used in recent years include calcium carbide residue, lime kiln dust, cement kiln dust, rice husk ash and bagasse. Potassium hydroxide and potassium silicate solution have also been explored as alkali activators for the stabilisation of demolition wastes.

Geopolymers have been evaluated for stabilisation of demolition wastes for road subgrades, subbases and bases (Mohammadinia et al., 2019, Cristelo et al., 2018). The effect of various temperatures and alkali contents have been studied to optimise the performance of geopolymers. Figure 8 shows UCS testing results from demolition wastes stabilised using potassium-based alkalis in combination with FA and S precursors.

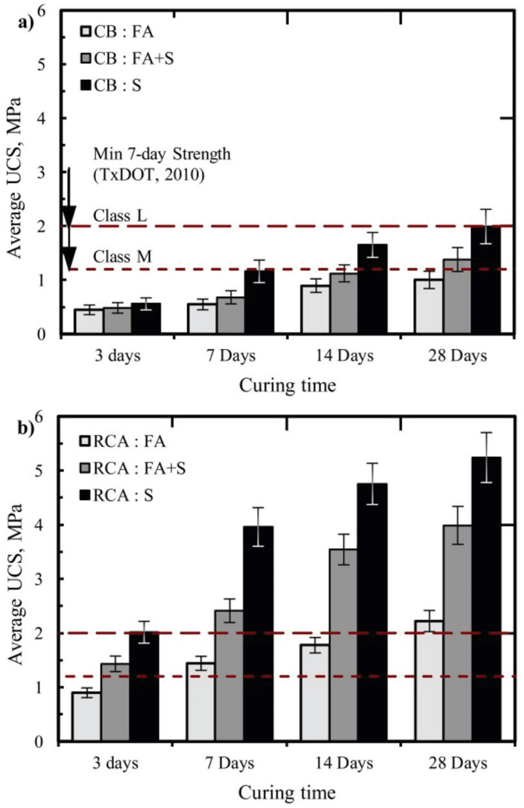


*Figure 8. UCS of C&D wastes stabilised with potassium-based geopolymers: a) CB and b) RCA. (Mohammadinia et al., 2019)*

Geopolymers have also been studied for the stabilisation of marine soils, for applications such as deep soil mixing. Figure 9 shows UCS testing results on a marine soil using geopolymers. Figure 10 shows the effect of temperature on the geopolymer stabilisation of a marine soil.

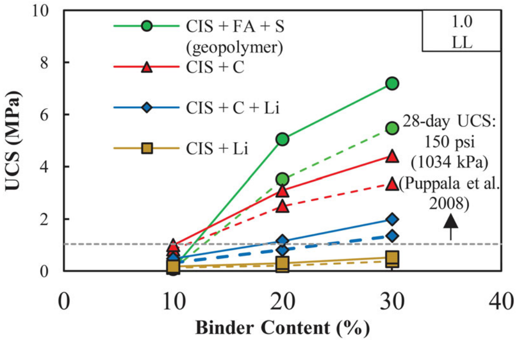


*Figure 9. UCS of Coode Island Silt stabilised with geopolymers (Arulrajah et al., 2018)*

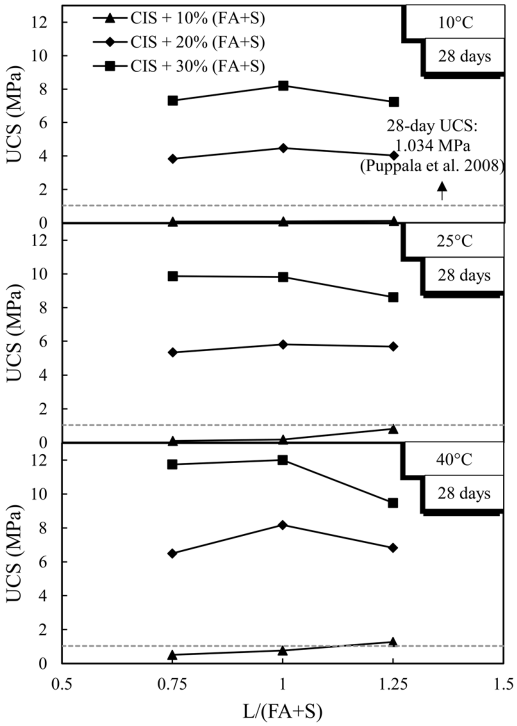


*Figure 10. Effect of temperature on a geopolymer stabilised marine soil (Yaghoubi et al., 2019)*

### 2.3 Field case studies

Following the completion of laboratory evaluation works, several field trial projects have been implemented in the state of Victoria, Australia.

#### 2.3.1 C&D materials in bases/subbases

Nine sections of unbound granular base pavements, comprising of up to 30% RG in blends with RCA and WR, were constructed on the main haul road at a recycling site in the state of Victoria, Australia.

The 200 mm thick pavement subbase layer was constructed with RAP. Figure 11 presents a site photo showing the pavement subbase during placement of the RAP layer. The 200 mm thick pavement base layer was constructed with RG/RCA or RG/WR blends in 7 sections and with RCA and WR for the 2 remaining control sections. Four sections were constructed with RCA with up to 30% RG content. Another three sections were constructed with WR with up to 30% content of RG. Figure 12 shows the laying of the RG base layer.

Field testing were undertaken after placement of the subbase and base layers with a Nuclear Density Gauge and Clegg Hammer. Figure 13 presents the Clegg Hammer results for the pavement base sections. The Clegg Hammer results met the specified minimum soaked field CBR of 80%. Figure 14 shows the compaction of the asphalt surface for the completed road.

*Figure 11. Construction of RAP subbase (Arulrajah et al., 2014)*

*Figure 12. Construction of RG/RCA base (Arulrajah et al., 2014)*

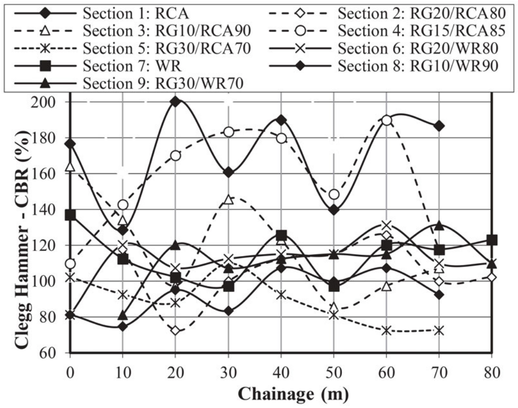


*Figure 13. Clegg Hammer test results for the RG blends in pavement base (Arulrajah et al., 2014)*

Figure 14. Construction of RAP subbase (Arulrajah et al., 2014)

### 2.3.2 Recycled glass in footpaths

An asphalt footpath for shared use by pedestrians and cyclists was constructed at the suburb of Manningham, Melbourne. The shared path comprised of a base layer of nominal 100 mm thickness, overlying a subgrade with a design soaked CBR greater than 3%. The base layer was overlaid by a 30 mm thick asphalt cover.

The asphalt footpath was constructed in three sections, with three different material blends of RG/WR in the footpath base layer. Three trial sections were constructed with 15% RG (RG15/WR85), 30% RG (RG30/WR70) and a control section comprising 100% WR.

Figure 15 shows the footpath sections after completion of field compaction of the base layer. Clegg Hammer test results as shown in Figure 16 were analysed to determine CBR values of the various footpath sections as well as to determine the strength ratios based on a required minimum soaked field CBR of 28% after field compaction.

## 3 GROUND IMPROVEMENT OF MINE TAILING SPOILS FOR A HIGH-SPEED RAILWAY PROJECT

A high-speed 110 km length railway project for trains of speeds of up to 160 km/h was constructed between Rawang and Bidor in Peninsular Malaysia. The railway project traversed a number of abandoned tin mine tailing ponds which had been disused since the end of the global tin mining boom in the late 1980s. Figure 17 shows the location of the railway project site.

The ground improvement methods adopted in the project included vibro-replacement with stone columns and dry deep soil mixing with cement columns. Ground improvement with deep inclusion techniques was required to ensure adequate performance of the embankments in terms of settlement and slope stability as well as completion of the project within the required project duration. The railway embankments in the project had heights ranging from 1 to 12 m. The soils encountered on the project site were highly variable mixtures of very soft silts and clays, as well as loose sands to depths of up to 30 m.

Figure 15. Footpath base sections with RG/WR blends (Arulrajah et al., 2013b)

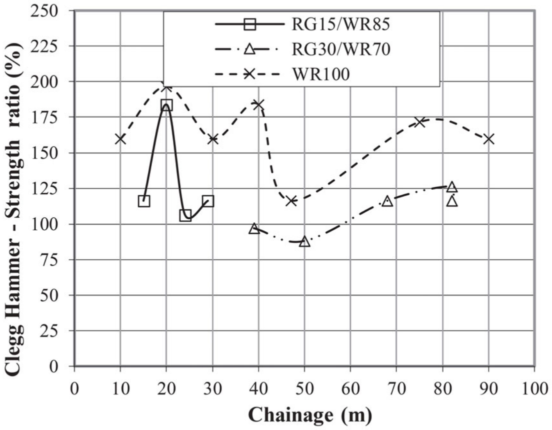


Figure 16. Clegg hammer results for footpath bases with RG/WR (Arulrajah et al., 2013b)

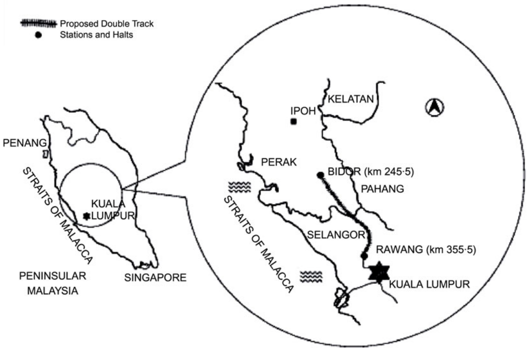


Figure 17. Location of the railway project site in Peninsular Malaysia (Arulrajah et al., 2009)

### 3.1 Stone columns

Vibro-replacement with stone columns is a subsoil improvement method in which large-sized columns of coarse backfill material are installed in the soil by means of special depth vibrators. The stone columns and the intervening soils form an integrated foundation support system having low compressibility and improved load-bearing capacity.

Vibro-replacement with stone columns allows for the treatment of a wide range of soils, from soft clays to loose sands, by forming reinforcing elements of low compressibility and high shear strength. In addition to improving strength and deformation properties, stone columns densify in situ soil, rapidly drain the generated excess pore water pressures, accelerate consolidation and minimise post-construction settlement (Tai et al., 2020, Basack et al., 2017, Indraratna et al., 2015, Gu et al., 2017a, Gu et al., 2017b).

Figure 18 shows a schematic of the vibro-replacement with stone column treatment scheme. Figure 19 presents typical results from a settlement plate installed on the project site. Figure 20 presents an Asaoka plot for a typical settlement plate, which indicates that the degree of consolidation of the improved ground at the location was 94%.

## 3.2 DEEP SOIL MIXING

Dry deep soil mixing (DSM) is a form of soil improvement involving mechanical mixing of in situ soft and weak soils with a cementitious compound such as lime, cement or a combination of both in different proportions. The mixture is often referred to as the binder. The binder is injected into the soil in a dry form. The moisture in the soil is utilised for the binding process, resulting in an improved soil with higher shear strength and lower compressibility (Yi et al., 2018, Chai et al., 2015, Puppala and Pedarla, 2017, Nguyen et al., 2019).

Ground improvement by means of DSM allows for the treatment of a wide range of soils, by forming stronger reinforcing elements of low compressibility and high shear strength. Cement was used as the binding agent in the project, consisting of standard Portland type, grain sizes 0–0.01 mm, and with approximately 65% of activated CaO. The amount of binder is usually in the range 100–150 kg/ $m^3$ of soil. The final result of the deep soil mixing process is a soil mass in the shape of a cylindrical column with improved deformation and shear resistance characteristics. Figure 21 presents a schematic diagram of dry deep soil mixing treatment scheme.

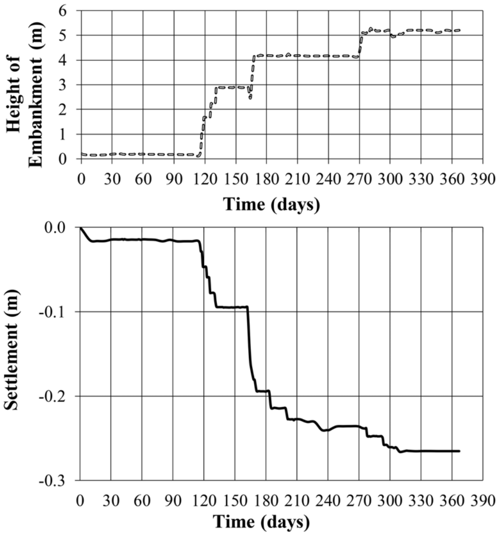


*Figure 19. Plot showing the result of a settlement plate (Arulrajah et al., 2015b)*

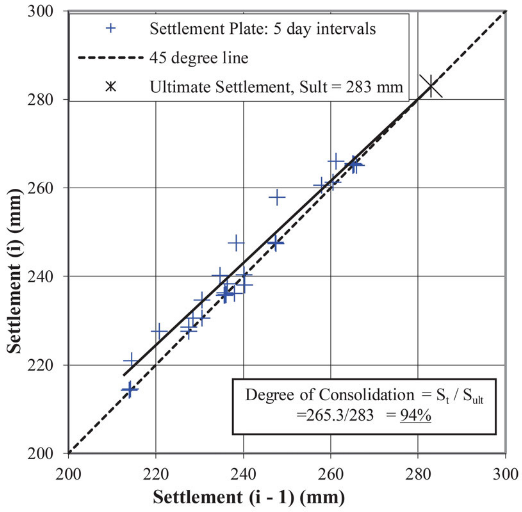


*Figure 20. Asaoka plot for a typical settlement plate (Arulrajah et al., 2015b)*

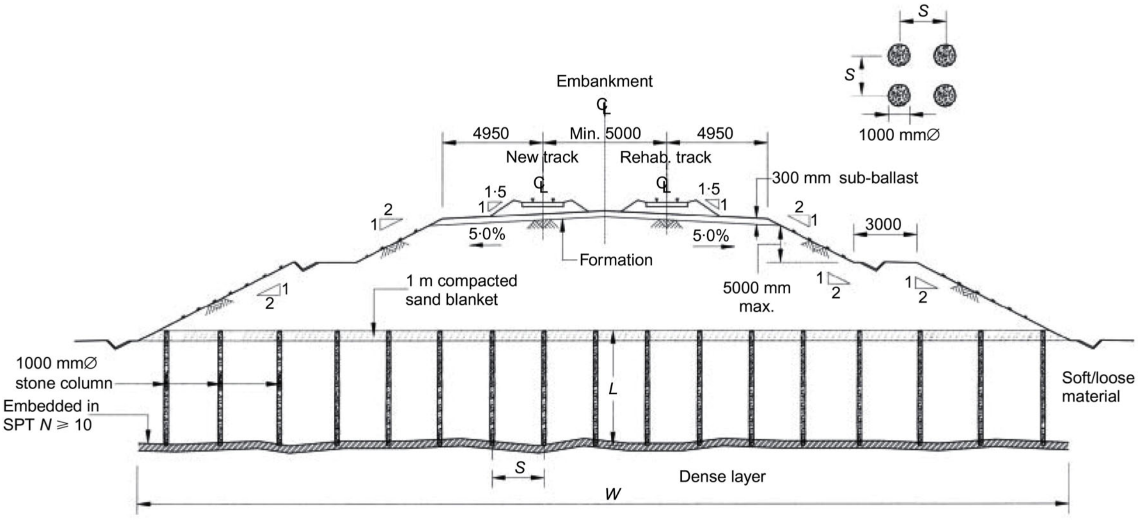


*Figure 18. Schematic of the vibro-replacement with stone column treatment scheme (Arulrajah et al., 2009)*

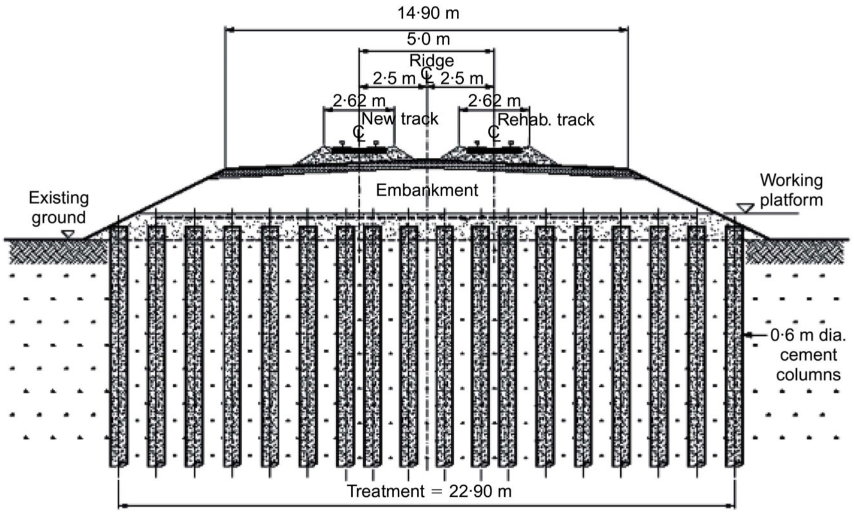


*Figure 21. Schematic of dry deep soil mixing treatment scheme (Arulrajah et al., 2015b)*

## 4 AIRPORT LAND RECLAMATION PROJECT USING DREDGED SPOILS

The Changi East reclamation project was carried out between 1991 and 2005 in five phases to create 2000 hectares of land for the expansion of the Changi International Airport and other infrastructure developments in Singapore. The water depths in the reclaimed area ranged from 5 to 15 m. The project involved hydraulic placement of 272 million m$^3$ of sand in seawater up to 15 m deep (Bo et al., 2018).

The majority of the land reclamation area was underlain by a highly compressible layer of Singapore marine clay, up to 50 m thick. The upper and lower marine clay were highly compressible and had a high water content. An intermediate stiff clay layer was present between the upper and lower marine clay layers at parts of the project site.

The ground improvement technique used to treat the underlying marine clay was with prefabricated vertical drains (PVDs) with surcharge. The total area of the soil improvement works was approximately 1200 ha. The location of the project site is shown in Figure 22.

Due to limitations with the dumping of dredged spoils outside the land reclamation area, the dredged spoils were deposited within the land reclamation site and subsequently treated with PVDs and surcharge. The project also included the land reclamation and ground improvement of a former sand mining tailing pond (locally termed as a Silt Pond), due to sand extraction works for an earlier phase of the Changi airport reclamation works.

### 4.1 Prefabricated vertical drains with surcharge

Approximately 170 million linear metres of PVDs together with surcharge up to 8 m were used to consolidate the seabed soft marine clay and improve its geotechnical engineering properties

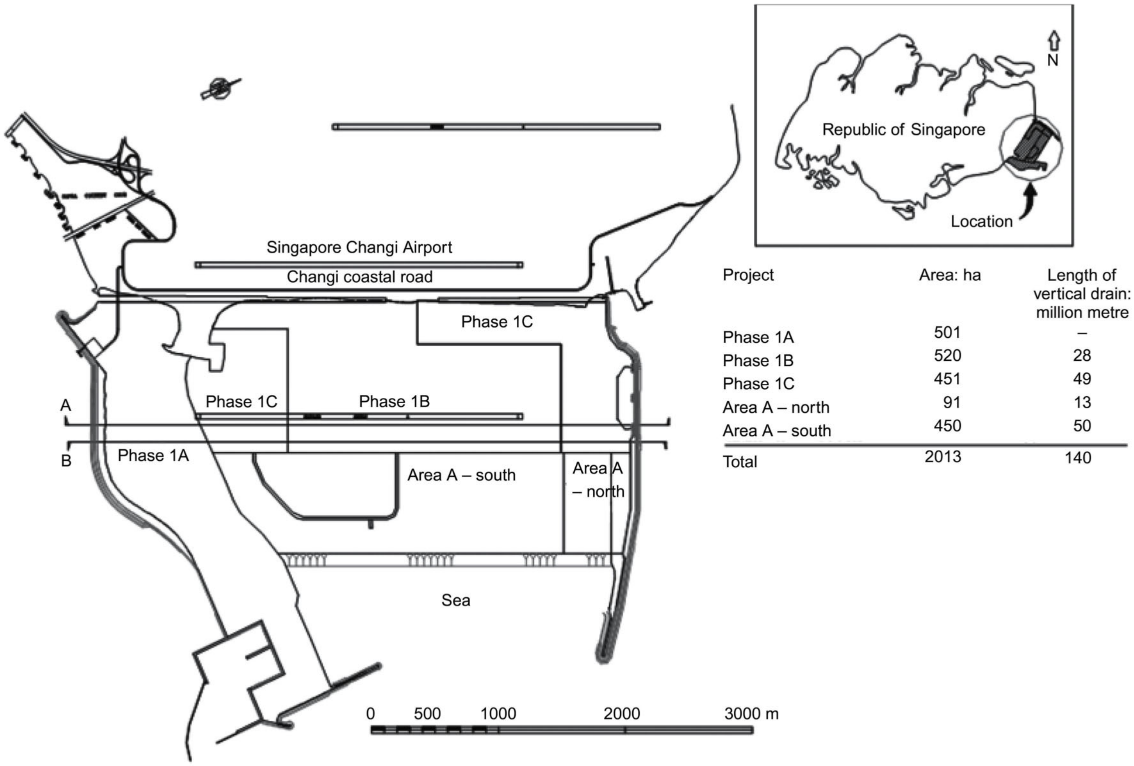
The PVDs were installed when the sand fill reached a level slightly above the high tide. A fill surcharge 8 to 12 m high was then applied. The fill surcharge was chosen based on the anticipated maximum future loads to be applied.

The design specification for the runway in the project was that a degree of consolidation of 90% should be achieved in 18 months, after which surcharge could be removed. Figure 23 shows typical settlement and pore pressure measurements during the project

### 4.2 Deep sand compaction

The hydraulically placed sand fill was generally in a loose state and deep sand compaction techniques were used to densify the sand fill. Three deep compaction methods were deployed: dynamic compaction using heavy pounders, vibroflotation and Muller resonance compaction. The compaction works had to meet specification performance requirements, based on cone resistance values.

Figure 24 shows the layout of deep compaction in the land reclamation project. Figure 25 shows cone resistance measurements at a dynamic compaction location while Figure 26 shows cone resistance at a vibroflotation location.



| Project | Area: ha | Length of vertical drain: million metre |
|---|---|---|
| Phase 1A | 501 | – |
| Phase 1B | 520 | 28 |
| Phase 1C | 451 | 49 |
| Area A – north | 91 | 13 |
| Area A – south | 450 | 50 |
| Total | 2013 | 140 |

*Figure 22. Location and site plan of the project (Bo et al., 2018)*

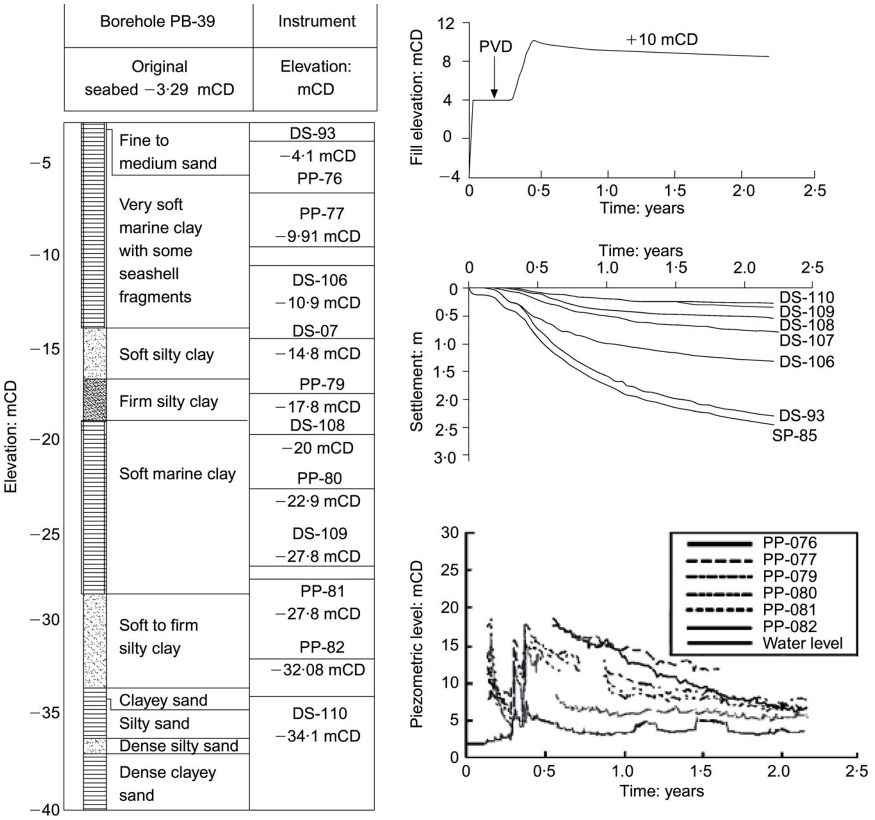


*Figure 23. Settlement and pore pressure monitored during reclamation (Chu et al., 2009)*

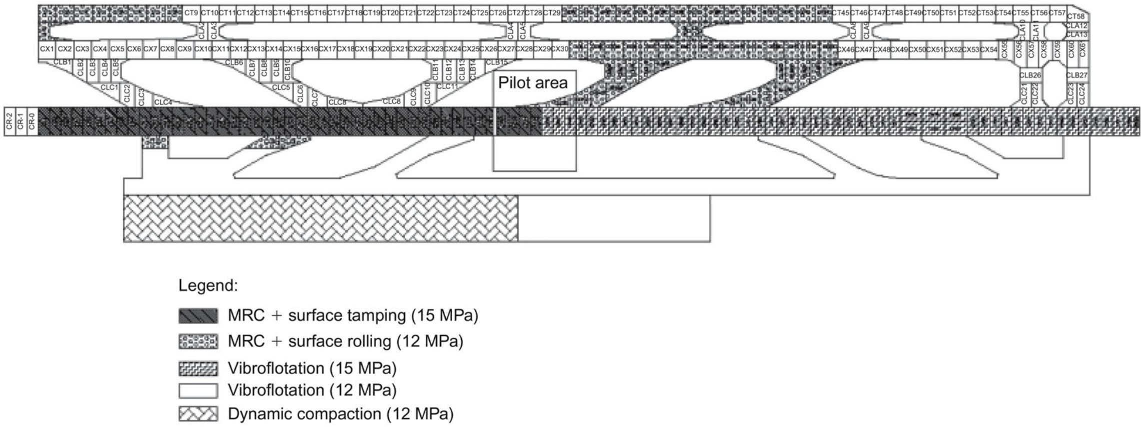


*Figure 24. Layout of deep compaction works in the Changi airport land reclamation project (Bo et al., 2009)*

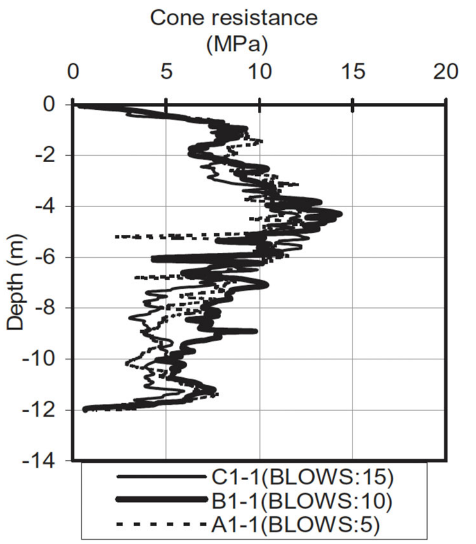


*Figure 25. Cone resistance measurement at a dynamic compaction location (Bo et al., 2015)*

## 5 CONCLUSIONS

This paper reports on the usage of recycled waste materials in several geotechnical engineering projects. The characterisation and implementation of recycled geomaterials for these civil infrastructure projects has been discussed. Several unique case studies have been described which describe the usage of recycled and waste materials in several national and international road, railway and airport projects.

Research on C&D materials for pavement bases/subbases in Australia has been undertaken over the past decade, resulting in these recycled materials becoming a mainstream road construction material. Significant quantities of C&D materials are currently being used in pavement and footpath projects in Australia and internationally. New research projects are presently looking at the usage of these materials in railway subballast/capping layers.

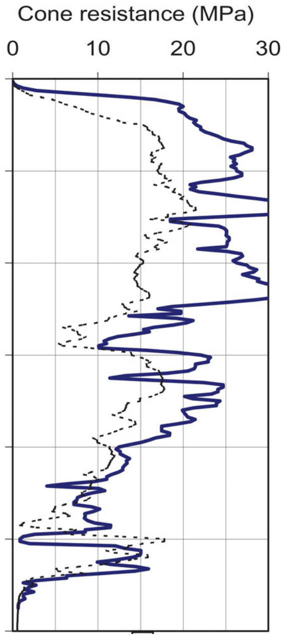


*Figure 26. Cone resistance measurement at a dynamic compaction location (Bo et al., 2015)*

Ground improvement techniques adopted for an international high-speed railway and an airport land reclamation projects using waste materials have also been described. In particular the usage of the PVDs, stone columns and deep soil mixing have been discussed. The ground improvement method to be used for the treatment of waste materials is dependent on various factors such as type of material, height of embankment and thickness of soft or loose deposits.

The usage of recycled waste materials in transportation geotechnics applications will result in a lower carbon footprint for civil engineering infrastructures. Recycled waste materials have in recent years also been found to provide cost and technical benefits. A sustainable engineering approach will assist to divert 7.9 Mt of wastes annually from Australian landfills and into future transportation geotechnics projects.

## 6 ACKNOWLEDGEMENTS

This research was supported under Australian Research Council's Linkage Projects funding scheme (project number LP170100072) and the Australian Research Council Industrial Transformation Training Centre for Advanced Technologies in Rail Track Infrastructure (IC170100006).

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