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Recycled aggregate blends for backfilling deep trenches in trafficable areas

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ABSTRACT

Limited supplies of natural aggregates for backfilling pipeline trenches in trafficable areas have led to considering secondary resources. Utilizing blends entirely made of recycled aggregates to backfill excavated trenches in trafficable areas is rare if any, where traditionally, natural crushed rock has been used. In this study, 18 blends of various proportions of recycled glass (RG), plastic (RP), tire (RT), and concrete aggregate (RCA) were proposed and studied as alternatives. First, typical pavement tests such as compaction and CBR were carried out to select 7 suitable mix designs based on available backfill specifications. The shortlisted blends were further investigated through a specialized testing program, in particular, repeated load triaxial to simulate site stress levels. The results showed that CBR and resilient modulus characteristics improved by the increase in RCA content and the reduction in RT content. Three recycled material blends were selected as the optimum mix designs, and were next compared with the surrounding natural clay subgrades of the study area. The resilient modulus response of optimum mix designs exhibited up to 1.6 times greater stiffness compared to the clay subgrades under the same stress levels. The outcomes of this study reduce the demand for natural aggregates and promote the use of sustainable materials for backfilling pipeline trenches located under traffic loadings.

1. Introduction

With the rapid growth in urban densities resulting in more land being covered by roads, inevitably, the percentage of sewer pipelines embedded in clay subgrades beneath trafficable areas is increasing. Trafficable areas include locations that receive frequent traffic, such as existing or proposed road carriageways and shoulders, driveways and car parks, access tracks and constructed footpaths [1]. In trafficable areas, the type of backfill materials recommended by the relevant guidelines, such as Melbourne Water Retail Agencies' Backfill Specifications [1] depends on the depth of the excavated trench. For trenches with depths less than 1.5 m, the backfill should be 20 mm Class 2 (CL2) crushed rock for the full depth. However, for trenches excavated to the depth of 1.5 m or greater, the 600 mm backfill beneath pavement layers should be 20 mm CL2 and the remaining depth should be backfilled with 20 mm Class 4 (CL4) crushed rock.

Several studies investigated the effect of traffic load, backfill compaction, backfill erosion and saturation state on the deformation of buried sewage pipelines [2–4]. However, these studies utilized the natural aggregates in backfilling excavated trenches with depths less than 1.5 m. To reduce the demand for natural aggregates (experiencing current shortages in many parts of the world including Australia) to backfill shallow (<1.5 m) and deep (≥1.5 m) excavated trenches, further investigation on alternative backfill materials is necessary.

The global trend towards sustainable practices and net zero targets motivates ongoing research into methods of repurposing and recycling secondary resources such as waste materials, for various applications. Given the substantial demand for building materials in construction projects, incorporating recycled materials is a crucial tactic for attaining net zero construction goals [5]. Several research studies have demonstrated the feasibility of utilizing recycled materials, in particular, recycled plastic, glass, tire and recycled concrete aggregate in base/subbase applications [6–11]. Nonetheless, these research studies employed limited amounts of recycled materials to enhance the

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Table 1
Results of environmental assessment obtained for RG, RP, RT [12] and RCA [14] along with the threshold values of TC and ASLP for different metals.

Metals	Thresholds for solid inert waste[a]		Drinking water standard[b] (mg/l)	Hazardous waste Designation (mg/l)	TC_{RG} / TC_{RP} / TC_{RT} / TC_{RCA} (mg/kg)	$ASLP_{RG}$ / $ASLP_{RP}$ / $ASLP_{RT}$ / $ASLP_{RCA}$ (pH = 5) (mg/l)	$ASLP_{RG}$ / $ASLP_{RP}$ / $ASLP_{RT}$ / $ASLP_{RT}$ (pH = 9.2) (mg/l)
	TC (mg/kg)	ASLP (mg/l)					
Arsenic	500	0.35	0.05	5	<7	<0.05	<0.05
					<7	<0.05	<0.05
					<7	<0.05	<0.05
					<5	<0.01	<0.1
Barium	6250	35	2	100	18	0.2	0.1
					39	0.2	0.03
					1	0.03	0.03
					88	0.34	<0.1
Cadmium	100	0.1	0.005	1	<0.4	<0.01	<0.01
					1	<0.01	<0.01
					<0.4	<0.01	<0.01
					<0.2	<0.002	<0.02
Chromium	500	2.5	0.1	5	8	<0.01	<0.01
					12	<0.01	<0.01
					<1	<0.01	<0.01
					15	<0.05	<0.1
Lead	1500	0.5	0.015	5	20	0.04	<0.03
					13	<0.03	<0.03
					2	<0.03	<0.03
					11	<0.01	<0.1
Mercury	75	0.05	0.002	0.2	<0.1	–	–
					<0.1	–	–
					<0.1	–	–
					<0.05	<0.001	<0.01
Selenium	50	0.5	0.05	1	<2	<0.12	<0.12
					<2	<0.12	<0.12
					<2	<0.12	<0.12
					<3	<0.01	<0.1
Sliver	180	5	0.05	5	<1	<0.05	<0.05
					<1	<0.05	<0.05
					<1	<0.05	<0.05
					<5	<0.01	<0.1

[a] EPA-Victoria [16] [b] US-EPA[17].

characteristics of the subgrade soil or focused on the base and subbase structural layers. Yaghoubi, et al. [12] and Teodosio, et al. [13] carried out studies that investigated the feasibility of utilizing blends of 100% recycled material being recycled glass, plastic and tire to backfill deep excavated trenches. However, these studies focused on "non-trafficable" areas. Yaghoubi, et al. [12] carried out an extensive laboratory program and developed two blends completely made of recycled materials (recycle glass (RG), recycled plastic (RP) and recycled tire (RT)) suitable for backfilling deep trenches situated in non-trafficable areas. These blends were next used to backfill and instrument two full-scale trial site and were field performance monitored for 17 months, results of which are reported by Teodosio, et al. [13]. The current study aims to extend the application of blends of 100% recycled materials to backfilling excavated trenches located in "trafficable areas" by introducing stiffer particles of recycled concrete aggregates (RCA) into the RG-RP-RT matrix. Yaghoubi, et al. [12] and Arulrajah, et al. [14] carried out environmental assessments of RG, RP, RT and RCA following the Australian Standard Leaching Procedure [15], and checked against the thresholds provided by EPA-Victoria [16] and US-EPA [17]. Their investigations on the total concentration of contaminants (TC) and Australian Standard Leaching Procedure (ASLP) showed that these recycled materials can safely be used as fill materials. The outcomes of the abovementioned studies are summarized in Table 1.

The Australian guidelines, Austroads [18], recommend determining the subgrade California Bearing Ratio (CBR) to design the structural thickness of pavements. The assessment of the subgrade fill response and performance using static experimental methods, such as CBR, is insufficient in imitating the conditions and behavior of a pavement system that is subjected to repeated vehicular traffic [21]. To obtain a more accurate evaluation of the performance and stress–strain reaction of pavement materials under repeated loading, the determination of resilient modulus (Mr) was considered in the current study to evaluate the stiffness characteristics of pavement materials. Zhalehjoo, et al. [22], Saberian and Li [23] and Saberian, et al. [24] conducted a comprehensive investigation on the resilient modulus of unbound granular materials using the RLT test. Their findings indicated that the test results correlated well with the field performance of pavements, allowing for accurate predictions of rutting and fatigue cracking. Several studies have assessed the effectiveness of enhanced subgrade soils through the resilient modulus characteristic typically obtained via Repeated Load Triaxial (RLT) experiments [7,25–27]. However, none of the above has worked on the resilient modulus properties of the backfill materials made of 100% recycled aggregates that perform as a pavement structural layer.

The objective of the current research is to investigate the utilization of blends of waste & recycled materials comprising RG, RP, RT and RCA as backfilling materials in deep excavated trenches for sewer pipelines to replace Class 4 (CL4) crushed rock. The proposed blends were evaluated against the relevant specification and guidelines [1,20]. The performance of the blends was compared with the surrounding clay subgrade. This research aims to contribute to a sustainable response to the current worldwide shortage of sand and gravels by promoting the use of recycled aggregates in the design and building of infrastructure projects.

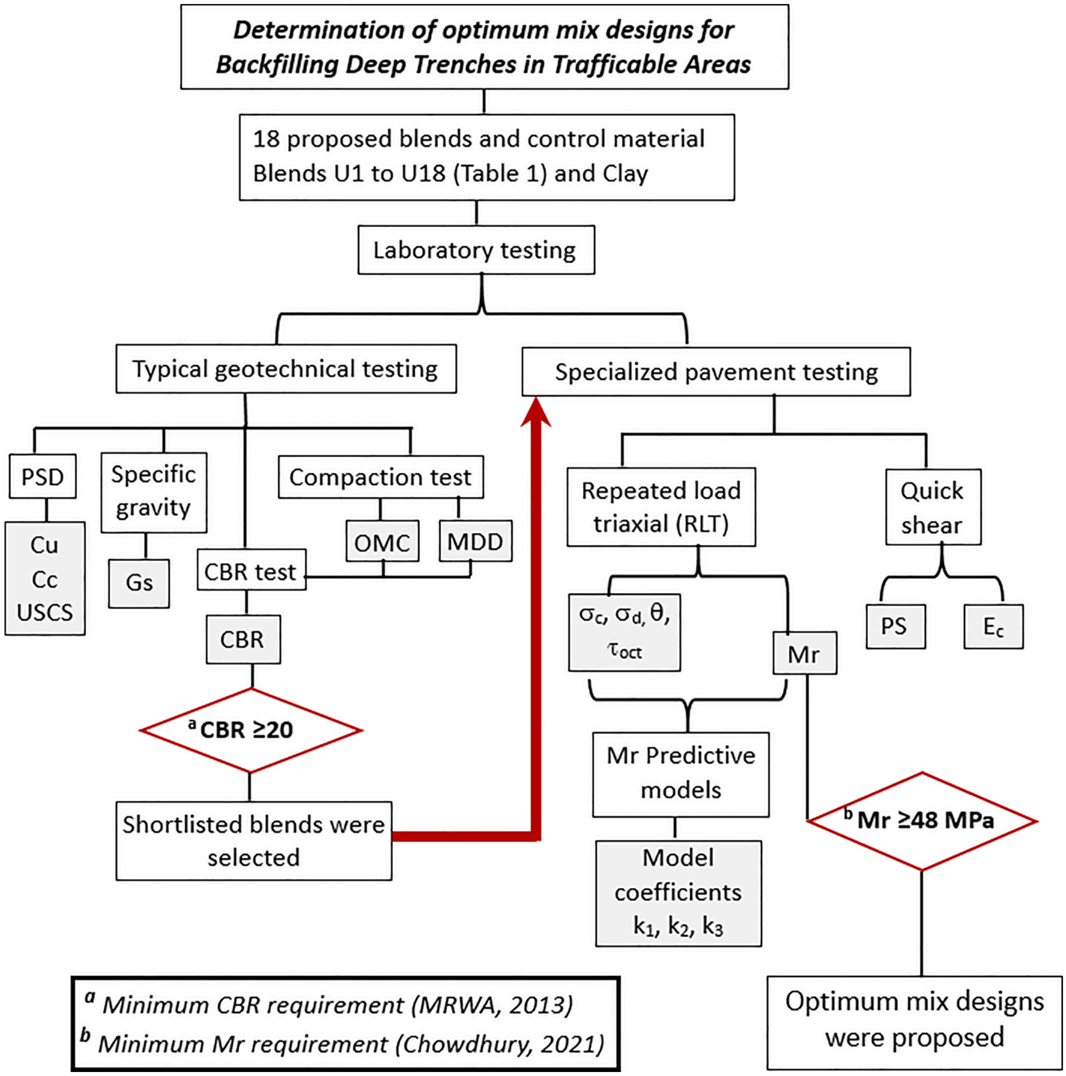


Fig. 1. The flowchart for the selection of suitable recycled blends to backfill deep trenches under traffic loading.

2. Materials and methods

2.1. The scheme for determining the optimum mix designs

The procedure to select blends of recycled materials comprising recycled glass (RG), plastic (RP), tire (RT) and recycled concrete aggregate (RCA) that are suitable for backfilling deep sewer pipeline trenches in trafficable areas is demonstrated in Fig. 1. The procedure can be summarized in the following steps:

1- Propose a set of recycled blends that have a spectrum of varied percentages of recycled materials with size distribution curves falling within Class 4 upper and lower gradation limits based on MRWA [1].
2- Carry out typical geotechnical tests, including specific gravity (Gs), particle size distribution (PSD) and compaction to determine the blend characteristics. From compaction test, measure the optimum moisture content (OMC) and maximum dry density (MDD), and subsequently prepare the California bearing ratio (CBR) samples under these specific conditions.
3- Determine CBR values of all proposed blends to select a shortlist of blends that achieved CBR $\geq$ 20, which is the minimum requirement recommended by MRWA [1]. Prepare and test triplicate specimens of shortlisted blends for more reliability of results.
4- Carry out specialized pavement testing including repeated load triaxial (RLT) and quick shear testing.
5- From RLT testing, determine resilient modulus (Mr) at different confining stress (σ_c) and deviator stress (σ_d) levels and calculate bulk stress (θ) and octahedral shear stress (τ_{oct}) to incorporate into Mr predictive models to determine model coefficients (k_1, k_2, k_3).
6- From quick shear test, measure the peak shear strength (PS) and Young modulus (Ec).
7- Calculate the average Mr and select blends that achieve minimum requirement recommended by Chowdhury [42]. These blends are considered as optimum mix designs.

2.2. Materials, proposed blends and physical properties

In the current research, four types of recycled aggregates along with natural expansive clay commonly occurring in Victoria, Australia were used as presented in Fig. 2. Recycled aggregates including recycled glass (RG), recycled plastic (RP), recycled tire (RT), and recycled concrete aggregate (RCA) were collected from local recycling industries in Melbourne, Australia. The reason behind selection of the abovementioned materials was consistency with a previous study by the authors to develop backfill materials for non-trafficable areas [12]. In the previous study, blends of RG, RT and RP showed satisfactory performance for backfilling deep excavated trenches in non-trafficable areas. In the

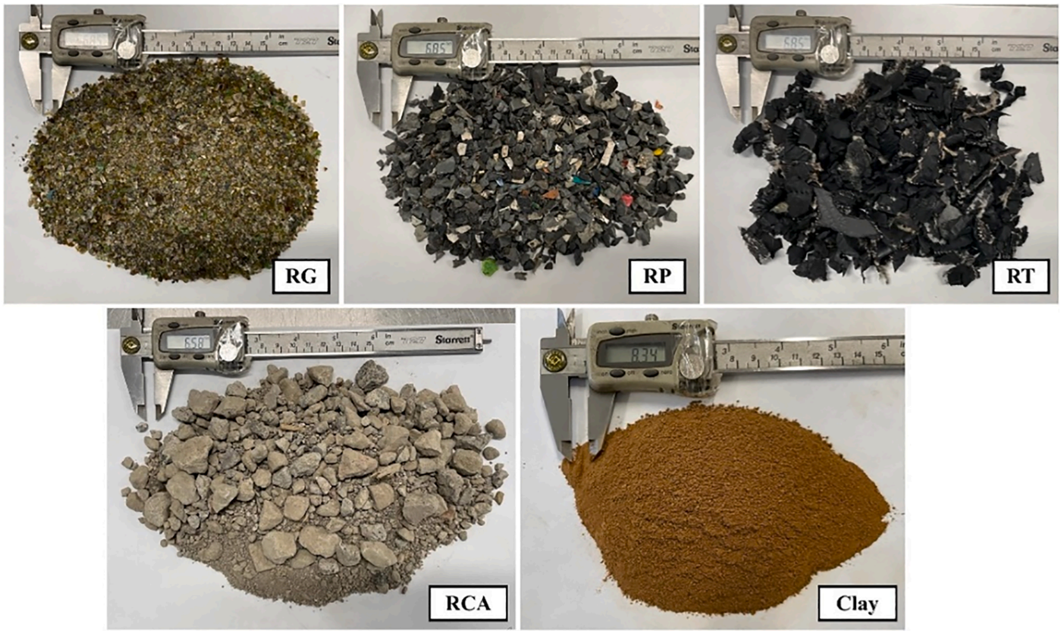
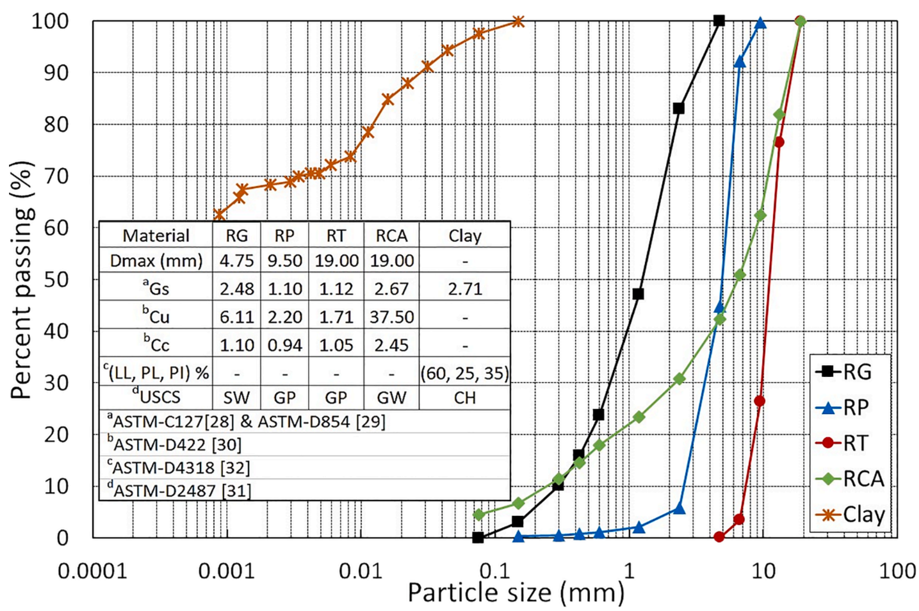


Fig. 2. Materials used in experiments of this study.



Material	RG	RP	RT	RCA	Clay
Dmax (mm)	4.75	9.50	19.00	19.00	-
[a]Gs	2.48	1.10	1.12	2.67	2.71
[b]Cu	6.11	2.20	1.71	37.50	-
[b]Cc	1.10	0.94	1.05	2.45	-
[c](LL, PL, PI) %	-	-	-	-	(60, 25, 35)
[d]USCS	SW	GP	GP	GW	CH

[a]ASTM-C127[28] & ASTM-D854 [29]
[b]ASTM-D422 [30]
[c]ASTM-D4318 [32]
[d]ASTM-D2487 [31]

Fig. 3. PSDs of recycled aggregates and expansive clay.

current study, due to the additional surcharge of the pavement structural layers and the vehicle loading, stiffer aggregates were required to be introduced into the original mixture of RG, RP and RT to suit the new application, and thus, RCA was selected as the fourth material. While the former three materials can be used for backfilling the parts of the excavated trench located in non-trafficable areas, upon reaching a trafficable area, RCA can also be added in the right proportion to make the mixture suitable for trafficable areas. The clay was collected from the western suburbs of Melbourne, where the current study is being carried out.

The specific gravities of the recycled materials, determined according to the ASTM-C127 [28] and ASTM-D854 [29] procedures, were 2.48, 1.10, 1.12 and 2.67 for RG, RP, RT and RCA, respectively. The particle size distributions obtained through ASTM-D422 [30] are presented in Fig. 3, along with the materials' specific gravity (Gs), maximum particle size (D_{max}), coefficient of uniformity (Cu) and coefficient of curvature (Cc). Based on the Unified Soil Classification System (USCS) [31], RG was categorized as well-graded sand (SW), while RP and RT were categorized as poorly-graded gravel (GP). The Gs [29], liquid limit (LL), plastic limit (PL) and plasticity index (PI) [32] of clay were measured to be 2.71, 60%, 25% and 35%, respectively. With these results, the clay was classified as clay with high plasticity (CH) following ASTM-D2487 [31]. The grain size distribution curve of the clay following ASTM-D7928 [33] is depicted in Fig. 3.

To develop recycled material mix designs, a set of 18 blends of recycled materials were selected to cover a range of proportions of recycled materials with the gradation of the blends aimed to fit within the lower and upper band of Class 4 (CL4) crushed rock gradation [20]. CL4 is a type of natural crushed rock suitable for subbase course of pavements and is also recommended to be used for the application of

Table 2
Proposed the recycled blends and mix proportions.

Blend ID	Materials proportion by mass (%)				Gs	Cu	Cc	USCS
	RG	RP	RT	RCA				
U1	69	8	13	10	1.98	11.18	1.31	SW
U2	62	7	11	20	2.06	13.24	1.28	SW
U3	54	6	10	30	2.11	11.76	1.34	SW
U4	46	5	9	40	2.17	13.71	1.17	SW
U5	76	4	10	10	2.13	8.82	1.19	SW
U6	67	4	9	20	2.17	10.71	1.71	SW
U7	67	9	4	20	2.15	8.57	1.37	SW
U8	59	3	8	30	2.23	12.73	1.62	SW
U9	60	7	3	30	2.24	10.91	1.47	SW
U10	51	3	6	40	2.27	14.55	1.42	SW
U11	57	9	14	20	1.96	11.90	1.07	SW
U12	37	9	14	40	1.98	15.12	1.16	SW
U13	64	5	11	20	2.10	10.00	1.17	SW
U14	44	5	11	40	2.12	19.33	1.29	SW
U15	77	9	–	14	2.25	6.67	1.17	SW
U16	85	5	–	10	2.35	7.31	1.36	SW
U17	50	7	3	40	2.26	13.33	1.74	SW
U18	40	7	3	50	2.28	13.75	1.39	SW

interest in the current study. Typical geotechnical testing was carried out on the proposed mixtures with the aim of determining the physical properties, including Gs, PSD and compaction properties achieved through applying modified compactive effort [34]. The proposed mixtures were compacted in 5 layers, 25 blows per layer using compactive effort of 2,700 kN-m/m^3 in a cylindrical mold of 101 diameter × 116 mm. Table 2 presents the proposed recycled blends, together with the abovementioned properties of the blends while compaction properties are presented in the Results and Discussion section.

In order to ensure reliable results are achieved through the experimental of this study, the following procedure was undertaken. Three identical samples were initially prepared and tested for the shortlisted blends using calibrated equipment. If the difference in the obtained results exceeded 5%, additional sample(s) was prepared and tested. This procedure was repeated until acceptable difference was achieved, and the average value was considered. Based on the above procedure, in this study, each blend was tested three to four times to validate the reliability of the results.

2.3. California bearing ratio testing

The California bearing ratio (CBR) value is a commonly used parameter to determine the thickness of pavement structural layers in empirical pavement design methods. A greater CBR value is an indication of better pavement performance in terms of stiffness and strength. Hence, the CBR value can be used as a criterion to assess the feasibility of a material to be used as a pavement construction material. Fig. 4 illustrates a schematic elevation view of the pavement system over a conventionally backfilled trench and a trench backfilled with proposed recycled material blends for trafficable areas, as well as the pavement structure over the surrounding natural subgrade. For natural subgrades (Fig. 4a), the minimum requirement for CBR is 3 [18]. However, for the fill subgrade (Fig. 4b and c), Schaefer, et al. [19] recommended that under traffic loadings, the CBR was advisable to be equivalent or equal to 10. Based on Melbourne Water Retail Agencies' Backfill Specifications, MRWA [1], and VicRoads [20], the minimum requirement for the CBR of materials used for backfilling excavated trenches in trafficable areas is 20.

Following the ASTM-D1883 [35] procedure, the CBR test was carried out on 18 blends to investigate the feasibility of using the proposed recycled material blends to backfill a deep excavated trench located in trafficable areas and for point of comparison with Melbourne Water Retail Agencies' Backfill Specifications [1] and VicRoads standards [20]. A shortlist of blends was suggested that met minimum CBR requirement (CBR = 20) for backfilling deep excavated trenches in trafficable areas. For blends that achieved CBRs close to or above 20, three identical specimens were prepared and tested to confirm the accuracy and consistency of the findings. In this study, the proposed blends were assessed as a lower subgrade layer in a pavement system. CBR samples were prepared at moisture contents equivalent to their optimum moisture contents (OMC) and compacted in 5 layers in a mold of 152 mm diameter × 177 mm height using modified compaction effort. The CBR value is defined as the ratio of stress required to penetrate the cylindrical piston at the rate of 1.25 mm/min into the material mass to that required for the corresponding penetration of standard material [35].

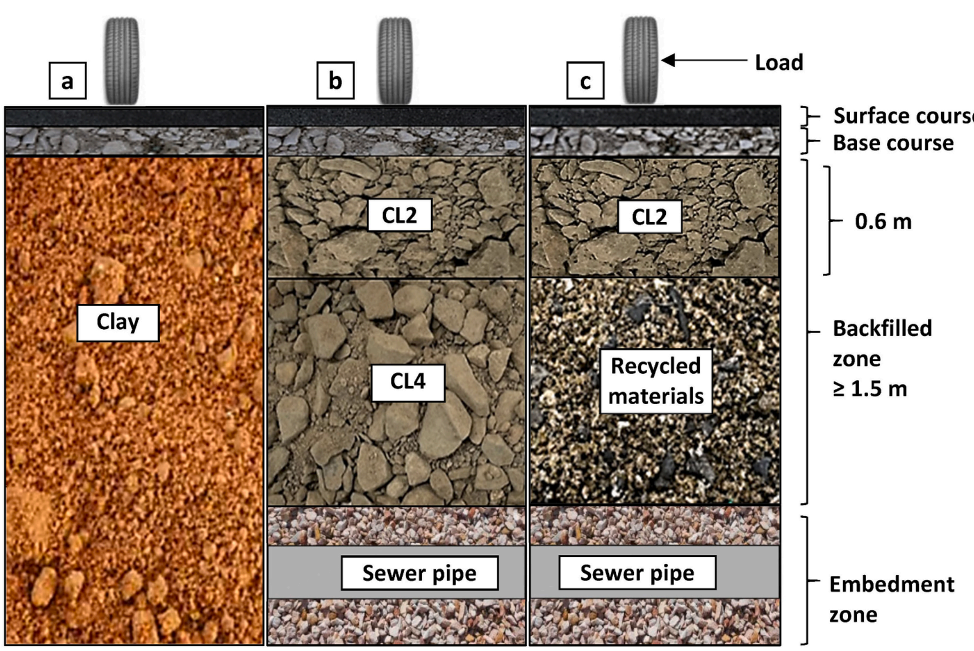


Fig. 4. A schematic elevation view of a pavement system over (a) surrounding natural subgrade, (b) conventional backfill for trafficable areas, and (c) proposed recycled material blends for trafficable areas.

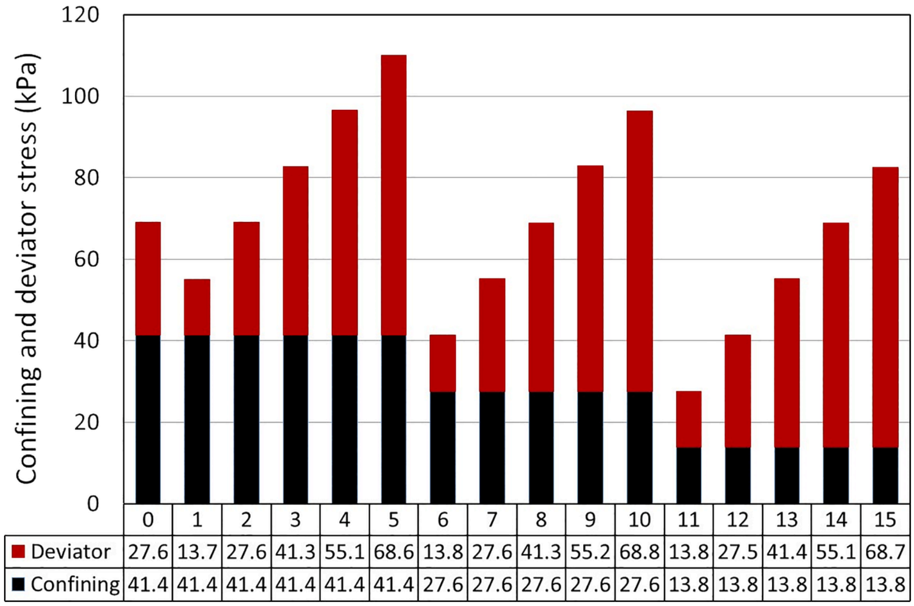


Fig. 5. Loading sequences for the resilient modulus test as per AASHTO T 307 procedure.

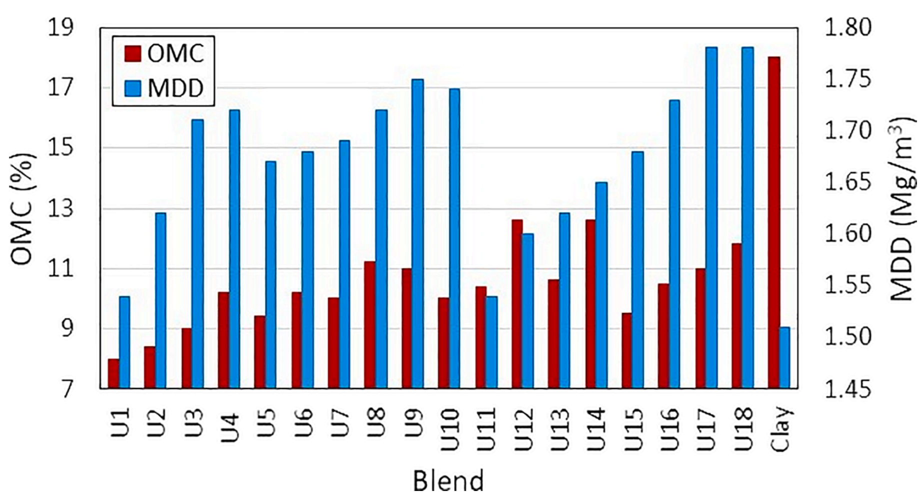


Fig. 6. Compaction properties of the blends.

2.4. Repeated load triaxial testing

The shortlist of blends recommended from CBR test was further investigated through repeated load triaxial (RLT) testing to simulate ground conditions, surcharge loads and repeated loads imposed by the moving vehicles on the pavement system as demonstrated in Fig. 4. The performance of these blend were evaluated against relevant authority and the optimal mix designs were recommended.

AASHTO [36] suggests incorporating resilient modulus (Mr) values of pavement materials in pavement design to simulate the effects of repeated vehicular traffic on pavements. These values are typically determined by subjecting undisturbed or reconstituted cylindrical samples to repeated load triaxial (RLT) tests [37]. When a vehicle wheel rolls over a pavement structure, it creates a stress pulse that contains confining and deviator stress components [38].

According to AASHTO-T307-99 [37], the RLT test consists of 15 loading sequences with 100 load repetitions in each, followed by a sequence called conditioning sequence including 1000-load repetitions at the start of the test. In each sequence, a target confining (σ_c) and deviator stresses (σ_d) are applied and the ranges of applied confining and deviator stresses are 13.8–41.4 kPa and 13.8–68.9 kPa, respectively, as illustrated in Fig. 5, following the application presented in Fig. 4. The Mr value of a sequence is determined by calculating the average of the Mr values obtained from the last five load repetitions for that sequence.

To prepare RLT specimen, dry recycled glass (RG), plastic (RP), Tire (RT) and recycled concrete aggregate (RCA) at target proportions shown in Table 2 were mixed to obtain a homogenous blend of approximately 3 kg. The mixture was wetted at optimum moisture content and mixed for 2–3 min to achieve moisture equilibrium. The blend was compacted in 8 layers, 25 blows per layer (equivalent to the modified effort of 2,700 kN-m/m^3) in a split steel cylindrical mold of 100 diameter × 200 mm high to achieve the corresponding maximum dry density obtained from the modified Proctor compaction. The diameter of the mold must be at least five times greater than the largest particle size in the blend which was 19 mm for both RT and RCA and the height to diameter ratio should be at least 2:1 [37]. After compaction, the mold was placed and centered over a porous stone to reduce the risk of damaging the compacted sample before removing the split parts of the mold. After removing the sample from the mold, the sample was covered with plastic films to avoid moisture loss. Before commencing the test, the specimens were

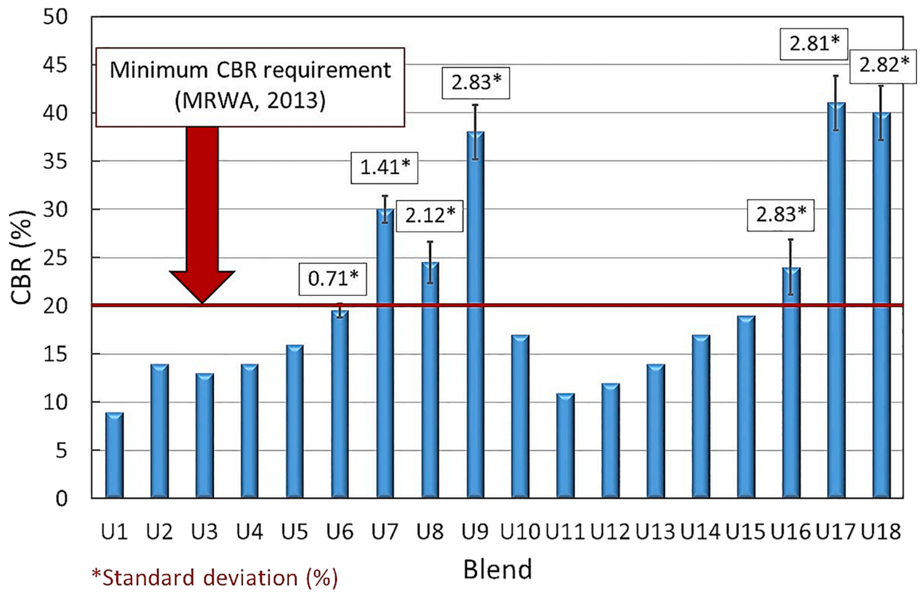


Fig. 7. CBR results on recycled materials blends.

Table 3
The CBR values for the proposed blends with the RG, RP, RT and RCA ranges.

Blend	CBR	Range of RG, RP, RT and RCA contents
U1	9	(61–70), (6–10), (11–15), 10
U2	15	(61–70), (6–10), (11–15), 20
U3	13	(51–60), (6–10), (6–10), 30
U4	13	(40–50), (0–5), (6–11), 40
U5	16	(71–90), (0–5), (6–10), 10
U6	20	(61–70), (0–5), (6–10), 20
U7	29	(61–70), (6–10), (0–5), 20
U8	23	(51–60), (0–5), (6–10), 30
U9	40	(51–60), (6–10), (0–5), 30
U10	17	(50–60), (0–5), (6–10), 40
U11	11	(40–50), (6–10), (11–15), 20
U12	12	(40–50), (6–10), (11–15),40
U13	14	(61–70), (0–5), (11–15), 20
U14	17	(40–50), (0–5), (11–15), 40
U15	21	(71–90), (6–10), (0–5), 10
U16	24	(71–90), (0–5), (0–5), 10
U17	41	(40–50), (6–10), (0–5), 40
U18	40	(40–50), (6–10), (0–5), 50

weighed to ensure the moisture loss is less than 0.5% as recommended by AASHTO-T307-99 [37] and to determine the dry density of the specimen. A porous stone was next placed on the specimen and the specimen was covered by the rubber membrane and sealed by exerting a set of O-rings on the pedestal and the top loading cap.

At the completion of the 15 sequences of the test, datasets of resilient modulus-confining stress-deviatoric stress (Mr-σ_c-σ_d) were collected to obtain the model coefficients (*k*) for two commonly utilized predictive resilient modulus models through regression analysis. The predictive Mr models utilized in this study were the two-parameter models [39] and modified universal model [40] as expressed in Eqs. (1) and (2), respectively:

$$M_r = k_1\theta^{k_2} \tag{1}$$

$$M_r = k_1\sigma_a\left[\frac{\theta}{\sigma_a}\right]^{k_2}\left[\frac{\tau_{oct}}{\sigma_a}+1\right]^{k_3} \tag{2}$$

where k_1, k_2 and k_3 are model coefficients, σ_a is atmospheric pressure, θ is the bulk stress ($\theta = \sigma_d + 3 \times \sigma_c$) and τ_{oct} is the octahedral shear stress ($\tau_{oct} = \sqrt{2}\,\sigma_d/3$).

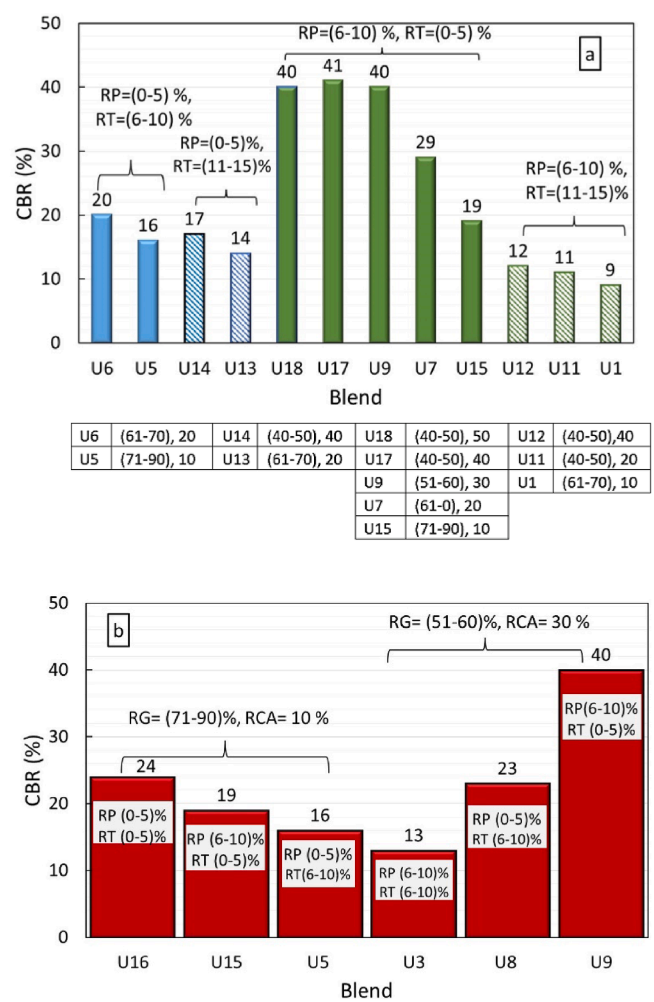


Fig. 8. Effect of RG, RP, RT and RCA on CBR results: effect of variation in a) RG and RCA contents, and b) RT and RP contents.

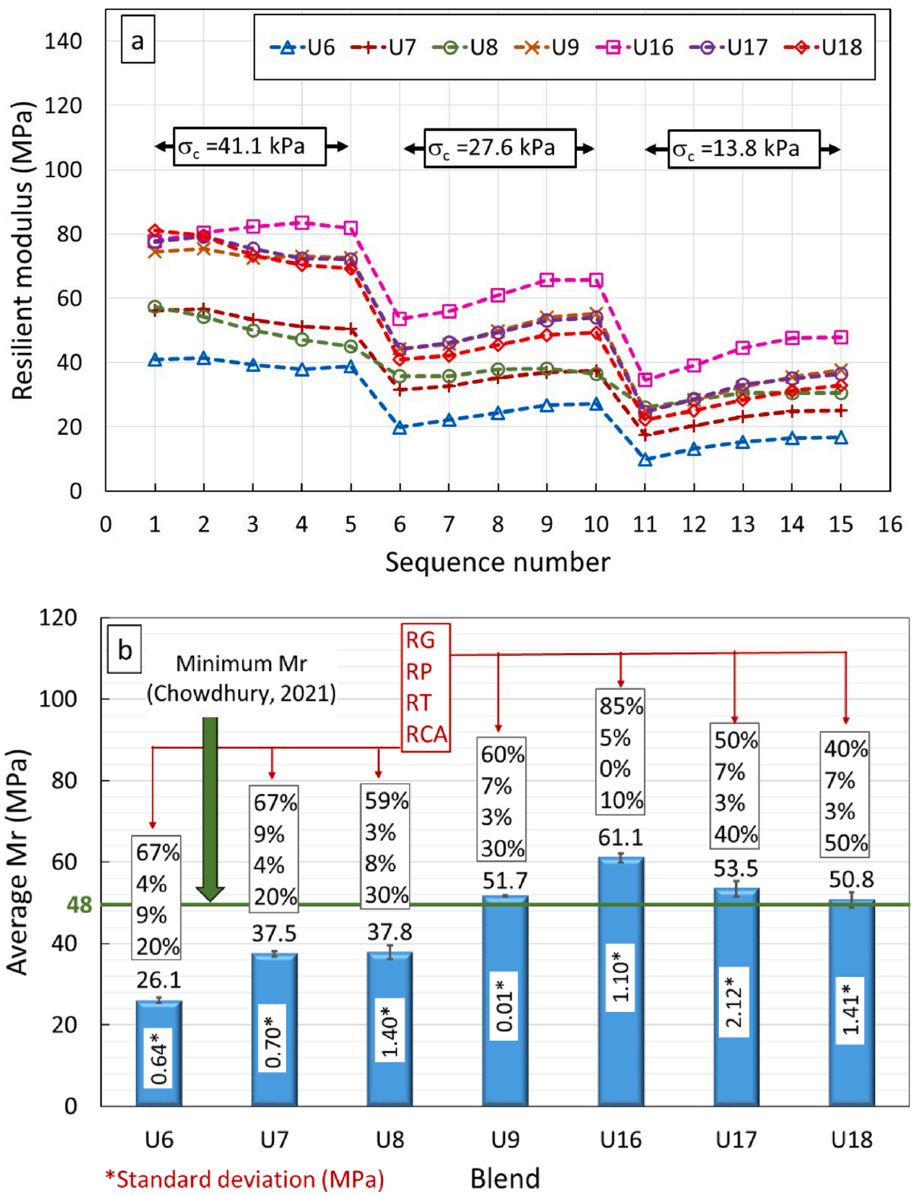


Fig. 9. RLT results: (a) Mr values in each loading sequence, and (b) average Mr of 15 loading sequences.

2.5. *Quick shear testing*

After completing the 15 sequences of repeated loads, a quick shear test was carried out to provide the material maximum shear strength in which the stress state cannot exist in the material beyond this value [37]. In this test, a confining stress of 27.6 kPa was applied and the vertical stress was increased to produce an axial strain rate of 1% per minute, as recommended by the standard. The test was ended once the vertical stress value decreased or the vertical strain exceeded 5%. Eventually, the peak shear strength of the material and the stiffness characteristics such as Young modulus under low confinement (E_c) were measured. Li, et al. [41] suggested that the Young modulus obtained from unconfined compressive strength remains unchanged under low confining pressures. Young's modulus, also referred to as elastic modulus, represents the slope of the stress–strain curve in the elastic range.

3. Results and discussion

This section presents a discussion on trends obtained through the California bearing ratio (CBR) and resilient modulus (Mr) results performed on a number of recycled blend specimens as presented in Table 2 and the natural clay. The CBR and repeated load triaxial test specimens were prepared at optimum moisture content (OMC) and targeting maximum dry density (MDD) values obtained through the modified compaction tests as demonstrated in Fig. 6. Fig. 6 illustrates an increase in MDD as recycled concrete aggregate (RCA) and recycled glass (RG) contents increased and recycled plastic (RP) and recycled tire (RT) contents decreased. This is attributed to the presence of a significant amount of fine particles in RCA and RG compared to that for RP and RT, which can potentially fill the larger voids between the larger particles, resulting in a greater MDD. Furthermore, an increase in RT content in a mixture can restrain the compaction process by preventing the particles from tightly packing together due to elastic and flexible behavior of these particles. As a result, the MDD decreases due to the increase in the volume of air-filled voids within the mixture. This behavior was also observed and reported by Gabryś [43]. Fig. 6 also showed that the OMC increased as RCA content increased and RT content decreased. Compared with other materials used in this study, RCA has a significantly higher moisture absorbing capacity [44], due to containing

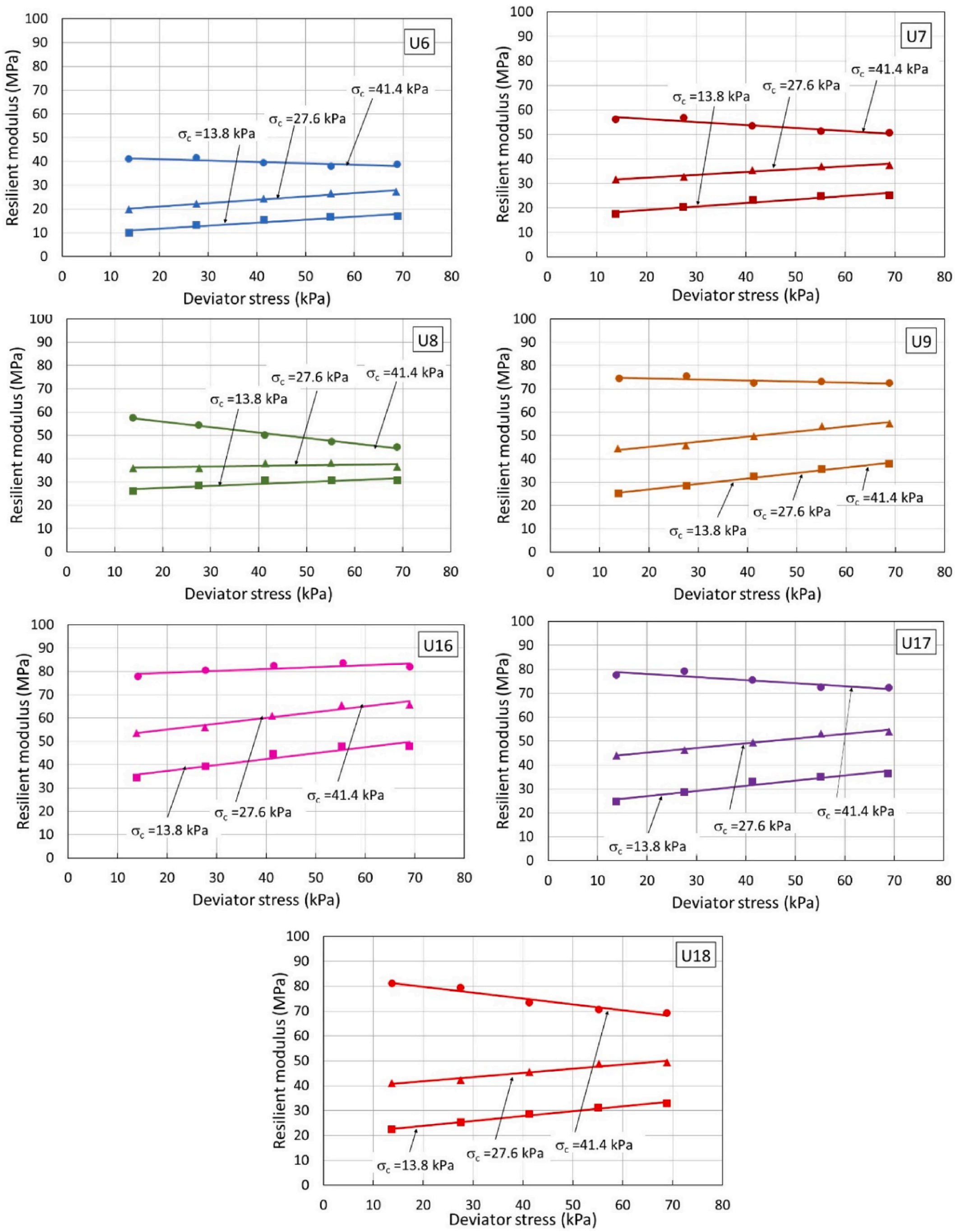


Fig. 10. Resilient modulus vs Deviator stress plots for the recycled blends.

unhydrated cement, high fine material content, and porous particle surfaces. Thus, increasing the RCA content led to an increase in the OMC. On the other hand, the increase in RT content results in a decrease in moisture-absorbing capacity of the mixture, leading to a lower OMC [45].

3.1. CBR results and the effect of material proportions

The California bearing ratio (CBR) test results of the 18 samples with various proportions of recycled glass (RG), plastic (RP), tire (RT) and recycled concrete aggregate (RCA) are presented in Fig. 7. The horizontal line drawn at CBR = 20 on the plot represents the minimum CBR required for CL4 as recommended by MRWA [1]. Fig. 7 shows that blends U6, U7, U8, U9, U16, U17 and U18, met the CBR requirement, and were thus selected for further investigation through repeated load triaxial (RLT) testing.

To interpret the effect of each material's content on the CBR value, the range of proportions for each material used in this study was divided into several groups. For RG, the range was divided into four groups being (40–50) %, (51–60) %, (61–70) % and (71–90) %. The range of RP was divided into (0–5) % and (6–10) %, while the proportion ranges of (0–5) %, (6–10) % and (11–15) % were selected for the RT used in this study. Eventually, RCA was added to the mixtures at 10%, 20%, 30%, 40% and 50% content. Table 3 presents the CBR values for the blends with the corresponding ranges of RG, RP, RT and RCA.

Fig. 8a demonstrates the behavior patterns of RG and RCA at a constant range of RP and RT. It can be deduced that there was a significant increase in the CBR value as RG decreased and RCA increased.

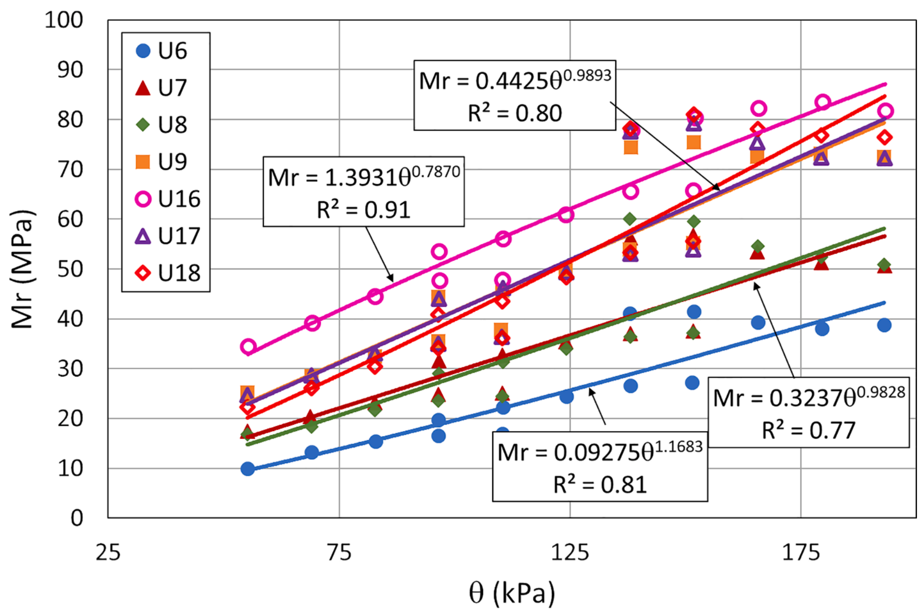


Fig. 11. Resilient modulus vs bulk stress plots for the selected blends.

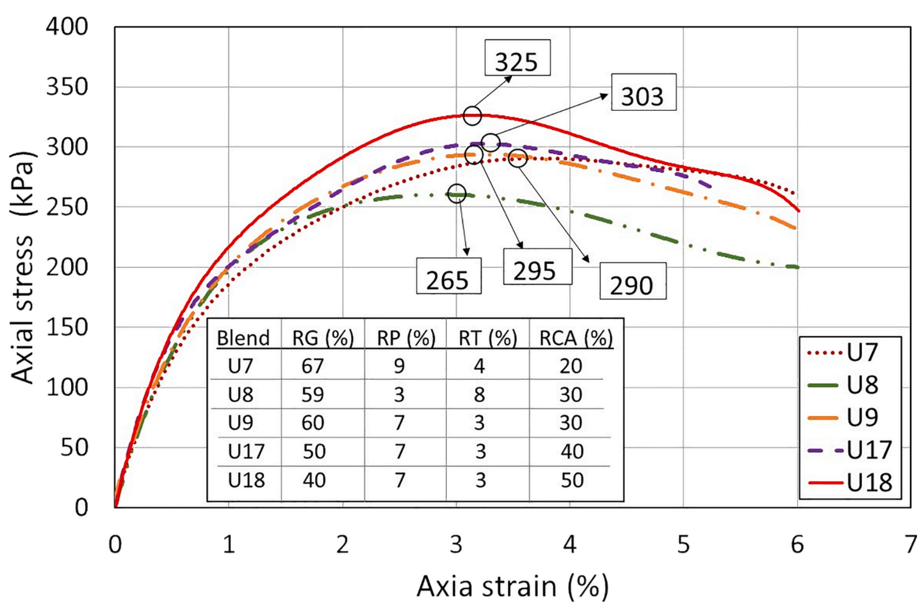


Fig. 12. The quick shear test results on selected blends.

RCA contained a higher fine particle content compared to RG (Fig. 3). During compaction, the greater percentage of fines could fill more voids resulting in higher density and thus higher CBR values [27]. For instance, in blends U6 and U5 containing (0–5)% RP and (6–10)% RT, the CBR values decreased by 20% when the RG range increased from (61–70)% to (71–90)% and the RCA decreased from 20% to 10%. Similarly, the trend can be observed for the blends containing (0–5)% RP and (11–15)% RT and blends containing (6–10)% RP and (11–15)% RT. However, the reduction in CBR was 50% when blends contained (6–10) RP and (0–5)% RT (low RT proportion). By providing a blend with a high percentage of RCA, the presence of RT with a high percentage (6–15% in this study) decreased the CBR up to 70% as clearly observed in bends U14 and U12. This is due to the fact that the flexibility of the RT particles was significantly higher compared to RG and RCA [46].

Fig. 8b shows the effect of RP and RT contents on CBR results. For blend U16 containing (71–90) % RG and 10 % RCA with minimum proportions of RP and RT (0–5) %, the CBR decreased by 20% when RP increased to (6–10) % (U15). However, the CBR value decreased by 35% when RT increased to the same proportion of (6–10)% (U5). This means that the increase in RT has a higher contribution in lowering the CBR rather than that of RP. This was attributed to the high degree of flexibility of RT particles that tend to deform under load, whereas RP particles were generally stiffer and less flexible. Therefore, the presence of a higher proportion of RT resulted in greater deformations and less CBR values compared to an increase in RP [47]. Another example confirming this trend was blend U3 which contained (6–10) % for both RP and RT. The decrease in RP content to (0–5) % caused an increase of about 75% in CBR, while the decrease in RT to (0–5) % caused an increase of about 200%. Consequently, the CBR results presented in Fig. 8 suggest that the main parameter that affected the CBR values was RT content followed by RCA content. To achieve the highest CBR, a minimum RT (0–5) and RCA ≥ 30% was therefore recommended. The secondary effective parameters

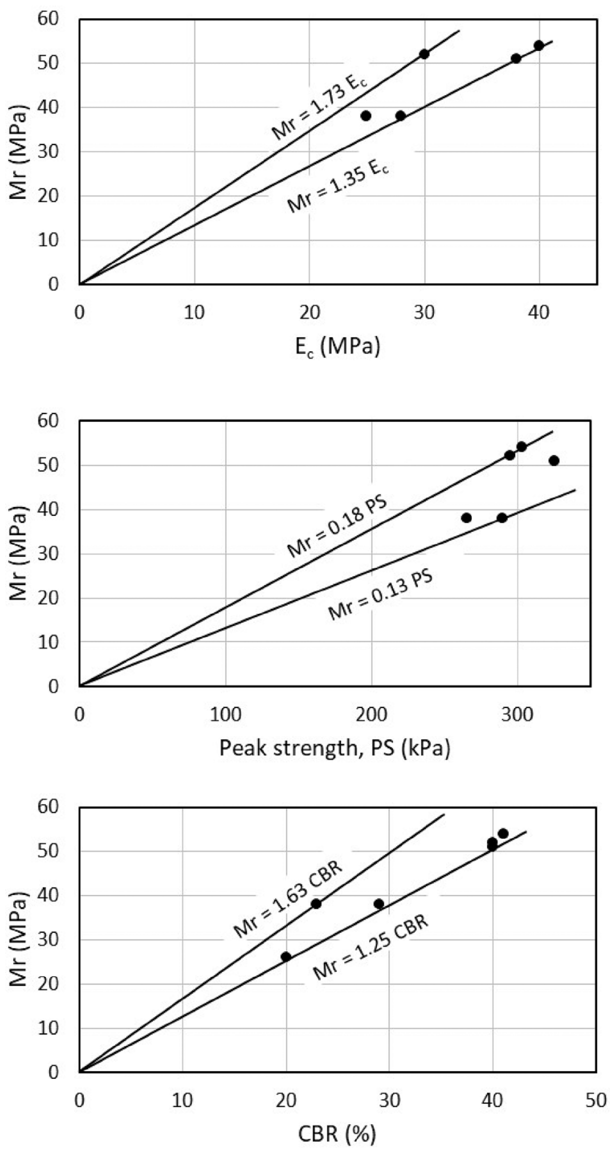


Fig. 13. Relationship between (a) Mr and E_c, (b) Mr and PS, and (c) Mr and CBR.

were the RG content followed by the RP content.

3.2. Resilient modulus responses

A set of repeated load triaxial (RLT) tests were carried out on blends nominated based on California bearing ratio (CBR) test results. Fig. 9a presents the values of resilient modulus (Mr) obtained from the 15 loading sequences for each blend. The average Mr values are depicted in Fig. 9b. The horizontal line plotted in Fig. 9b at Mr = 48 MPa represents the lower range of Mr achieved for subbase applications (CL4) by Lee, et al. [48], Park, et al. [49] and Chowdhury, et al. [42], who tested various subbase materials and achieved a resilient modulus range of 48–130 MPa. Fig. 9 shows that generally, the main parameter that affected Mr values was RT content. The Mr increased as recycled tire (RT) content decreased and the maximum Mr value was achieved for a blend with 0% RT content (U16). This generally aligned with the behavior observed in CBR results; however, due to the low recycled concrete aggregate (RCA) proportion (≤10%) in U16 with 0% RT, CBR was lower than U9 with 3% RT. During the CBR testing, the axial stress was applied through a penetration plunger with a diameter of 50 mm, therefore the axial strain was affected by the particle properties located

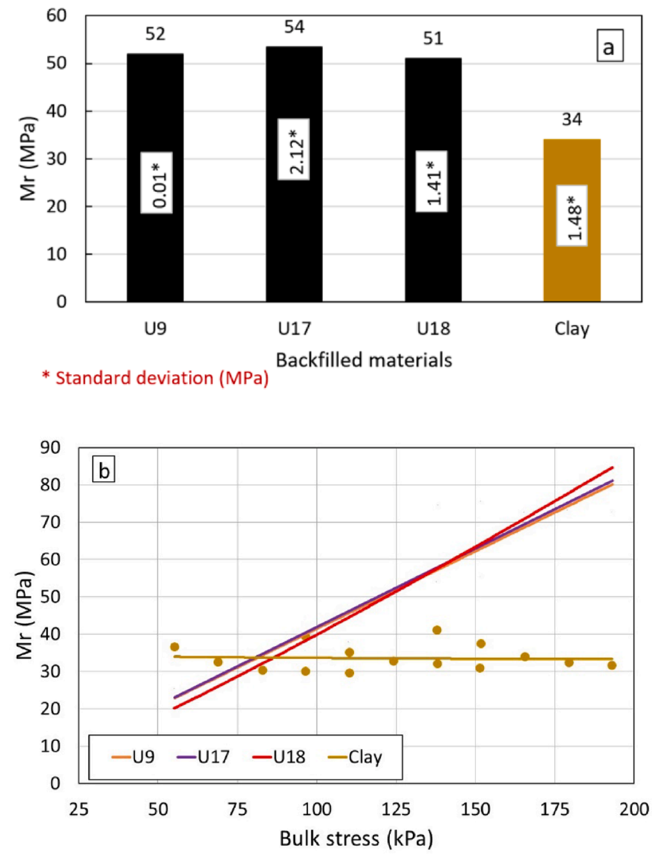


Fig. 14. RLT results for recommended recycled blends and expansive clay subgrade.

in the loading path. With the RCA proportion less than 10%, the probability of stiff RCA particles being within the loading path was low. In RLT testing, the axial stress was applied on the whole block of the specimen. This is further evidence for CBR not being the most suitable design parameter for the new pavement system as previously recommended by Thach Nguyen and Mohajerani [21].

Fig. 9b also shows that in blends with low RT content (0–5) %, insignificant changes in Mr values were achieved as long as blends contained RCA with contents equal to or greater than 30% (U9, U17 and U18). In other words, existing RCA with 30% content in a blend containing low RT was sufficient to achieve high Mr value. This was also observed in CBR test results. This minor change in Mr values by decreasing the RCA content to 30% was attributed to the minor changes in the dry density of the specimens containing RCA ≥ 30% and low RT contents as achieved for specimens U9, U17 and U18 (refer to Fig. 6). Another reason was that the expected decrease in strength due to the decrease in RCA content was compensated with the increase in the inter-particle interlocking due to the increase in RG content [50].

Fig. 10 illustrates plots of resilient modulus versus deviator stress of the blends, in which Mr values increased as confining stress increased. When a blend was subjected to higher confining stress, the inter-particle interlocking and internal friction of the particles increased, resulting in less recoverable strains (ε) and thus, a greater Mr ($Mr = \sigma_d / \varepsilon$) [21,51]. At constant confining pressure, the Mr increased as deviator stress increased. This phenomenon may arise from the specimens undergoing stress hardening after enduring 100 or more repetitions of higher deviator stress, as explained by Puppala, et al. [52].

The plot depicted in Fig. 11 displays the changes in Mr values in relation to bulk stress (θ), which can be estimated by utilizing trend lines derived from a power function. The coefficient of determination (R^2) for the trend lines falls between the range of 0.844 to 0.917. Based on these

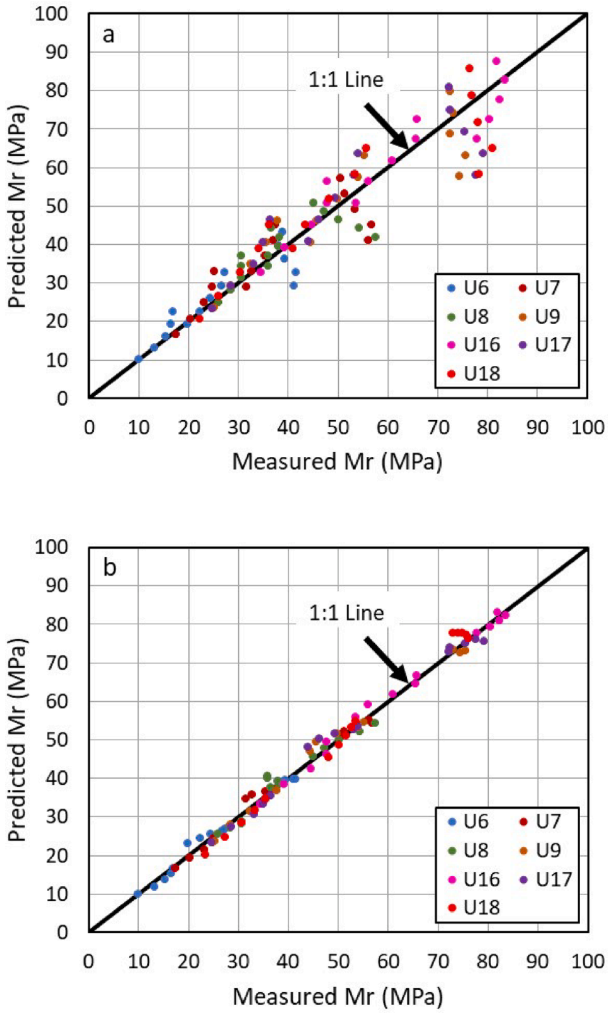


Fig. 15. Relationship between measured and predicted Mr values using (a) the two-parameter model and (b) the modified universal model.

trend lines, it becomes apparent that the increment in Mr values is not only due to the rise in bulk stress, but also due to the reduction in RT contents.

3.3. Shear test results and correlations with resilient modulus

Fig. 12 presents the stress–strain curves of the quick shear tests following AASHTO-T307-99 [37] procedure. For the point of reference, the proportion by mass of the recycled materials, and the peak shear strength (PS) corresponding to each blend (in kPa) is also provided in Fig. 12. It can be seen that U8 shows lower peak strength as this blend contained the highest recycled tire (RT) proportion (8%). However, U7, U9, U17and U18 exhibited a slower increase in strength due to an increase in recycled concrete aggregate (RCA) proportion with the presence lower proportion of RT (3%). These results align well with the behaviors observed through the California bearing ratio (CBR) and repeated load test results and confirmed that the RT is the aggregate that adversely affected the strength characteristics of the blends.

Fig. 13a–c present the relationship between resilient modulus (Mr) and Young modulus (E_c), Mr and peak shear strength (PS), and Mr and CBR, respectively, for blends U6, U7, U8, U9, and U18 that included all four types of recycled aggregates. The range between the upper and lower envelopes of all plots is noticeably small. The Mr (MPa) was 1.35–1.73, 0.13–0.18 and 1.25–1.63 times E_c (MPa), PS (kPa) and CBR (%), respectively.

Based on studies carried out by Lee, et al. [48], Park, et al. [49] and Chowdhury, et al. [42], the typical range of Mr for CL4 unbound aggregates was 48–130 MPa. Blends U9, U16, U17 and U18 presented in Fig. 9 exhibited resilient modulus responses within the range of traditional natural crushed rock. As this study aimed to use recycled material blends incorporating all RG, RP, RT and RCA, blends U9, U17 and U18 were recommended as optimum mix designs to replace CL4 aggregates as shown in Fig. 1 to backfill excavated trenches with depths greater than 1.5 m.

3.4. Comparison with surrounding subgrade soils

It is known that when the road alignment intersects with a backfilled trench, the pavement thickness design is based on the strength properties of the surrounding natural subgrades, unless the backfilled area shows lower bearing capacity. The CBR of natural clay selected in this study was found to be 3 which is acceptable for designing the structural thickness of pavements lying on natural subgrade [18]. This value wasn't compared with the corresponding values for the optimum mix designs because the minimum CBR required for materials used to backfill deep trenches located under traffic load is 20 [1]. Therefore, the CBRs of recommended blends were compared with value of 20.

To compare the resilient modulus (Mr) achieved from the recommended blends with the surrounding clay subgrade, the Mr of clay was determined and found to be 34 MPa as shown in Fig. 14. Fig. 14a indicates that the Mr obtained from the three optimum mix designs was approximately 1.6 times the corresponding values obtained for the expansive clay. It can be deduced that the pavement life over the backfilled trench would not be compromised, since the pavement would be designed based on the clay's bearing capacity which is lower than that of recommended blends of this study.

Fig. 14b shows that in contrast with the trend observed for the recycled material blends, the Mr of clay decreased as bulk stress increased. This was attributed to the fact that RLT specimens were prepared at optimum moisture content which represents about 85%-90% degree of saturation [53,54] and during RLT testing the strain softening occurred as bulk stress increased due to the increase in pore

Table 4
The "*k*" coefficients and assessment of the "Goodness of Fit" for the two models employed.

Two-parameter model							
Model Parameter	U6	U7	U8	U9	U16	U17	U18
k_1	0.0927	0.3237	2.5596	0.4661	1.3931	0.4425	0.2130
k_2	1.1683	0.9828	0.5676	0.9774	0.7870	0.9893	1.1393
R^2	0.808	0.771	0.602	0.847	0.907	0.799	0.837
Goodness of fit	Good	Good	Fair	Good	Excellent	Good	Good
Modified universal model							
k_1	0.2849	0.4216	0.4735	0.5516	0.6171	0.5793	0.5516
k_2	1.5262	1.3060	0.8231	1.2222	0.9257	1.2871	1.4498
k_3	−2.4684	−2.3871	−2.0787	−1.8641	−1.1196	−2.2049	−2.1741
R^2	0.983	0.986	0.946	0.991	0.991	0.986	0.985
Goodness of fit	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

pressure which decreased the effective confining stress and hence, decreased the Mr values [55].

3.5. Incorporation of results in predictive models

The applicability of the two-parameter and modified universal models to estimate the resilient modulus of the blends was investigated using the repeated load test data obtained for blends U6, U7, U8, U9, U16, U17 and U18. Fig. 15 demonstrates the comparison between the 105 measured and predicted resilient modulus (Mr) values. The modified universal model exhibited a higher density of data points close to the 1:1 line, which suggests a more precise prediction.

Table 4 displays the k coefficients obtained by conducting a regression analysis of the test results for the two-parameter and modified universal models. This table also presents the coefficient of determination (R^2) and "goodness of fit" of each model according to Witczak, et al. [56] criteria. Witczak, et al. [56] suggested criteria to determine the goodness of fit based on the R^2. The goodness of fit can be categorized as Excellent, Good, Fair, and Poor when $R^2 \geq 90$, $0.70 \leq R^2 \leq 0.89$, $0.40 \leq R^2 \leq 0.69$, and $0.20 \leq R^2 \leq 0.39$, respectively are achieved. Based on the obtained R^2 values (Table 4) while the two-parameter model displays a level of agreement with the experimentally determined Mr values ranging from "Fair" to "Excellent," the modified universal model demonstrates an "Excellent" level of agreement with the results obtained for all seven blends. This could be due to the fact that *k* coefficients of two-parameter model were obtained based on variations of two parameters including Mr and bulk stress (θ), while in the modified universal model, the *k* coefficients were determined based on variations of three parameters including Mr, θ and octahedral shear stress (τ_{oct}) which can make the regression analysis more accurate. Therefore, "*k*" coefficients determined from the modified universal model were adopted to analyze the Mr of the backfilled material blends proposed in this study. In this model, the value of k_1 is directly proportional to the modulus of elasticity and thus k_1 should be a positive value; k_2 is predicted to be positive since an increase in bulk stress results in stress hardening of the specimen and, consequently, an increase in the resilient modulus. However, k_3 should be negative due to stress softening that is induced by an increase in octahedral shear stress, leading to a reduction in the resilient modulus [57].

4. Conclusions

In this study, blends of recycled glass (RG), plastic (RP), tire (RT) and recycled concrete aggregate (RCA) were utilized to investigate the feasibility of replacing the natural crushed rock (Class 4), commonly utilized to backfill deep excavated trenches located in trafficable areas. An extensive laboratory testing program was carried out to assess the proposed blends in terms of strength and resilient characteristics through California bearing ratio (CBR) and repeated load triaxial (RLT) tests, respectively. The optimum mix designs were suggested and compared with the typical natural crushed rock and natural clay properties. The following outcomes were achieved:

- Seven out of the eighteen proposed blends met the minimum CBR requirement (CBR = 20) to be used as alternatives to the natural crushed rock for backfilling depths below 0.6 m in an excavated trench located in trafficable areas. These blends included U6, U7, U8, U9, U16, U17 and U18 that comprised no more than 13% RP and RT together.
- The main factor that affected the strength and resilient characteristics of the recycled material blends was RT content followed by RCA content. When the proportion of RT was lower (less than 5%) and the content of RCA was higher (at least 30%), it resulted in greater strength and resilient characteristics.
- Blends U9, U17 and U18 achieved resilient modulus that fell in the typical range of resilient modulus for Class 4 crushed rock. Therefore, these blends were recommended as optimum mix designs. The RG:RP:RT:RCA contents were 60:7:3:30, 50:7:3:40, 40:7:3:50 for U9, U17 and U18, respectively.
- The resilient modulus achieved by the optimum blends was approximately 60% higher than the corresponding values obtained for the surrounding clay subgrades, noting that the strength properties of surrounding clay subgrades are typically used for the pavement design.
- The obtained resilient modulus values for the recycled blends fit well within the modified universal model that was originally developed for soils and natural aggregates. Therefore the RLT results can be incorporated in pavement design and analysis software for the real-life application in new developments where a backfilled pipeline trench is located under a new road, urban street or a driveway.

As a result, to replace traditional backfill (class 4 crush rock) by recycled materials comprising RG, RP, RT and RCA, this study, recommends utilizing blends containing RT content ≤ 3%, RP content ≤ 7% and RCA ≥ 30%.

The outcomes of this study provide the road and water authorities with experimental evidence for the feasibility of using recycled materials in pavement construction and hence, reducing the demands for the natural resources and divert significant amount of waste from landfill.

CRediT authorship contribution statement

Asmaa Al-Taie: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Ehsan Yaghoubi:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ernie Gmehling:** Writing – review & editing, Resources, Methodology, Formal analysis. **Sam Fragomeni:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Mahdi Disfani:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Maurice Guerrieri:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition.

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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