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Strength and resilient modulus characteristics of emulsion-stabilised demolition wastes in pavement structures

Ehsan Yaghoubi [a,d,**], Behnam Ghorbani [b], Mohammad Saberian [c,*], Rudi van Staden [a], Maurice Guerrieri [d], Sam Fragomeni [a]

[a] College of Sport, Health and Engineering, Victoria University, Melbourne, 3011, VIC, Australia
[b] pitt&sherry, Melbourne, Australia
[c] School of Engineering, RMIT University, Melbourne, Victoria, Australia
[d] Institute for Sustainable Industries and Liveable Cities, Victoria University, Melbourne, Australia

A R T I C L E I N F O

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A B S T R A C T

The use of bitumen emulsion has commonly been limited to pavement surface treatments or stabilising virgin aggregates. There is a lack of experimental evidence about the resilient modulus responses of bitumen emulsion-stabilised recycled demolition wastes in pavement applications. The aim of this study is to evaluate the effect of bitumen emulsion on the tensile strength and resilient modulus responses of recycled crushed concrete aggregate and crushed brick for pavement base/subbase course applications. A type of slow-set anionic bitumen emulsion was used at different contents of 0, 1, 2, and 3 % by dry weight of aggregates to prepare compacted specimens. The specimens were dried back to 70 and 90 % of the compaction moisture content to simulate the field conditions. Specimens were next investigated through a comprehensive testing program, including indirect tensile strength, indirect tensile modulus, and repeated triaxial loading tests. Results showed that the tensile strength of the mixtures generally increased as the emulsion content increased. The inclusion of 2 % and 3 % bitumen emulsion to RCC and CB provided the highest indirect tensile resilient modulus (ITM_r) at 359 and 310 MPa, respectively, for those samples cured for 3 h. The highest ITM_r results were obtained from samples cured for 3 days at 40 °C in a dry state with the inclusion of 2 % emulsion. For CB and RCC specimens, the results were 2808 and 3361 MPa, respectively. However, specimens of CB and RCC with 3 % emulsion that were cured for 3 days at 40 °C and then soaked in water at 25 °C exhibited the highest ITM_r at 1981 and 2900 MPa, respectively. The resilient modulus in the majority of the specimens peaked at 2 % emulsion content, which was recommended as the optimum emulsion content. Results also indicated an enhanced resistance to moisture damage in demolition wastes through emulsion stabilisation. This study proposes, validates and promotes the sustainable approach of emulsion stabilisation of recycled aggregates used in the construction of pavement structures.

* Corresponding author.
** Corresponding author.
E-mail addresses: ehsan.yaghoubi@vu.edu.au (E. Yaghoubi), bghorbani@pittsh.com.au (B. Ghorbani), mohammad.saberian@rmit.edu.au (M. Saberian), rudi.vanstaden@vu.edu.au (R. van Staden), maurice.guerrieri@vu.edu.au (M. Guerrieri), sam.fragomeni@vu.edu.au (S. Fragomeni).

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1. Introduction

Sustainability has become a critical aspect of the material-consuming highway engineering sector, where the use of greener materials and technologies is highly encouraged. In order to contribute to sustainability targets through the use of greener construction materials, it is important to adopt a mindset of conserving virgin aggregates and instead utilising recycled or waste materials where permitted. Such an approach would undoubtedly help mitigate the adverse impact of the construction industry on the environment by enabling a circular economy within the industry. Furthermore, the difficulty of sourcing natural aggregates is becoming an increasingly challenging endeavour owing to the fast depletion of finite natural reserves [1,2]. Consequently, it is important to reduce the dependence on virgin quarried materials as their current rate of utilisation is unsustainable.

A wide variety of waste types are generated globally, where construction and demolition (C&D) wastes are among the types of waste that are produced in the largest quantities. C&D materials are produced through a multitude of engineering activities, such as the construction of new structures, as well as the knocking down of existing buildings and infrastructures, including pavement structures, among others [3]. Hundreds of millions of tonnes of C&D aggregate are generated around the world each year owing to these activities. The most common types of C&D materials include reclaimed asphalt pavement (RAP), recycled crushed concrete (RCC), crushed rock, and crushed brick (CB). C&D wastes have been investigated for several civil engineering applications to highlight their importance as valuable alternatives to natural aggregates; RCC [4,5], CB [6,7] and RAP [8,9]. Several other studies have highlighted the associated economic [10,11] and environmental [12,13] benefits of utilising construction and demolition aggregates.

Recycled crushed concrete (RCC) can be classified as granular soil. It is a C&D waste material that is produced in immense quantities, with approximately 27 million tonnes generated each year within Australia, where the current research is undertaken, of which only 60 % of the RCC generated is recycled [14]. RCC has earned a stellar reputation and has been increasingly acknowledged as a valuable road base/subbase aggregate. Along with the increasing popularity of RCC, many studies, such as [15,16], among others have explored its usefulness as an unbound granular road base aggregate, thereby allowing for a more comprehensive understanding of its behaviour. Several studies have reported that RCC records California bearing ratio (CBR) values that satisfy the local standards for road base and subbase applications [17,18]. Resilient modulus (M_r) testing is another vital test for evaluating the performance of pavement aggregates, where existing literature report that RCC meets the specified requirements for road subbase applications [19,20], thus providing further evidence on the potential of RCC as an aggregate in the construction of roads. The presence of partially hydrated cement or adhered mortar in the RCC can be noted as a key contributing factor that compliments the high stiffness and resilient engineering properties of RCC [21,22].

Crushed brick is another type of C&D aggregate that is accumulated in large amounts, where at least 1.3 million tonnes of CB are stockpiled annually in Australia [23]. CB has several desirable construction properties, such as low density and high porosity, although it suffers from relatively low compressive strength when compared against high-quality natural aggregates [24]. Low-density aggregates such as CB are useful in regulating the overburden pressure of road layers on subgrades, thereby improving the service life of the road infrastructure. Furthermore, the high porosity of aggregates is a desirable material property in structural pavement layers, as porous aggregates provide better drainage, which is critical when constructing premium-quality roads, in particular, those prone to wetting and drying as a result of precipitation [25,26]. CBR testing conducted on recycled crushed concrete partially replaced with CB is reported to achieve a CBR of above 30 %, which satisfied the local requirement for subbase aggregates in Hong Kong [27]. Field CBR testing on subgrade soils conducted by Al-obaydi et al. [28] revealed that the inclusion of CB aggregate led to improvement in the CBR values while adding that finer size aggregates showed greater improvement. The findings relating to the shear strength characteristics of CB containing 5 % polyethylene terephthalate (PET) plastic from Perera et al. [29] revealed that the CB-PET blends could satisfy the shear strength requirements of roads' base and subbase.

Research studies in the past have assessed the strength and resilient behaviour of construction aggregates containing C&D materials (RCC & CB) mixed with other solid waste such as glass [30,31], plastics [32,33] and crumb rubber [34,35]. The incorporation of such materials allows the C&D composites to acquire unique material characteristics owing to the disparate engineering properties possessed by the different solid wastes. Whilst unbound RCC and CB have inherent desirable strength properties, previous studies have investigated on improving their performance through chemical stabilisation using binders such as cement [36,37] and fly ash [38,39]. Despite cement stabilisation improving the compressive strength of the C&D aggregates, there are concerns about the susceptibility of the aggregates to shrinkage cracks at high cement dosages [40]. Moreover, the production of cement is associated with the generation of a large amount of carbon dioxide [41], which contributes to global warming. It is widely accepted that the production of a single tonne of cement results in the generation of one tonne of CO_2 [42]. In addition, producing cement is an energy-intensive process, which is not in agreement with the industries' stride towards sustainability. Even though fly ash is a waste product of the coal industry and, thus, has a lower carbon footprint in comparison to cement, previous studies have raised concerns regarding the immobilisation of heavy metals, which pose environmental and carcinogenic risks [43]. In addition, to reach the effective strength, curing of fly ash stabilised aggregates should be undertaken at temperatures above the normal ambient temperature (typically 40 °C) [44]. This causes some practical challenges and hence, hesitation from practitioners and pavement engineers. Therefore, alternative binders should be considered for the stabilisation of C&D as the structural pavement layers.

Several research projects have explored the stabilisation of RCC and CB with common cementitious materials, including cement and fly ash. Nevertheless, very limited studies have considered the performance of bitumen-stabilised C&D pavement aggregate, and those, such as Yaghoubi et al. [45] and Gómez-Meijide & Pérez [46] have focused on the permanent deformation resistance of bitumen-stabilised C&D. Even fewer studies have investigated the effect of adding bitumen emulsion on the resilient modulus response. For instance, Gómez-Meijide & Pérez [47] investigated the elastic behaviour of bitumen-stabilised C&D. However, their investigation of the resilient modulus behaviour was limited to dynamic triaxial tests. Given the widely accepted use of bitumen for pavements, this material can be deemed as a viable alternative as opposed to other chemical binders when considering the environmental impact. Bitumen has been studied extensively as an asphalt binder and has proven to be within the allowable limits for harmful leachates [48,49]. Furthermore, the resilient modulus is a critical parameter concerning the design of pavement base layers as the testing procedure simulates dynamic traffic loading as experienced by pavement structural layers, thereby enabling to obtain an understanding of the response of aggregates to such loading. Owing to the above, the current study explores the stabilisation of RCC and CB with bitumen emulsion in terms of their strength characteristics and resilient modulus response.

2. Materials and methods

2.1. Materials

The demolition waste aggregates used in this research included crushed brick (CB) and recycled crushed concrete (RCC). RCC and CB were known by the commercial names of Class III 20 mm crushed concrete and Class IV 20 mm crushed concrete, respectively. According to VicRoads [50], Class III is a premium upper subbase material suitable for heavy-duty, unbound, flexible pavements. It should meet minimum permeability standards to ensure effective drainage for sub-surface drains and the layer of unbound pavement above. In cases where specified, Class III can serve as a base for lightly travelled pavements, provided that it generates an adequate amount of cohesive fines during compaction. Class IV serves as a subbase material for heavy-duty unbound/bound roads or as a subbase for various other pavement types. In this study, RCC and CB were considered as base and subbase unbound aggregates, both conforming to VicRoads specification 820 [51]. Fig. 1 shows the particle size distributions (PSD) curves together with images of the RCC and CB used in this study. The PSD test was conducted following ASTM D6913/D6913 M [52]. Table 1 presents the physical and compaction properties of the aggregates, including the maximum and mean particle sizes (D_{max} and D_{50}), fine (<0.075 mm), sand (0.075< <4.75 mm) and gravel (>4.75 mm) portions, as well as the maximum dry density (MDD) and optimum moisture content (OMC) [53]. Both materials can be classified as well-graded gravel following the unified soil classification system.

An anionic slow-set bitumen emulsion was utilised for treating the RCC and CB. The pH and sieve residue values of the anionic slow-set bitumen emulsion were measured to be 12 and 0.05 %, respectively, following the AS 2341.32 [54] and AS 2341.26 [55] standards, orderly. It is worth mentioning that the specification limit for pH of anionic slow-set bitumen emulsion is recommended in the range of 11–13 based on the AS 2341.32 [54]. Also, as per AS 2341.26 [55], the maximum sieve residue is suggested to be 0.15 %. The viscosity test was carried out on the bitumen emulsion at 60 °C using a Brookfield LVT viscometer with a #1 spindle at 60 rpm following the ASTM D2196 [56]. The viscosity was obtained at 42 cp, which is in the recommended range of 30–90 cp based on the standard. The binder content of the emulsion was also obtained at 60.9 % following the AS/NZS 2341.23 [57], which is higher than the minimum value of 60 % as per the standard.

2.2. Sample preparation and mixtures

The AS 1289.5.2.1 [53] was followed to conduct the modified compaction test and obtain the optimum water content and maximum dry density of RCC and CB. The RCC and CB aggregates were oven-dried for at least one day at 105 °C, and next, various water contents were added to the samples and mixed thoroughly. The blends were then kept in air-tight sealed containers for 2 h to allow the absorption of water evenly by the aggregates [53]. Afterwards, the samples were compacted inside the cylindrical steel mould of 115.5 mm in height and 105 mm in diameter in 5 layers. Each layer received 25 blows by the modified compaction hammer of 4.9 kg, dropping from a height of 450 mm [53]. The maximum dry densities of CB and RCC are presented in Table 1. The optimum

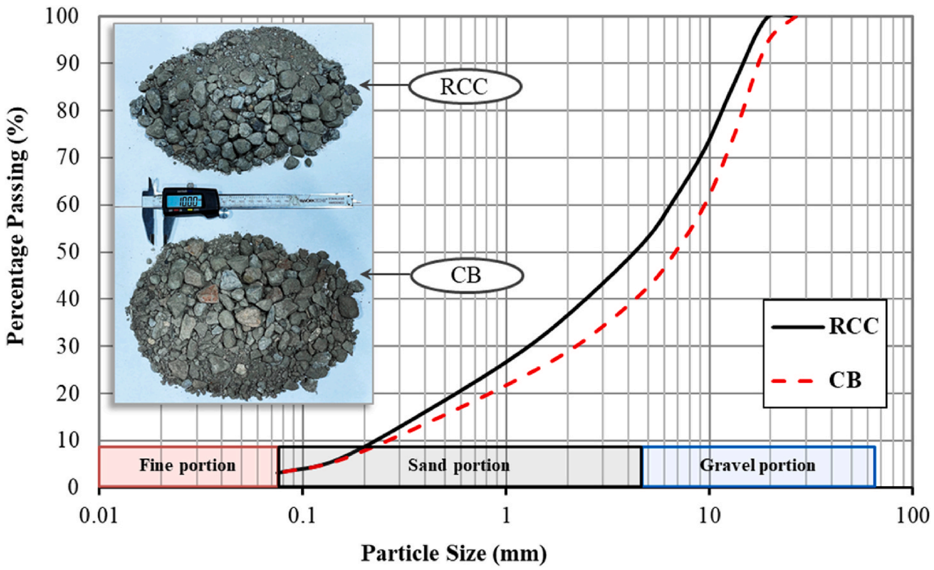

Fig. 1. PSD curves of RCC and CB.

Table 1
Physical and compaction properties of CB and RCC.

Property	RCC	CB
D_{max} (mm)	20.0	20.0
D_{50} (mm)	4.1	6.5
% Fines	3.1	3.1
% Sand	38.6	49.0
% Gravel	58.3	47.9
Coeficient of Uniformity	29.5	32.5
Coefficient of Curvature	1.30	1.73
Classification	GW	GW
MDD, t/m^3 (modified proctor)	1.99	2.00
OMC, % (modified proctor)	11.00	10.88

water content values were adopted for the preparation of the blends incorporating different amounts of the anionic slow-set bitumen emulsion at 0, 1, 2, and 3 % by dry weight of the recycled demolished aggregates. Since the bitumen emulsion includes approximately 40 % water, the required water to be added was recalculated to reach optimum water content based on the weight of the emulsion used for each mixture.

2.2.1. Indirect tensile strength (ITS) and indirect tensile modulus (IDT) specimens

The ITS and IDT samples were firstly mixed by an asphalt mixer for a minimum of 10 min and next compacted in a standard Marshall mould having a diameter of 100 mm, receiving 50 blows at each side of the sample, following AS/NZS 2891.5 [58]. Based on AGPT/T305 [59], three sets of identical ITS and three sets of identical IDT samples were prepared under three different curing conditions; namely, 3 ± 0.5 h at 25 ± 1 °C, 72 ± 2 h at 40 ± 5 °C and 72 ± 2 h at 40 ± 5 °C then inundated in 25 °C water for 24 h. The inundated specimens were next surface dried and mounted in the IDT jig for testing without delays. The ITS and IDT sample preparation conditions and procedures are demonstrated in Fig. 2. The mixtures and their corresponding sample IDs are provided in Table 2. Three replicate samples were prepared and tested for each dosage and curing condition.

2.2.2. Repeated load triaxial (RLT) specimens

AASHTO T307-99 [60] was followed for RLT sample preparation and testing. After mixing RLT samples with water and bitumen emulsion, the compaction of the samples was achieved within the confinement of a cylindrical split mould bearing a height of 200 mm and a diameter measuring 100 mm, using a modified compaction hammer. It is worthy of note that the samples were compacted at their OMC under modified compaction energy levels to achieve a compaction level of 98 % MDD. The samples were then trimmed to remove any excess soil protruding beyond the mould, at which point, the clasps of the split mould were loosened, releasing the sample from the mould. The compacted specimens were next dried back to 70 and 90 % of their OMC to simulate the field conditions. For this, two identical specimens of each mixture were compacted and left at room temperature (~25 °C for curing and drying). Specimens were next checked regularly until the desired 70 and 90 % of OMC was reached. Once the desired moisture content was achieved, the samples were sealed using plastic wrap to avoid moisture loss and to achieve an even distribution of the moisture before testing. RLT sample preparation conditions and procedures are illustrated in Fig. 2. The mixtures and their corresponding sample IDs are provided

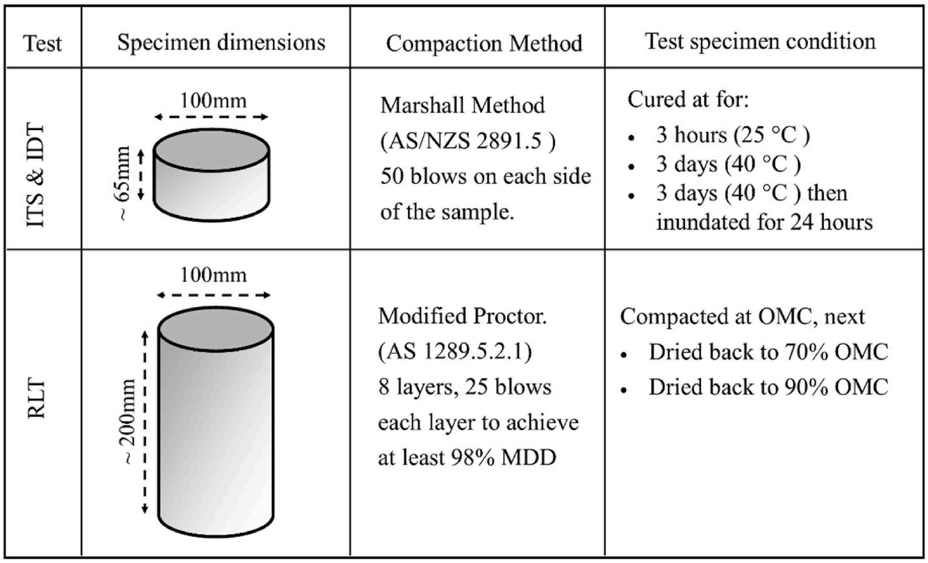

Fig. 2. Summary of specimen preparation procedures and conditions.

Table 2
Mixtures, preparation conditions and corresponding sample IDs.

Test	Sample ID	Preparation procedure
RLT	CB1-70	BEC[a] = 1 %, dried back to 70 % OMC
	CB1-90	BEC = 1 %, dried back to 90 % OMC
	CB2-70	BEC = 2 %, dried back to 70 % OMC
	CB2-90	BEC = 2 %, dried back to 90 % OMC
	CB3-70	BEC = 3 %, dried back to 70 % OMC
	CB3-90	BEC = 3 %, dried back to 90 % OMC
	RCC1-70	BEC = 1 %, dried back to 70 % OMC
	RCC1-90	BEC = 1 %, dried back to 90 % OMC
	RCC2-70	BEC = 2 %, dried back to 70 % OMC
	RCC2-90	BEC = 2 %, dried back to 90 % OMC
	RCC3-70	BEC = 3 %, dried back to 70 % OMC
	RCC3-90	BEC = 3 %, dried back to 90 % OMC
ITS & IDT	CB1-3hc	BEC = 1 %, cured for 3 h at 40 °C
	CB1-3dc	BEC = 1 %, cured for 3 days at 40 °C
	CB1-3dc-I	BEC = 1 %, cured for 3 days at 40 °C then inundated for 24 h
	CB2-3hc	BEC = 2 %, cured for 3 h at 40 °C
	CB2-3dc	BEC = 2 %, cured for 3 days at 40 °C
	CB2-3dc-I	BEC = 2 %, cured for 3 days at 40 °C then inundated for 24 h
	CB3-3hc	BEC = 3 %, cured for 3 h at 40 °C
	CB3-3dc	BEC = 3 %, cured for 3 days at 40 °C
	CB3-3dc-I	BEC = 1 %, cured for 3 days at 40 °C then inundated for 24 h
	RCC1-3hc	BEC = 1 %, cured for 3 h at 40 °C
	RCC1-3 dc	BEC = 1 %, cured for 3 days at 40 °C
	RCC1-3dc-I	BEC = 1 %, cured for 3 days at 40 °C then inundated for 24 h
	RCC2-3hc	BEC = 2 %, cured for 3 h at 40 °C
	RCC2-3 dc	BEC = 2 %, cured for 3 days at 40 °C
	RCC2-3dc-I	BEC = 2 %, cured for 3 days at 40 °C then inundated for 24 h
	RCC3-3hc	BEC = 3 %, cured for 3 h at 40 °C
	RCC3-3dc	BEC = 3 %, cured for 3 days at 40 °C
	RCC3-3dc-I	BEC = 3 %, cured for 3 days at 40 °C then inundated for 24 h

[a] BEC = Bitumen emulsion content.

in Table 2. For each dosage and curing condition, triplicate samples were prepared and tested.

2.3. Testing procedures

Three laboratory experiments were conducted to evaluate the performance of emulsion-treated aggregates, namely indirect tensile strength (ITS), indirect tensile modulus (IDT) and repeated load triaxial (RLT) tests.

The ITS test was performed to compare the potential of the mixtures in failure due to bottom-up cracking. Generally, the tensile strength of the bound pavement surface layers, such as asphalt or emulsion-stabilised aggregates governs the fatigue life of pavements

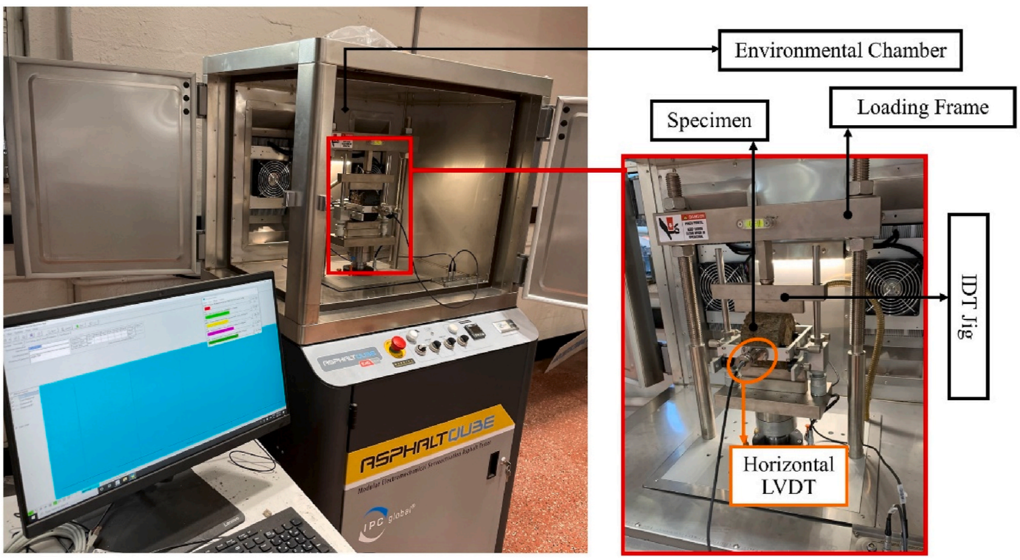

Fig. 3. IDT testing machine, setup and mounted specimen.

and the potential for fatigue cracking [22]. The ITS testing was performed following AS 1012.10 [61] and Maghool et al. [62]. ITS specimens were tested at 25 °C for which the samples were left in the environmental chamber for two-three hours to equilibrate to the test temperature. A diametrical load was subjected to a displacement-controlled mode with a displacement rate of 50.8 mm per minute, and the peak force to split the sample was collected. Note that since the RCC and CB aggregates do not have a tensile strength, the ITS samples for untreated RCC and CB could not be prepared and tested. Equation (1) was used to calculate the ITS.

$$\mathrm{ITS} = \frac{2P}{\pi DL} \times 1000 \tag{1}$$

where ITS is the indirect tensile strength (kPa); P is the maximum applied load (N); D is the diameter of the sample (mm); and L is the length of the sample (mm) within a range of 57 mm–70 mm.

The determination of the resilient modulus of stabilised samples using the indirect tensile method was carried out following AS/NZS 2891.13.1 [63]. As recommended by AGPT/T305 [59], IDT specimens were tested at 25 °C. Specimens were placed in the environmental chamber for at least 2 h prior to the commencement of the test to equilibrate to the test temperature. A modular electromechanical testing machine capable of exerting haversine loads pulses of 0.04 s loading and 3.0 s pulse repetition with an accuracy of 0.005 s (as specified in AS/NZS 2891.13.1 [63]) was used. Fig. 3 shows the testing machine and a specimen mounted in the environmental chamber of the machine. The sample mounted in the machine was next subjected to five load pulses to determine the resilient modulus.

The repeated load triaxial (RLT) test enables a crucial assessment of the behaviour of aggregates utilised in the construction of roads. The RLT testing program consists of multiple sequences, with each sequence having several cycles of repeated impulse loading. Each sequence has specific loading parameters, where the loading conditions utilised in the current study are detailed in the AASHTO T307-99 [60]. These loading cycles carefully simulate the dynamic loads encountered by road layer aggregates due to moving vehicles, thereby providing a greater understanding of how these aggregates respond to such loads, especially in terms of their stiffness. The sample was then mounted into the UTS-16P machine which was used to perform the RLT testing. A haversine loading pulse was applied with a loading cycle consisting of 0.1 s for loading and another 0.9 s for unloading. Table 3 manifests various stress combinations considered in the current study following AASHTO T307-99 (2003).

3. Results and discussions

3.1. *Indirect tensile strength*

Fig. 4 shows the indirect tensile strength (ITS) of the 3-h cured samples at 25 °C, as well as the samples cured for 3 days at 40 °C and those cured for 3 days at 40 °C and inundated in water. Evidently, by increasing the content of bitumen emulsion from 1 to 3 %, the ITS of CB-3hc samples reduced from 79 to 59 kPa; however, the ITS of RCC samples firstly reduced from 47 to 45 kPa by increasing the emulsion content from 1 to 2 % and then increased to 56 kPa by adding 3 % emulsion. On the other hand, increasing the curing time from 3 h to three days resulted in higher ITS values of both CB and RCC samples. The observed phenomenon can be attributed to the specific characteristics of the bitumen emulsion employed in this research. This emulsion is classified as an anionic slow-set variant, necessitating a curing duration of a minimum of 1–2 days to achieve optimal performance, as per the guidance provided by the supplier. Furthermore, it is crucial to recognise that the underlying mechanism responsible for the strength development in samples stabilised with this bitumen emulsion becomes operational once the water content within the samples undergoes evaporation throughout the curing process. Besides, comparing the results of the 3-day cured samples either in dry condition or saturated condition, the ITS of the samples increased by increasing the bitumen emulsion from 1 to 3 %. For instance, the ITS of CB samples increased from 393 to 454 kPa by increasing the emulsion from 1 to 3 %. A noticeable observation was the improvement in the soaked samples with increasing the bitumen emulsion content. That is, samples tended to retain higher ITS values as the bitumen emulsion content increased, most notable for the samples with 3 % bitumen emulsion. This enhancement can be related to the effect of emulsion at

Table 3
Stress levels applied to the samples during the RLT tests.

Sequence No.	Confining Pressure (kPa)	Maximum Axial Stress (kPa)	Bulk Stress (kPa)
1	20.7	20.7	82.8
2	20.7	41.4	103.5
3	20.7	62.1	124.2
4	34.5	34.5	138.0
5	34.5	68.9	172.4
6	34.5	103.4	206.9
7	68.9	68.9	275.6
8	68.9	137.9	344.6
9	68.9	206.8	413.5
10	103.4	68.9	379.1
11	103.4	103.4	413.6
12	103.4	206.8	517.0
13	137.9	103.4	517.1
14	137.9	137.9	551.6
15	137.9	275.8	689.5

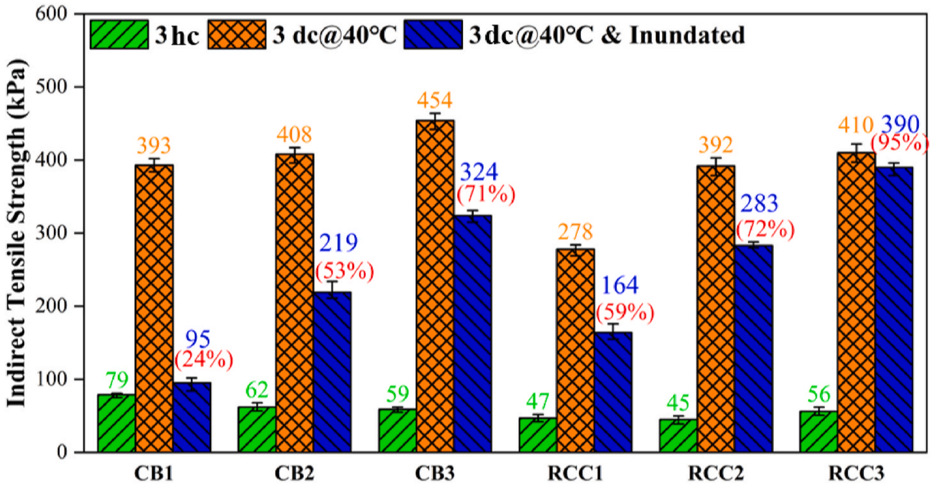

Fig. 4. ITS of samples cured for 3 h, 3 days at 40 °C, and cured for 3 days at 40 °C then inundated.

higher contents, which could provide better binding with the particles of RCC and CB and reduce the detrimental effect of moisture. Therefore, it can be concluded that the bitumen emulsion stabilisation has beneficial effects in terms of enhancing the tensile strength moisture sensitivity of the RCC and CB. Fig. 4 also shows the ratio of the ITS of 3-day cured and inundated samples to 3-day cured samples (values (%) in parentheses). The increase in the ratio shows the positive effect of the addition of bitumen emulsion on increased residence to moisture damage.

3.2. Indirect tensile modulus

Fig. 5 shows the indirect tensile resilient modulus (ITM_r) of the IDT samples described in Table 2. According to the results, the inclusion of 2 % and 3 % bitumen emulsion to RCC and CB provided the highest ITM_r for those samples cured for 3 h, respectively. Also, similar to ITS results, the curing period had a significant impact on the ITM_r results, as the ITM_r increased considerably at 3 days of curing than the 3 h of curing due to using a slow-set bitumen emulsion, requiring 1–2 days for optimal curing. Additionally, the evaporation of water during the curing helped in strength improvement in emulsion-stabilised samples. Among the samples cured for 3 days at 40 °C, the addition of 2 % emulsion provided the highest ITM_r results; however, the inclusion of 3 % emulsion to the aggregates cured for 3 days and next inundated in water led to the highest ITM_r values compared to the results of the samples tested in this study. Also, as can be seen, the saturated RCC samples provided higher results compared to those of the saturated CB samples. This can be attributed to the reaction between bitumen emulsion and unhydrated cement attached to the RCC aggregates, as the negative charges of the anionic emulsion were absorbed onto the positively charged sites on the surface of cement particles, providing higher strength in the saturation state. The ITM_r results indicated that the bitumen emulsion stabilisation had significant beneficial effects in terms of enhancing the moisture sensitivity of the RCC and CB. The ratios of the ITM_r of 3-day cured and inundated samples to 3-day cured samples (values (%) in parentheses) are also shown in Fig. 5. The ratio increased from 37 % to 74 % and 62 %–88 % for the CB and RCC

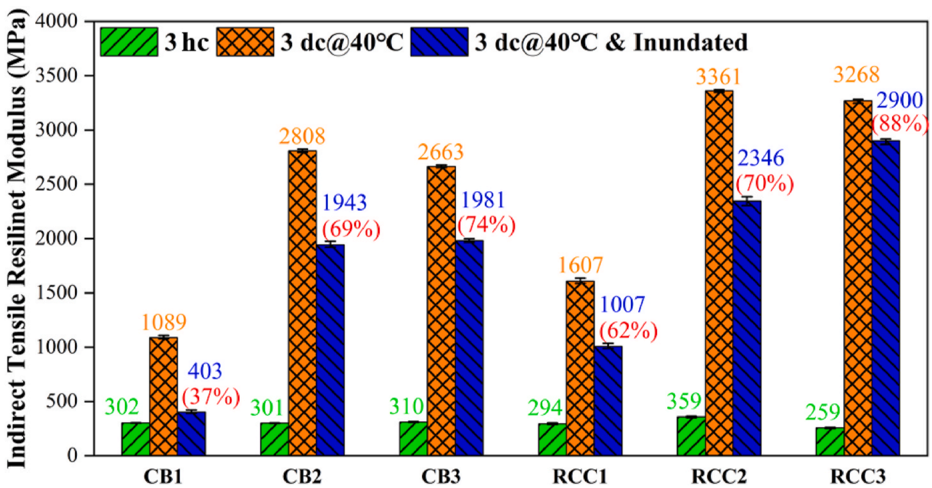

Fig. 5. ITM_r of samples cured for 3 h, cured for 3 days at 40 °C, and cured for 3 days at 40 °C then inundated.

samples, respectively, by increasing bitumen emulsion content from 1 to 3 %.

3.3. Resilient modulus

Fig. 6 depicts the resilient modulus of samples obtained from the average of the 15 sequences of loading, as described in Table 3. The RLT test results show that, in general, RCC samples provided higher M_r values compared to the CB samples with the same dried-back moisture content and emulsion content. For instance, RCC1-90 had a M_r value of 315.98 MPa, while the sample CB1-90 resulted in a M_r value of 182.29 MPa. This can be attributed to the presence of unhydrated cement attached to the RCC aggregates, which could react with the bitumen emulsion and provide higher strength. RCC is known to contain between 3.2 % and 17.5 % mortar [64], and a study carried out by Kulisch et al. [65] on quantification of the unhydrated cement content in cement paste revealed a potential range of 6 %–36 % unhydrated cement in the mortar. This is also in agreement with previous studies [66,67]. In fact, the negative charges of the anionic emulsion were absorbed onto the positively charged sites on the surface of cement particles [68]. The anionic emulsion was selectively adsorbed onto the positively charged sites on the surface of cement particles, such as those occupied by the aluminate phase, C_3A, or certain parts of silicate phases, C_2S and C_3S, through anionic emulsifier via electrostatic adsorption or electrostatic interaction [69,70].

Experimental results illustrated in Fig. 6 also show that among the CB samples targeted at 70 % moisture, by increasing the bitumen emulsion content from 1 to 3 %, the M_r increased from 254.18 to 277.96 MPa. However, comparing those CB blends tested at 90 % moisture, the sample incorporating 2 % bitumen emulsion experienced the highest M_r at 236.26 MPa. On the other hand, RCC2-70 provided the highest M_r at 339.84 MPa between the RCC samples tested at 70 % moisture, but the inclusion of higher amounts of bitumen emulsion at higher moisture content level (i.e., 90 %) resulted in reducing the resilient modulus of RCC blends; so that by increasing the emulsion content from 1 to 3 %, M_r decreased from 315.97 to 269.81 MPa. Therefore, it can be stated that the increased moisture content had a negative impact on the resilient modulus of CB and RCC samples. This could be due to the excessive water that interfered with the reactions between the negative ions of the emulsion and the positive ions of the aggregates and cement.

According to AASHTO [71], the recommended resilient modulus values for base and subbase are at least 79 MPa and 42 MPa, respectively. Based on the RLT test results, all the samples can be adopted for the construction of the road base and subbase applications. Based on the resilient modulus results and with economical considerations, for the base and subbase course applications, 2 % and 3 % emulsion content can be recommended for roads located in wet and dry climates, respectively.

Fig. 7 shows the resilient modulus of the samples at different stress stages (sequences), as provided in Table 3, as well as the average of the 15 M_r values for each mixture. It is well proven in the literature that by increasing the confining stress, the internal friction and inter-particle interlocking of the particles increase, leading to increasing the resilient modulus of granular aggregates. Also, at a given confining pressure, the increase of the axial stress results in increasing the resilient modulus. This is because of the stress hardening of the samples [22,72]. As can be seen from Fig. 7, the bitumen emulsion stabilised RCC and CB samples exhibited a similar trend.

3.4. Analysis of M_r values using predictive models

In this study, two models were adopted to evaluate the resilient modulus results collected from the RLT test results. The models included the two-parameter (also known as bulk stress) model (Equation (2)) and three-parameter model (Equation (3)) proposed by Hicks and Monismith [73] and NCHRP Project 1–28A [74], respectively. The experimental results were used to obtain the coefficients (k) of the predictive models through regression analyses. As can be observed from Table 4, presenting the obtained regression models, the three-parameter model could predict the resilient modulus with higher accuracies compared to the two-parameter model.

$$M_r = k_1 \times \theta_2^k \tag{2}$$

$$M_r = k_1 \times p_a \times \left(\frac{\theta}{p_a}\right)^{k_2} \times \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \tag{3}$$

where k_1, k_2, and k_3 are coefficients; θ is the bulk stress $= 3\sigma_c + \sigma_d$ (where σ_c denotes the confining stress) p_a is atmospheric pressure = 100 kPa; and τ_{oct} denotes the octahedral shear stress ($\frac{\sqrt{2}}{3}\sigma_d$, where σ_d denotes the deviator stress).

To demonstrate the goodness-of-fit of the prediction models, specifically the NCHRP model, the relationships between the experimentally measured M_r and the predicted M_r for four randomly selected samples, i.e., CB2-90 and RCC3-90 based on the NCHRP

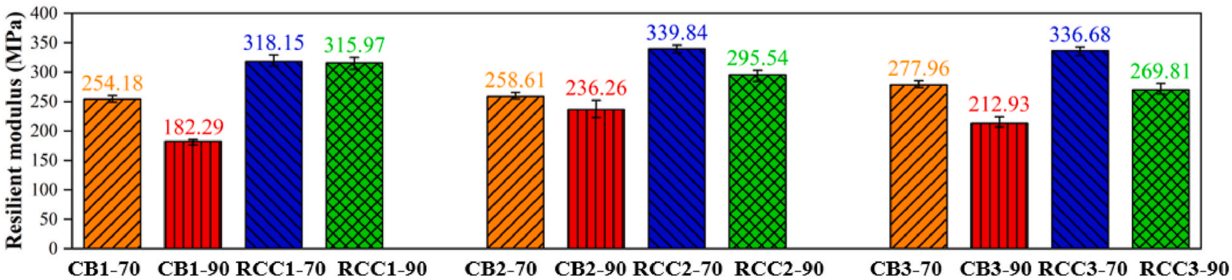

Fig. 6. Resilient modulus of samples obtained from the average of all 15 sequences.

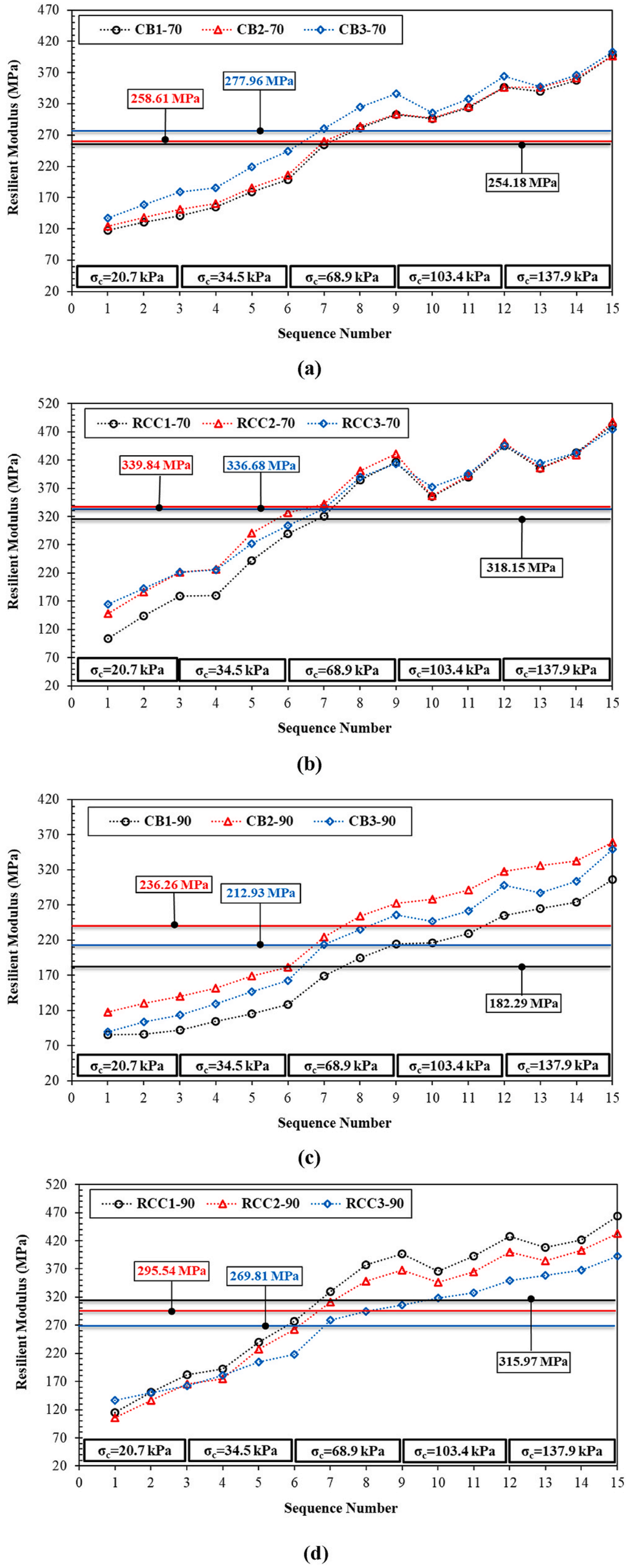

Fig. 7. Resilient modulus values at different stress stages for the mixtures of (a) CB at 70 % OMC, (b) RCC at 70 % OMC, (c) CB at 90 % OMC, and (d) RCC at 90 % OMC.

Table 4
Regression models obtained from the bulk stress and the three-parameter models.

Sample ID	Bulk stress model	R^2	NCHRP model	R^2
CB1-70	$M_r = 8.129 \times \theta^{0.601}$	0.992	$M_r = 1.315 \times p_a \times (\frac{\theta}{p_a})^{0.629} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.108}$	0.994
CB1-90	$M_r = 3.873 \times \theta^{0.670}$	0.992	$M_r = 0.872 \times p_a \times (\frac{\theta}{p_a})^{0.719} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.188}$	0.995
CB2-70	$M_r = 9.884 \times \theta^{0.570}$	0.993	$M_r = 1.389 \times p_a \times (\frac{\theta}{p_a})^{0.599} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.112}$	0.995
CB2-90	$M_r = 9.682 \times \theta^{0.558}$	0.992	$M_r = 1.298 \times p_a \times (\frac{\theta}{p_a})^{0.603} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.173}$	0.998
CB3-70	$M_r = 15.949 \times \theta^{0.5}$	0.982	$M_r = 1.589 \times p_a \times (\frac{\theta}{p_a})^{0.485} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.057}$	0.982
CB3-90	$M_r = 5.202 \times \theta^{0.647}$	0.993	$M_r = 1.037 \times p_a \times (\frac{\theta}{p_a})^{0.669} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.084}$	0.994
RCC1-70	$M_r = 6.596 \times \theta^{0.675}$	0.927	$M_r = 1.456 \times p_a \times (\frac{\theta}{p_a})^{0.643} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.124}$	0.925
RCC1-90	$M_r = 8.540 \times \theta^{0.630}$	0.938	$M_r = 1.566 \times p_a \times (\frac{\theta}{p_a})^{0.643} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.050}$	0.939
RCC2-70	$M_r = 18.441 \times \theta^{0.510}$	0.925	$M_r = 1.872 \times p_a \times (\frac{\theta}{p_a})^{0.447} \times (\frac{\tau_{oct}}{p_a} + 1)^{0.241}$	0.932
RCC2-90	$M_r = 7.390 \times \theta^{0.643}$	0.935	$M_r = 1.450 \times p_a \times (\frac{\theta}{p_a})^{0.668} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.093}$	0.939
RCC3-70	$M_r = 20.458 \times \theta^{0.491}$	0.966	$M_r = 1.938 \times p_a \times (\frac{\theta}{p_a})^{0.466} \times (\frac{\tau_{oct}}{p_a} + 1)^{0.094}$	0.967
RCC3-90	$M_r = 13.608 \times \theta^{0.523}$	0.984	$M_r = 1.562 \times p_a \times (\frac{\theta}{p_a})^{0.584} \times (\frac{\tau_{oct}}{p_a} + 1)^{-0.237}$	0.994

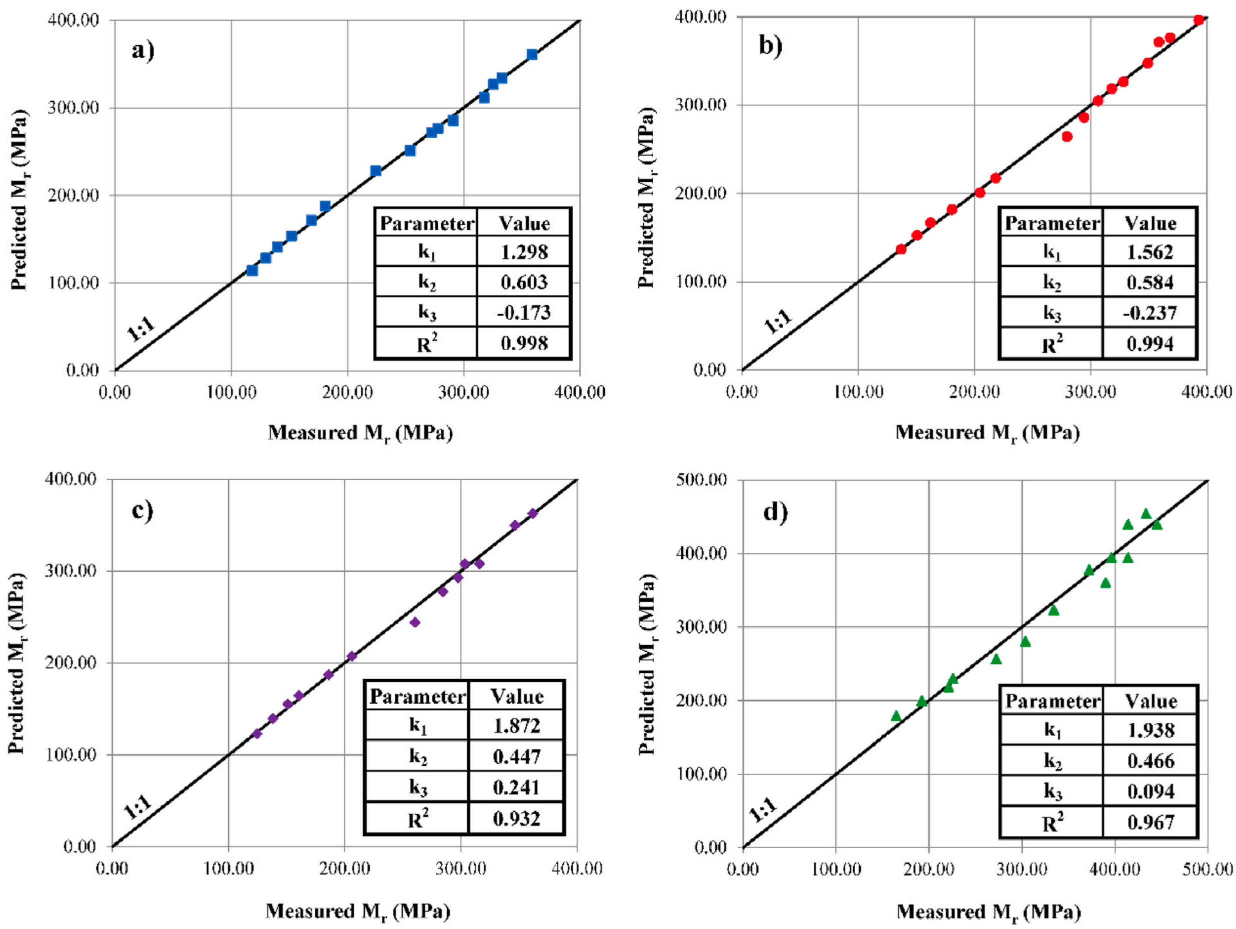

Fig. 8. Correlations between the experimentally measured and analytically predicted resilient modulus values of the samples (a) CB2-90 (NCHRP model), (b) RCC3-90 (NCHRP model), (c) CB2-70 (bulk stress model), and (d) RCC3-70 (bulk stress model).

model and CB2-70 and RCC3-70 based on the bulk stress model, are shown in Fig. 8. The plots of Fig. 8 show that there is a strong correlation between the analytically predicted and experimentally measured resilient modulus values. This also indicated that the resilient modulus predictive models developed for unbound granular aggregates could be effectively used for aggregates treated with up to 3 % bitumen emulsion.

4. Conclusions

In this study, a slow-set anionic bitumen emulsion was used to stabilise recycled demolition wastes (i.e., recycled crushed concrete aggregate and crushed brick) for the pavement base and subbase applications. The anionic bitumen emulsion was added to RCC and CB at different percentages, and a series of mechanical tests were performed on identical samples that were conditioned/cured in different ways. Based on the ITS test results, the ITS of CB specimens cured for 3 h was reduced from 79 to 59 kPa by increasing the bitumen emulsion content from 1 to 3 %; however, the ITS of the RCC samples was firstly reduced from 47 to 45 kPa by increasing the emulsion content from 1 to 2 % and then increased to 56 kPa by adding 3 % emulsion. Curing time also provided higher ITS for both CB and RCC samples because the adopted bitumen emulsion, which was an anionic slow-set emulsion, required at least 2 days for the best curing performance. Also, the increase in the emulsion content from 1 to 3 % led to a rise in the ratio of the ITS of 3-day cured and inundated samples to 3-day cured samples from 24 % to 71 % in CB and 59 %–95 % in RCC. This implies the improvement of residence to moisture damage by the addition of bitumen emulsion. In addition, the inclusion of 2 % and 3 % bitumen emulsion to RCC and CB provided the highest resilient modulus achieved through the IDT test (ITM_r) at 359 and 310 MPa, respectively, for those samples cured for 3 h. Based on the RLT resilient modulus test results, RCC specimens exhibited higher M_r values than the CB specimens, possibly due to the negative charges of the anionic emulsion that were adsorbed onto the positively charged sites on the surface of unhydrated cement particles attached to the RCC aggregates.

A significant outcome of this study was that both ITS and IDT results proved that the bitumen emulsion stabilisation remarkably enhanced the resistance of RCC and CB to moisture damage in pavement layers. The outcome of this study aims to promote the use of demolition wastes in the construction of pavements by evaluating the innovative technique of stabilisation of RCC and CB using bitumen emulsion. The following investigations, which were not within the scope of the current research project, can be recommended for future studies: evaluating the effects of 7-day curing on the samples; the effect of using rapid-set bitumen emulsion on the strength and resilient modulus characteristics of the demolition wastes; and the long-term fatigue performance of the emulsion stabilised materials.

CRediT author statement

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

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