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Transportation Geotechnics 39 (2023) 100934

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Permanent deformation response of demolition wastes stabilised with bitumen emulsion as pavement base/subbase

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ARTICLE INFO

Keywords:
Demolition wastes
Bitumen emulsion
Base stabilisation
Granular base
Permanent deformation

ABSTRACT

The stabilisation of the granular base course using binders has been adopted for many years; however, the use of bitumen emulsions has been emerging in recent times. Nevertheless, there is limited knowledge on the deformation behaviour of bitumen emulsion-stabilised recycled demolition wastes, particularly in pavement base and subbase applications. In this study, the effect of bitumen emulsion on the permanent deformation behaviour of two types of recycled demolition wastes, recycled concrete aggregate (RCA) and crushed brick (CB) is evaluated. The aggregate samples were blended with an anionic slow-set bitumen emulsion at different contents of 0, 1, 2, and 3 % by dry weight of aggregates. Compacted specimens were partially dried to achieve target values of 70 and 90 % of their optimum moisture contents to investigate the effect of in-service moisture content. Specimens were next subjected to repeated loading triaxial tests that comprised of multiple stages at varying stress levels to simulate moving loads of vehicles. The shakedown theory was adopted to characterise the blends based on their permanent deformation responses. Most of the proposed blends exhibited a Range B behaviour, i.e., plastic creep responses. Also, CB samples generally experienced higher permanent strain accumulations and hence, inferior permanent deformation responses compared to RCA. The inclusion of bitumen emulsion to the aggregates generally caused a decrease in resilient strains, showing that emulsion-stabilised RCA and CB could provide increased resistance under repeated traffic loading. It was also concluded that higher moisture contents led to higher permanent strains and permanent strain rates.

Introduction

The current practice of pavement construction mainly relies on quarried rock and aggregates. However, the quarried materials typically sourced from aggregate mines for civil construction applications are becoming scarce [13]. The use of virgin materials in high-material-consuming projects, such as construction projects, is known to be an unsustainable practice. At least a third of carbon emissions and generated solid wastes are produced due to construction activities [11]. Therefore, more sustainable approaches, such as the use of recycled materials instead of virgin quarry aggregates, have been adopted and investigated for developing road infrastructures because recycled materials have considerable carbon savings compared to those of virgin materials [31].

Construction and demolition (C&D) wastes comprise solid waste generated during the demolition of existing structures or the construction of new infrastructures. C&D materials are commonly generated as a result of excavations, the demolition of infrastructures, and the maintenance and rehabilitation of buildings [19]). Among the many types of C&D materials, four common occurring types include recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), crushed brick (CB) and waste rock. These have been identified to exhibit properties

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https://doi.org/10.1016/j.trgeo.2023.100934
Received 7 December 2022; Received in revised form 9 January 2023; Accepted 10 January 2023
Available online 13 January 2023

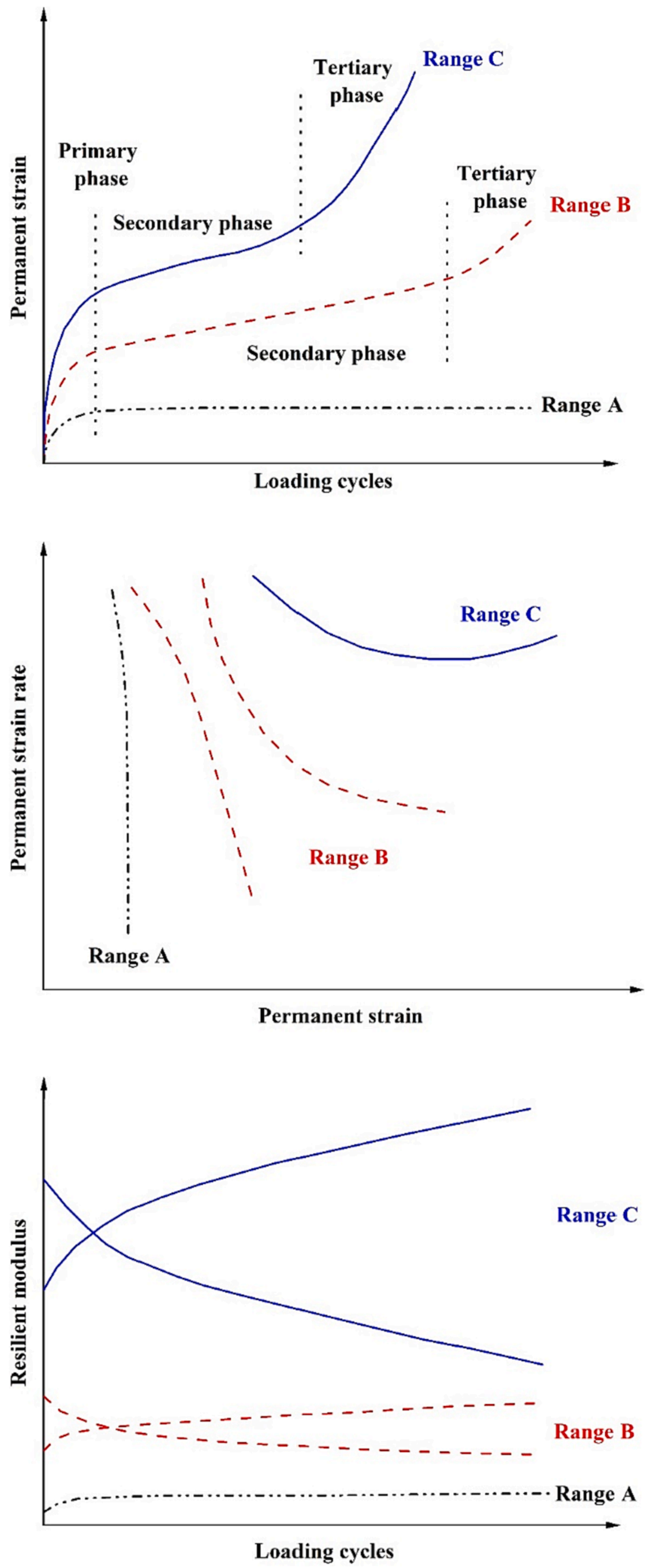

Fig. 1. Permanent deformation response of unbound granular aggregates according to shakedown theory: (a) permanent strain *vs* load cycles, (b) permanent strain rate *vs* permanent strain, and (c) resilient modulus *vs* loading cycles (modified after Werkmeister et al. [34].

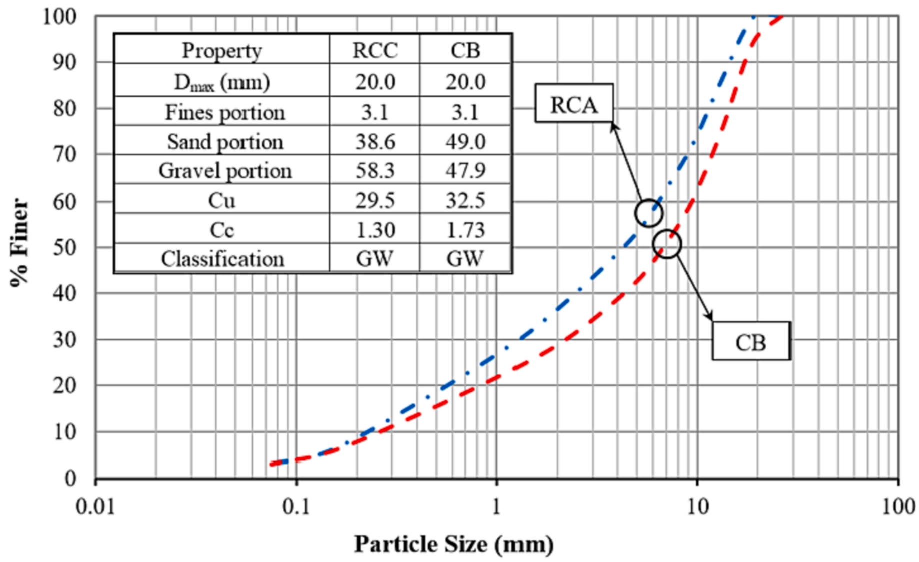

Fig. 2. Particle size distributions of RCA and CB.

Table 1
Properties of the anionic slow-set bitumen emulsion.

Property	Test method	Specification limit	Results
pH	AS 2341.32 [7]	11–13	12
Viscosity (cP)	ASTM D2196 (2020) [9]	30–90	42
Binder content (%)	AS 2341.23 [6]	Minimum 60	60.9
Sieve residue (%)	AS 2341.26 [8]	Maximum 0.15	0.05

Table 2
Sample ID and mix designs.

Sample ID	Bitumen emulsion content	Targeted OMC
RCA-70 %	0 %	70 %
RCA-90 %	0 %	90 %
RCA1-70 %	1 %	70 %
RCA1-90 %	1 %	90 %
RCA2-70 %	2 %	70 %
RCA2-90 %	2 %	90 %
RCA3-70 %	3 %	70 %
RCA3-90 %	3 %	90 %
CB-70 %	0 %	70 %
CB –90 %	0 %	90 %
CB1-70 %	1 %	70 %
CB1-90 %	1 %	90 %
CB2-70 %	2 %	70 %
CB2-90 %	2 %	90 %
CB3-70 %	3 %	70 %
CB3-90 %	3 %	90 %

comparable to natural aggregates [32]. The C&D aggregates have recently been considered for several civil engineering applications such as road base and subbase [27,39], asphalt [15,37], mortar [14], concrete [24], road embankments [22], backfilling of slopes and retaining walls [30], pipe-bedding [4], and footpaths [20].

To increase the strength properties and cyclic responses of C&D materials, several research studies evaluated the effects of solid by-products, including crumb rubbers [26], glass [29]), and plastics [38], while numerous other studies assessed the effect of chemical binders, including cement [42], lime [12], fly ash [36], and slag [3], for the treatment of these materials in particular for unbound pavement layers. Binder stabilisation of C&D materials can provide high strength and stiffness for road base and subbase; however, the inclusion of high dosages of binders such as cement and lime can lead to temperature and shrinkage cracking [21]. Moreover, the incorporation of these binders causes negative environmental impacts due to the energy-intensive processes of cement and lime production, which result in significant CO_2 emissions [25]. Therefore, to mitigate the shortcomings of using the binders in terms of cracking and negative environmental impacts, the adoption of new materials and binders in an optimised dosage for the stabilisation of C&D aggregates is very imperative.

Unbound granular materials, including C&D aggregates, experience repetitive cyclic loading due to vehicular traffic, where these forces have varying magnitudes depending on the vehicle type and loads present. These materials will not break down abruptly with cyclic loads, but the failure can gradually occur, and it is influenced by the number of load cycles and the magnitude of the stresses. The imposed stresses result in both recoverable and irrecoverable strains in the pavement structural layers. During each loading cycle, the developed permanent deformation of granular aggregates may be relatively minor. However, the accumulation of such minor permanent deformations may cause the pavement base/subbase layers to fail as a result of excessive rutting [28]. According to Zhang et al. [41] and Arulrajah et al. [2], deviator stress, confining stress, moisture content, and degree of compaction are the main influencing parameters on the permanent deformation of granular aggregates, including recycled C&D materials.

The shakedown limit is the crucial stress level below which the granular materials exhibit resilient behaviour following a pre-determined number of cycles of loading. Thus, it is crucial to establish the shakedown limit of unbound aggregates used in pavement base and subbase layers using the well-established shakedown theory in order to assess how well these materials function when subjected to the maximum applied stresses [18]. According to the shakedown theory, unbound granular aggregates subjected to cyclic loads may experience up to three phases of deformation through three defined ranges (Fig. 1) [34]. At first, the compacted unbound granular aggregates immediately undergo densification during the primary phase of deformation. In all three ranges of A, B and C, for a limited load cycle count, the response of aggregates is plastic with a permanent strain rate reduction. Thereafter, the behaviour can be merely elastic, which demonstrates resilient behaviour following compaction. This is called Range A – plastic shakedown, where $\varepsilon_{p,\,5000} - \varepsilon_{p,\,3000} < 4.5 \times 10^{-5}$ ($\varepsilon_{p,\,5000}$ and $\varepsilon_{p,\,3000}$ are the cumulative plastic strains observed at the 5000th loading cycle and at the 3000th loading cycle, orderly). For Range B, in the second phase of deformation behaviour which may be demonstrated by a linear line, the rate of permanent deformation is generally lower compared to that of the primary phase. In other words, in the early loading cycles, the

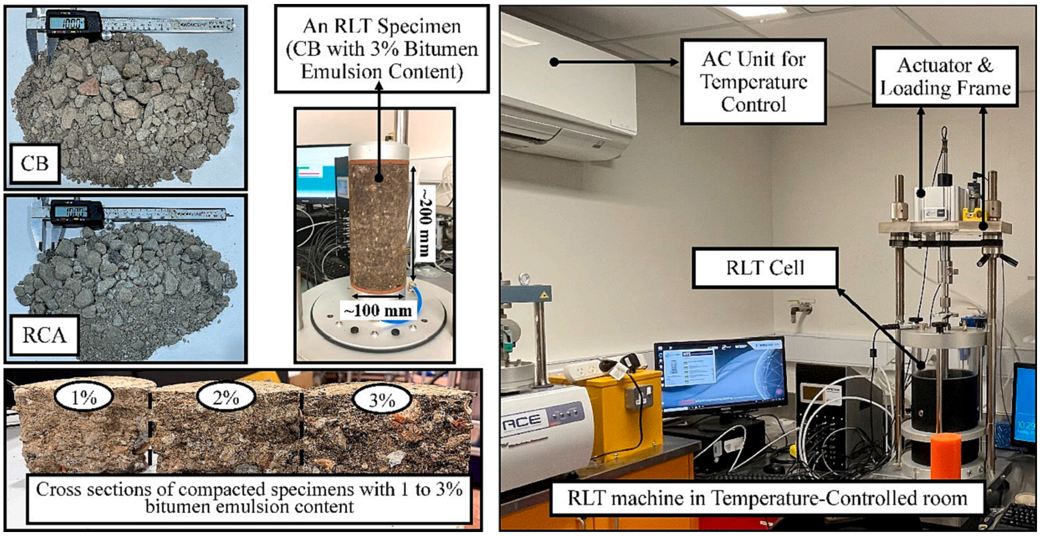

Fig. 3. RLT testing machine in a temperature-controlled room, raw materials, a compacted RLT specimen, and cross sections of 3 compacted specimens.

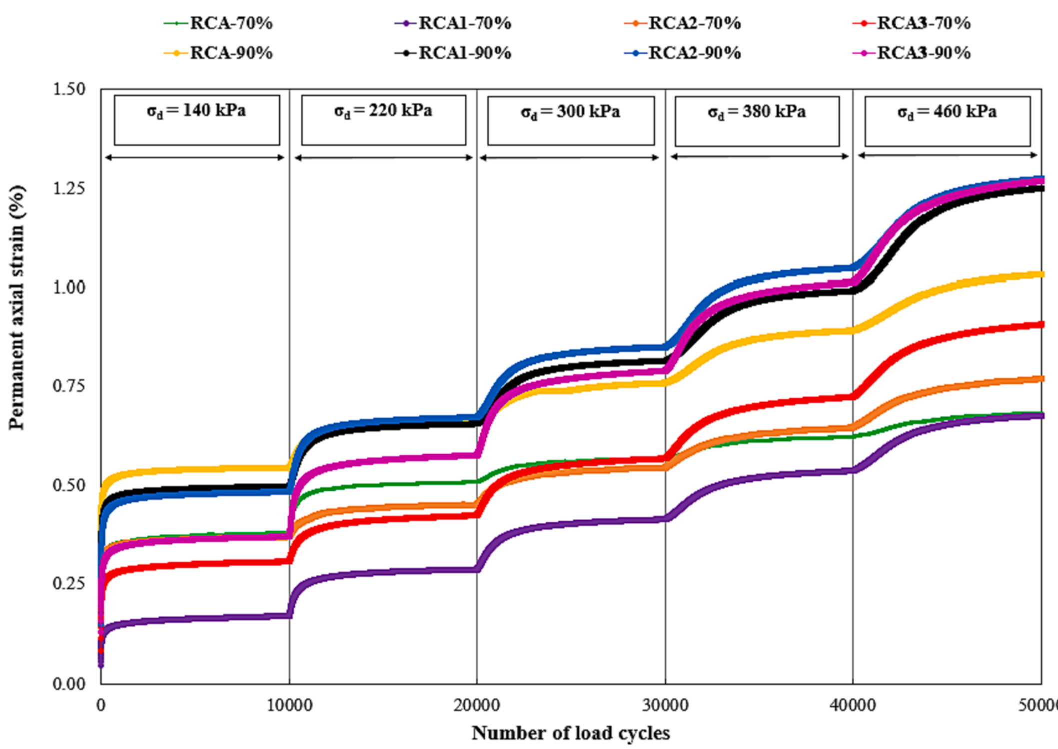

Fig. 4. Permanent axial strain (%) responses of RCA blends *vs* the load cycle count.

materials undergo a high permanent strain rate, which gradually declines to a low or constant strain rate. In Range B, $4.5 \times 10^{-5} < \varepsilon_{p,\ 5000} - \varepsilon_{p,\ 3000} < 4 \times 10^{-4}$. In Range C, compacted aggregates may experience a gradual rise in permanent strain and move closer to an "incremental collapse" following the application of a significant number of loading cycles. During the tertiary phase in Range C, unbound granular materials experience a gradual decrease in their permanent strain rate, but failure occurs after a very small number of loading cycles as the permanent strain increases steadily with consecutive load cycles. In Range C, $\varepsilon_{p,\ 5000} - \varepsilon_{p,\ 3000} > 4 \times 10^{-4}$.

This research intends to assess the permanent deformation response of RCA and CB stabilised with an anionic bitumen emulsion under different ranges of cyclic loading. A suite of multi-stage repeated load triaxial (RLT) tests at five distinct combinations of confining stress and deviator stress was carried out on the blends to assess the permanent deformation of the samples, considering their application as the base and subbase layers of pavements. This loading regime was chosen to improve the likelihood of extracting all three shakedown ranking ranges discussed above. By analysing the results, the blends could be classified based on the shakedown theory to enable the adoption of bitumen emulsion for the stabilisation of C&D wastes. This study adopts an innovative approach of stabilising C&D waste aggregates as a step forward towards sustainability in the design and construction of transportation infrastructures. This is accomplished through improving the properties of the recycled aggregates to make them a suitable alternative to precious virgin aggregates that are used in structural layers of pavements.

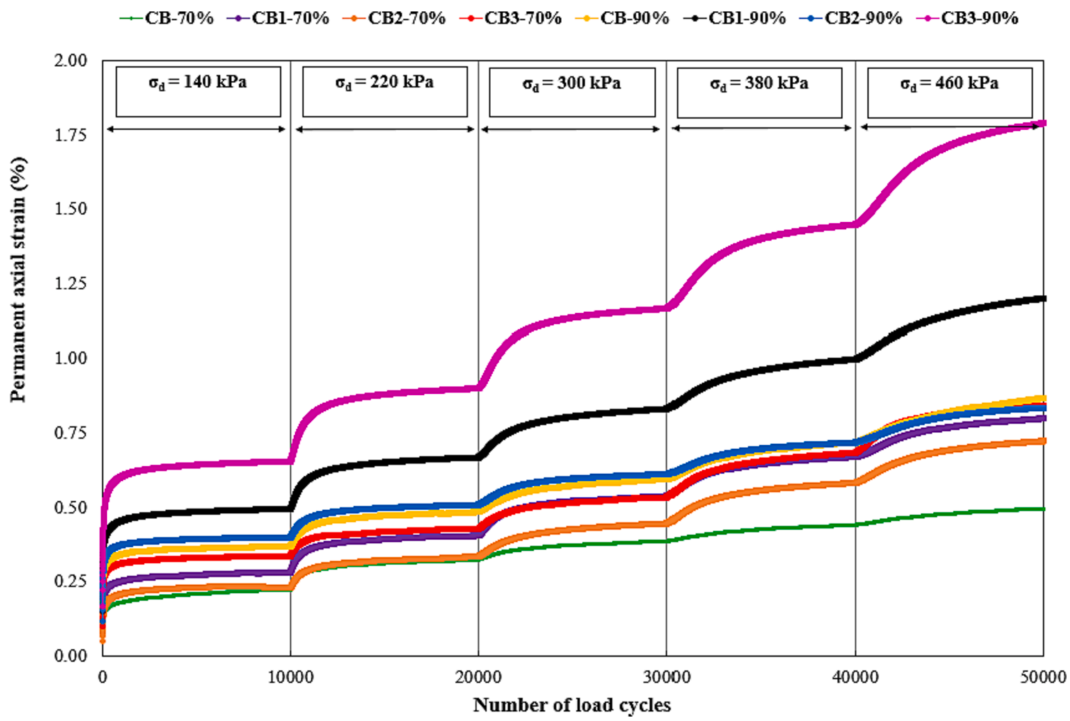

Fig. 5. Permanent axial strain (%) responses of CB blends *vs* the load cycle count.

Materials and methods

Recycled concrete aggregate (RCA) and crushed brick (CB)

This study utilised two separate classes of aggregates, recycled concrete aggregate of 20 mm size (also known as Class 3 crushed concrete) and crushed brick sized 20 mm (also known as Class 4 crushed concrete). These recycled materials, conforming to VicRoads specification 820 [33], were obtained locally from a recycling facility located in Melbourne, Victoria, Australia. The particle size distributions of the materials, demonstrated in Fig. 2, were obtained as per ASTM D6913/D6913M [10]. Fig. 2 also presents the gradation properties of RCA and CB, including the coefficient of curvature, C_c, coefficient of uniformity, C_u, and their classification following the Unified Soil Classification System.

Bitumen emulsion

In this study, an anionic slow-set bitumen emulsion was used for stabilising the RCA and CB aggregates. The properties of the bitumen emulsion, such as pH, viscosity, binder content, and sieve residue, are provided in Table 1. The evaluation of the viscosity was conducted at 60 °C using a Brookfield LVT viscometer with a #1 spindle at 60 rpm.

Sample preparations and testing procedures

The optimum moisture content (OMC) and maximum dry density (MDD) were obtained following the modified compaction test [5], where the 24-hour oven-dried RCA and CB were mixed with various moisture contents. The mixes were then kept in sealed containers and allowed to pre-cure for 2 h. This process was performed for the purpose of even water absorption by the unbound granular aggregates, as suggested by AS 1289.5.2.1 [5]. Then, the samples were compacted in 5 layers in a UCS cylindrical steel mould having a height and diameter of 115.5 mm and 105 mm, respectively, with each layer hit by 25 blows from a modified compaction hammer of 4.9 kg, reducing from a height of 450 mm [5]. The OMC and MDD of RCA were obtained at 11 % and 1.99 t/m^3, respectively. Also, CB provided OMC and MDD values of 10.88 % and 2.00 t/m^3, respectively. The OMC values were considered for samples containing various contents of the anionic slow-set bitumen emulsion at 0, 1, 2, and 3 % by dry weight of the granular aggregates; however, since the emulsion contains approximately 40 % water, the water content was deducted from the OMCs. The blends were then mixed with the relative water content and bitumen emulsion thoroughly using an asphalt mixer. In the selection of the bitumen emulsion contents, a major road construction company in Australia was consulted who considered both practical and economical aspects. Accordingly, up to 3 % emulsion content with 1 % increments was selected. Due to the difference between the bitumen emulsion contents of only 1 %, significant care was taken in the sample preparation to mitigate potential errors.

Table 2 shows the sample ID and mix designs. The sample preparation procedure for the permanent deformation test started by mixing the relative water content and bitumen emulsion with the aggregates using the asphalt mixer. After preparing the blends, a split cylindrical steel mould having a height of 200 mm and a diameter of 100 was utilised to compact the permanent deformation samples. The samples were compacted in their OMC under the modified compaction energy levels to reach the corresponding MDD. Two sets of identical samples were prepared by adopting the drying back procedure, targeting to be tested at 70 and 90 % of the OMC. For this aim, the samples were kept at room temperature, and the moisture contents of the samples were checked at regular intervals. Once the desired moisture levels, i.e., 70 or 90 % of OMCs, were achieved, the samples were fully wrapped using plastic bags to avoid moisture loss and were kept at room temperature for an additional 2 days before being tested to reach moisture equilibrium.

After the completion of the curing stage, the evaluation of the permanent deformation behaviour of the bitumen emulsion stabilised granular aggregates was carried out employing a repeated load triaxial (RLT) test making use of an RLT testing scheme that comprised multiple testing stages. Fig. 3 shows the RLT testing machine, which, together with compacted specimens, were kept in a temperature-controlled room set to 20° C to mitigate the effect of temperature on the characteristics of the specimens. Fig. 3 also shows CB, RCA, a compacted RLT sample, and

Table 3
Grading of blends at various stress level stages, based on Werkmeister et al. [34] criteria.

Sample	Stage	$\varepsilon_{p,\ 5000}$ - $\varepsilon_{p,\ 3000}$	Werkmeister's criteria
	1	0.00500	Plastic Creep
RCA-70 %	2	0.00564	Plastic Creep
	3	0.00732	Plastic Creep
	4	0.01124	Plastic Creep
	5	0.01273	Plastic Creep
	1	0.00411	Plastic Shakedown
RCA-90 %	2	0.00831	Plastic Creep
	3	0.00469	Plastic Creep
	4	0.02621	Plastic Creep
	5	0.03455	Plastic Creep
	1	0.00472	Plastic Creep
RCA1-70 %	2	0.00705	Plastic Creep
	3	0.01140	Plastic Creep
	4	0.01860	Plastic Creep
	5	0.02734	Plastic Creep
	1	0.00456	Plastic Creep
RCA1-90 %	2	0.00931	Plastic Creep
	3	0.01869	Plastic Creep
	4	0.03478	Plastic Creep
	5	0.06320	Incremental Collapse
	1	0.00412	Plastic Shakedown
RCA2-70 %	2	0.00700	Plastic Creep
	3	0.00999	Plastic Creep
	4	0.01476	Plastic Creep
	5	0.02307	Plastic Creep
	1	0.00514	Plastic Creep
RCA2-90 %	2	0.00957	Plastic Creep
	3	0.01887	Plastic Creep
	4	0.03274	Plastic Creep
	5	0.05023	Incremental Collapse
	1	0.00560	Plastic Creep
RCA3-70 %	2	0.00929	Plastic Creep
	3	0.01431	Plastic Creep
	4	0.02230	Plastic Creep
	5	0.03187	Plastic Creep
	1	0.00560	Plastic Creep
RCA3-90 %	2	0.01046	Plastic Creep
	3	0.01778	Plastic Creep
	4	0.02852	Plastic Creep
	5	0.04580	Incremental Collapse
	1	0.00986	Plastic Creep
CB-70 %	2	0.00809	Plastic Creep
	3	0.00910	Plastic Creep
	4	0.01031	Plastic Creep
	5	0.01095	Plastic Creep
	1	0.00483	Plastic Creep
CB −90 %	2	0.01174	Plastic Creep
	3	0.01503	Plastic Creep
	4	0.02287	Plastic Creep
	5	0.03152	Plastic Creep
	1	0.00516	Plastic Creep
CB1-70 %	2	0.00900	Plastic Creep
	3	0.01504	Plastic Creep
	4	0.01845	Plastic Creep
	5	0.02286	Plastic Creep
	1	0.00796	Plastic Creep
CB1-90 %	2	0.01418	Plastic Creep
	3	0.02191	Plastic Creep
	4	0.02903	Plastic Creep
	5	0.04040	Incremental Collapse
CB2-70 %	1	0.00629	Plastic Creep
	2	0.00949	Plastic Creep
	3	0.01581	Plastic Creep
	4	0.02114	Plastic Creep
	5	0.02578	Plastic Creep
	1	0.00525	Plastic Creep
CB2-90 %	2	0.00853	Plastic Creep
	3	0.01361	Plastic Creep
	4	0.01928	Plastic Creep
	5	0.02501	Plastic Creep
	1	0.00559	Plastic Creep
CB3-70 %	2	0.00979	Plastic Creep
	3	0.01322	Plastic Creep
	4	0.02274	Plastic Creep
	5	0.02258	Plastic Creep
	1	0.00987	Plastic Creep
CB3-90 %	2	0.01860	Plastic Creep
	3	0.03064	Plastic Creep
	4	0.04797	Incremental Collapse
	5	0.07080	Incremental Collapse

cross sections of 3 compacted specimens mixed with 1 to 3 % bitumen emulsions. Five combinations of confining stress (σ_c) and deviator stress (σ_d) were exerted on the specimens through a fixed σ_c of 40 kPa in conjunction with σ_d values of 140, 220, 300, 380 and 460 kPa, following similar previous investigations by Arulrajah et al. [2], Ghorbani et al. (2021), and Maghool et al. [23] to cover a wide range of stress ratios (σ_d/σ_c) ranging between 3.5 and 11.5, to be applicable to base layers under a thick surface/binder course to those under a thin bituminous surface, respectively. Such a wide range of stress levels was adopted to evaluate the effectiveness of the bitumen emulsion stabilisation for improving the deformation responses of the samples. Every stage of the permanent deformation test consisted of 10,000 cycles. In each cycle, a pulse loading and unloading sequence was applied, with 0.1 s for loading and 0.9 s for unloading. It is worth mentioning that triplicate samples were prepared and tested for every blend, where the values reported are averaged.

Results and discussions

Permanent deformation responses

The correlations of the permanent axial strain versus the number of loading cycles for the respective blends are provided in Fig. 4 and Fig. 5. Considering the results of the selected multi-stage RLT tests, the permanent deformation responses of the samples when subjected to a substantial number of load cycles and a variety of stress levels can be investigated. By comparing the results, it was noticed that the CB samples generally experienced higher permanent strain accumulations compared to those of the RCA samples. This has been accelerated at higher stress ratios. For RCA, the addition of bitumen emulsion generally increased the permanent deformation values at σ_d > 300 kPa and decreased the permanent deformation when σ_d < 300 kPa. At 90 % OMC, all bitumen emulsion stabilised blends exhibited a relatively similar response and achieved a permanent strain of about 1.26 % after 50,000 cycles, which was higher than the permanent strain of the control samples (RCA-90 %) at 1.03 %. Similarly, for the samples prepared at 70 % OMC, the bitumen emulsions stabilised RCA generaly experienced higher and lower permanent strains at σ_d > 300 kPa and σ_d < 300 kPa, respectively, compared to the control sample (RCA-70 %). Similar trends were observed for CB, showing that the permanent strains increased with increasing the moisture content. However, the addition of bitumen emulsion generally resulted in an increased permanent deformation at all deviatoric stresses, most evident for the CB3-90 % at 1.79 %.

The shakedown range criteria were adopted in this study to classify the samples based on their permanent deformation responses. The grading results of the samples at various stress level stages using Werkmeister's criteria [34] are provided in Table 3. It can be observed that most of the samples experienced the second phase, which is Range B. However, at more demanding stress ratios, mainly stage 5, some of the blends fell under the tertiary stage, which is the "(Range C" region. In addition, the blends tested at 90 % of their OMC underwent higher permanent axial strains compared to those tested at 70 % OMC. This is more obvious at higher stress ratios. Therefore, it can be stated that higher moisture content would result in higher permanent strains.

Overall, the permanent deformation test results suggest that bitumen

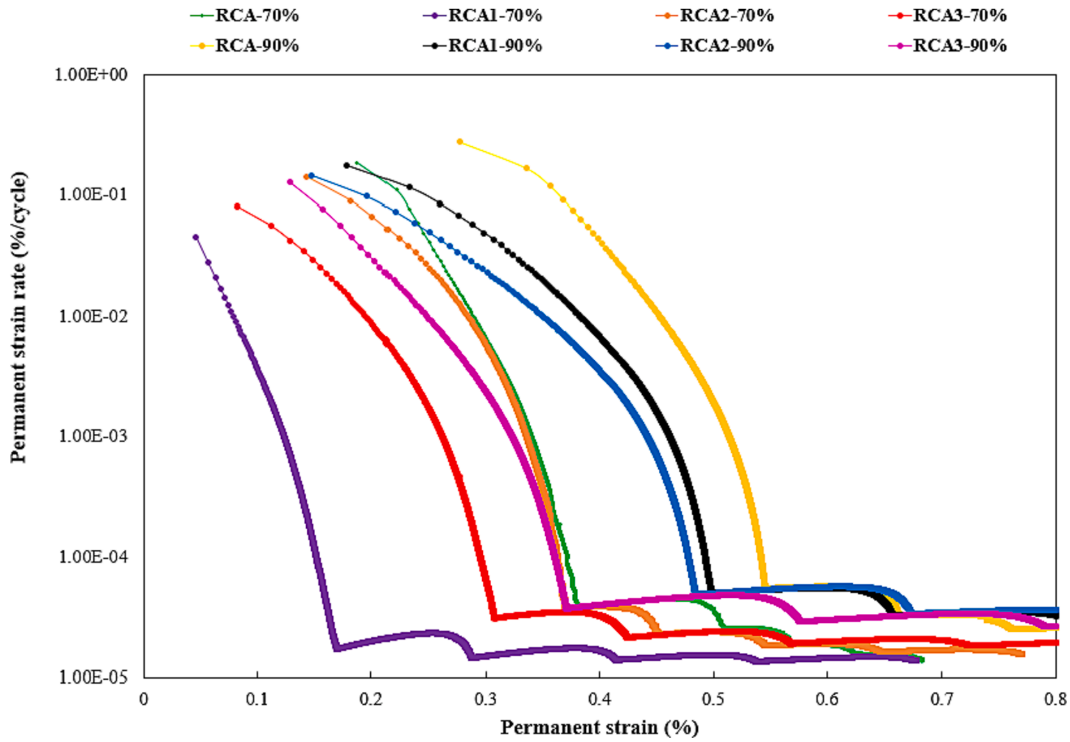

Fig. 6. Permanent strain rate (%/cycle) *vs* permanent strain (%) for RCA blends.

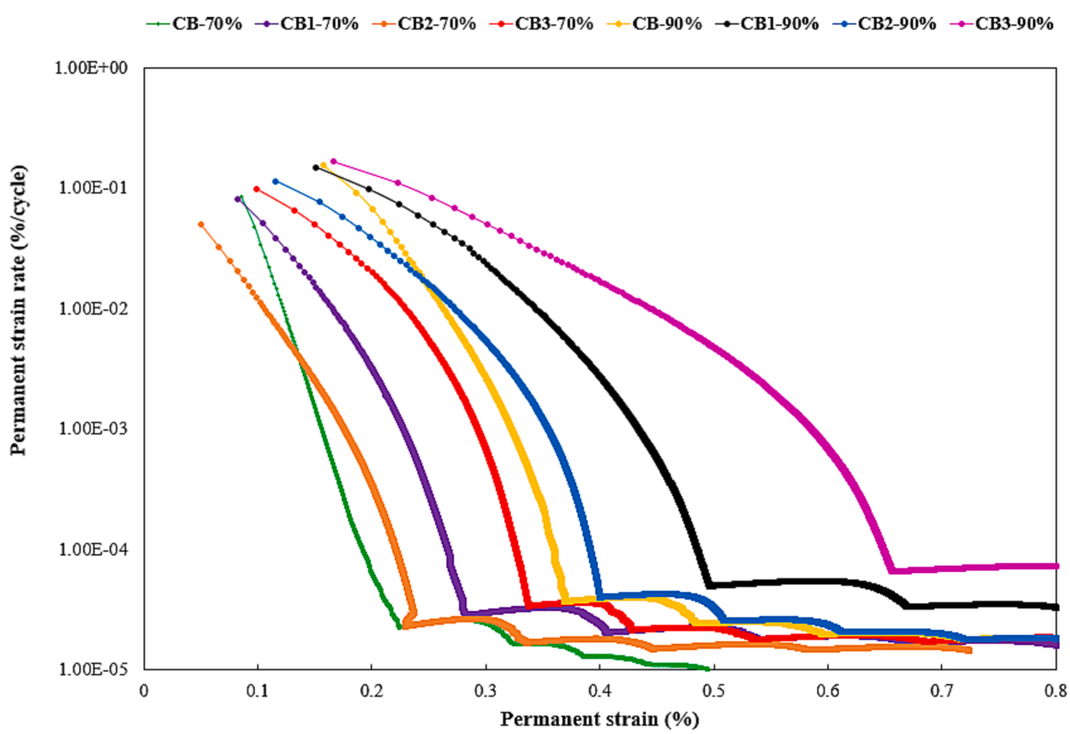

Fig. 7. Permanent strain rate (%/cycle) *vs* permanent strain (%) for CB blends.

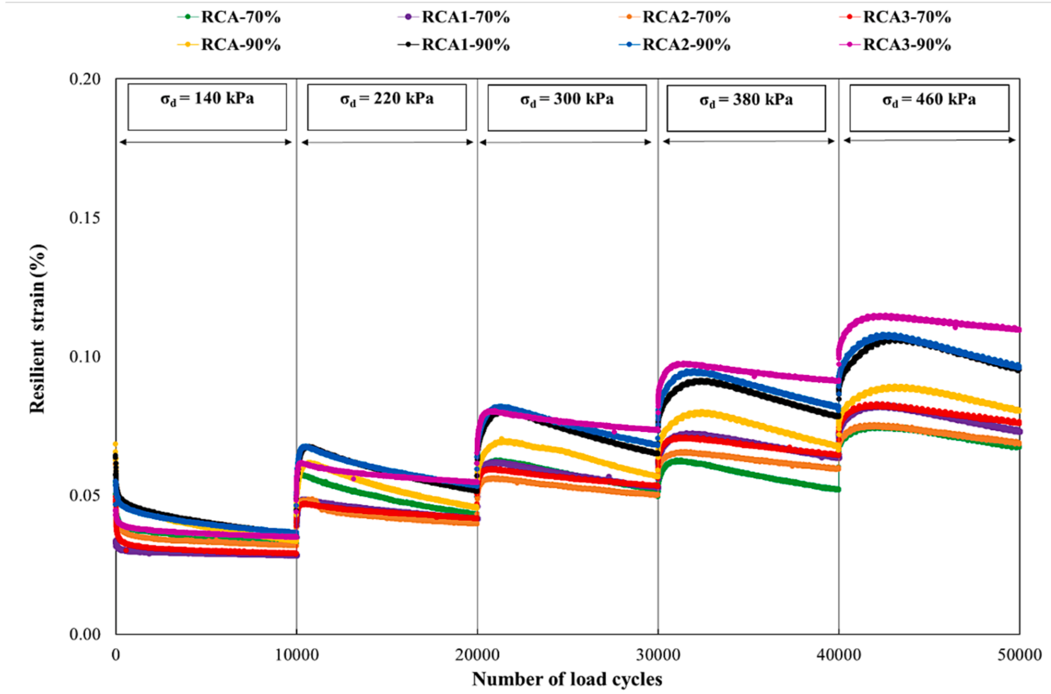

Fig. 8. Resilient strain (%) *vs* the load cycle count for RCA blends.

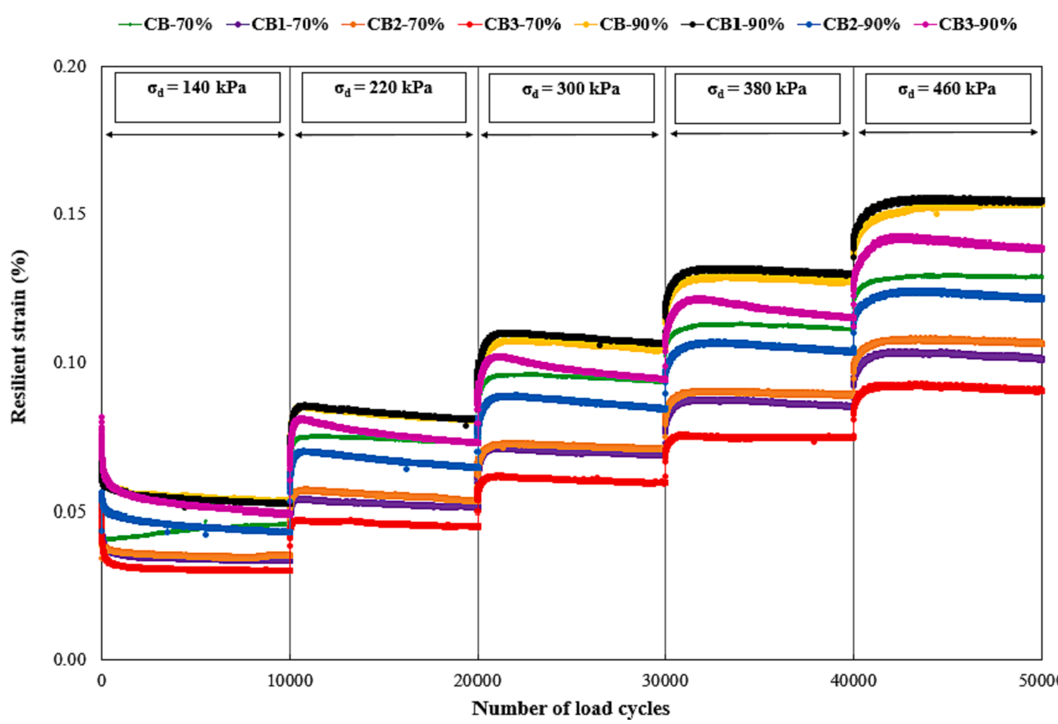

Fig. 9. Resilient strain (%) *vs* the load cycle count for CB blends.

emulsion stabilisation did not have a noticeable effect in terms of improving the permanent deformation responses of the blends. However, in the majority of the case, the Range B behaviour was observed, as can be seen from Table 3, which makes the blends suitable for the application as the base and subbase layers. The addition of emulsion bitumen can result in an improved resilient modulus of the RCA and CB, which will be discussed in the next section.

Permanent strain rates

The association of the permanent strain rate with the permanent strain of the RCA mixes and CB samples are provided through Figs. 6 and 7, respectively. As observed, the inclusion of bitumen emulsion in CB and RCA aggregates resulted in increasing and decreasing permanent strain rates, respectively. In addition, the RCA and CB blends tested at 90 % of OMC experienced higher permanent strain rates compared to those of the samples tested at 70 % of OMC. Therefore, it can be

Table 4
Properties pertaining to the permanent deformation (Equation (2)) and obtained resilient modulus of the blends.

Sample	Stage	Resilient strain (%) at the end of each stage	Resilient modulus (MPa)	ε_0(%)	ε_m(%)	ρ	β	R^2	RMSE
	1	0.0325	398.4	0	0.4105	0.44	0.2529	0.994	0.28
	2	0.0431	450.1	0.3792	0.1238	10054.87	14.4622	0.933	1.03
RCA-70 %	3	0.052	524.0	0.5041	0.0580	20969.10	16.2963	0.981	1.12
	4	0.052	589.2	0.5666	0.0528	31563.68	19.5964	0.992	0.23
	5	0.0672	642.2	0.6213	0.0586	42024.05	22.8240	0.996	0.17
	1	0.0334	361.1	0	0.5651	0.43	0.3340	0.996	0.19
	2	0.0453	418.7	0.5458	0.1123	10483.89	12.7989	0.974	0.60
RCA-90 %	3	0.0568	470.6	0.6576	0.0928	21101.95	16.5331	0.972	0.83
	4	0.0676	510.8	0.7539	0.1296	31699.29	21.0410	0.997	0.25
	5	0.0804	538.9	0.8886	0.1400	42177.89	22.1972	0.998	0.18
	1	0.0283	479.9	0	0.2196	3.35	0.1652	0.988	1.10
	2	0.0414	494.8	0.1681	0.1136	10107.37	11.7652	0.946	1.92
RCA1-70 %	3	0.0529	524.1	0.2833	0.1220	20632.93	19.9162	0.975	2.31
	4	0.0636	556.9	0.4092	0.1191	31274.21	22.1854	0.992	0.63
	5	0.073	587.5	0.5329	0.1366	41646.97	26.7108	0.996	0.41
	1	0.036	345.6	0	0.5164	1.30	0.3712	0.998	0.17
	2	0.0516	376.4	0.4980	0.1526	10412.49	14.6874	0.968	0.90
RCA1-90 %	3	0.0649	412.7	0.6505	0.1540	21088.30	19.5819	0.992	1.03
	4	0.0783	444.8	0.8101	0.1731	31688.18	22.2772	0.998	0.28
	5	0.0953	454.6	0.9876	0.2541	42066.11	26.5467	0.999	0.26
	1	0.0318	418.3	0	0.3877	0.79	0.3215	0.998	0.16
	2	0.0397	518.8	0.3694	0.0784	10433.11	9.3623	0.977	0.57
RCA2-70 %	3	0.0501	566.4	0.4485	0.0909	20736.52	15.9521	0.977	0.87
	4	0.0594	606.4	0.5417	0.0974	31259.10	19.3206	0.990	0.44
	5	0.0686	636.5	0.6423	0.1202	41589.12	23.8660	0.993	0.41
	1	0.0366	350.2	0	0.5041	2.11	0.3783	0.998	0.22
RCA2-90 %	2	0.0532	371.5	0.4839	0.1821	10303.49	15.9677	0.958	1.12
	3	0.068	400.8	0.6659	0.1713	20948.48	20.3159	0.987	1.29
	4	0.0816	428.9	0.8442	0.1914	31454.32	24.0521	0.995	0.41
	5	0.096	449.8	1.0419	0.2210	41909.76	26.4929	0.998	0.27
	1	0.029	462.4	0	0.3381	1.87	0.2720	0.998	0.37
	2	0.0417	501.2	0.3068	0.1123	10279.93	9.2177	0.961	1.15
RCA3-70 %	3	0.0533	534.1	0.4194	0.1384	20645.69	17.3402	0.973	1.54
	4	0.0645	561.1	0.5622	0.1502	31159.13	21.0914	0.987	0.69
	5	0.0764	578.7	0.7179	0.1783	41522.07	25.2291	0.993	0.54
	1	0.0349	384.7	0	0.3998	1.92	0.3005	0.999	0.16
	2	0.0546	384.6	0.3703	0.1977	10090.69	13.4969	0.933	1.68
RCA3-90 %	3	0.0733	392.8	0.5683	0.2042	20586.62	20.6949	0.968	2.04
	4	0.0912	403.9	0.7804	0.2134	31095.55	24.0599	0.986	0.75
	5	0.1094	410.7	1.0033	0.2475	41599.66	26.4595	0.993	0.53
	1	0.0459	319.4	0	0.3561	51.30	0.1405	0.974	1.58
	2	0.0727	296.2	0.2211	0.0963	10152.61	7.2292	0.953	1.40
CB-70 %	3	0.0938	315.4	0.3198	0.0607	21256.67	10.6696	0.983	1.79
	4	0.1114	338.0	0.3834	0.0567	31928.39	13.1462	0.991	0.35
	5	0.1292	356.4	0.4397	0.0558	42458.53	16.3917	0.992	0.30
	1	0.0534	254.1	0	0.4225	0.47	0.2024	0.993	0.42
	2	0.0805	266.1	0.3699	0.1110	10379.67	8.6612	0.958	1.06
CB −90 %	3	0.1045	282.7	0.4793	0.1063	21241.17	11.9871	0.984	1.26
	4	0.1277	296.2	0.5899	0.1225	31643.40	15.6510	0.987	0.58
	5	0.1538	303.0	0.7135	0.1541	42363.35	16.2137	0.992	0.47
	1	0.0336	406.1	0	0.3336	2.88	0.2180	0.998	0.34
	2	0.0514	419.5	0.2816	0.1188	10243.18	8.8518	0.949	1.45
CB1-70 %	3	0.069	429.4	0.4008	0.1261	20745.93	15.9971	0.973	1.80
	4	0.0856	439.4	0.5314	0.1271	31277.47	18.7863	0.982	0.76
	5	0.1013	448.5	0.6645	0.1254	41783.73	22.4925	0.991	0.47
	1	0.0524	258.0	0	0.5440	2.17	0.2821	1.000	0.12
	2	0.081	264.6	0.4958	0.1658	10394.70	9.5842	0.959	1.15
CB1-90 %	3	0.1067	276.6	0.6613	0.1568	21086.44	13.7125	0.982	1.36
	4	0.1301	290.3	0.8247	0.1634	31670.65	16.2499	0.990	0.51
	5	0.1546	298.6	0.9922	0.2013	42173.87	18.5424	0.993	0.45
	1	0.0353	394.4	0	0.2617	9.88	0.3282	0.973	1.21
	2	0.0536	397.6	0.2360	0.1005	10336.63	8.4374	0.953	1.52
CB2-70 %	3	0.0712	417.9	0.3292	0.1075	21168.20	12.3930	0.984	2.05
	4	0.0891	423.7	0.4416	0.1323	31318.18	18.1359	0.986	0.83
	5	0.1067	429.1	0.5772	0.1373	41718.47	21.8028	0.991	0.57
	1	0.0432	307.8	0	0.4225	2.46	0.3503	1.000	0.14
	2	0.0648	326.8	0.4001	0.1043	10426.42	10.0283	0.963	0.88
CB2-90 %	3	0.0846	345.5	0.5043	0.0992	21073.40	14.8126	0.984	1.05
	4	0.104	360.6	0.6078	0.1039	31638.29	18.0777	0.992	0.39
	5	0.1219	374.0	0.7149	0.1162	42068.93	20.7962	0.995	0.30
	1	0.0303	453.2	0	0.3655	1.63	0.2881	0.999	0.23
	2	0.0452	476.5	0.3369	0.0872	10242.85	8.1700	0.938	1.06
CB3-70 %	3	0.0596	496.1	0.4243	0.1031	20954.09	12.3400	0.974	1.35
	4	0.0751	507.7	0.5300	0.1446	31306.17	17.7190	0.984	0.79

(continued on next page)

Table 4 (*continued*)

Sample	Stage	Resilient strain (%) at the end of each stage	Resilient modulus (MPa)	ε_0(%)	ε_m(%)	ρ	β	R^2	RMSE
	5	0.0906	502.6	0.6776	0.1546	41224.03	25.9922	0.983	0.70
CB3-90 %	1	0.0492	267.1	0	0.7027	4.39	0.3471	0.999	0.34
	2	0.0732	288.0	0.6562	0.2352	10435.57	10.9888	0.965	1.14
	3	0.0946	306.2	0.8911	0.2538	20950.12	17.4260	0.984	1.39
	4	0.1152	320.8	1.1548	0.2738	31509.65	20.2734	0.992	0.54
	5	0.1387	328.1	1.4378	0.3356	41961.12	22.4941	0.995	0.45

concluded that moisture contents in excess of 70 % would have a detrimental effect on the permanent deformation responses of granular aggregates.

Resilient strains

The relationships connecting the resilient strain with the applied load cycle count at various stress level ratios for RCA and CB blends are manifested in Fig. 8 and Fig. 9, respectively. The results exhibit a general decrease in the resilient strains (increase in the resilient modulus, which is the ratio of applied deviator stress (σ_d) to resilient deformation (ε_r)) for CB-70 % samples as the emulsion content increased, while for the CB-90 % samples, the resilient modulus peaked at 2 % emulsion content. Based on plots of Fig. 8 and Fig. 9, for the RCA-70 % samples, the addition of 2 % emulsion generally resulted in the greatest resilient modulus among emulsion-stabilised samples. In contrast, in the RCA-90 % samples, no improvement in the resilient modulus was observed. It should be noted that the testing regime adopted for the resilient modulus and permanent deformation testing [16] was different from the stress states suggested in AASHTO T307 [1]. In the first two out of the five stages, the testing method of this research was within the ranges of AASHTO T307 [1], but at stages 3, 4 and 5, more demanding stress combinations (lower confinement and greater deviatoric stress) were applied. Besides, it can be seen that there is a clear stress-dependence characteristic for the samples, as increasing the deviator stress resulted in increasing the resilient modulus. Zhang et al. [40] and Gu et al. [17] also indicated that granular C&D aggregates show stress-hardening behaviour, and deviator stress leads to strengthening the aggregates and producing smaller elastic deformations under the load.

Determination of prediction model parameters

Several models have been proposed to predict the permanent deformation of recycled demolition aggregates as well as unbound (loose) granular materials. Among these, the model proposed by Tseng and Lytton (1989) (Equation (1)) is one of the most commonly used models for determining the association between the cumulative permanent strain and the load cycle count. This model was suggested for predicting the permanent deformation results obtained from single-stage RLT tests. However, in the current study, 5-stage RLT tests were carried out. Therefore, a new parameter, ε_0 (the predicted permanent strain at the end of the previous stage), was added to the model to be able to predict the permanent deformation properties with high accuracy. The modified model is provided in (Equation (2)).

$$\varepsilon_p = \varepsilon_m e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{1}$$

$$\varepsilon_p = \varepsilon_0 + \varepsilon_m e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{2}$$

Where, ε_p is the permanent strain; ε_m is the maximum permanent strain; ρ is the scale (multiplier) factor; β is the shape factor; N is the number of load cycles; and ε_0 is the predicted permanent strain of the last cycle of a former stage.

It is worth mentioning that the ε_0 of the first stage of each sample is zero. The values for the permanent deformation properties, β, ρ and ε_0, are obtained by performing a regression analysis of the experimental test results. The results achieved through the experimental testing scheme were adopted to obtain the properties relating to the permanent deformation of the blends, where these properties and obtained resilient modulus are provided in Table 4 together with R^2 and root-mean-square deviation (RMSE) values. The closer values of the RMSE to zero indicate a greater fit of the predicted data to the measured data. Based on Table 4, all predicted permanent strains exhibit an "excellent fit" to the measured data following Witczak et al. [35].

Fig. 10 shows the relationships between the measured permanent strain (ε_p (%)) and the predicted permanent strain of four randomly selected samples, i.e., RCA1-90 %, RCA2-70 %, CB1-70 %, and CB2-90 %, to demonstrate the "excellent fit" of the predicted data. In Fig. 10, R2 and RMSE are also presented to show that there is a strong correlation between the experimentally measured and analytically predicted permanent strains. In Fig. 10, n is the number of data points collected and incorporated in the regression analysis of data for each stage.

Conclusions

The effect of slow-set anionic bitumen emulsion on the permanent deformation responses of recycled concrete aggregate and crushed brick was evaluated in the current study. A series of multi-stage RLT tests at five distinct combinations of confining stress and deviator stress were conducted on the samples at targeted moisture contents of 70 % and 90 % of their OMC. The shakedown theory was adopted to classify and characterise the samples. The following conclusions could be drawn from the results.

1. CB samples experienced higher permanent strain accumulations than the RCA samples, which have been accelerated at higher stress ratios.
2. With respect to the shakedown theory, the majority of blends fell under the Range B, which makes the blends suitable for application as the base and subbase layers; however, at higher stress ratios, Range C was encountered in the case of a few samples.
3. The addition of bitumen emulsion to RCA resulted in a reduced permanent deformation under lower deviatoric stresses, and increased permanent deformation at higher stresses. However, CB samples generally showed greater permanent deformation under all testes stresses when mixed with bitumen emulsion. The addition of bitumen emulsion to RCA and CB caused a decrease and increase in the permanent strain rate, respectively.
4. By increasing the emulsion content, the resilient strains of the CB-70 % samples were reduced, implying an increase in the resilient modulus; however, among the CB-90 % samples, the maximum resilient modulus (lower resilient strain) was achieved at 2 % emulsion content. Besides, the inclusion of 2 % emulsion to the RCA-70 % samples generally led to the highest resilient modulus, while no improvement in the resilient modulus was observed among the RCA-90 % samples.
5. The samples tested at 90 % of their OMC underwent higher permanent axial strains, higher permanent strain rates, and higher resilient strains compared to those tested at 70 % OMC. This was more evident at higher stress ratios. Therefore, higher moisture contents resulted in higher permanent strains, higher permanent strain rates, and lower resilient modulus.

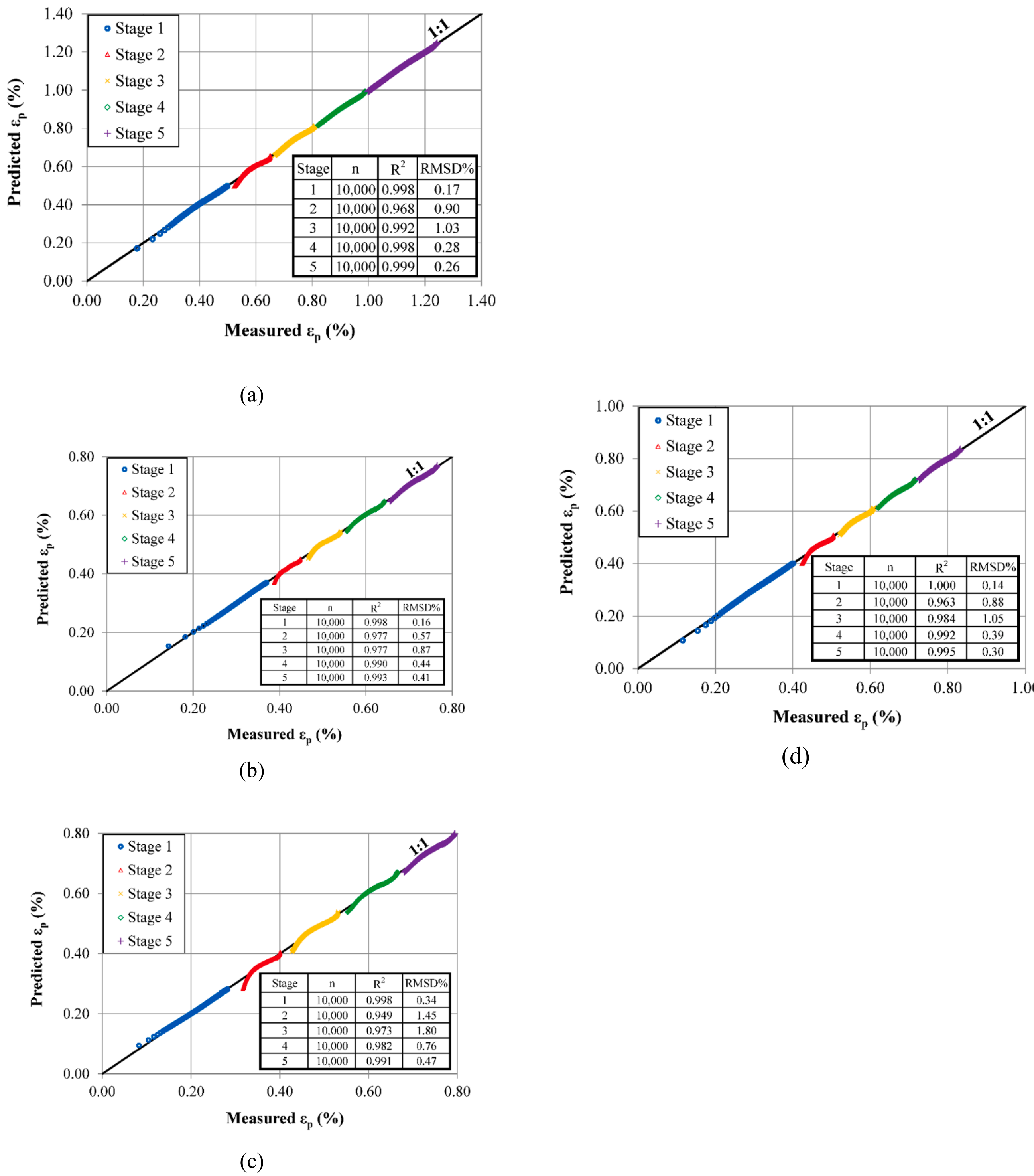

Fig. 10. Correlations between the experimentally measured and analytically predicted permanent strains of the samples (a) RCA1-90 %, (b) RCA2-70 %, (c) CB1-70 %, and (d) CB2-90 %.

6. The inclusion of bitumen emulsion to the aggregates caused RCA2-70 % and CB3-70 % to exhibit superior permanent deformation performance. Hence, based on the permanent deformation performance, 2 % and 3 % bitumen emulsion contents can be recommended as the optimum contents for RCA and CB, respectively.
7. The modified prediction model was able to predict the permanent strains of the samples with very high accuracies by showing a R^2 close to 1 and a RMSE close to zero.

The outcomes of this study aim to result in an evidence-based promotion of the use of recycled materials and greener pavement design and construction approaches. For future studies, it is suggested to evaluate the effects of temperature, including high temperatures and the freezing-thawing processes, on the behaviour of samples. It is also recommended to explore the effect of bitumen emulsion on the mixture of CB and RCA.

Data availability statement

The datasets generated during and analysed during the current study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Ehsan Yaghoubi: Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Behnam Ghorbani:** Investigation, Conceptualization, Methodology, Writing – review & editing. **Mohammad Saberian:** Formal analysis, Visualization, Writing – original draft, Software. **Rudi van Staden:** Conceptualization, Visualization, Project administration, Funding acquisition, Writing – review & editing. **Maurice Guerrieri:** Resources, Conceptualization, Funding acquisition, Writing – review & editing. **Sam Fragomeni:** Supervision, Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by the Victoria State Government, Australia. The aggregates and emulsions used in this project were donated by “Repurpose It” and “Downer Group”, respectively, and the authors would like to thank them for their support.

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