# Recycled Concrete Aggregates in Roadways: A Laboratory Examination of Self-Cementing Characteristics

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**Abstract**

This paper presents an examination of the self-cementing phenomenon of the road construction material known as recycled concrete aggregate (RCA). Two RCA types were selected as the RCA study materials: 1) high grade RCA (HRCA); a quality RCA manufactured from relatively high strength concrete structures, and 2) road base RCA (RBRCA); a quality grade RCA blend combined with brick and general clean rubble (road base material). A series of laboratory tests were performed to obtain the unconfined compressive strength, indirect tension dynamic modulus, and resilient modulus of the test samples in order to examine their hardening characteristics when subjected to varying curing periods. These tests were performed in conjunction with micro-structure analyses from X-ray diffractometry (XRD) and scanning electron microscope (SEM) techniques. The HRCA samples, which were prepared and subjected to varying curing conditions, transformed from an initially unbound material into a bound (fully stabilized) material. The results of XRD and SEM analyses clearly demonstrate that secondary hydration occurred. The RBRCA samples were able to maintain their unbound granular properties, with non-significant self-cementing, thus supporting the hypothesis that the mixing of non-active materials like bricks and clean rubble into RCA will lessen the tendency of RCA toward self-cementing.

**Keywords:** Recycled concrete aggregate; Construction and Demolition (C&D) materials; Base/Subbase course; Self-cementing

## Background

In this era of global warming, the roadway construction sector has been pressured to move towards greater sustainability in the aim for 'clean and green' technology. The use of Construction and Demolition (C&D) materials has recently gained more popularity to be a sustainable option for road and highway construction industry. C&D materials which mainly consist of recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), and crushed brick and rubble are usually generated from the demolition of old and/or out-of-service concrete structures (e.g., buildings, pavements, bridges). These materials have been successfully used in road and highway construction over the past 30 years in its capacity as a sub-standard material suitable for low traffic-volume roads (Jitsangiam et al. 2009). In recent years, research has been undertaken to explore novel and effective mechanical or/and chemical stabilization techniques to treat C&D materials before their reuse in roadway construction (Taha et al. 2002; Hoyos et al. 2011; Puppala et al. 2011; Mohammadinia et al. 2014). However, RCA as unbound granular base/subbase materials are still increasingly being used in road pavement applications.

RCA itself could potentially replace commonly used pavement base materials (i.e., in the base and sub-base layers) due to its strong and stiff core particles. Increases in RCA manufacturing, with improved material properties, make it suitable for specific-purpose road and highway construction around the world. In Australia for example, 10% of the 160 million metric tons of annually-produced quarry aggregate provides sustainable aggregate, of which more than 2 million metric tons is RCA (Department of Innovation Science Research and Tertiary Education 2013).The early development stages and studies in the use of RCA for roadway construction have placed emphasis on RCA's physical and geotechnical properties (Jitsangiam et al. 2009; Arulrajah et al. 2012; Gabr and Cameron 2012; Tatsuoka et al. 2013), along with its performance as an unbound granular material, measured via its resilient modulus and permanent deformation characteristics (Nataatmadja and Tan 2001; Jitsangiam et al. 2009; Cameron et al. 2012; Arulrajah et al. 2013). Specifications for RCA as a roadway construction material have been published in Australia, for example, Pavement Specification 501, (Main Roads Western Australia 2008; 2010; 2011), the ARRB group report (Leek and Siripun 2010), and Specification 3051 (Roads and Maritime Services 2013). For investigation into the long-term performance of RCA pavements, pavement trials have already been performed across the world, using RCA as base and/or sub-base materials, to examine the longevity of such pavements in comparison with design expectations and traditional pavement construction. To date, no conclusion regarding RCA's long-term behaviour has been determined from the trials due to investigations still being underway.

In Western Australia (WA), where pavement trials were conducted using RCA as base and sub-base materials, a sudden and unexpected collapse occurred on a particular RCA pavement trial; the poorly-structured pavement having been in existence for some years. Western Australian road authorities and practitioners have theorised that this type of unexpected collapse in RCA layers is the result of the inherent self-cementing phenomenon of RCA, which appears to occur in the later stages of pavement life. It is believed that this self-cementing phenomenon is probably caused from the secondary hydration reaction of compacted RCA under particular conditions. A considerable increase in the strength of the RCA caused by self-cementing could subsequently result in major damage in the form of reflective cracking in the road surface. The most effective way of examining the effects of self-cementing, such as reflective cracking, is through forensic investigation of pavement damage. However, this is a long and costly process of waiting until the damage occurs. Therefore a laboratory study of self-cementing would provide a solid platform from which to gain a deeper understanding of this phenomenon.

This paper examines whether self-cementing in RCA can occur under laboratory conditions. In addition, changes in RCA properties over varying curing periods are also investigated. A series of laboratory tests were performed under conditions matching those in the field. The tests included the re-creation of the hardening characteristics of RCA (from hydration reactions) which result from transverse cracking in ageing RCA. The intention of the investigation was to provide an enhanced material assessment of RCA, along with a greater understanding of the long-term performance of RCA in pavements, from a laboratory perspective.

***Moduli and performance of RCA in pavements***

In the early stages of its use in roadway (road pavement) construction, RCA's role was to replace the unbound granular material (e.g., crushed rocks). However, the post-construction modulus of RCA is likely to increase over time, unlike a bound granular material which has a relatively constant modulus, ranging from 350-450 MPa (Austroads 2010), throughout a pavement life. An increase in RCA modulus after construction can cause severe damage (e.g., transverse cracking with consequent block cracking) on the RCA pavement.

In this paper the results of pavement trials in Perth, WA, present a view of the long-term performance of flexible RCA pavement in comparison with an unbound granular pavement. This was based on the Falling Weight Deflectometer (FWD) test data from two pavement trials of a RCA-base course layer, constructed in 2003 in Gilmore Avenue (Cheema 2004), and the Kwinana highway extension of crushed rock base course layer (Rehman 2012), constructed in 2009. These trials were utilised to investigate pavement layer moduli and performance after construction. Figure 1 shows a series of the modulus values of a RCA layer in Gilmore Ave, compared to those of the crushed rock base (CRB) layer in the Kwinana highway extension, at different times after construction. The modulus values shown in Figure

1 were derived from back-calculating linear moduli, using EFROMD3 (an enhanced version of EFROMD2 (Voung 1991)), which is based on pavement deflection bowls of the FWD tests performed in both pavement trials.

As the modulus results show in Figure 1, there was a clear growth in the RCA layer moduli over time. It is possible for the RCA modulus to roughly double within the first year after construction and almost triple after three years of construction. With the crushed rock base layer, its moduli were observed as being relatively constant over the period of observation. These modulus results obviously demonstrate why RCA is currently not suitable for road bases. In the visual inspection of Gilmore Avenue on an approximate grid of 1.5m (Leek 2008), minor rutting (i.e., less than10 mm) was apparent, but extensive fine block cracking was evident. The modulus value of a typical RCA layer was more than triple its value after construction. The significant damages occurring show that the material classification and property determination of RCA for use as a road base material require addressing. This should prevent pavement damage which would result from the re-cementing which causes increases in the material modulus over time.

## Materials

### *Recycled concrete aggregates (RCA)*

Two types of RCAs were used in this study to investigate RCA's self-cementing phenomena. The RCAs were sourced from the main supplier in the Perth metropolitan area, namely Capital Recycling. Both materials consisted of:

- High grade RCA (HRCA): a quality recycled concrete material manufactured from the demolition materials of relatively high-strength concrete structures, i.e., buildings and bridges. HRCA was prepared to comply with the given specifications (Main Roads Western Australia 2011) for a base course material.

- Road base RCA (RBRCA) is a high-grade recycled concrete blend combined with approximately 5% (by mass) of brick and general clean rubble which is made to comply with MRWA Specification 501 (Main Roads Western Australia 2011). This specification is particular to RBRCA's use as a road base construction material for WA roads and highways. RBRCA is now used as a commercial product for road and highway construction in WA.

HRCA and RBRCA were then re-examined in the laboratory at the Department of Civil Engineering, Curtin University. The conventional properties investigated were: (Particle Size Distribution, PSD; Liquid Limit, LL; Plastic Limit, PL; Linear Shrinkage, LS; Flakiness Index, FI; Maximum Dry Compressive Strength, MDCS; and California Bearing Ratio, CBR) following MRWA specifications (Main Roads Western Australia 2011). Figure 2 shows the PSD of HRCA and RBRCA, which corresponds to the average particle size of the MRWA (Main Roads Western Australia 2011) base course specifications used in this study. It demonstrates that both materials are almost identical, and that they comply with the specifications in terms of gradation characteristics. Comparisons of the important properties of both materials and specifications were made and are shown in Table 1.

The modified compaction tests of HRCA and RBRCA were performed in accordance with MRWA Test Method WA 133.1 (Main Roads Western Australia 2012) to determine the optimum moisture content (OMC) and maximum dry density (MDD) of both materials. This resulted in an average MDD for HRCA of 2.15 ton/$m^3$ at an OMC of 8.6%, and an average MDD for RBRCA of 2.05 ton/$m^3$ at an OMC of 11.5%.

***Hydrated Cement Treated Crushed Rock Base (HCTCRB)***

To investigate the self-cementing characteristics of RCA in pavements through micro-structural analysis Hydrated Cement Treated Crushed Rock Base (HCTCRB), the most commonly-used road base material in WA, was the reference material used in this investigation. HCTCRB is a unique road base material produced by adding 2% Portland cement (by mass) to  standard crushed rock base (Main Roads Western Australia 2012) at an optimum moisture condition, with particular hydration and retreating processes. More information on HCTCRB can be found in (Jitsangiam et al. 2014).

**Methodology and Experimental Works**

In this study, a special test program was set up in the Geomechanic and Pavement laboratory at Curtin University to produce self-cementing RCA. The length of the test program was set at one year to ensure that RCA self-cementing was based on compaction conditions which replicated given densifications found in real pavements. Note that this laboratory program did not consider the effect of traffic loads on the occurrence of RCA self-cementing. All test samples (HRCA and RBRCA) were prepared at 98% maximum dry density (MDD) and 95% optimum moisture content (OMC). To simulate real pavement conditions after compaction, without traffic loads, all samples were sealed in compaction moulds, wrapped in plastic and stored in a controlled chamber at 80% relative humidity and at constant temperature of 23°C until reaching the target curing periods of 1, 7, 14, 30, 90, 180 and 360 days.

As a first step in investigating the strength and modulus gains of the RCA, the strength properties of compacted HRCA and RBRCA with varying curing periods were examined. This was followed by a series of tests of unconfined compressive strength (UCS). No previous test protocol exists for the determination of the modulus (stiffness) of fully bound pavement materials. Therefore, the indirect tensile modulus test (IDT), in accordance with AS 2891.13.1-1995 (Standards Australia 1995) for asphalt concrete, and the repeated load triaxial test for the resilient modulus ($M_R$) (Austroads 2007) for unbound granular materials were adopted. Finally, the development of compacted HRCA and RBRCA strength and modulus in terms of unconfined compressive strength values, indirect tensile modulus and resilient modulus (i.e., from repeated load triaxial tests) against curing times were observed.

To observe the secondary hydration of RCA, its micro-structure was examined via X-ray diffractometry (XRD) techniques, along with optical investigation through a scanning electron microscope (SEM). The XRD technique establishes the chemical and mineralogical composition of HRCA and RBRCA in comparison with HCTCRB, the reference material, to detect cementitious products, for example, crystalline, $Ca(OH)_2$, and calcium silicate hydrates (CSH). To visibly validate the cementitious products of RCA from the results of the XRD technique, the SEM technique was used to observe and analyse the surface morphology of HRCA, RBRCA, and HCTCRB. As depicted in Table 2, the XRD technique was performed on the specimens at various curing points ranging from 7 days up to 360 days, and the SEM technique was only used after 360 days curing.

### ***Experimental Procedures***

#### *Unconfined compressive strength (UCS)*

The UCS test is a commonly used laboratory strength test; it provides a basic indicator of the strength of compacted samples and is used for quality control in construction in the field. In this study, the UCS tests were performed according to standard test method WA 143.1 (Main Roads Western Australia 2012). During the tests, a UCS test machine applied a monotonic compression load to the specimens at a displacement rate of 1 mm/minute until the tests were completed.

The test samples, 100 mm in diameter and 200 mm in height, were compacted by modified compaction into eight equal layers. All samples were cured for 1, 7, 14, 30, 90, 180, and 360 days and then then extruded from their moulds prior to setting up the tests.

*Indirect tension (IDT) dynamic modulus test*

Based on general mechanistic pavement design approaches, an elastic dynamic modulus determined from repeated load tests is required as a design input. Generally, the elastic dynamic modulus, which is obtained after a certain number of cyclic loading repetitions, is called the resilient modulus ($M_R$); expressed as the ratio between the magnitude of the applied repeated load and total recoverable strain. Standard repeated load triaxial tests, for example, AASHTO Standard T307(AASHTO 2005), BS-EN 13286-7 (British Standards Institution 2004), and AG:PT/T053 (Austroads 2007) are for granular and fine grain soils (unbound mixtures), while standard indirect tension (IDT) dynamic (resilient) modulus tests, for example, ASTM D4123 (American Society for Testing and Materials 1995), BS-EN 12697-27 (British Standards Institution 2001), and AS 2891.13.1-1995 (Standards Australia 1995), are for asphalt concrete and asphalt stabilized materials. At present, there is no specific standard protocol that has been developed to assess the elastic dynamic modulus of fully bound (stabilized) road base materials.

Consequently, in this study, self-cementing RCA, which may become a fully bound material at a certain curing period, was subjected to IDT dynamic modulus tests adapted from the IDT test for asphalt concrete, AS 2891.13.1-1995 (Standards Australia 1995). Due to the unique rheological characteristics of self-cementing RCA and asphalt concrete, appropriate adjustments were required. The peak load was adjusted to achieve a suitable peak transient horizontal deformation within the range of 10-20 micro-strains rather than the 50 micro-strains recommended by AS 2891.13.1-1995 (Standards Australia 1995). This adjustment was made to allow for the relatively high stiffness of self-cementing RCA under test conditions.

A series of tests was performed under a controlled temperature of 25˚C, based on AS 2891.13.1-1995 (Standards Australia 1995). In the test, each specimen was subjected to an applied sinusoidal loading. The rise time, which is the time that loading is increased from 10% to 30% of a peak load, was set at 40 ms; and the recovered horizontal strain was targeted at 15 micro-strains. During the test, five pulses of preconditioning load were initially applied, and this was followed by a set of five pulses of loading. The IDT dynamic modulus value was achieved from the average modulus from the last five pulses.

The test specimens; 100 mm in diameter and 65 mm in height, were compacted using a gyratory compactor to achieve the target MDD and OMC based on the modified compaction test results. All samples were then extruded from the gyratory moulds and cured for 1, 7, 14, 30, 90, 180, and 360 days.

*Resilient modulus ($M_R$) tests*

The test specimens for $M_R$ tests were produced in a standard 100 mm diameter, 200 mm high mould, using a modified compaction method. The specimens were then cured from 1 to 180 days in wrapped moulds to prevent moisture loss. Once curing time was achieved, each specimen was removed from its mould and set up in succession upon the RLT apparatus. The top platen was placed on the specimen and a rubber membrane placed over the specimen and both platens. Finally, the sample was sealed in the system with o-rings at the top and bottom.

For self-cementing RCA, which retains its unbound granular characteristics at a certain curing period, resilient modulus tests were performed according to standard test method AG:PT/T053 (Austroads 2007). These tests were performed under applied stress conditions over 66 stress stages with differing deviator and confining stresses, in order to simulate complex traffic loadings. The stress ratio between the deviator stress and the confining stress ($\sigma_d/\sigma_3$) varied from 2 in the first stage to 25 at the final stage. The deviator stresses varied from 100 kPa to 600 kPa, while the confining stresses ranged from 20 kPa to 50 kPa. One thousand loading cycles of pre-conditioning was carried out prior to the tests. The aim of the process was to allow the end caps to bed-in to the specimen and to ensure that the applied stresses and resilient strains became stable under the imposed stress conditions. Subsequently, 66 stress stages were applied to each specimen in order to conduct the resilient modulus test. At each stress stage, a minimum of fifty loading cycles was applied to the specimen. Each stage terminated when the standard deviations of the last six values of the resilient moduli were less than 5%, or until two hundred loading cycles were reached. The stages then continued in order until all given stress stages were completed.

*X-ray diffractometry (XRD) and a scanning electron microscope (SEM)*

The uncompacted HRCA and RBRCA samples of 7 days curing (i.e., simulating the original condition of materials after mixing with water and before compaction) for the XRD technique, and the compacted HRCA and RBRCA of 360 day-curing periods for the XRD and SEM techniques were ground into a fine powder. The powder was then sieved in order to obtain test particles smaller than 75 µm (i.e., the aperture of sieve no. 200) for analysis. These micro- structure evaluations were performed to establish the chemical and mineralogical composition (i.e., from XRD) and the microscopic images (i.e., from SEM) of the study materials. The evaluations were also conducted to observe the cementitious products (e.g., crystalline $Ca(OH)_2$, calcium silicate hydrates (CSH), calcium aluminium silicate hydrate (CASH), and ettringite), resulting from the self-cementing properties of RCA. In this study, HCTCRB, the most commonly used base course material in WA, with 2% cement (by mass) admixture, was used as a reference material to compare the initial cementitious products of HCTCRB with the likely secondary cementitious product of RCA after re-cementing. In this study the PANalytical X-ray diffractometer at the Mae Fah Luang University, Thailand was used for XRD analysis with CuKa radiation. The SEM samples were coated with gold and scanned using the JEOL scanning electron microscope (SEM) located at Chiang Mai University, Thailand.

## Results and Discussion

The test results clearly exhibit that the strength and the moduli of HRCA and RBRCA, in terms of UCS, IDT dynamic modulus and $M_R$, increase as the length of curing time is extended. However, based on the trends of the UCS and IDT dynamic modulus shown this study, the strength and modulus development of RBRCA samples tends to cease before those of the HRCA (see Figures 3 and 4). Moreover, Figures 3 and 4 also demonstrate that the difference in strength between the two materials is not considerable in the early stages but becomes more evident over longer curing periods. The $M_R$ results confirm the trends of the UCS and IDT dynamic modulus, in that HRCA is prone to be a bound material at a certain curing period, but RBRCA can maintain its unbound granular material behaviour.

### *Unconfined Compressive Strength*

The UCS values for both materials over the range of 1 to 360 curing days are presented in Figure 3. When considering the UCS values in this study, compacted HRCA and RBRCA samples may not be defined as “bound” materials where the UCS is more than 1000 kPa at the 7-day UCS point, following Main Roads Western Australia classifications (Main Roads Western Australia 2010). From Figure 3, it may be seen that the RBRCA strength measures 650 kPa at the first day of curing and its strength continues to develop up to approximately 770 kPa at 90 days. After this point it becomes relatively stable up the 360 day curing point. The initial UCS value of HRCA in Figure 3 illustrates a slightly higher value than that of RBRCA. However, its strength development is more pronounced and continues longer, for up to 180 days. The UCS values of HRCA are then likely to become stable at a slightly higher pressure than 1,000 kPa. When compared the stable UCS values of HRCA to those of cement stabilized materials, around 1,000 kPa of HRCA is approximately the UCS values of 2% cement-stabilized RCA at one day of curing (Mohammadinia et al. 2014), and less than the minimum required value of 4MPa for cement-stabilized crushed rock subbase at 7-day curing, generally used in the state of Victoria, Australia (VicRoad 2013).

Even though the UCS values of a material cannot entirely capture a material response under traffic (cyclic) loading conditions, they can empirically indicate the qualities of a material under applied compressive pressure from vehicle tyres. Based on the UCS results of this study and the threshold of a bound material at 1000 kPa of UCS value, it is noteworthy that HRCA, which can gain UCS of more than 1000 kPa of a bound material's regime, can transform from an initially unbound granular material into a bound material after 180 days. This would indicate that after 180 days, a pavement constructed from HRCA would have a tendency towards failure from transverse cracking, caused by a considerably thick bound layer of HRCA in the pavement. The gain in RCA strength up to the point where it becomes a bound RCA can make a difference to the material concept of HRCA which was originally designed following the unbound granular principle. The RBRCA, which is produced to prevent any strength gain after construction, by blending non-active materials such as bricks and clean rubbles into RCA, exhibits a convincing result in maintaining unbound granular material behaviour (i.e., when the UCS values are less than 1000 kPa).

***IDT Dynamic Modulus***

Figure 4 shows the IDT dynamic modulus results for the materials over the various curing periods of 1 to 360 days. IDT dynamic modulus values for HRCA were slightly higher than those of RBRCA during the first 30 days. IDT dynamic modulus values for both materials developed significantly after 30 days and up to 90 days of curing. At the 90-day point, a difference in IDT dynamic modulus values was more noticeable, as was also the case at levels of 8000 MPa and 6100 MPa for HRCA and RBRCA respectively. After 90 days, the IDT dynamic modulus values for RBRCA increased slightly and became quite stable after 180 days. However, HRCA gained marginally more strength, up to approximately 10000 MPa at 360 days.

As previously mentioned, the results shown in Figure 4 were obtained from adapted standard tests of asphalt concrete, in accordance with AS 2891.13.1-1995 (Standards Australia 1995). It should be noticed that in this study, the peak load was selected as 15 micro-strains to induce a target horizontal strain (i.e., 50 micro-strains introduced for asphalt concrete based on the standard practice AS 2891.13.1-1995), which is usually considered within a range of 10-20 micro-strains. This range of strain values was chosen to generate a peak load of between 30% and 50% of test sample strength, in order to avoid fatigue and to maintain the induced strains within an elastic behaviour regime. To identify the target horizontal strain of 10-20 micro-strains, indirect diametrical tensile strength tests were performed to obtain a typical tensile stress-strain curve. A target horizontal stain range could then be defined, in conjunction with the results of the dynamic diametrical tests, with increasing values of horizontal deformations.

The IDT dynamic modulus would be a more effective parameter within which to represent material behaviour under repeated loading of traffic than would the UCS. The results of the test practice adapted to find the IDT dynamic modulus in this study were in line with the presumptive modulus values of traditional cement-stabilized natural aggregate and cement-stabilized recycled concrete aggregates. This was within the respective range of 10000 MPa-30000 MPa, as reported in previous studies (Jameson 1995; Marradi and Laccieri 2008). When comparing the results in Figure 4 with the aforementioned range of cement-stabilized material, it was found that at around the 1-year point, HRCA makes gains in its elastic dynamic modulus up to the lower boundary of 10,000 MPa of a cement-stabilized material. The IDT dynamic modulus results also confirm that HRCA can transform from an initially unbound granular material into a bound material after a certain period after compaction; a similar result to that of the UCS test.

***Resilient Modulus***

Figure 5 shows the $M_R$ test results for the two materials, with curing times from 1 day up to 180 days. The results demonstrate that the $M_R$ values of HRCA and RBRCA increased with longer curing periods, and HRCA provided higher $M_R$ values than those of RBRCA for all curing periods.

To observe the self-cementing of both materials via the $M_R$ results, all $M_R$ test results were then analysed by fitting the results with the k-θ model, as shown in Eq.1 (Hick and Monismith 1971), which shows the relationship between $M_R$ values and mean normal stress.

$$M_R = k_1 \theta^{k_2} \qquad (1)$$

where $M_R$ = resilient modulus in MPa; $\theta$ = Bulk stress in kPa = ($\sigma_1 + \sigma_2 + \sigma_3$); $\sigma_1$ = major principal stress in kPa; $\sigma_2$ = intermediate principal stress kPa; $\sigma_3$ = minor principal stress or confining pressure in kPa; and $k_1$and $k_2$ = regression constant.

Figure 5 also illustrates the relationship of $M_R$ and mean stress, and the regression parameters derived from these data and Eq. 1 are summarised in Table 3. Generally, with a series of applied stress conditions using the $M_R$ test based on Eq.1; a value of $k_1$ represents the magnitude of the resilient modulus, while that of $k_2$ expresses the influence of the mean stress on a $M_R$ value under a given applied stress condition. A value of $R^2$ generally presents the degree of correlation between data of a specified equation and a set of experimental data. In this study, $R^2$ values were used to evaluate the stress dependency property of the materials by considering $M_R$ with mean stress. In general, an unbound granular material has a stress dependency property (Uzan 1992; Liu et al. 2013), of which the resilient modulus value depends upon an applied stress condition, or a resilient modulus changes when an applied stress is changed, but stress dependency is not a property of a bound material. Based on this stress dependency concept, it could be said that when an effective correlation of Eq.1 and test data is sound, with a high $R^2$ value, a material would behave as an unbound granular material. However, for a bound material, its $R^2$ value is expected to be relatively low. Table 3 shows that the magnitude of $M_R$ for HRCA tends to increase with an increase in curing periods. However, it is also noted that the stress dependency of HRCA becomes insignificant at 180 days of curing, as the $R^2$ of both materials is below 60%, in comparison with the $R^2$ of approximately 98% during the first 90-day curing period. Based on the MR results, HRCA samples would transform into a bound material after a 180-day curing period. For RBRCA samples, the MR results confirm that they still behave in the manner of an unbound granular material.

***X-ray Diffractometry (XRD) and Scanning Electron Microscope (SEM)***

The XRD patterns of HRCA, RBRCA and HCTCRB samples at 7 days (uncompacted materials) and 360 days (compacted materials) are shown in Figure 6 (a) and (b). The XRD results demonstrate that all samples similarly contain A; albite ($NaAlSi_3O_8$), C; calcite ($CaCO_3$), CAH; calcium aluminium hydrate ($CaAl_2O_4.10H_20$), CSH; calcium silicate hydrate ($Ca_5Si_6O_{16}(OH)_2$), E; ettringite ($C_6A\check{S}_3H_{32}$), G; gismodine ($CaAl_2Si_2O_8.4H_2O$), Q; quartz ($SiO_2$) and W; wollastonite ($CaSiO_3$) while the P; portlandite ($Ca(OH)_2$) phase was only found in the 7-day HCTCRB sample due to a renewed hydration reaction from the additional cement in the HCTCRB.

Considerably higher intensity peaks were exhibited in the compacted 360-day curing samples compared to the uncompacted 7-day curing samples. This could demonstrate that compaction conditions of a certain curing period (i.e., 360 days) would provide a more continuous matrix in material grain arrangement, along with suitable conditions for a secondary hydration reaction, leading to generation of a higher amount of hydration products such as CSH.

The CSH phase, mostly detected in HRCA, could enhance strength and lead to self-cementing after compaction. This would be due to the secondary hydration of CaO with the remaining cementitious products as it may be caused by the pozzolanic material (silica), which produces or is instrumental in the additional CSH and may also be caused by additional reaction with the wollastonite phase. The high potential for the occurrence of self-cementing in HRCA can be mitigated by using: RBRCA which contains a small amount of crystalline products of albite and gismodine, and lower CSH phases compared to those of HRCA.

The SEM images of HRCA, RBRCA and HCTCRB samples after 360 days curing are shown in Figure 7. The SEM images show that all samples similarly contain the fabric hydration product (CSH), with a needle-like product (ettringite) on their surfaces and pores. The ettringite crystals in HRCA are easily observed which indicate the advancement of cement hydration. The CSH and ettringite filled the pores, created a dense matrix and contributed to a development in the strength of the sample and/or the self-cementing characteristics. The amount of CSH detected in RBRCA and HCTCRB was lower than that found in the HRCA. The introduction of non-active materials (e.g., bricks and tyres) in RBRCA could reduce the amount of fabric structure, and thus result in lower strength.

**Concluding Remarks**

This paper examined the self-cementing characteristics of RCA prepared under laboratory conditions. The strength and modulus development of compacted RCA samples of HRCA and RBRCA with varying curing periods were investigated. This was undertaken in conjunction with micro-structure analysis using XRD and SEM techniques. The following conclusions can be drawn from the study:

- Self-cementing in HRCA can be instigated under laboratory conditions. HRCA, which contains recycled concrete rubble of sound quality, produced from relatively high strength concrete structures, exhibits more obvious self-cementing properties with longer curing periods. This is demonstrated in HRCA samples prepared under specific compacting conditions (i.e., of a target density and with water added) to replicate a given density as found in the field. Note that in these investigations, densification conditions in the field from the secondary compaction of traffic loads were not included. These observations point towards the necessity for a more effective assessment of the characteristics and the long-term performance of RCA, based on a laboratory regime, in conjunction with existing field investigations.

- The HRCA samples prepared and subjected to curing conditions were obviously transformed from an initially unbound mixture into a bound (fully stabilized) material. The results of the XRD and SEM analyses clearly demonstrate that secondary hydration occurred. This confirms the results from pavement trials in previous field studies. In those studies, a RCA pavement layer, which was originally designed in line with the unbound granular principle, mostly transformed into a mostly bound material over a period of years following construction.
- The test results of UCS, IDT dynamic modulus, and resilient modulus in this study indicated that after approximately 6 months, the HRCA samples exhibited considerable bound material properties. However, the RBRCA could maintain properties in the range of those found in an unbound granular material. However, based on the results of the Gilmore Avenue observations (see Figure 1), it was approximately 2-3 years post-construction before a RCA layer reached a bound condition (i.e., the modulus trend was constant). Based on the results of this study, a definitive conclusion of exactly when RCA transformed into a bound material cannot be made.
- The test results for the RBRCA used in this study suggest that the mixing of non-active materials like bricks and clean rubble into the RCA may reduce the subsequent negative effects of self-cementing. RBRCA samples can maintain unbound granular properties with non-significant self-cementing. This means that using the unbound granular principle in pavement design may apply to the entire life of a pavement built from RBRCA.
- The explicit trends in the UCS and IDT dynamic modulus results for HRCA (see Figures 3 and 4), which represents a normal RCA, conformed to the trend of the modulus development of the Gilmore Avenue example, which was built from RCA

material (see Figure 1). However, modulus values from laboratory tests (UCS and IDT dynamic modulus) and field tests (FWD) are obviously not comparable.

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## List of Tables

Table 1. Important properties of HRCA and RBRCA

| Methods[1] | Test | HRCA | RBRCA | Specification |
|---|---|---|---|---|
| WA 120.2 | Liquid Limit | N/A | N/A | <35% |
| WA 123.1 | Linear Shrinkage | 0.7% | 0.6% | <3% |
| WA 220.1 | LA Abrasion | 29% | 34% | <40% |
| WA 140.1 | Max. Dry Compressive Strength | 2628 kPa | 2432 kPa | > 1700 kPa |
| WA 141.1 | CBR[2] | 120 | 118 | >100% |
| WA 143.1 | UCS[3] | 0.68 MPa | 0.65 MPa | < 1 MPa |

Note:

[1]Test methods in accordance with MRWA Test Methods (Main Roads Western Australia 2011)

[2]CBR tested for samples prepared at 98% MDD, 100% OMC and 4-day soaked

[3]UCS tested for samples cured for at 7 days and soaked for 4 hours

Table 2. The testing scheme

| Materials | Curing days | UCS | IDT | $M_R$ | SEM | XRD |
|---|---|---|---|---|---|---|
| HRCA | 1 | T | NT | T | NT | NT |
| | 7 | NT | NT | NT | NT | T |
| | 14 | T | NT | NT | NT | NT |
| | 30 | T | T | NT | NT | NT |
| | 90 | T | T | T | NT | NT |
| | 180 | T | T | T | NT | NT |
| | 360 | T | T | NT | T | T |
| RBRCA | 1 | T | NT | T | NT | NT |
| | 7 | NT | NT | NT | NT | T |
| | 14 | T | NT | NT | NT | NT |
| | 30 | T | T | NT | NT | NT |
| | 90 | T | T | T | NT | NT |
| | 180 | T | T | T | NT | NT |
| | 360 | T | T | NT | T | T |
| HCTCRB | 180 | NT | NT | NT | T | T |
| | 360 | NT | NT | NT | T | T |

Note: T=Tested; NT= Not tested

Table 3. Regression parameters for the resilient modulus test results of HRCA and RBRCA

| Material | Curing days | Regression parameters | | |
|---|---|---|---|---|
| | | $k_1$ | $k_2$ | $R^2$ |
| HRCA | 1 | 6.9 | 0.792 | 0.982 |
| | 90 | 98.5 | 0.399 | 0.975 |
| | 180 | 305.6 | 0.265 | 0.560 |
| RBRCA | 1 | 3.0 | 0.931 | 0.982 |
| | 90 | 61.2 | 0.464 | 0.977 |
| | 180 | 69.2 | 0.462 | 0.935 |

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