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Geotechnical characteristics of cement-treated recycled materials in base and sub-base applications

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ABSTRACT

One of the major challenges of the current world and Australia is sustainable waste management. The major proportion of waste material within landfills is Construction and Demolition material (C&D). C&D material can be a suitable alternative for quarry material in pavement applications. Typically, quarried materials are used in pavement base/subbase layers. With the increasing demand for high quality pavement materials and greater limitation of economic natural resources in many parts of Australia, replacement of traditional quarried materials with alternative materials is increasingly preferred from both environmental and economic perspectives. Cement stabilization of pavement bases/subbases is increasingly used in high-traffic metropolitan roads in Australia and worldwide. This paper reports on an investigation of cement stabilization of recycled C&D material in pavement base/subbase applications. Unconfined Compressive Strength (UCS) and Repeat Load Triaxial (RLT) and other geotechnical characterization tests on three type of C&D material treated by cement, have been undertaken.

The process of strength development has been studied to evaluate the properties of Portland cement and its' effect on the strength development of C&D material. The geotechnical properties obtained were compared with existing local and state road authority specifications for pavement base and subbase applications (Austroads, 2009, VicRoads, 2011). UCS tests shows significant strength development in Portland cement treated recycled C&D material. The laboratory testing results indicate that controlling temperature and humidity during the curing time insures the strength development in cement-treated materials. Keeping the moisture content above 98% will facilitate the hydration process.

Keywords: Cement Treatment; Pavement Base; Demolition Material; Secant Modulus

1 INTRODUCTION

Research on the use of commercial and industrial waste material in civil engineering applications has generated interest in recent years. The reuse of these recycled materials will result in a lower carbon footprint, considering that these recycled materials have significant carbon savings compared to extracting virgin quarried materials (Horpibulsuk, et al., 2012, Kampala, et al., 2013). Construction and Demolition (C&D) material constitutes a major proportion of waste materials presented at landfills worldwide. C&D material have been used in recent years in various civil engineering applications such as roads, embankments, pipe bedding and backfilling (Rahman, et al., 2014b).

C&D material investigated in recent years in pavement and footpath applications include granular stabilization of unbound C&D material such as Recycled Concrete Aggregate (RCA) (Gabr and Cameron, 2012, Poon and Chan, 2006), Crushed Brick (CB) (Arulrajah, et al., 2012, Rahman, et al., 2014a), Recycled Asphalt Pavement (RAP) (Hoyos, et al., 2011, Puppala, et al., 2011, Taha, et al., 2002), waste rock (Akbulut and Gurer, 2007, Chakrabarti and Kodikara, 2007) and waste glass (Grubb, et al., 2006, Wartman, et al., 2004). Arulrajah, et al. (2014) investigated the strength parameters and shear strength responses of C&D material. Han and Thakur (2013) conducted extensive literature review for geosynthetic-reinforced recycled material and concluded that geosynthetic-reinforced C&D material can be successfully used in roadway and railway applications.

The objective of this research study is to evaluate the performance of cement-treated C&D material in pavement base/subbase applications, particularly as a majority of metropolitan road pavements are traditionally constructed with the cement-treated quarry aggregates (Rahman, et al., 2014, VicRoads, 2011). The assessment of the performance of cement-treated C&D material, will clarify the existing strength properties. Improving the strength properties by cement stabilization to the level that C&D material can be acceptable for geotechnical applications, will lead to higher uptake of this alternative material and enable the diversion of significant quantities of C&D material from landfills. The assessment of the performance of cement-treated C&D material will insure the performance of stabilized material under critical situation and will result in increased confidence in the usage of these alternative lower carbon materials by end-users, contractors and design consultants alike.

2 EXPERIMENTAL PROGRAM

A series of basic and advanced test have been completed on C&D material for evaluation of their application in base and sub-base layer of pavements. Three types of C&D material was chosen for this research include class 3 Crushed Brick (CB), class 3 Recycled Concrete Aggregate (RCA) and Recycled Asphalt Pavement (RAP). Basic characterization test including particle size distribution, plasticity index tests, pH test, Particle density, water absorption, Los Angeles degradation and modified compaction was carried out for characterization of unbound material. UCS test was then carried out on unbound and stabilized material to determine the strength development. For those blends that show an acceptable UCS value according to local authority (VicRoads, 2011) resilient modulus test was performed to ascertain the performance of the stabilized material under repeated loads.

2.1 Characterization tests

Sieve analysis tests were conducted on materials from three separate stockpiles of C&D material obtained from a well-known recycling facility in Melbourne for consistency purposes and comparison between the results. The particle size distribution (PSD) curves of the untreated C&D material included hydrometer test results. The PSD curves were compared with upper and lower bound size limits specified by the local state road authority shown in Table 1 (VicRoads, 2011).

Table 1: Grading limits for 20mm Class 1 or 2 base for Rocks

Sieve Size (mm)	Limits of Grading (% Passing by Mass)
26.5	100
19.0	95 – 100
13.2	78 – 92
9.5	63 – 83
4.75	44 – 64
2.36	30 – 48
0.425	14 – 22
0.075	07 – 11

Table 2 presents the geotechnical properties of the untreated C&D material. The pH values indicate that the C&D material is alkaline by nature. The foreign material content of the C&D material was visually assessed. RCA comprised of 1.2% CB material and 1.4% RAP material by weight and a very small fraction of other foreign material such as glass, wood and gypsum. CB contained up to 70% brick component, with the balance proportions comprising predominantly of RCA and less than 2% of other foreign materials. RAP contained less than 1% of foreign material.

Table 2: Geotechnical properties of C&D material

Geotechnical Properties	Units	Test Standards	CB	RCA	RAP
Particle density – coarse	ton/m^3	Standards Australia (2000a)	2.68	2.69	2.64
Particle density – fine	ton/m^3	Standards Australia (2000b)	2.64	2.65	2.52
Water absorption – coarse	%	Standards Australia (2000a)	7.02	6.05	3.47
Water absorption – fine	%	Standards Australia (2000b)	10.60	13.60	5.22
Water absorption - average	%	Standards Australia (2000b)	9.0	9.7	4.3
Organic content	%	ASTM (2007b)	1.72	3.07	5.15
Foreign material content	%	Vicroads (2008)	1.8	2.9	0.5
pH		Standards Australia (1997)	10.92	11.85	9.79
Fine Content (%)	%	ASTM (2007a)	7.7	6.0	4.4
Sand Content (%)	%	ASTM (2007a)	33.8	31.5	29.1
Gravel content (%)	%	ASTM (2007a)	58.5	62.5	66.5
Coefficient of uniformity (C_u)		ASTM (2007a)	37.9	38.8	12.9
Coefficient of curvature (C_c)		ASTM (2007a)	1.6	1.3	1.9
USCS		ASTM (2011)	GW*	GW*	GW*
Flakiness index		British Standard (2000)	25.90	16.44	10.63
Los Angeles abrasion loss	%	ASTM (2006)	35.47	30.80	20.81
Max dry density	ton/m^3	Standards Australia (2003)	1.99	1.96	2.06
Optimum moisture content	%	Standards Australia (2003)	11.38	12.49	6.59

* GW: Well Graded Gravel.

Compaction characterization of the materials was assessed using the modified compaction test. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were reasonably close to those of untreated material. Figure 1 shows the compaction curves obtained from modified compaction test. The R^2 of the fitted curves are higher than 0.95 and hence the OMC and MDD was derived from the fitted curve for each of the material.

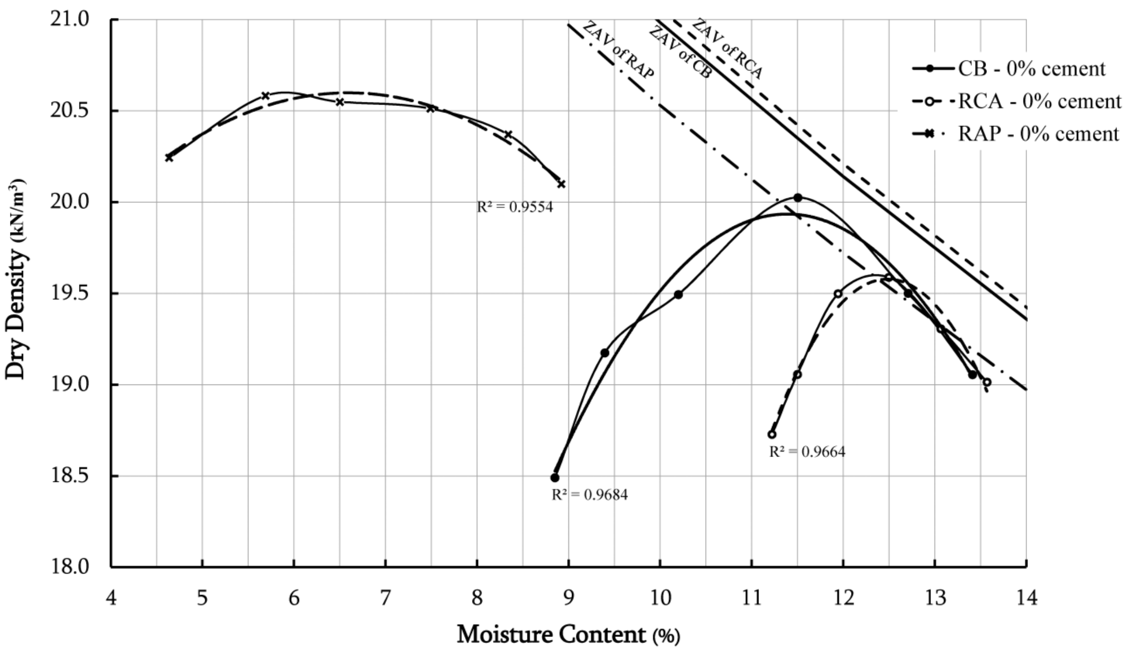

Figure 1. Compaction curves for untreated CB, RCA and RAP

2.2 Unconfined compressive strength

VicRoads (2013) has specified a minimum required value of 4MPa for UCS for 7 days cement-treated pavement base/subbase. UCS tests on untreated C&D material with no curing (immediately after compaction) were undertaken for comparisons between the respective C&D material types. UCS tests were then undertaken on cement-treated C&D material using 2% and 4% cement content by weight. Figure 2 presents the effects of cement content and curing duration on the development of UCS of cement-treated material. RAP had the highest UCS among the untreated control materials, followed by RCA and CB.

The UCS values were compared with low duty cement-treated pavement base/subbase requirements of the local and state road authority (Austroads, 2009, VicRoads, 2011). Texas Department of Transportation (2010) specify 7 days of the curing, however tests at both 1 day and 28 days of curing were also carried out to better understand the strength development of the cement-treated C&D material. For 7days curing time the UCS of the CB, RCA and RAP increased by 680%, 420% and 185% respectively.

Significant increases in UCS values are evident between cement-treated and untreated C&D material, further increases in UCS values was observed as the curing duration increased from 1 to 7 days while moderate increases were observed as the curing period increases from 7 to 28 days. The hydration process was found to progress with time, creating a stronger bond between the aggregates, which leads to improvement in unconfined strength. Higher cement content also increased the resultant UCS values. It is evident from the results that the hydration process in CB an RAP slows down with time. In other words, the UCS starts to increase at a rapid rate at the beginning of the curing period and starts to plateau after 28 days. However RAP continues to gain strength after 7days of curing.

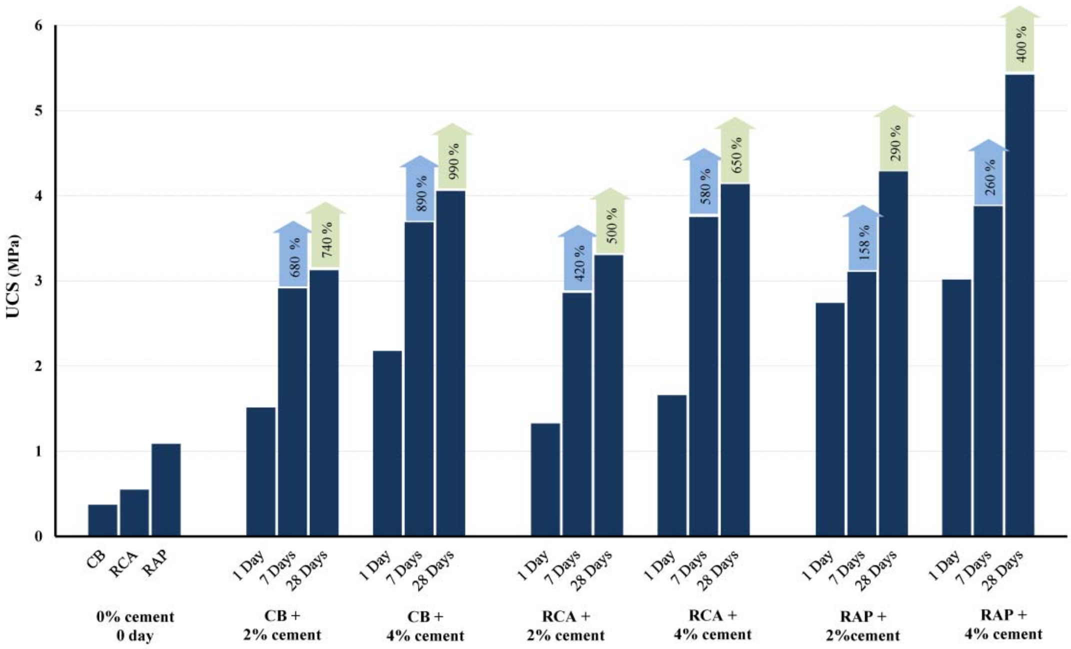

Figure 2. Development of UCS in C&D material with curing time

UCS results for RAP, RCA were found to be higher than CB for both the untreated and the cement-treated options. The strength improvement behaviour of the CB and RCA is slightly different from RAP. RAP showed the highest UCS strength among the C&D material, with 75 to 80% of the final 28 days cured strength of RAP due to cement improvement over the initial untreated material strength. The initial strengths of untreated CB and RCA materials were lower compared to RAP, with 85% to 90% of final 28 days cured strength of CB and RCA material attributed to cement treatment. This indicates that cement treatment enhanced the strength properties of CB and RCA materials compared to RAP material.

2.3 Resilient characteristics

An important aspect of pavement design is obtaining resilient modulus (M_R) of the materials under different confining pressures (σ_c). Figure 3 illustrates resilient modulus for untreated C&D specimens and suggests that the resilient modulus increases as the confining stress increases.

This could be due to the fact that untreated materials tend to get denser as confinement increases (i.e. the stiffness increases), hence, yielding lower recoverable deformations which in turn resulted in higher resilient modulus. Observing the material behaviour under a constant confining pressure under varying deviator stress levels suggests that M_R increases with an increase in deviator stress. The rate of increase in MR due to an increase in deviator stress is higher for low confining pressures, since this stress condition is closer to the failure criteria. As confinement increases and the material gets denser and stiffer, the effect of deviatoric stress on the resilient moduli becomes more moderate. CB has the lowest M_R among the untreated materials and RAP yields the highest MR. This relationship is echoed in the UCS results.

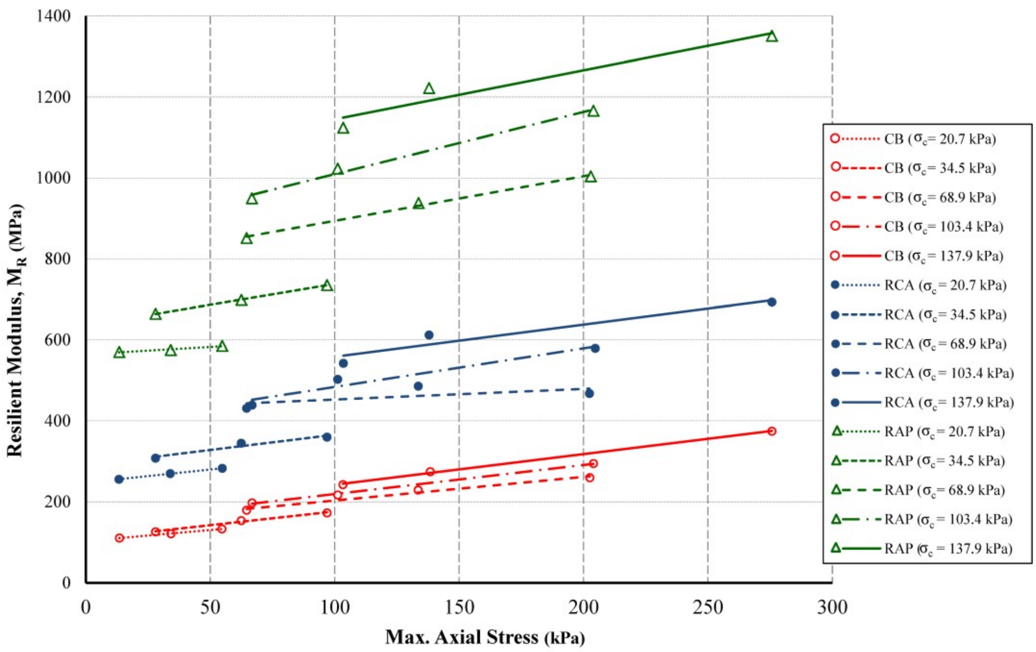

Figure 3. Resilient modulus results for untreated C&D material (Mohammadinia, et al., 2014)

3 SPECIMEN MEASUREMENTS

One of the issues of measuring the vertical deformation over the whole length of the sample while doing UCS or RLT test is that the overall deformation if not realistically measured. The total deformations are distributed through the height of the sample and are far from the failure zone in the middle of the sample. This will lead to lower overall strain on the specimen. The stiffness or secant modulus calculated from these measurements will yield higher Young or Secant Modulus. However, the failure zone for C&D material with bulging failure mechanism usually happened in approximately the middle one-third of the sample (ACI, 2001). Measuring the local vertical deformation can help with more precise interpretation of parameters such as Young modulus and poison ratio (ACI, 2001). Figure 4 shows the setup for measuring the vertical deformation on the approximate failure zone. The setup measures the vertical deformation on the middle 45% of the specimen.

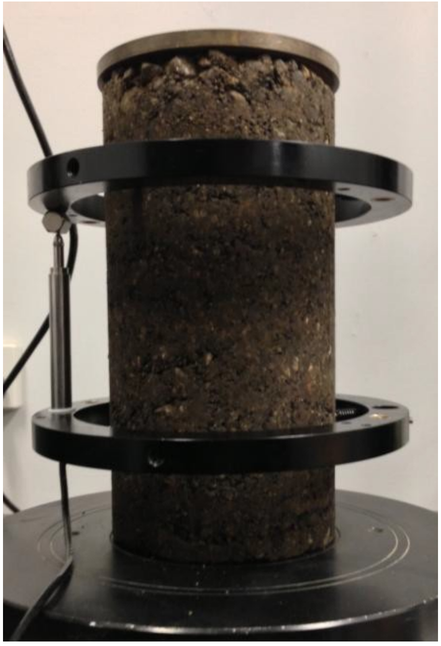

Figure 4. On-Specimen Measurement of Vertical Deformation

Figure 5 shows the secant modulus (E_{50}) measured from the overall strain (i.e. deformation of the top of the specimen) of the treated and untreated UCS samples. Figure 6 shows the secant modulus measured from the same specimens using local measurement (on the middle 45% of the specimen) of vertical deformation at failure zone.

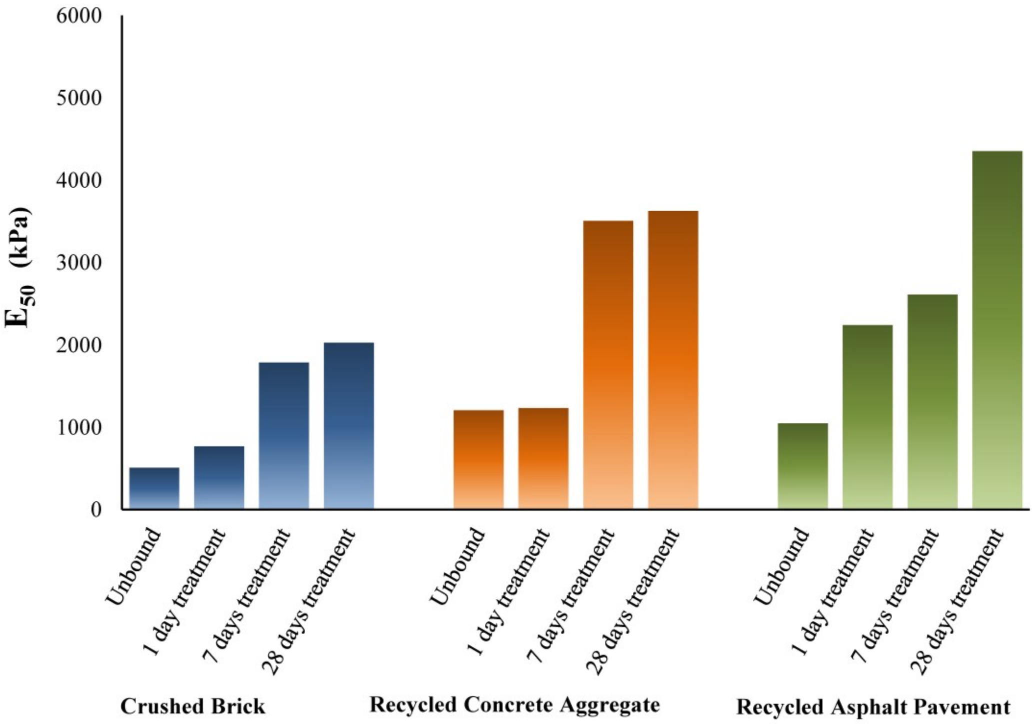

Figure 5. Secant modulus (E_{50}) measured by strain on the top of the sample in C&D material stabilized with 4% cement due to curing time

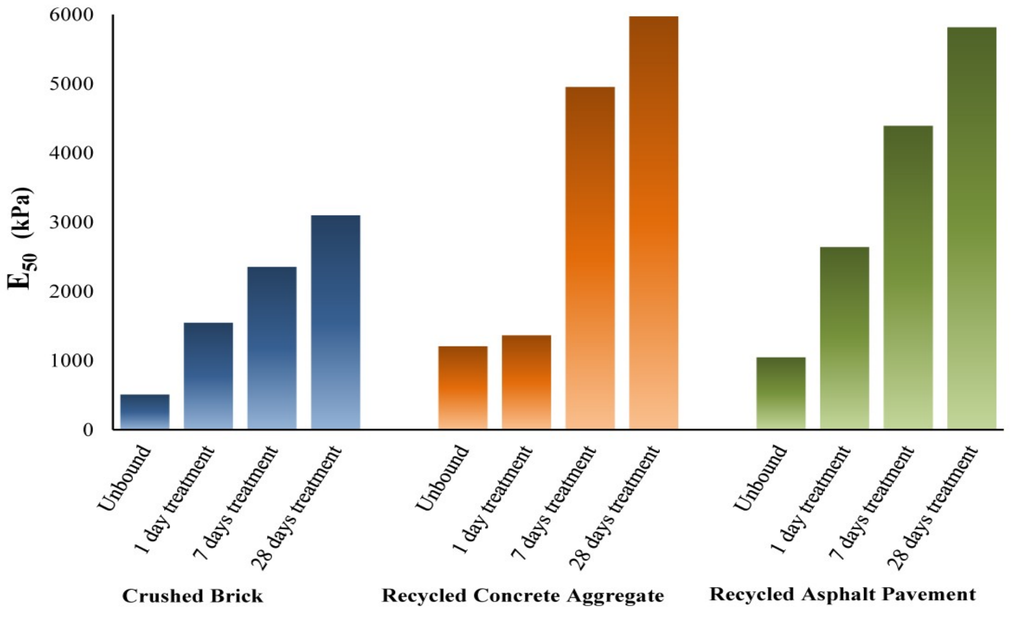

Figure 6. Secant modulus (E_{50}) measured by on the middle 45% of the specimen of strain on the middle of the sample in C&D material stabilized with 4% cement due to curing time

Comparing Figures 5 and 6, the reduction on secant modulus is evident with changing the strain measurement method which suggests the stiffness obtained from standard UCS measurements on C&D material samples by conventional measurments may be misleading and further investigation is encouraged to clarify relevance to these observations.

4 CONCLUSION

The geotechnical properties of cement-treated C&D material were evaluated to assess their performance in pavement base and subbase applications. The effect of curing duration on the strength of the C&D material was analysed for the UCS and RLT tests. Random repetition of the test has been performed to insure the repeatability of the test results. RAP showed lowest OMC for compaction which can be contributed to presence of bitumen and low water absorption of the aggregates. It has also highest dry density followed by CB and RCA.

RAP was found to require 2% cement and 7 days of curing to meet the local and state road authority requirements while RCA and CB required 4% cement with 28 days of curing. RAP was found to have more strength than RCA and CB in all cases with the same cement content and under the same curing duration while RCA was stronger than CB. This can be attributed to the presence of bitumen which results in RAP aggregates. The flexibility of bitumen will results in denser specimen with higher density compared to CB and RCA which will lead to higher UCS strength in unbound RAP compared to other unbound C&D material. Initial dry density of RAP aggregates makes the initial strength of untreated RAP samples high. This gives the indication that the initial strength of aggregates is an important factor on the final UCS strength. Among the C&D material, stabilized RAP has the lowest relative increase in strength compared to its initial unbound strength which shows that cement stabilization was not effective for RAP as much as it was for CB and RCA. However, the final UCS values suggest that RAP is performing the best among the investigated C&D material.

This research study indicates that cement-treated C&D material may be viable alternative materials for cement-treated pavement base/subbase applications.

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REFERENCES

ACI (2001). "Guide for the design and construction of concrete reinforced with FRP bars." A. Committee, ed., American Concrete Institute.

Akbulut, H., and Gurer, C. (2007). "Use of aggregates produced from marble quarry waste in asphalt pavements." *Journal of Building and Environment*, 42, 1921-1930.

Arulrajah, A., Disfani, M. M., Horpibulsuk, S., Suksiripattanapong, C., and Prongmanee, N. (2014). "Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications." *Construction and Building Materials*, 58(0), 245- 257.

Arulrajah, A., Piratheepan, J., Bo, M. W., and Sivakugan, N. (2012). "Geotechnical characteristics of recycled crushed brick blends for pavement sub-base applications." *Canadian Geotechnical Journal*, 49(7), 796-811

ASTM (2006). "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine." ASTM C131, ed., ASTM International, West Conshohocken, PA.

ASTM (2007a). "Standard test method for particle-size analysis of soils. ASTM Standard D422 - 63." ASTM International, West Conshohocken, PA.

ASTM (2007b). "Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils. ASTM Standard D2974." ASTM International, West Conshohocken, PA.

ASTM (2011). "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." *ASTM standard D2487 - 11*, ASTM International, West Conshohocken, PA. Austroads (2009). "Guide to Pavement Technology." A. G. Kieran Sharp, ed., Austroads Limited.

British Standard (2000). "Method for Determination of Particle Shape; Flakiness Index. British Standard 812-105.1." British Standard Institution, London, UK.

Chakrabarti, S., and Kodikara, J. (2007). "Direct tensile failure of cementitiously stabilized crushed rock materials." *Canadian Geotechnical Journal*, 44, 231-240.

Gabr, A. R., and Cameron, D. A. (2012). "Properties of Recycled Concrete Aggregate for Unbound Pavement Construction." *Journal of Materials in Civil Engineering*, 24(6), 754-764.

Grubb, D. G., Gallagher, P. M., Wartman, J., Liu, Y., and III, M. C. (2006). "Laboratory Evaluation of Crushed Glass–Dredged Material Blends." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 132(5), 562 - 576.

Han, J., and Thakur, J. K. (2013). "Use of geosynthetics to stabilize recycled aggregates in roadway construction." 473-480.

Horpibulsuk, S., Suddeepong, A., Chinkulkijniwat, A., and Liu, M. D. (2012). "Strength and compressibility of lightweight cemented clays." *Applied Clay Science*, 69, 11-21.

Hoyos, L. R., Puppala, A. J., and Ordonez, C. A. (2011). "Characterization of cement fiber-treated reclaimed asphalt pavement aggregates: Preliminary investigation." *Journal of Materials in Civil Engineering, ASCE*, 23(7), 977 - 989.

Kampala, A., Horpibulsuk, S., Chinkullijniwat, A., and Shen, S. L. (2013). "Engineering properties of recycled Calcium Carbide Residue stabilized clay as fill and pavement materials." *Construction and Building Materials*, 46, 203-210.

Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M., Bo, M., and Darmawan, S. (2014). "Laboratory Evaluation of the Use of Cement-Treated Construction and Demolition Materials in Pavement Base and Subbase Applications." *Journal of Materials in Civil Engineering*, 0(0), 04014186. Poon, C. S., and Chan, D. (2006). "Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base." *Construction and Building Materials*, 20, 578-585

Puppala, A. J., Hoyos, L. R., and Potturi, A. K. (2011). "Resilient Moduli Response of Moderately Cement-Treated Reclaimed Asphalt Pavement Aggregates." *Journal of Materials in Civil Engineering, ASCE*, 23(7), 990 - 998.

Rahman, M. A., Arulrajah, A., Piratheepan, J., Bo, M. W., and Imteaz, M. A. (2014a). "Resilient modulus and permanent deformation responses of geogrid-reinforced construction and demolition materials." *Journal of Materials in Civil Engineering*, 26(3), 512-519.

Rahman, M. A., Imteaz, M., Arulrajah, A., and Disfani, M. M. (2014b). "Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials." *Journal of Cleaner Production*, 66, 75-84.

Standards Australia (1997). "Soil chemical tests—Determination of the pH value of a soil—Electrometric method." *Australian standard AS 1289.4.3.1,*, Australian standard, Sydney, Australia. Standards Australia (2000a). "Particle density and water absorption of coarse aggregate - Weighing- in-water method. Australian Standard 1141.6.1." Australian Standard, Sydney, Australia.

Standards Australia (2000b). "Particle density and water absorption of fine aggregate. Australian Standard 1141.5." Australian Standard, Sydney, Australia.

Standards Australia (2003). "Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using modified compactive effort." Australian Standard 1289.5.2.1, Australian Standard, Sydney, Australia.

Taha, R., Al-Harthy, A., Al-Shamsi, K., and Al-Zubeidi, M. (2002). "Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases." Journal of Materials in Civil Engineering, ASCE, 14(3), 239 - 245.

Texas Department of Transportation (2010). "Cement Treatment (Plant-Mixed), Item 276 "Austin, TX.

Vicroads (2008). "Manual of Testing: Foreign Materials in Crushed Concrete, ." RC 372.04, ed. VicRoads (2011). "SECTION 812 - CRUSHED ROCK FOR PAVEMENT BASE AND SUBBASE."Contract

Documents, VicRoads. VicRoads (2013). "SECTION 815 - CEMENTITIOUS TREATED CRUSHED ROCK FOR PAVEMENT SUBBASE "Contract Documents, VicRoads,.

Wartman, J., Grubb, D. G., and Nasim, A. S. M. (2004). "Select engineering characteristics of crushed glass." Journal of Materials in Civil Engineering, 16(6), 526-539.