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Cement and fly ash-treated recycled aggregate blends for backfilling trenches in trafficable areas

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ABSTRACT

The shortage of natural aggregates available for filling excavated pipeline trenches in trafficable areas has prompted the exploration of alternative resources. This study investigates the feasibility of using cement and fly ash-treated recycled aggregates as trench backfill materials subjected to traffic loadings. Blends of recycled glass (RG), plastic (RP), and tire (RT) were treated with different proportions of cement and fly ash, resulting in a total of 8 treated blends. Geotechnical tests including compaction and California Bearing Ratio (CBR) were conducted to evaluate the mixtures according to backfill specifications. Specialized pavement testing, such as repeated load triaxial testing (RLT) and quick shear, simulated real-life stress levels at trafficable areas. Scanning electron microscope (SEM) images were taken to investigate the microstructural characteristics of the cement and fly ash-treated samples. The results showed that the CBR and resilient modulus of the treated blends improved with higher cement, fly ash, and RG contents, while they decreased with increased RT content. Cement-treated blends demonstrated significant improvements in peak shear strength with increased cement and RG contents and decreased RT content. Fly ash-treated blends showed minor improvement in peak shear strength when the fly ash, RG, and RT contents varied. Only cement-treated blends exhibited properties comparable to Class 4 (CL4) crushed rock, which was the control material. Under the same stress levels, cement-treated blends demonstrated up to 1.17 and 2.62 times greater stiffness than CL4 and clay subgrades, respectively. The SEM analyses confirmed that the inclusion of cement in the recycled blends resulted in the formation of greater bonds between particles compared to fly ash, which led to higher strength. These findings highlight the potential of sustainable materials in backfilling pipeline trenches under traffic loadings, reducing the reliance on natural aggregates for this application.

Introduction

The percentage of sewer pipelines located beneath trafficable areas and embedded in clay subgrades is increasing due to the rapid urbanization and growth in urban densities resulting in a consequent increase in the amount of land covered by roads. There is a relationship between road traffic safety and the backfill above sewer pipes. Inappropriate backfilling causes subsidence and damage to the road surface [36]. Trafficable areas refer to places that encounter frequent traffic, such as already existing or planned roadways and their adjacent areas, parking lots, driveways, access roads, and constructed walkways [44].

The type of materials used to backfill excavated trenches in trafficable areas is determined by guidelines such as the Backfill Specifications of Melbourne Water Retail Agencies MRWA [44]. The depth of the excavated trench is a crucial factor in this determination. For trenches with depths less than 1.5 m, it is recommended to use 20 mm Class 2 (CL2) crushed rock for the full depth. However, for trenches that are deeper than 1.5 m, the backfill beneath pavement layers should be 20 mm CL2 to a depth of 600 mm from the surface, and the remaining depth should be filled with 20 mm Class 4 (CL4) crushed rock.

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Several studies such as Fang et al. [24], Alzabeebee [9], and Qin and Moore [54] investigated the impact of traffic load and backfill characteristics, including erosion, compaction, and degree of saturation on the deterioration of buried sewage pipelines. In these studies, natural aggregates were supplied to backfill trenches excavated at depths less than 1.5 m. A persistent and growing need for natural aggregates in urban and developing regions has resulted in a greater demand for such resources. However, the challenge of finding and approving new sites for sourcing natural aggregate leads to higher transportation expenses for delivering these materials to construction sites. This rising cost, coupled with the reduced availability and increased expense of landfill areas for waste disposal, creates a financial motive to promote the use of recycled aggregate materials [48].

The current worldwide movement toward sustainable practices and achieving net zero targets has spurred continuous exploration into ways of reusing and repurposing secondary resources, including waste materials, in engineering applications. Since there is a high demand for construction materials in building projects, incorporating recycled materials is an essential strategy to accomplish net zero construction objectives [53]. Various studies investigated the suitability of using sustainable materials, in particular, recycled plastic (RP), glass (RG), and (RT) tire in the subgrade and pavement applications [3,8,27,46]. Some studies incorporated cement and geopolymer binders such as fly ash into the recycled materials-subgrade matrix to improve subgrade layers in pavement systems [30,42,45,61]. The studies above investigate the application of pavement layers above or at subgrade layers and not a backfilled trench. Studies conducted by Yaghoubi et al. [66], Al-Taie et al. (2023a) and Teodosio et al. [62] investigated the possibility of using blends of 100% recycled materials, being RG, RP, and RT to fill deep trenches. However, these studies were focused only on areas that are not intended for traffic loadings. Yaghoubi et al. [66] performed a comprehensive laboratory investigation and developed two blends comprised entirely of recycled materials suitable for filling deep trenches in non-trafficable areas. These blends were then used to fill two full-scale test sites and were monitored for field performance for a year and a half. The results of this monitoring were reported by Teodosio et al. [62] and Al-Taie et al. [7]. The current study aims to extend the application of the abovementioned blends to backfilling trenches in "trafficable areas" by introducing binding agents such as cement and fly ash into the RG-RP-RT blends.

The determination of subgrade California Bearing Ratio (CBR) is recommended to design the pavement structural thickness [19]. For trenches excavated to embed sewer pipelines in clay (Fig. 1), MRWA [44] and VicRoads [64] recommended a minimum CBR of 20 to fill the subgrade layer located under traffic loadings. Using static experimental methods, such as CBR to evaluate the performance of subgrade backfill materials is known to be insufficient to simulate a pavement system behavior subjected to vehicular traffic repeated loadings [63]. For a more realistic assessment of the performance of subgrade backfill materials under repeated loading, the current study determined the resilient modulus (Mr) to evaluate the stiffness characteristics of pavement materials. Several studies utilized the resilient modulus characteristics generally determined from repeated load triaxial (RLT) testing to assess the performance of pavement layers [8,32,35,69]. However, the resilient properties of the backfill materials made of 100% recycled aggregates treated using chemical additives to perform as subgrade or lower subbase course were underestimated.

The objective of the current study is to evaluate the utilization of cement and fly ash-treated recycled aggregate blends comprising RG, RP, and RT as backfill materials in deep excavated trenches for sewer pipelines to replace Class 4 (CL4) crushed rock as shown in Fig. 1b. A set of 8 recycled materials blends treated with various cement and fly ash contents were suggested for typical pavement testing, including compaction and CBR. Next, to simulate ground conditions, surcharge loads and repeated loads imposed by the moving vehicles on the pavement layer, the proposed blends were further assessed through RLT and quick shear testing. The microstructural characteristics of the blends with different cement and fly ash proportions were examined by studying the scanning electron microscope (SEM) images. The optimum mix designs were recommended and their performances were evaluated against the Melbourne Water Retail Agencies' Backfill Specifications and VicRoads standards. The performance of the blends was compared with that of natural aggregates (CL4) and the surrounding clay subgrade. Also, the relationship between CBR, shear strength and the

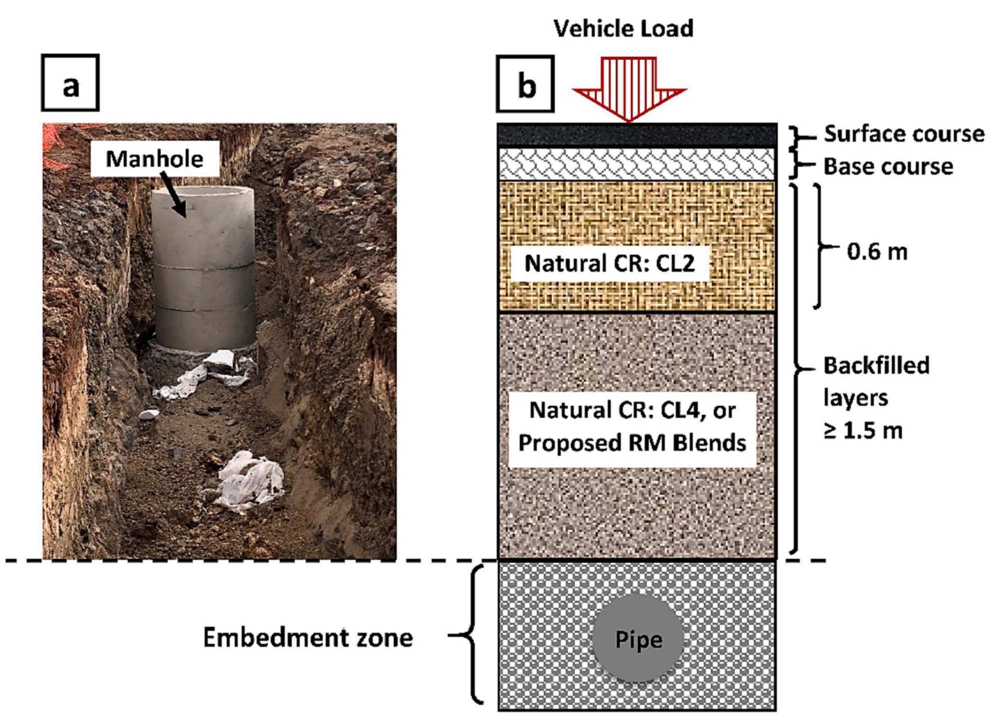


Fig. 1. Images of (a) an excavated trench with sewer pipe buried in the embedment zone, and (b) a schematic elevation view of an excavated trench showing the backfilled zones.

Young's modulus, with the resilient modulus of the blends were determined and compared with those of CL4. The obtained resilient modulus datasets were incorporated into two well-known predictive models originally developed for natural aggregate and exhibited excellent goodness of fit. The findings in this study aid to provide a sustainable solution to the global shortage of sand and gravel by advocating for the use of recycled materials in the design and construction of infrastructure projects while provide new data on performance of these bound recycled mixes under simulated traffic conditions.

Mechanisms of stabilization by cement and fly ash

The process of hydration and pozzolanic reaction in cement stabilized aggregates can be described as follows: when water comes into contact with cement, the cement undergoes rapid hydration. The primary products of this hydration are calcium silicates hydrate (CSH), calcium aluminates hydrate (CAH), calcium aluminum silicates hydrate (CASH), calcium monosulfoaluminate (AFm) and ettringite (AFt) [22,43].

In fly ash stabilization, when NaOH is added to aggregates comprising recycled glass which primarily consists of approximately 70% SiO_2 and 10% CaO [55], the pH value of the water that exists in the pores is increased. The addition of strong bases causes the dissolution of silica and alumina from fly ash and silica from both the liquid alkaline activator (Na_2SiO_3) and the recycled glass. In the pozzolanic reaction, in the presence of water, the calcium available in the recycled glass and fly ash reacts with the soluble alumina and silica derived from both materials. This reaction produces stable calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which contribute to the long-term strength improvement properties of the soil. These reactions are presented through Eqs. (1) to (4) [58].

$$CaO + H_2O \rightarrow Ca(OH)^2 + Heat \tag{1}$$

$$Ca(OH)_2 \rightarrow Ca^{+2} + 2(OH)^- \tag{2}$$

$$Ca^{+2} + 2(OH)^- + SiO_2 \rightarrow CSH \tag{3}$$

$$Ca^{+2} + 2(OH)^- + Al_2O_3 \rightarrow CAH \tag{4}$$

Materials and methods

Individual testing materials

Recycled materials comprising recycled glass (RG), recycled plastic (RP), and recycled tire (RT), binding agents namely cement and fly ash, liquid alkaline activator, a type of natural aggregates being Class 4 (CL4) crushed rock, and a type of natural expansive clay were the materials utilized in this study. The idea behind using fly ash was developing backfill blends that were completely made of waste/recycled aggregates to be assessed for their performance in comparison with CL4 and cement was selected due to availability and its common use in cement-treated pavement base and subbase layers.

Recycled aggregates were collected from recycling industries in Victoria, Australia. The specific gravities of RG, RP, and RT obtained following the ASTM-C127 [12] and ASTM-D854 [14] procedures, were 2.48, 1.10, and 1.12, respectively. The particle size distributions of RG, RP, and RT according to ASTM-D422 [13] are presented in Fig. 2 together with images of the individual aggregate types. Following the Unified Soil Classification System (USCS) [17], the particle distribution of RG could be classified as well-graded sand (SW), and the particle distribution of both RP and RT could be classified as poorly-graded gravel (GP). The individual recycled aggregates were selected based on the outcomes of the Yaghoubi et al. [66] study. Yaghoubi et al. [66] recommended two mix designs comprising RG, RP, and RT to backfill deep excavated trenches located in non-trafficable areas and evaluated the field performance of these blends in a full-scale site [7,62]. The current study developed the performance of these mix designs to be suitable to carry additional surcharges imposed by pavement structural layers and vehicle loads. The increased bearing capacity was aimed to be achieved by developing bonds between aggregate particles through cement and fly ash. This was a supply chain strategy, so that an additional type of material is not required in case a trench in a non-trafficable area reaches a trafficable area. In this case, RG, RP and RT can be used in both areas, where only in the trafficable areas a binder is added to the mix.

Fly ash (FA) was supplied by a local supplier in Victoria, Australia. Table 1 presents the chemical composition and loss on ignition (LOI) of the fly ash determined by X-ray Fluorescence (XRF). From Table 1, it is evident that the proportion of Al_2O_3, CaO and SiO_2 (the main components of the FA participating in the process of pozzolanic reaction in FA-

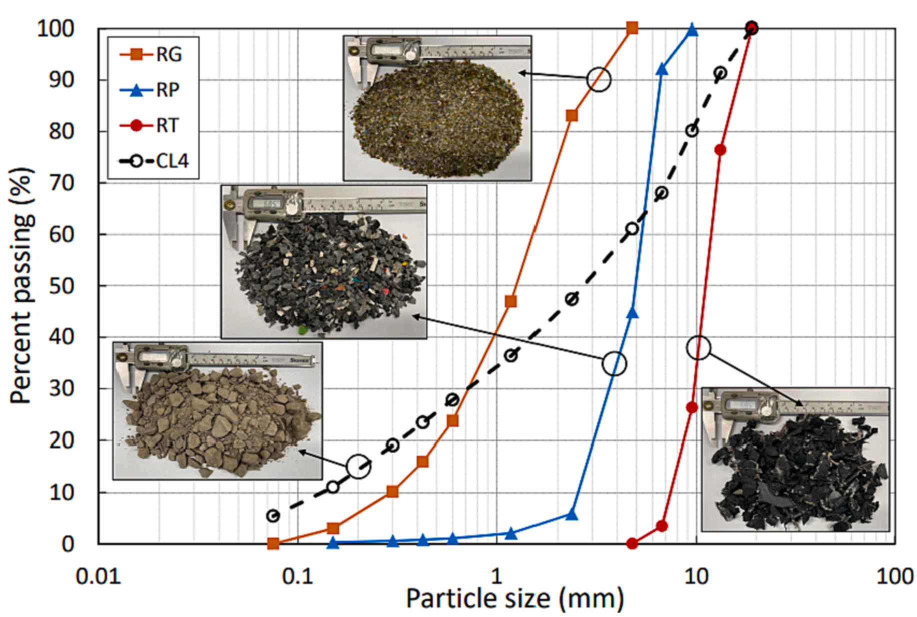


Fig. 2. PSDs of recycled aggregates and natural aggregates.

Table 1
Chemical composition of fly ash determined by XRF.

Chemical	Component (%)
Al_2O_3	23.50
CaO	1.30
SO_3	<0.10
Fe_2O_3	3.30
K_2O	1.39
MgO	0.50
Na_2O	0.46
P_2O_5	0.20
SiO_2	66.60
TiO_2	1.00
LOI	1.90

stabilized aggregates) were 23.5%, 1.30 % and 66.6%, respectively. The low amount of CaO could affect the pozzolanic reaction process.

The liquid alkaline activator used in this study was a mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions with a concentration of 5 M. A low NaOH concentration of 5 M was considered in this study to avoid health harm to workers and to have cost-effectiveness [51]. The Na_2SiO_3 had a specific gravity of 1.4 and a modulus ratio (MR) equal to 3.2 (where MR = SiO_2/ Na_2O, Na_2O = 8.9%, and SiO_2 = 28.6%).

Class 4 crushed rock was collected from a local construction material producer in Melbourne, Australia, and was used as the benchmark material. An image and the particle size distribution of the crushed rock are presented in Fig. 2.

Clay was collected from the western suburbs of Melbourne and tested for its Gs [14], liquid limit (LL), plastic limit (PL), and plasticity index (PI) [18], with results indicating values of 2.71, 60%, 25%, and 35%, respectively. Based on these results and the ASTM-D2487 [17] standard, the clay was identified as high plasticity clay (CH). The Physical properties of the materials used in this study are presented in Table 2.

The proposed mix designs

The two unbound mix designs, Blend 1 and Blend 2, recommended by Yaghoubi et al. [66] contained RG:RP: RT at proportions of 77:9:14 and 84:5:11 by mass, respectively. These blends were selected after experimental and field testing on a spectrum of various proportions of RG, RP, and RT with gradation curves falling as much as possible within the Class 4 upper and lower gradation limit of VicRoads [64] as recommended by MRWA [44] and shown in Fig. 3. Cement and fly ash (FA) was added to Blends 1 and 2 at contents shown in Table 3 to establish 8 treated blends. Initially, 1%, 2% and 3% cement and FA contents were targeted for a preliminary assessment of the mixtures. However, the compacted specimens with 1% cement and 1% or 2% FA did not exhibit sufficient cohesion and could not be retrieved soundly without cracks from the compaction mold, which also indicated their low strength properties. Also, observing the low bearing capacity of the specimens with 3% FA through the California Bearing Ratio (CBR) test results led to exploring the addition of 4% FA as well. Thus, 2% and 3% cement content and 3% and 4% FA contents were selected. The reason for not selecting higher cement and FA dosages was economic considerations associated with the shortage of supplies and significantly higher costs of binders compared to aggregates. Geotechnical testing was carried out with the aim of determining the physical properties of the proposed blends and natural aggregates. The physical properties included specific gravity, particle size distribution, and compaction characteristics achieved through applying modified compaction effort [15]. Table 3 presents the proposed recycled treated blends and natural aggregates, together with the specific gravity (Gs), coefficient of uniformity (Cu), coefficient of curvature (Cc), and unified soil classification system (USCS).

Specimen preparation

The recycled materials of RG, RP, and RT were oven-dried at 40 °C for 3 days, and the blends based on proportions shown in Table 3 were prepared. Cement was added to the RG:RP: RT mixture at the contents of 2% and 3% to create treated blends of B1, B2, B3, and B4 while the FA content was added at 3% and 4% contents to create treated blends of B5, B6, B7, and B8.

To prepare the cement-treated blends, aggregates and cement with proportions presented in Table 3 were mixed by a soil mixer to ensure homogeneity. To determine the optimum moisture content (OMC) and maximum dry density (MDD), the predetermined water was gradually added to the mixture of aggregates and cement during the mixing process. The mixture was next compacted under modified compaction effort according to ASTM-D1883 [16]. The procedure was repeated at various moisture contents to develop the dry density versus moisture content plots using which the OMC and MDD were determined. The specimens for target tests shown in the following sections including California Bearing Ratio (CBR), repeated load triaxial (RLT), quick shear and scanning electron microscopy were prepared at the OMC and MDD and cured for 28 days in a humidity tank with a relative humidity of 95% and a temperature of 20 °C (Fig. 4).

To prepare FA-treated blends, the RG, RP, RT, and FA were mixed by the soil mixer for 5 min in the dry state. Next, a liquid alkaline activator (LAA) with a Na_2SiO_3/NaOH ratio of 2.5 was sprayed on the mixture during mixing. The LAA to total mass of FA (LAA/FA) was controlled at 0.4. Nematollahi and Sanjayan [47] recommended using LAA with a Na_2SiO_3/NaOH ratio of 2.5 to prepare a multi-compound activator and considered LAA/FA of 0.4 as the optimum ratio. The OMC and MDD determination procedure and specimens preparation for the planned tests adopted for cement-treated blends were applied to FA-treated blends. However, the compacted FA-treated specimens were cured in an oven at 40 °C as shown in Fig. 4. A 40 °C temperature was used to simulate an average heat temperature on pavement subgrades in countries with a tropical climate including Australia. Curing a specimen containing FA geopolymers at 40 °C is known to exhibit higher strength than those cured at room temperature [50]. A preliminary laboratory assessment showed that samples cured at room temperature are too weak, which was consistent with the studied literature, and thus a curing temperature of 40 °C was used.

To ensure obtaining reliable results throughout the experimental program of this study, two identical samples were initially prepared and tested using calibrated equipment. If the variation between the obtained

Table 2
Physical properties of the materials used in this study.

Material	Gs	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Cu	Cc	USCS	LL (%)	PI (%)
RG	2.48	0.27	0.70	1.65	6.11	1.10	SW	–	–
RP	1.10	2.50	3.60	5.50	2.20	0.94	GP	–	–
RT	1.12	7.30	9.80	12.5	1.71	1.05	GP	–	–
Cement	3.12	–	–	–	–	–	–	–	–
Fly ash	2.10	–	–	–	–	–	–	–	–
CL4	2.67	0.13	0.78	4.5	34.62	1.04	SW	–	–
Clay	2.71	–	–	–	–	–	CH	60	35

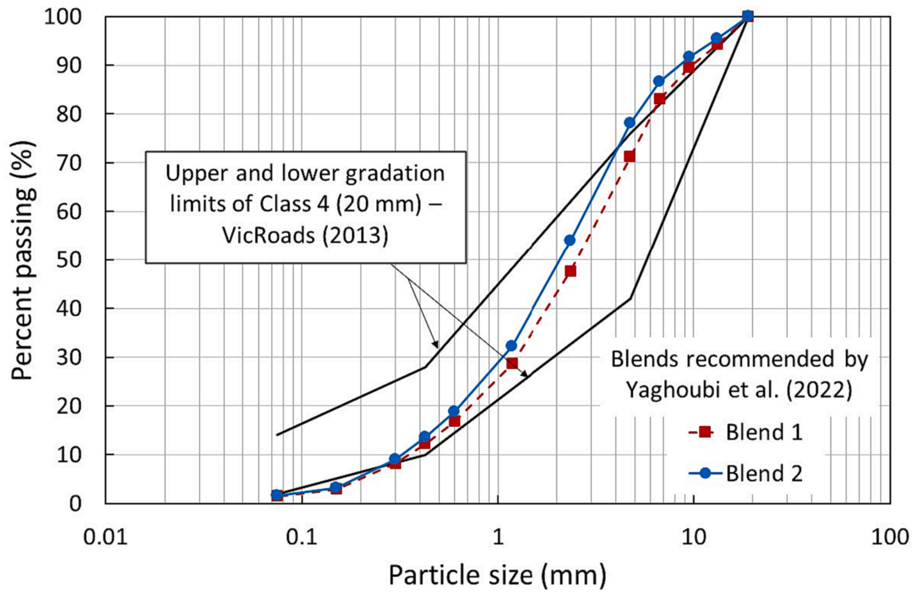


Fig. 3. PSD of two mix designs proposed by Yaghoubi et al. [66].

Table 3
Proposed recycled blends and mix proportions.

Blend ID	Materials proportion by mass (%) RG	RP	RT	Cement	Fly ash	Gs	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Cu	Cc	USCS
B1	77	9	14	2	–	1.93	0.35	1.35	3.50	10	1.49	SW
B2				3	–							
B3	84	5	11	2	–	2.07	0.32	1.10	2.90	9.06	1.30	SW
B4				3	–							
B5	77	9	14	–	3	1.93	0.35	1.35	3.50	10	1.49	SW
B6				–	4							
B7	84	5	11	–	3	2.07	0.32	1.10	2.90	9.06	1.30	SW
B8				–	4							

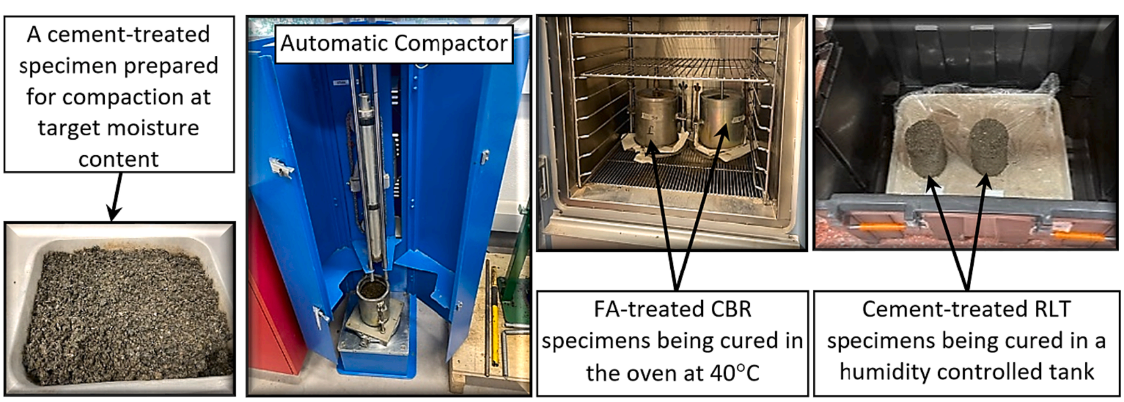


Fig. 4. Preparation of cement and fly ash-treated specimens: mixed aggregates and cement, compaction, curing in humidity controlled tank and an oven.

results exceeded 5%, further sample(s) were prepared and tested. This process was repeated until an acceptable difference was achieved, and the average value was considered. Following this procedure, for each blend two to four identical specimens were prepared to ensure the reliability of the findings.

Determination of the CBR

The California Bearing Ratio (CBR) value is commonly utilized to determine the thickness of pavement structural layers. Therefore, following the ASTM-D1883 [16] procedure, the CBR test was carried out to investigate the feasibility of using the proposed treated recycled material blends for backfilling deep excavated trenches located under traffic loading and to compare them with the relevant authority's guidelines [44,64]. The proposed blends prepared at OMC were compacted in a mold of 152 mm diameter × 177 mm high under modified compaction effort according to ASTM-D1883 [16]. The compaction procedure for each specimen was completed within 30 min. A surcharge mass of 4.5 kg was placed on the surface of the compacted specimens to simulate the confining effect of overlying pavement layers. The cement-treated or FA-treated CBR specimens were cured for 28 days in a humidity controlled tank or ovens at 40 °C, respectively, and then soaked in the water for 24 hrs before testing. The load was applied to penetrate the cylindrical piston at the rate of 1.25 mm/min into the compacted specimen as shown in Fig. 5 (part a).

Repeated load triaxial testing

The resilient modulus of treated blends was determined in accordance with the procedure described in specimens AASHTO-T307-99 [1]. The resilient modulus (Mr) test replicates in situ soil or pavement material's behavior under traffic wheel loading through cyclic loading on specimens [52]. Values of Mr are typically obtained through repeated load triaxial (RLT) testing on undisturbed or reconstituted cylindrical specimens [1]. A vehicle wheel moving on a pavement structure establishes a stress pulse comprising confining and deviator stress components [25]. According to AASHTO-T307-99 [1], the test consists of 15 loading sequences with a 100 load repetitions each and a sequence called conditioning sequence including a 1000 load repetitions. In each sequence, a target confining (σ_c) and deviator stresses (σ_d) are applied. 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. 6.

In order to prepare the RLT specimens, samples moisture-conditioned to the OMC were compacted in 8 layers, 25 blows per layer to provide the equivalent modified compaction effort of 2,700 kN-m/m^3. A split steel cylindrical mold of 100 diameter × 200 mm high was used. The diameter of the mold was five times the maximum particle size in the blend (19 mm) and the height/diameter ratio was 2:1 as specified by AASHTO-T307-99 [1]. The cement-treated samples were cured for 28 days in a curing tank with a relative humidity of 95% and temperature of 20 °C, while the FA samples were cured for 28 days in an oven set at a temperature of 40 °C.

After conducting 15 sequences of the test (Fig. 6), data sets of resilient modulus - confining stress - deviator stress (Mr-σ_c-σ_d) were collected to determine the model coefficients (k) for two frequently used resilient modulus prediction models. The two models used in this study were the two-parameter models [29] and the modified universal model [2], expressed in Eqs. (5) and (6), These models were developed for soils and granular materials:

$$M_r = k_1\theta^{k_2} \tag{5}$$

$$M_r = k_1\sigma_a\left[\frac{\theta}{\sigma_a}\right]^{k_2}\left[\frac{\tau_{oct}}{\sigma_a}+1\right]^{k_3} \tag{6}$$

Where:

k_1, k_2, and k_3: are the model coefficients,

σ_a: is the atmospheric pressure,

θ: is the bulk stress ($\theta = \sigma_d + 3 \times \sigma_c$), where $\sigma_d = \sigma_1 - \sigma_3$, and $\sigma_c = \sigma_2 = \sigma_3$, and.

τ_{oct}: is the octahedral shear stress ($\tau_{oct} = \sqrt{2}\sigma_d/3 = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2(\sigma_1-\sigma_3)^2(\sigma_2-\sigma_3)^2}$).

σ_1, σ_2 and σ_3 are the principal stresses. When the wheel load is directly above the element under consideration, the principal stresses of that element align with the Cartesian coordinates of the pavement sections. However, as the wheel load moves away from the element, the principal stresses begin to rotate in relation to the Cartesian coordinates. Nonetheless, since the stress state of interest is specifically focused on an element positioned directly beneath the wheel load, σ_1 corresponds to σ_z, and σ_2 and σ_3 are equal to σ_h [39]. The Cartesian axis z (in σ_z) aligns with the direction of σ_1, and h in σ_h represents either the transverse direction, or the traffic direction, both of which align with the direction of σ_c.

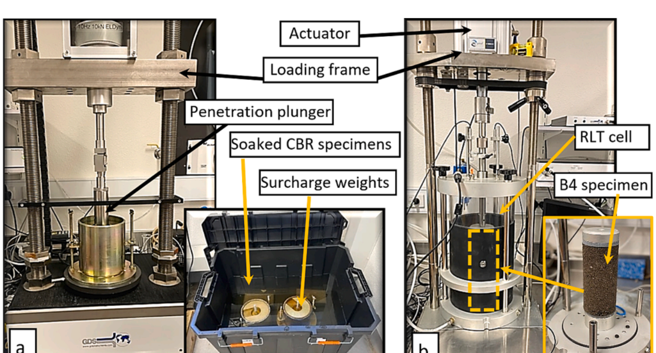


Fig. 5. Images of (a) CBR tester with soaked specimens (b) RLT tester with compacted RLT specimen.

Quick shear testing

Following the completion of 15 repeated load sequences, a quick shear test was performed to determine the maximum shear strength of the material in low confinements. The quick shear strength represents the stress state beyond which the pavement material cannot bear the loads [1]. A confining stress of 27.6 kPa was applied, and the axial stress was gradually increased to achieve an axial strain rate of 1% per minute. The test was terminated either when the axial stress value decreased or the axial strain exceeded 5%. Upon completion of the test, the maximum shear strength and stiffness characteristics, such as the Young's modulus under low confinement (E_c), were obtained. The Young's modulus determined from unconfined compressive strength remains constant under low confining pressure, as reported by Li et al. [40]. The Young's modulus represents the stress–strain curve's slope within the elastic range.

Scanning electron microscopy

Scanning electron microscopy (SEM) images were taken using Phenom XL G2 on blends B3, B4, B7 and B8 to carry out a microstructural study on the cement and fly ash-treated specimens. To prepare SEM specimens, small segments of cement and fly ash-treated samples were extracted from the center of the cured RLT specimens. The specimens were next attached to a specimen holder using double-sided adhesive tape as demonstrated in Fig. 7. A thin layer of gold was applied to the specimens using the Quorum Sputter Coater to enhance conductivity. The specimens were then positioned within the specimen chamber of the Phenom XL G2. The imaging parameters were adjusted, ensuring an accelerating voltage of 15 kV and a desired magnification of 6000 times, and the SEM images of the specimens were captured. The procedure of preparing and taking SEM images from specimens is shown in Fig. 7.

Results and discussion

The modified compaction tests were carried out to determine the optimum moisture content (OMC) and the target maximum dry density (MDD) (at 98–100%) that were required to prepare the CBR and RLT samples. Fig. 8 demonstrates the OMC and MDD for the proposed treated blends and natural crushed rock (CL4). Fig. 8 shows that for the cement-treated blends, the OMC increased as the cement content increased. Cement is a binding material that contributes to the formation of a cementitious matrix. As the cement content increases, more water is required to achieve proper hydration and binding with the other components of the mixture. This increased hydration demand leads to a higher optimum moisture content [4]. Fig. 8 also showed that the OMC increased as the RG content increased and the RT content decreased. In comparison to other materials used in the study, RG exhibited a significantly higher capacity to absorb moisture due to its high proportion of fine materials and porous particle surfaces. As a result, an increase in RG content led to an increase in the OMC [60]. Conversely, an increase in the RT content resulted in a decrease in the moisture-absorbing capacity

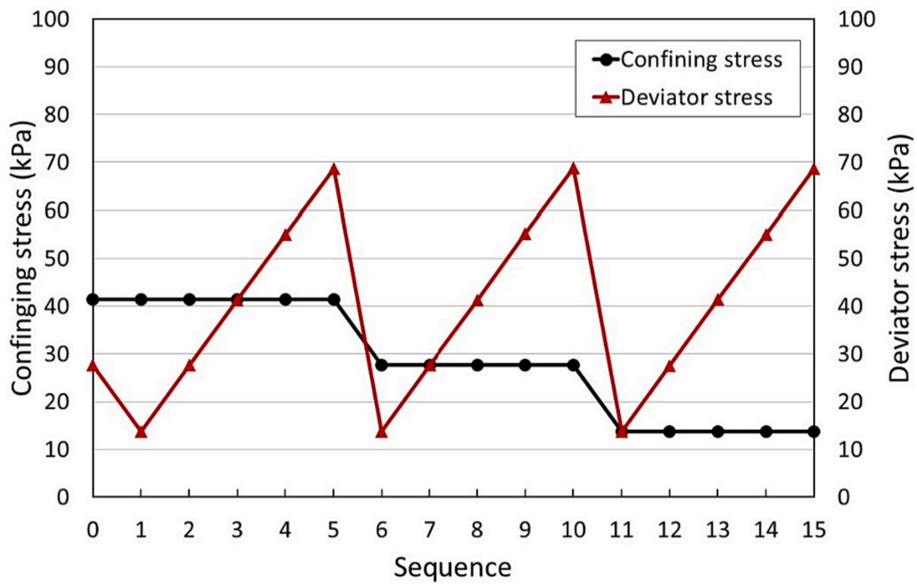


Fig. 6. The loading regime used for the resilient modulus tests of this study.

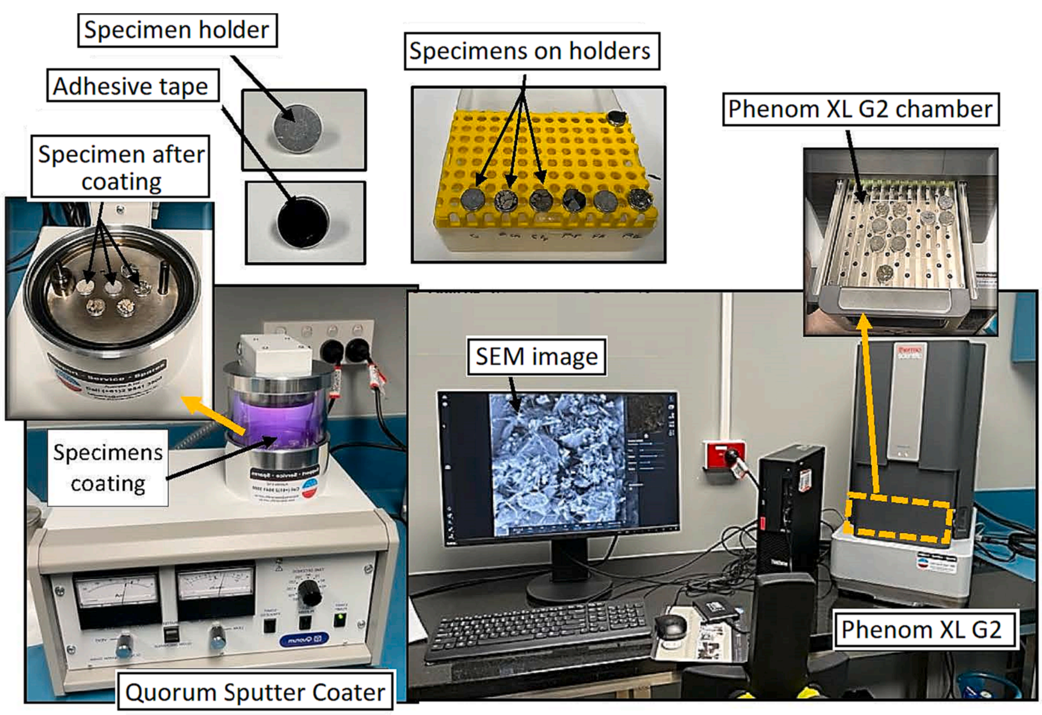


Fig. 7. The procedure for capturing SEM images of cement and FA-treated specimens.

of the mixture, leading to a lower OMC [33]. A similar behavior was observed for FA-treated blends. Fig. 8 indicated that the MDD increased as cement and FA increased and this attributed to the particle packing. In addition to binding, cement and FA act as a filler material that fills the voids between particles in the mixture. As the cement and FA contents increase, more fine particles are introduced into the mixture, improving particle packing and increasing the density [37].

This section provides the experimental results and discussions on the treated recycled material blends presented in Table 3.

Evaluation of the CBR results

Fig. 9 presents the California Bearing Ratio (CBR) results of the Class 4 (CL4) and eight samples prepared with various RG, RP, RT proportions and cement and FA contents. Two to four identical specimens of each blend were tested to verify the accuracy and repeatability of the results. The values presented in Fig. 9 are the average value of the repeated CBR tests.

Results presented in Fig. 9 indicate that the samples treated with cement had significantly greater CBR compared to the corresponding samples treated by FA. This could partially be due to the greater achieved MDDs of the cement-treated samples by about 6% compared to the corresponding FA-treated samples leading to greater air voids and hence more potential to settlement under the load. Also, the hydration and pozzolanic reaction process in cement-treated aggregates occur rapidly once the water comes in contact with cement [10]. However, in the FA-

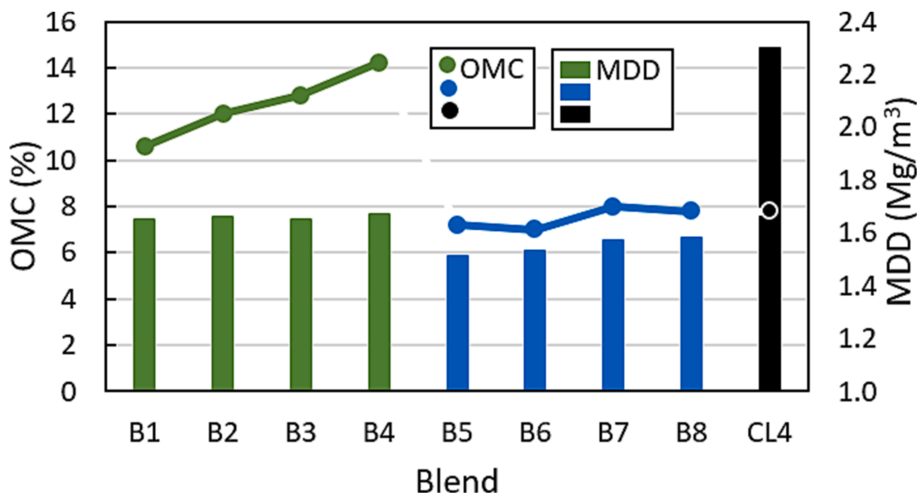


Fig. 8. The obtained OMC and MDD of the proposed blends and CL4.

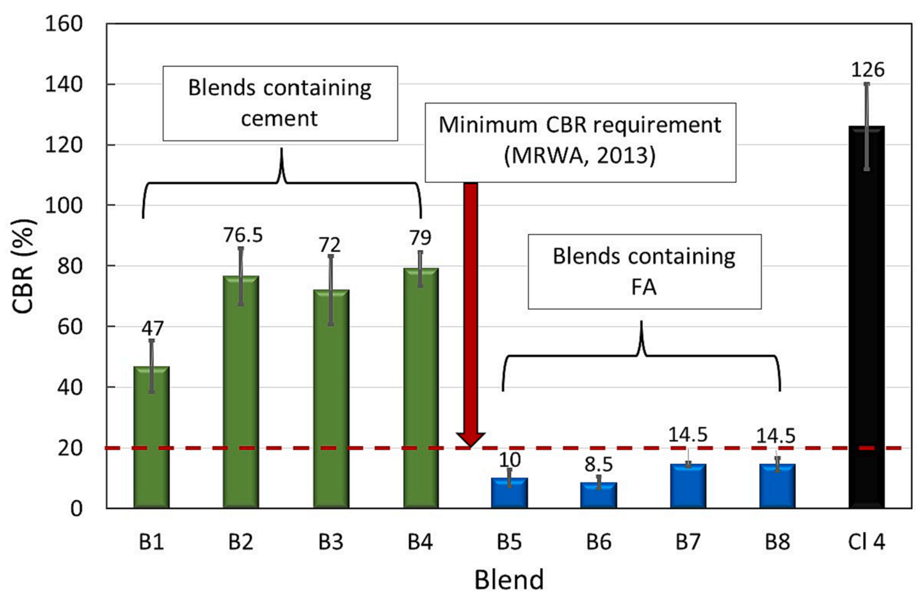


Fig. 9. CBR results on recycled materials blends and natural aggregates.

aggregates stabilization, the pozzolanic reaction depends on presence of CaO, Al_2O_3, SiO_2, and Na_2O components [56]. As CaO component was low in the FA-treated samples, it was necessary to add an alkaline activator to increase the pozzolanic reactions. The FA proportion determined the proportion of the alkaline activator that should be added to a blend which was 0.4 of the FA proportion in this study following the recommendations of Nematollahi and Sanjayan [47]. Therefore, the added activator might not have been sufficient to induce the pozzolanic reaction and hence, less bonding was developed, resulting in lower CBR compared to cement-treated samples.

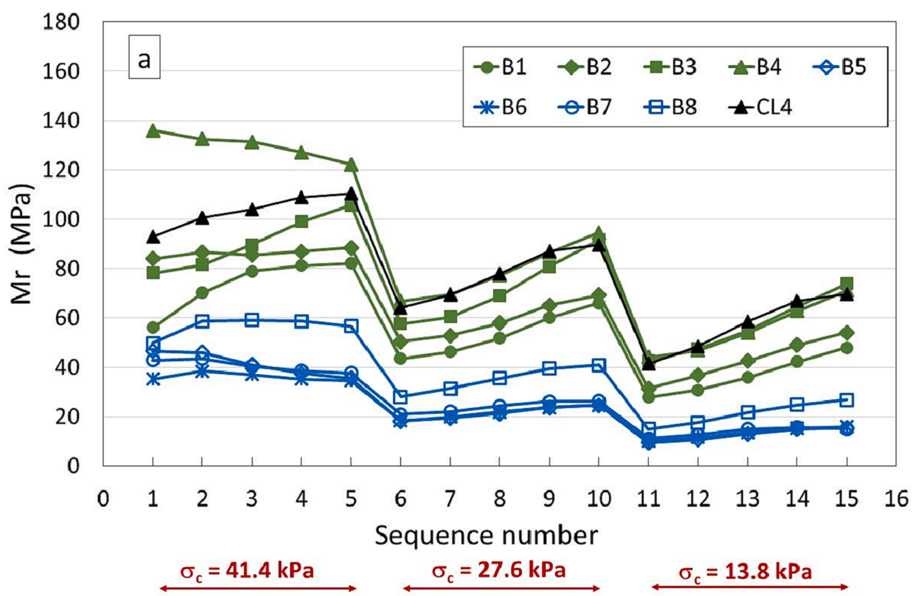
Fig. 9 also showed that at constant RG, RP, and RT contents, the CBR increased as cement content increased. For instance, for B1 and B2 with RG: RP: RT contents of 77%:9%:14%, the CBR increased by 63% when the cement content increased from 2% (B1) to 3% (B2). However, an insignificant change in the CBR values occurred when FA content increased from 3% to 4% (B7 and B8). At constant cement and FA contents, the increase in RG and decrease in RT proportions had an obvious effect in increasing the CBR for all cement and FA-treated samples tested. This is due to the fact that the flexibility of the RT particles was significantly higher compared to RG in which higher deformation could be achieved under load and lower CBR. The increase in CBR reached about 50%, as observed in B1 and B3, B5 and B7, as well as B6 and B8 CBR results.

According to MRWA [44], the minimum CBR required for CL4 is 20 and that is represented in a horizontal dash line depicted in Fig. 9. From Fig. 9, it is obvious that all specimens stabilized using cement (B1, B2, B3, and B4) achieved significant CBR improvement. The maximum CBR achieved for cement-treated samples was about 0.64 times that for CL4 selected in this study. While in all specimens stabilized with fly ash (B5, B6, B7, and B8), CBR values less than 20 were achieved. Hence, according to [44] and based on the CBR results, these blends are not suitable to replace CL4 to backfill the deep sewer trenches in trafficable areas. Irrespective, it was decided that all 8 specimen types would be further investigated through RLT testing, to study their resilient modulus response and interpret the relationship between their CBR and resilient modulus.

Resilient modulus results

A set of repeated load triaxial (RLT) tests was applied on all treated blends. Multiple identical samples of each blend type, between two to four samples, were tested to confirm the precision and consistency of the findings. Fig. 10a presents the resilient modulus (Mr) obtained from 15 loading sequences for each blend. The Mr values presented in Fig. 10a and 10b were the average values achieved from testing identical specimens. In Fig. 10b, the horizontal line corresponds to a Mr of 48 MPa, which was the minimum Mr obtained by Chowdhury et al. [23] who investigated several subbase materials (CL4). Fig. 10 shows that the resilient modulus achieved by the blends containing cement, i.e., B1, B2, B3, and B4 were 0.73, 0.82, 0.97, and 1.17 times greater than the corresponding values achieved for CL4. Although the CBR of B4 was about 0.64 times the corresponding value for the CL4 (Fig. 9), B4 achieved an Mr that was 1.17 times higher than that of CL4. The reason for this was that the CBR test applied axial stress using a 50 mm-diameter plunger, which was sensitive to the particle arrangement in the loading path. When the loading path consisted of larger particles, the axial strain was expected to be lower. Additionally, the confining pressure prevented the attainment of horizontal strain, and the particles surrounding the plunger supported the particles in the loading path, thus reducing axial strain and increasing the CBR. In contrast, in RLT testing, the stress could be applied on all particles of the specimen, thus all particles of the specimen participated in resisting the stresses. Furthermore, the maximum confining pressure applied to a specimen was 41.4 kPa that allowed horizontal strain to be induced resulting in greater axial strain and lower Mr. Fig. 10 also showed that the maximum Mr achieved for the specimens treated with FA was about half of that achieve for CL4, as shown by the B8 trend for example.

Based on studies carried out by Lee et al. [38], Park et al. [49], and Chowdhury et al. [23], the typical range of Mr for CL4 unbound aggregates was 48–130 MPa. All cement-treated blends presented in Fig. 10 exhibited resilient modulus responses within the range of traditional natural crushed rock. However, all FA-treated blends achieved resilient modulus below the natural crushed rock. Thus, because of both Mr and CBR outcomes, B1, B2, B3, and B4 were recommended as optimum mix designs to replace CL4 aggregates where shown in Fig. 1 to backfill excavated trenches with depths greater than 1.5 m.



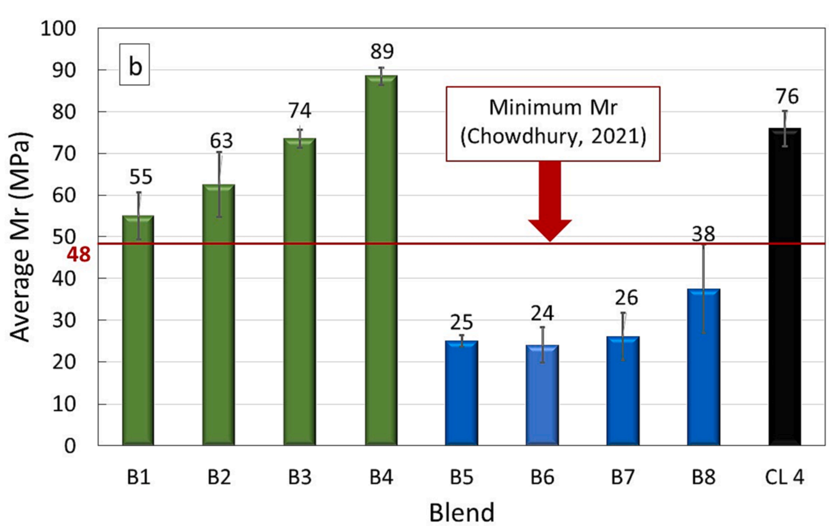


Fig. 10. RLT test results: (a) Mr values in each loading sequence, and (b) average Mr of 15 loading sequences.

The plots of resilient modulus versus deviator stress for the treated recycled material blends are presented in Fig. 11. This figure indicates that as the confining stress increased, the Mr values also increased. When a blend is subjected to higher confining stress, there is an increase in inter-particle interlocking and internal friction, which leads to a decrease in strains (ε) and an increase in Mr ($Mr = \sigma_d/\varepsilon$) [21,63]. As the deviator stress increased at a constant confining pressure, the value of Mr also increased. This could be attributed to the increased stress hardening of the samples, which was observed after subjecting them to 100 repetitions of higher deviator stress, as explained in the research conducted by Puppala et al. [52] and Yaghoubi et al. [67].

Fig. 12 shows the variation of Mr values with bulk stress (θ) which can be estimated through trend lines based on a power function with the coefficient of determination (R^2) ranging 0.67–0.97. From these trend lines, it is evident that Mr values increase not only due to the increase in θ but also in combination with the increase in RG, cement, and FA contents and the reduction in RT contents.

Shear test results and correlations with Mr

The results of the quick shear tests conducted in accordance with the AASHTO-T307-99 [1] procedure are shown in Fig. 13. For cement-treated blends, the peak shear strength (PSS) increased as cement and RG contents increased and the RT content decreased. However, for FA-treated blends, minor changes in PSS were noticed regardless of RG, FA, and RT contents. The addition of inadequate activator to FA-treated blends may have resulted in weak bonds formation and limited pozzolanic reaction, leading to few bond formations. By slightly increasing the FA content, the activator level also increased, resulting in the creation of marginally more bonds and only a slight increase in PSS. The maximum PSS achieved by cement and FA-treated blends were about 1.7 and 0.9 times the corresponding value achieved by CL4. The findings are consistent with the trends observed in the CBR and RLT outcomes, demonstrating that the dominant factor influencing the strength properties of the cement-treated mixtures is the cement content, with RG content being the next most important factor.

Fig. 14a, 14b and 14c present the relationships between Mr and Young's modulus (Ec), Mr and PSS, as well as Mr and CBR, respectively, for cement-treated blends and FA-treated blends separately as well as for CL4 crush rock used in this study. The gap between the upper and lower ranges in all plots is relatively small. For blends treated with cement, the Mr (MPa) was 0.96–1.26, 0.17–0.18, and 0.82–1.17 times Ec (MPa), PPS (kPa), and CBR (%), respectively. While, for blends treated with FA, the Mr (MPa) was 0.53–0.83, 0.09–0.13, and 1.79–2.5, respectively. For CL4, the correlations of Mr-Ec, and Mr-PSS fall within the boundaries of cement-treated blends. However, the Mr-CBR correlation falls below the boundaries defined by cement-treated.

Microstructural analysis of CBR and RLT results using SEM images

The influence of stabilizing recycled blends with two different types of binders, namely cement and fly ash (FA), as well as varying binder contents, on their microstructure is presented in Fig. 15. Fig. 15 illustrates the microstructure of B3 and B4 specimens, which were composed of RG:RP:RT proportions of 84%:5%:11% and stabilized with cement at 2% and 3% contents, respectively. Images of Fig. 15 reveal that cement-treated samples exhibit needle-like and filament-like hydration products. These needle-like crystals are calcium monosulfoaluminate (AFm) and ettringite (AFt), formed during cement hydration, along with calcium silicate hydrate (CSH). Similar findings were previously reported by Bahmani et al. [20], MolaAbasi et al. [43], Luo et al. [41], He and Liao [28] and Amiri et al. [11]. Amiri et al. [11] analyzed the XRD results of red soil treated with 2% and 6% cement contents. The analysis revealed that the main hydration products contributing to the increase

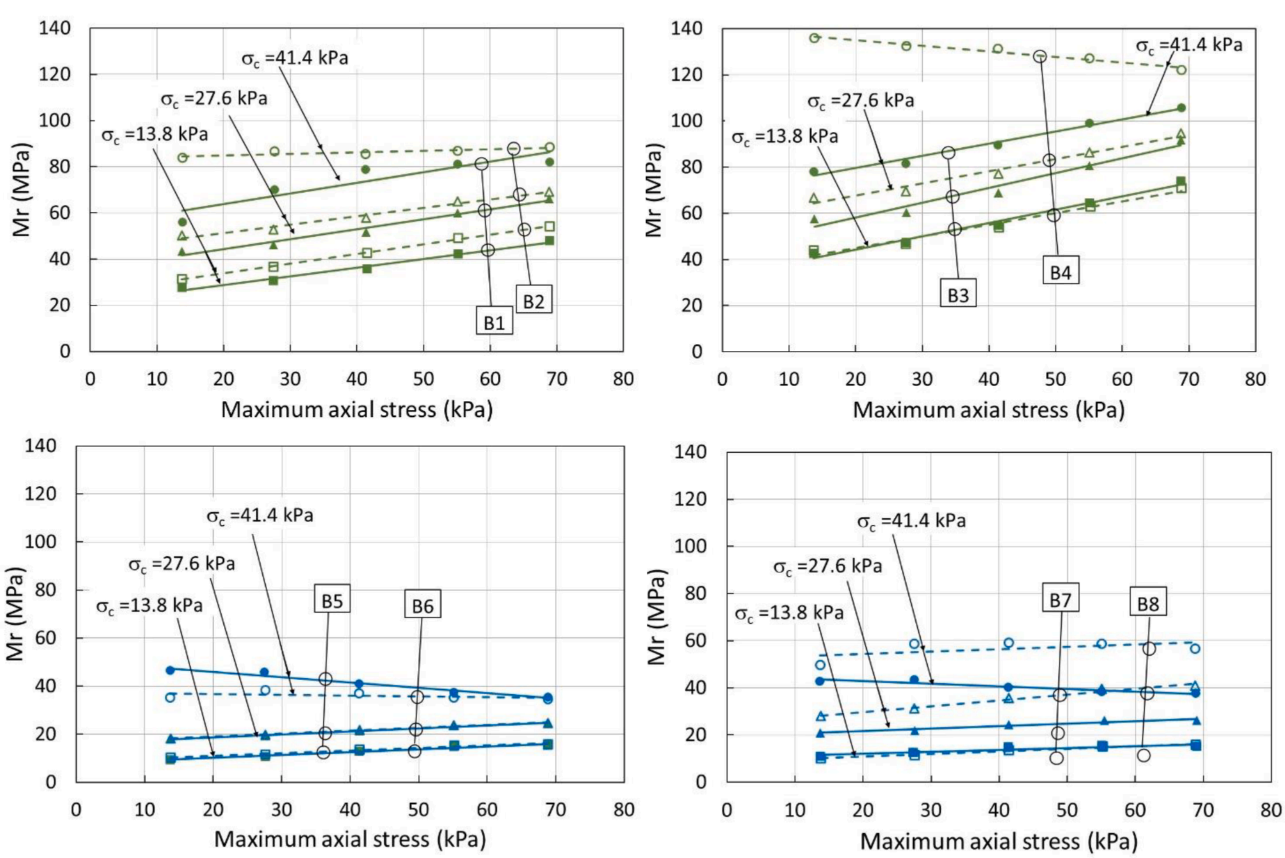


Fig. 11. Resilient modulus vs deviator stress plots for the treated recycled material blends.

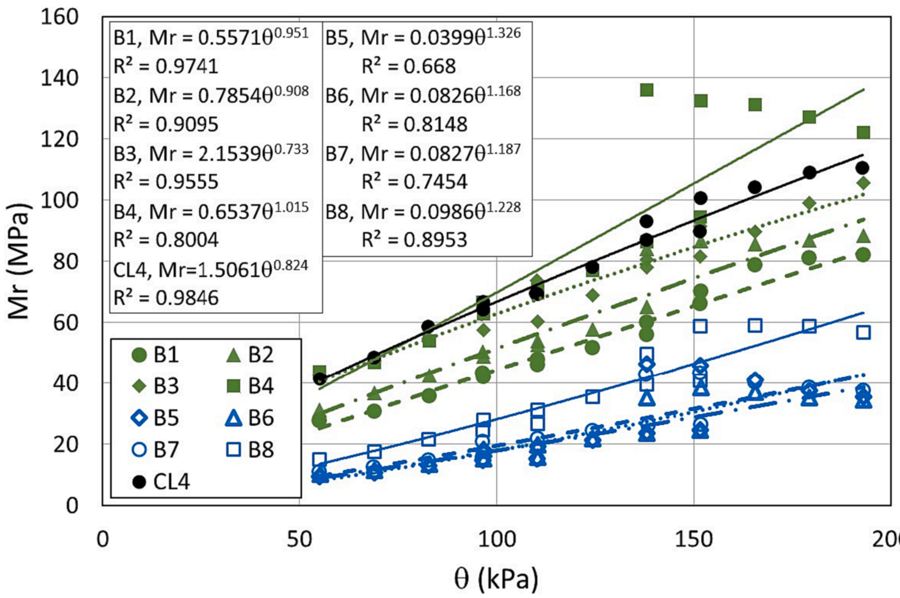


Fig. 12. Plot of resilient modulus vs bulk stress for the treated blends.

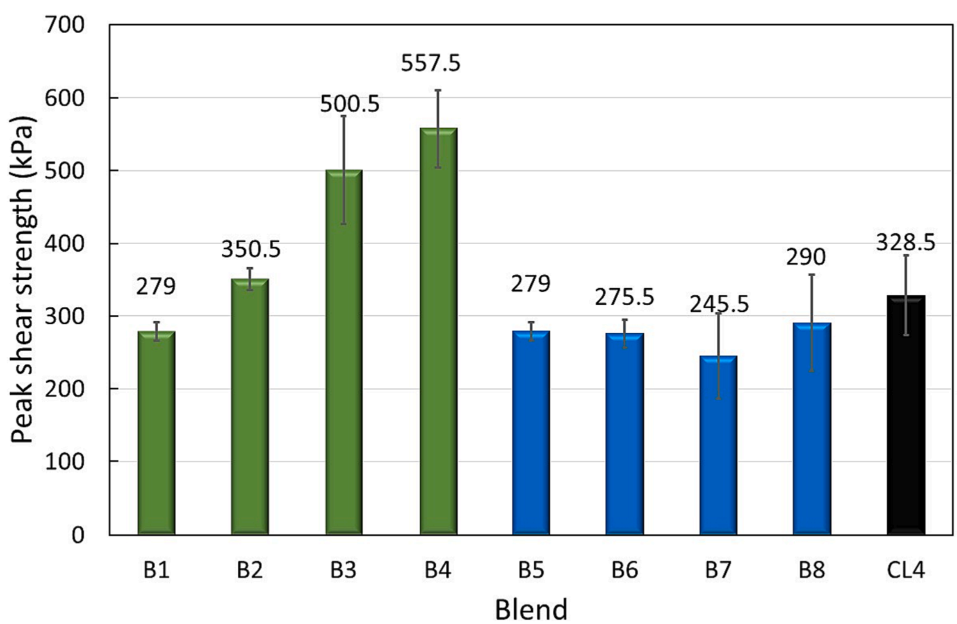


Fig. 13. Shear testing results.

in soil strength were CSH and AFt. The image shown in Fig. 15 reveals that B4 exhibits a higher presence of hydration products including AFm, Aft and CSH, compared to B3. This aligns with California Bearing Ratio (CBR), repeated load triaxial (RLT) and peak shear strength (PSS) results as shown in Figs. 9, 10 and 13, in which B4 exhibited superior stiffness and strength properties. As the hydration products of FA-treated samples (B7 and B8) were exclusively composed of CSH (refer to Fig. 15), a noticeable inferior CBR, RLT and PSS results were expected for the FA-treated samples compared to the cement-treated samples (B3 and B4). This confirms the CBR, RLT and PSS results shown in Figs. 9, 10 and 13. This result was consistent with the findings of Yoobanpot et al. [68], who conducted XRD analysis on clay soil stabilized with 10% cement and 20% FA. Their study also noted that CSH and AFt were the primary reaction products in the cement-clay samples. However, for the FA-clay sample, only CSH was identified as the reaction product with smaller amount compared to the cement-clay samples. Fig. 15 also presented the effect of the increase in FA content from 3% (B7) to 4% (B8) on the microstructure of recycled blends. The images clearly indicated a greater production of CSH in B8 compared to B7, and thus excepting higher strength and stiffness properties and was confirmed with the findings of the RLT and PSS tests.

Comparison with surrounding subgrade soils

It is common practice to determine the pavement thickness design based on the strength characteristics of the natural subgrades surrounding a road alignment that crosses a filled trench unless the backfilled section exhibits lower bearing capacity. To compare the Mr achieved from the recommended treated blends with the surrounding clay subgrade, the Mr of clay samples prepared at OMC of 18% and MDD of 1.59 Mg/m^3 were determined and the average was found to be 34 MPa. Fig. 16a presents the ratio of the Mr achieved by the optimum

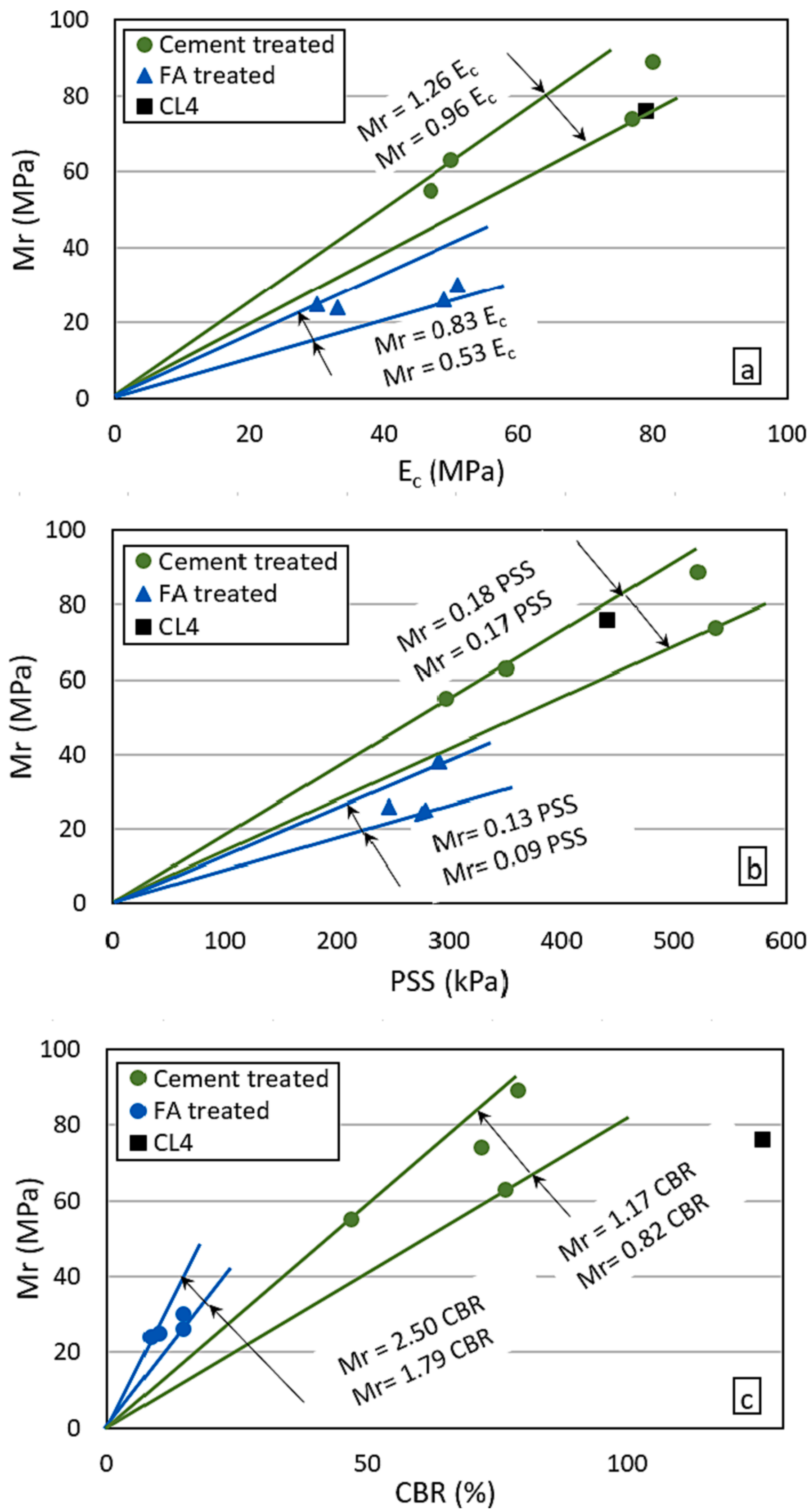


Fig. 14. Relationship between (a) Mr vs E_c (b) Mr vs PSS (c) Mr vs CBR.

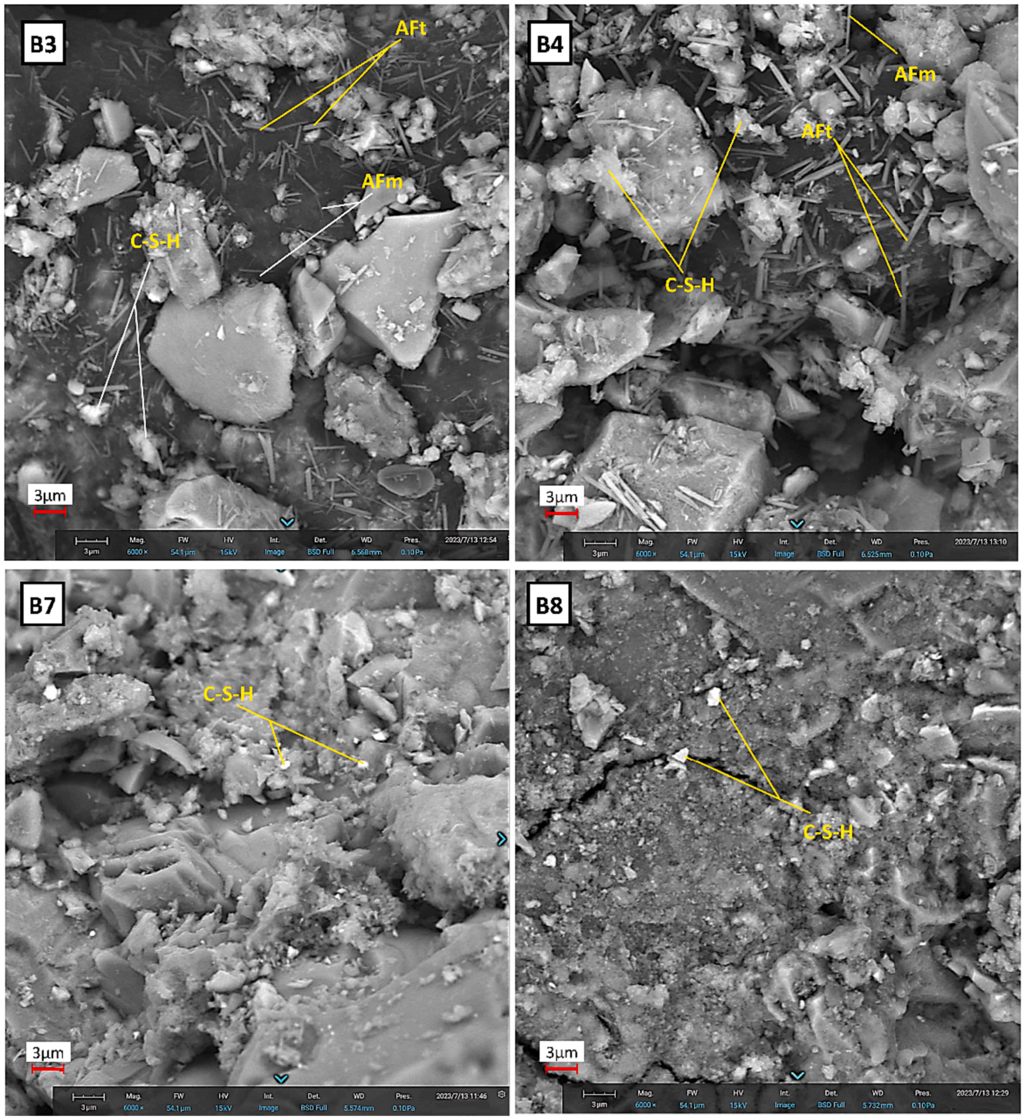


Fig. 15. SEM images of cement-treated blends at 2% (B3) and 3% (B4) and FA-treated blends at 3% (B7) and 4% (B8).

blends (Mr_{op}) to the Mr achieved for natural clay (Mr_c). Fig. 16a indicates that the Mrs obtained from the four optimum blends fell in the range of 1.62–2.62 times the corresponding values obtained for the natural clay. Based on the lower bearing capacity of the clay used in the pavement design over the filled trench, which is lower than the recommended mixtures in this study (typically 2–3), it can be inferred that the pavement's lifespan over the backfilled trench would not be impacted.

Fig. 16b indicates that unlike the pattern observed for the cement treated blends, the resilient modulus of the clay reduced as the bulk stress increased. This decline can be explained by the fact that the RLT samples were prepared at OMC, which was equivalent to about 85%-90% saturation level [5,6]. During the RLT test, the strain softening occurred as the bulk stress increased which in turn, increased pore pressure, lowered the effective confining stress, and led to a reduction in the Mr values, as per the findings of Khasawneh [34].

Analysis of the results using predictive models

The current study examined the suitability of the two-parameter models [29]and the modified universal model [2] in estimating the resilient modulus of the treated blends and natural crushed rock (CL4) by analyzing the RLT data collected for blends B1 to B8. The results, as presented in Fig. 17, compared the 135 measured and predicted Mr values. The modified universal model had more data points clustered closely to the 1:1 line, indicating a more accurate prediction.

Fig. 18 illustrates the k coefficients derived from a regression analysis of the test results for the two-parameter and modified universal models. Additionally, Fig. 18 presents the coefficient of determination (R^2) and the "goodness of fit" of each model using the criteria proposed by Witczak et al. [65]. The criteria proposed by Witczak et al. [65] to assess the goodness of fit based on the R^2 value suggests that the fit is excellent, good, fair, or poor when R^2 is greater than or equal to 90, between 0.70 and 0.89, between 0.40 and 0.69, and between 0.20 and 0.39, respectively.

Fig. 18 shows that the modified universal model exhibits an "Excellent" level of agreement with the results obtained for all eight blends, whereas the two-parameter model ranges from "Fair" to "Excellent." The reason for this difference in performance is attributed to the fact that the k coefficients of the two-parameter model were derived using only two parameters (Mr and θ), whereas the modified universal model utilized three parameters (Mr, θ, and τ_{oct}) to determine the k coefficients, resulting in a more precise regression analysis. Thus, the modified universal model was used to analyze the Mr of the treated backfilled material blends proposed in this study by utilizing "k" coefficients. The value of k_1 is directly proportional to the modulus of

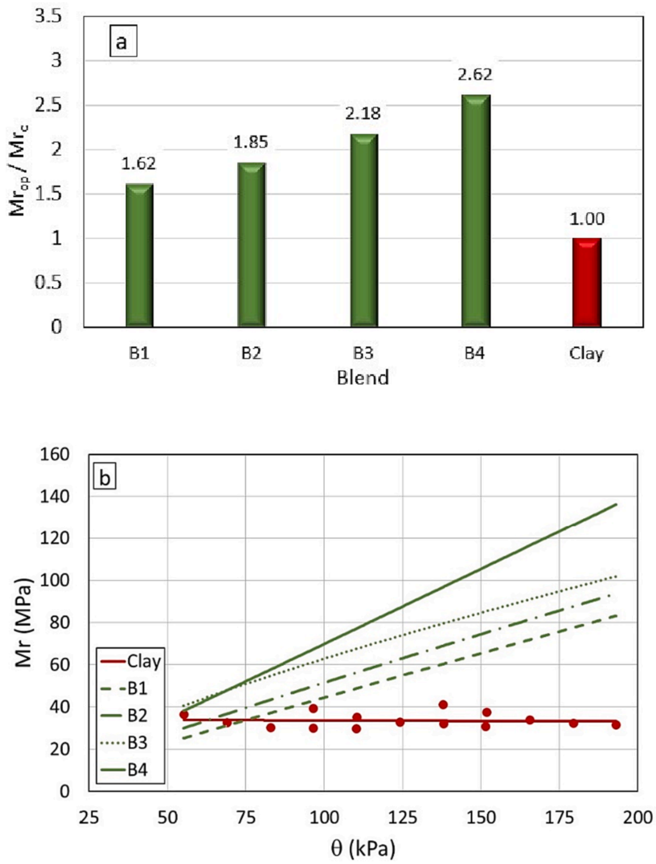


Fig. 16. RLT results for recommended treated blends and expansive clay.

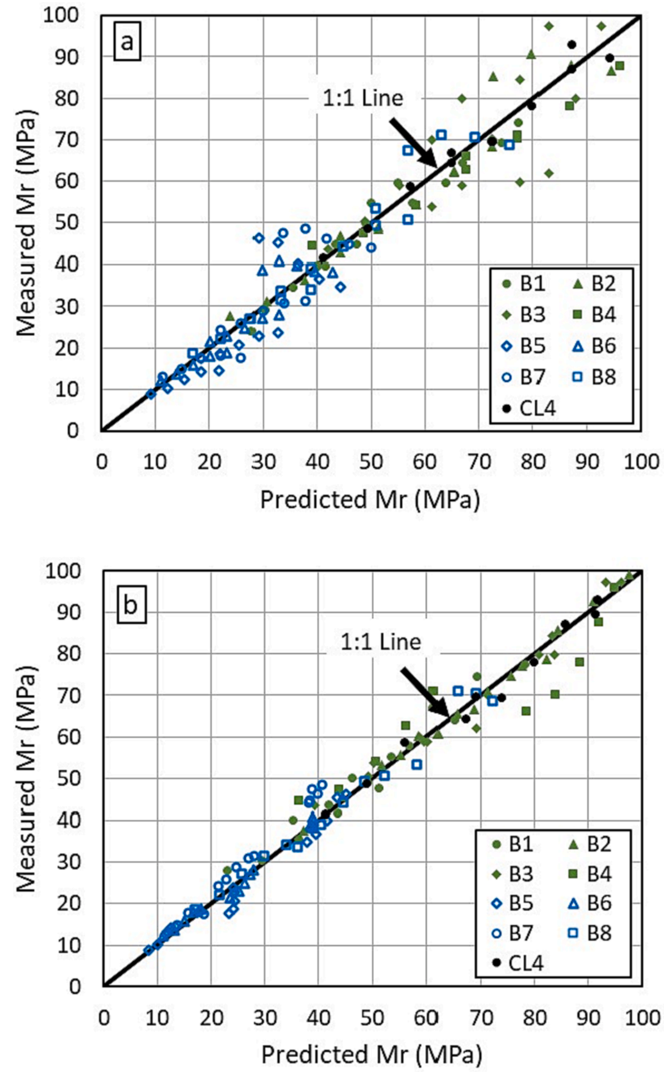


Fig. 17. Measured versus predicted Mr values using (a) the two-parameter model and (b) the modified universal model.

elasticity, so it should be a positive value. Similarly, k_2 is expected to be positive because an increase in bulk stress results in stress hardening of the specimen, leading to an increase in the resilient modulus. On the other hand, k_3 should be negative because an increase in octahedral shear stress induces stress softening, which reduces the resilient modulus [26].

Discussion on the comparative costs

The comparative cost analysis of recycled and virgin construction materials is an essential aspect when considering their potential use as alternatives in construction [57]. The economic attractiveness of recycled material aggregates is crucial for promoting their adoption in the industry. While the primary focus of this study is on the strength and resilient modulus response of the blends, it is important to provide a preliminary cost comparison to demonstrate the cost-effectiveness of the proposed blends that met the minimum CBR requirement (B1 to B4).

To obtain indicative costs, construction, consulting, and recycled material producing companies in Melbourne, Victoria were enquired, and the costs per ton of the materials were concluded the following: RG - $20/ton, RP - $140/ton, RT - $55/ton, ordinary Portland cement - $200/ton, and crushed rock (CL4) - $55/ton. It should be noted that the RP and RT used in this study were the least costly portions achieved during their recycling process and not suitable for top pavement structural layer applications, but proved to be suitable for the application proposed in this this study. By referring to the proportions presented in Table 3, the cost of the recycled material blends B1 to B4 would range between $33 and $40/ton, depending on the proportions of the materials and the percentage of cement used. This cost range is lower than that of CL4, indicating the potential cost advantage of the recycled material blends. However, it is essential to note that these estimations are preliminary and do not take into account various factors. For instance, the recycled material blends require further mixing through a stationary or portal batching plant, which will add to the costs. On the other hand, on the positive side, if these materials are not used for construction and instead sent to landfills, additional landfill levy charges would be incurred [59]. Utilizing the materials for construction can help avoid these charges. Furthermore, using recycled materials in construction can save natural resources, specifically natural crushed rock [31]. As an example, per 50-meter length of a 3-meter deep excavated trench approximately 450 tons of crushed rock is required for backfilling.

While these estimations serve as a reasonable basis for the economically justifiable blends proposed in this study, they are not precise. A detailed cost analysis and life cycle analysis will be conducted in the next stage of this project. This more comprehensive analysis will provide a clearer understanding of the economic viability and long-term sustainability of the proposed recycled material blends compared to their virgin natural counterparts.

The study aimed to improve the properties of mixtures containing recycled glass (RG), plastic (RP), and tire (RT) using cement and fly ash (FA) binders. These treated blends were intended to replace conventional natural crushed rock (Class 4) commonly used for filling deep trenches subjected to traffic loadings. Extensive laboratory tests, including California Bearing Ratio (CBR) and repeated load triaxial (RLT) tests, were conducted to evaluate the strength and resilient

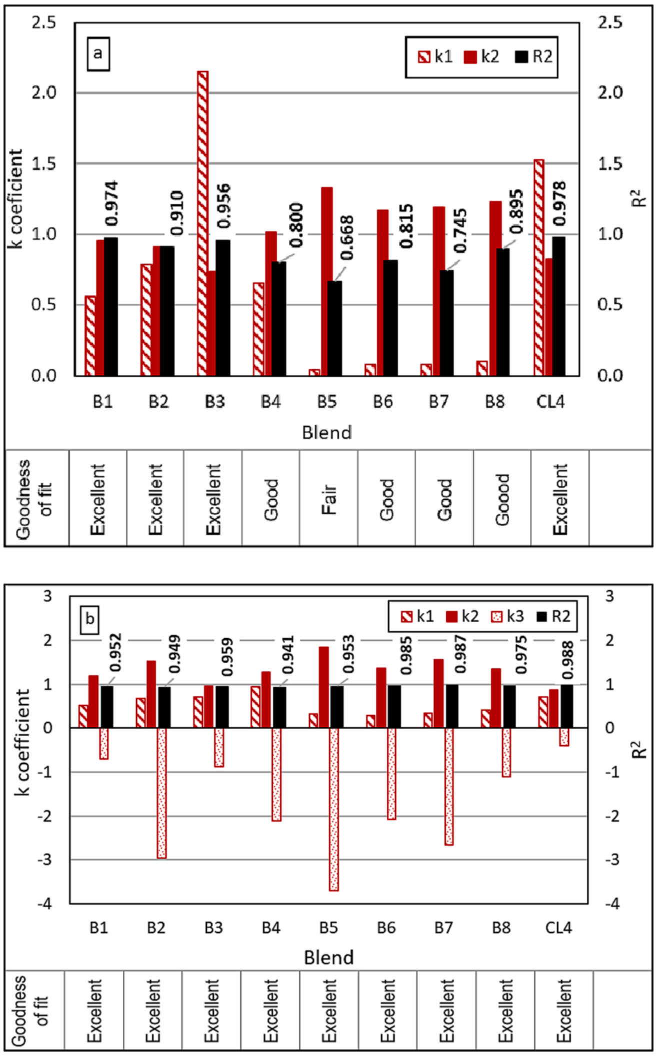


Fig. 18. The “k” coefficients of the Mr predictive models and “Goodness of Fit” assessment.

modulus (Mr) characteristics of the suggested blends. Scanning electron microscopy was employed to investigate the mechanism of cement and FA. The study recommended optimal mix designs and compared them with the properties of traditional natural crushed rock (Class 4) and clay subgrade, which are used in pavement design over the backfilled trench.

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Conclusions

The study aimed to improve mixtures of recycled glass (RG), plastic (RP), and tire (RT) using cement and Fly ash (FA) binders. These enhanced blends were selected as alternatives to traditional crushed rock (Class 4, CL4) for filling trenches under traffic loads. Comprehensive tests, including California Bearing Ratio (CBR) and repeated load triaxial (RLT) tests, evaluated their strength and resilient modulus. The cement and Fly ash mechanism was investigated through scanning electron microscope (SEM) analysis. The optimum mix designs were recommended and compared to traditional crushed rock and clay subgrade properties, often used for pavement design over backfilled trenches. The study produced the following results.

- All cement-treated blends (B1 to B4) satisfied the minimum CBR and RLT requirements and hence, could be utilized as a replacement for natural crushed rock for filling depths below 0.6 m in an excavated trench located in areas accessible to traffic. However, all fly ash-treated blends (B5 to B8) did not achieve the minimum requirements which made them unsuitable for the application investigated in this study.
- For cement-treated blends, the dominant factor that influenced the strength and resilient characteristics of the treated blends was the cement content followed by the RG and RT contents. However the impact of varying FA, RG and RT contents on the strength and resilient characteristics was found to be minimal for FA-treated blends.
- SEM micrographs showed that the higher strength and resilient observed in cement-treated blends compared to FA-treated blends resulted from the formation of ettringite and calcium monosulfoaluminate crystals which were responsible for increasing the bonds and the strength.
- Cement-treated recycled material blends yielded resilient moduli that were up to about 17% and 162% higher than the corresponding value obtained for the CL4 and clay subgrade used in this study.
- The resilient modulus values for the treated recycled blends aligned with a modified universal model, making them suitable for pavement analysis and design in construction projects involving filled pipeline trenches under traffic loadings.

Consequently, this study suggests using recycled material blends consisting of a minimum of 77% RG, a maximum of 14% RT, a maximum of 9% RP, and a minimum of 2% cement as a replacement for traditional backfill materials, such as class 4 crush rock. The findings of this research provide the road and water management authorities with empirical proof of the practicability of incorporating recycled materials in infrastructure construction activities, thus diminishing the need for natural resources and diverting a substantial volume of waste from being disposed of in landfills.

CRediT authorship contribution statement

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

Acknowledgement

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