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Recycled Aggregate Mixtures for Backfilling Sewer Trenches in Nontrafficable Areas

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Abstract: Sewer infrastructures that are backfilled with available onsite expansive soils may be exposed to damages due to seasonal ground movements. Therefore, for deep excavated trenches located in nontrafficable areas, the suitability of utilizing mixtures of recycled materials as alternative backfilling materials with lower sensitivity to moisture variations was studied. Extensive environmental and geotechnical testing programs were carried out on the performance of four proposed blends comprising different proportions of recycled glass, plastic, and tire aggregates in order to determine an optimum mix design. First, potential environmental hazards of the individual recycled materials were assessed. The investigation was advanced by the development of an application-specific geotechnical testing program utilizing geomechanics theories and methods associated with granular materials. The program included the determination of the maximum dry density achieved using a sand-rain technique (SRT) to simulate the real-life backfilling procedure of excavated trenches, and the determination of the compressibility of the blends using a modified oedometer test. In addition, the potential for the migration of finer particles within the recycled material blends and the possible long-term settlement of the backfilled area were studied. The environmental test results showed that the blends could safely be used as fill materials. The SRT test results revealed that the dry density increased as the moisture content and the height of drop increased and the tire content of the mixture decreased. At moisture contents ≥ 15%, the maximum dry densities obtained through the SRT and the standard Proctor compaction were close, achieving relative densities greater than 80%. Furthermore, by simulating precipitation, inconsiderable segregation of particles was observed in the proposed blends. Based on the results of the developed experimental program, two blends were recommended as the optimum mixtures. **DOI: 10.1061/(ASCE)GM.1943-5622.0002297**.

Author keywords: Recycled aggregates; Sewer infrastructure; Trench backfill; Sand-rain technique; Compressibility; Field compaction.

Introduction

The local external factors that affect the stability of sewer pipelines include surface use, surface loadings, groundwater level, and the soil or backfill material type over the pipelines. Davies et al. (2001) stated that among these factors, the backfill material type, which is the focus of the current research, provides the most significant effect on the stability of the sewer pipelines. Investigations on the distribution of structural defects of sewer infrastructures buried in various types of soils have revealed that the highest and lowest rates of defects belong to clayey and gravely soils, respectively (Harvey and McBean 2014). The presence of hydrophilic minerals, such as montmorillonite and illite, makes expansive clays remarkably sensitive to moisture variations. This can result in significant damages to the lightweight structures buried in or founded on such soils (Li et al. 2016; Yaghoubi et al. 2021). This is due to expansive soils' potential for swell–shrink behavior and significant volume changes upon alterations in their moisture content (Al-Taie et al. 2020; Thyagaraj et al. 2017).

The damage exerted to sewer infrastructures by expansive soils can bring about environmental consequences, as well as significant repair and rehabilitation costs to water authorities. As an example, a 2008 Water Services Association of Australia report has estimated the annual cost of urban water assets to be more than $1 billion (NWC 2011). Rajeev and Kodikara (2011) investigated pipe breakages in soils having swell–shrink potential ranging from moderate (3%–6% volume change) to high (6%–9% volume change) and to very high (more than 9% volume change). They reported that the highest frequency of breakages occurred in the pipelines buried in soils with the greatest plasticity indices, and most of the breakages occurred when the water content increased in soils that had dried during the summer.

In Australia, about 20% of surface soils are categorized as expansive clay (Karunarathne 2016). Sewer infrastructures backfilled with expansive clay or large soil clods are prone to poor backfill compaction during variable seasonal cycles. Heavy winter rains amplify these conditions and result in unexpected ground movements and subsequent failures, especially in rigid sewer pipes. This issue is aggravated in narrow trenches with small-diameter sewer pipes that are excavated deeper than 1.5 m, where the quality control of the backfilled trenches can be challenging. This is primarily due to safety limitations restricting field staff from entering the trench. The lack of proper quality control can lead to further settlements at the surface and affects both building structures and boundary fence lines located in the vicinity of the backfilled trench. A potential solution is the application of blends of recycled materials that have lower sensitivity to moisture changes and/or require less

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compactive effort to reach the desired relative density (RD) and thus exhibit less settlement on the surface compared with the site-won clayey soils. The term "site-won soil" refers to natural soils on site that become available through excavation activities.

The worldwide movement toward "sustainable solutions" encourages continuous and persistent studies on new strategies of recycling and reusing waste material in a range of applications (Lindsey 2011). Since civil engineering construction projects have a significant demand for construction materials, the alternative use of recycled materials is ideal (Qi et al. 2019). Various studies have shown the suitability of using recycled materials, in particular recycled plastic, glass, and tire in civil engineering applications (Imteaz et al. 2018; Fauzi et al. 2016). However, all these studies utilized small percentages of recycled materials to improve soil properties. The current study aims to investigate the utilization of blends of 100% recycled material as trench backfill materials in order to minimize the settlement at the surface level.

The first issue with using recycled materials to backfill sewer trenches is the environmental risk in terms of contaminants leaching into the water streams, natural soils, or the ground water. The second issue is the potential for segregation of the granular materials such as the blends proposed in this study. The segregation of granular materials in geostructures is a commonly occurring and problematic phenomenon (Wang et al. 2018). The segregation is often governed by a combination of mechanisms that depend on the nature of the flow, differences in the particle sizes, density of the geostructure, and the shape and properties of the surface (Gajjar et al. 2016; van der Vaart et al. 2015; Gillemot et al. 2017). Therefore, a comprehensive investigation on these aspects was required.

The current study is pioneering research that proposes and investigates blends of 100% recycled material to be utilized for backfilling deep excavated trenches located in nontrafficable areas. Innovative testing methodologies were developed in order to simulate field conditions and to identify compaction properties, stress–strain behavior, the potential for segregation, and environmental risks of using the blends of recycled materials. The results of the experimental program were used to determine the optimum mix design that offered the best performance for the backfilling application. The outcomes of the current study provide robust experimental evidence backed with geomechanics theories to promote the utilization of recycled aggregates in the design and construction of infrastructures.

Materials and Methods

Materials and Proposed Blends

The recycled materials used in this research included recycled glass (RG), recycled plastic (RP), and tire-derived aggregates (TDA). The materials were supplied from local recycling facilities in Victoria, Australia. The specific gravities of the recycled materials were obtained following the ASTM-D854 (ASTM 2010) procedure to be 2.48, 1.10, and 1.12 for RG, RP, and TDA, respectively. The particle size distribution (PSD) of these materials is presented in Fig. 1, together with the materials' specific gravity (G_s), maximum particle size ($D_{\max}$), coefficient of uniformity (C_u), and coefficient of curvature (C_c). The RG, RP, and TDA had particle sizes ranging between 4.75 and 0.075, 12 mm and 0.075, and 19 mm and 0.075 mm, respectively. According to the Unified Soil Classification System (USCS) (ASTM-D2487, ASTM 2011b), RG can be classified as well-graded sand (SW), while RP and TDA can be classified as poorly graded gravel (GP).

The strategy used to determine a suitable blend was to design mixes that had a spectrum of different percentages of recycled materials with gradation curves falling within the Class 4 upper and lower gradation limit of VicRoads (2013) specifications, as recommended by Melbourne Water Retail Agencies' Backfill Specifications (MRWA 2013). Using these guidelines, four blends with different recycled material contents were formulated, as presented in Table 1. Fig. 2 demonstrates individual materials, as well as one of the proposed blends (Blend 2). Based on the USCS, all blends can be classified as SW.

Leaching Test

The environmental assessment of RG, RP, and TDA was undertaken following the Australian Standard Leaching Procedure (AS4439; AS 1997) and checked against the thresholds provided by EPA (2009 and 1999). As leaching metals from a solid material may significantly be affected by the pH of the leaching solution (WADER 2015), the leachate tests were separately performed with both acidic (pH = 5.0) and alkaline (pH = 9.2) solutions. Each test was performed on three random samples of the materials and average values were obtained. The leachates were tested for potential contaminants including metals and metallic compounds (BOEBC 2016).

Compaction and Relative Density

The standard Proctor compaction test was performed according to ASTM-D698 (ASTM 2012). This test was carried out to obtain the optimum moisture content (OMC) and maximum dry density (MDD) based on the traditional compaction method and to compare these values with the OMC and MDD achieved from the sand-rain technique. Recycled material mixtures at various moisture contents were placed into a mold in three layers with each layer compacted using a compactive effort of 596 kJ/m^3.

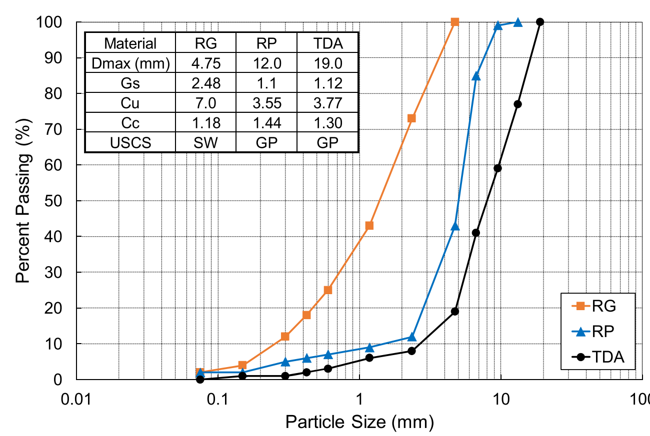

Fig. 1. PSD properties of RG, RP, and TDA.

Table 1. Proportions of RG, RP, and TDA in Blends 1, 2, 3, and 4

Recycled materials	Blend 1 % by volume	Blend 2 % by volume	Blend 3 % by volume	Blend 4 % by volume
RG	60	60	50	70
RP	10	15	10	10
TDA	30	25	40	20
G_s	1.93	1.93	1.80	2.07
$D_{\max}$	19	19	19	19
C_u	9.72	10	11.25	9.06
C_c	1.34	1.49	1.42	1.30
Classification	SW	SW	SW	SW

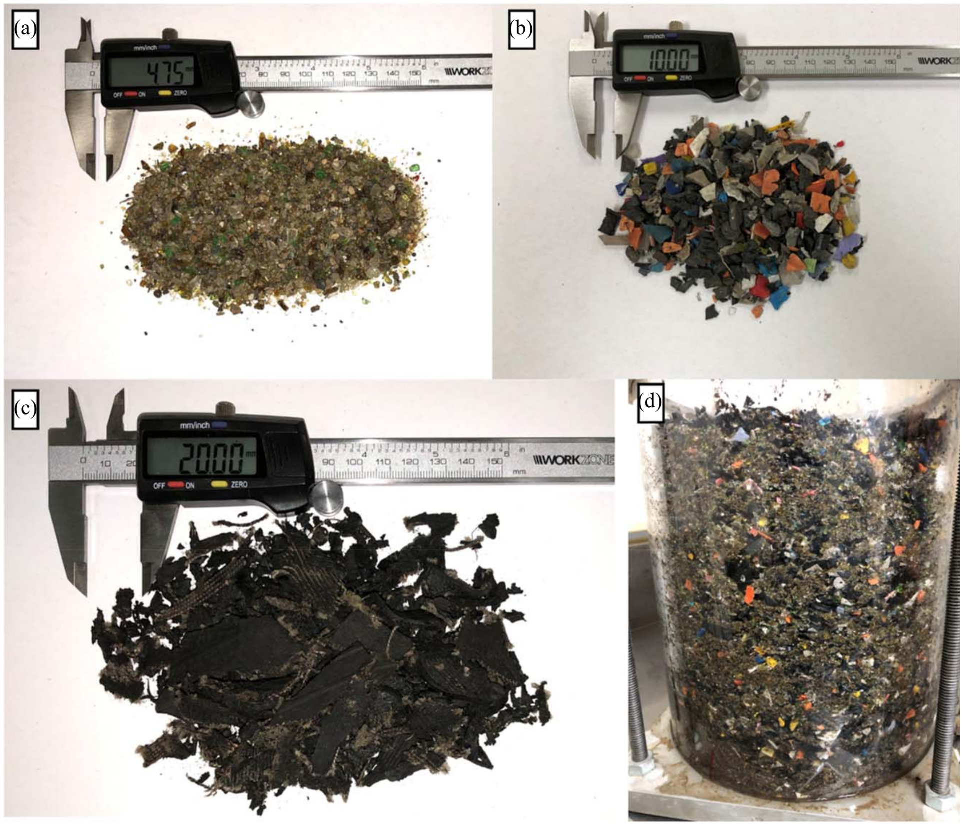

Fig. 2. Images of (a) RG; (b) RP; (c) TDA; and (d) Blend 2.

Following the ASTM-D4254 (ASTM 2016b) and ASTM-D4253 (ASTM 2016a) procedures, the maximum and minimum densities were determined for each blend. For the minimum density, a mold of 150 mm in diameter and 170 mm in height was filled by placing the materials as loosely as possible using a scoop. For the maximum density, the mold was filled with the materials using a scoop, and the surface was leveled. Next, the sides of the mold were struck a few times using a rubber hammer. Based on maximum particle size, an appropriate surcharge (11 kg in the current research) was placed on the surface, and the mold was attached to the vibrating table and vibrated for 10 min. According to the maximum and minimum densities, the RD for a particular blend was determined using

$$RD = \frac{\gamma_{d\max}\,(\gamma_d - \gamma_{d\min})}{\gamma_d\,(\gamma_{d\max} - \gamma_{d\min})} \tag{1}$$

where RD = relative density; $\gamma_{d\max}$ and $\gamma_{d\min}$ = maximum and minimum dry densities, respectively; and γ_d = dry density of the blend. In the current study, γ_d = MDD obtained from standard Proctor or sand-rain technique (SRT) compaction methods.

Sand-Rain Technique

The pluviation technique is extensively used for the specimen preparation of granular materials because in this method, high relative densities are achievable and preparation of large-scale test specimens within a short time is possible (Rodriguez and Lade 2013; Gade and Dasaka 2016). Specimens can be pluviated in air, water, or under vacuum. The air pluviation (also known as the SRT) is typically preferred to achieve uniform and repeatable granular specimens. In the air pluviation method, from a certain height of drop (HD) and with a constant velocity, dry particles are poured through the air from a hopper into the specimen container. Tabaroei et al. (2017) reported that the RD increases as the HD increases due to an increase in the velocity of dropping particles. Once the velocity of the particles reaches a certain amount, the effect of increasing the HD on the RD becomes insignificant.

The SRT can simulate the backfilling of the excavated trenches, which is typically carried out using an excavator bucket. In this research, the SRT compaction was utilized for the determination of compaction properties of recycled material blends. The insufficient densification of the backfilling materials can result in subsequent settlements, and hence the development of a mixture of aggregates that exhibits self-compacting properties would be beneficial.

The SRT setup developed in this study is demonstrated in Fig. 3 and consisted of five parts: beam with adjustable height, hanging rod, hopper, Perspex tank, and the sample collector mold. The hopper was equipped with an adjustable lid that could provide an opening up to 50 mm. A mold of 150 mm in diameter and 180 mm in height was placed in the Perspex tank to be used for the determination of the density of specimens after dropping. The base plate of the mold had 2 mm through holes (approximately 1,200 holes/m^2) to allow for drainage. The position of the hopper was adjusted by moving the beam vertically to allow for various HD of the materials. The HD was measured as the distance between the opening of the hopper and the midheight of the mold. In this research, the HD varied from 500 to 2,000 mm. During the raining process, the hopper was moved back and forth horizontally within a distance of approximately 400 mm to ensure that the density at the edge of the mold was the same as the center.

The initial moisture content (MC_i) of the blends varied from 3% to 18%. After a few rounds of trial and error, the moisture content of 18% was selected as the maximum MC_i in this research, as wetter samples did not lead to a considerable increase in the dry density (DD). At high moisture contents (>12%), after dropping the

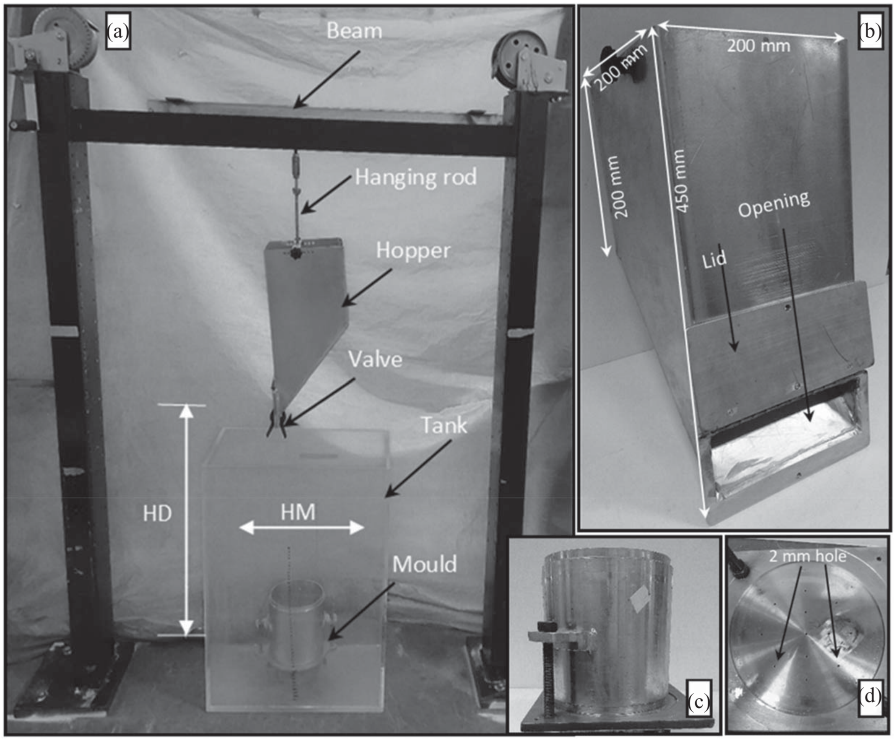

Fig. 3. SRT setup: (a) the setup; (b) the hopper; (c) the mold; and (d) the mold base plate with through holes.

materials from the hopper, the blend was left in the mold allowing the water to drain from it. The sample was left to stand for approximately 15 min to reach the field capacity, which is a moisture state of geomaterials after which no excess water is drained off the sample due to gravity. In this study, the moisture content after drainage was expressed as post-test moisture content (MC_p). For the $MC_i \leq 12\%$, no considerable drainage occurred at the end of the test; therefore, the MC_p was equal to MC_i. However, for $MC_i > 12\%$, after the blends were dropped from the hopper, the water drained from the sample. Consequently, the moisture content reduced to reach the field capacity, and, thus, the MC_p was close to the field capacity. Using the MC_p of the sample collected in the mold, the DD obtained by dropping materials from a specific HD at a known MC was determined. This procedure was repeated for various MC_is and HDs for the four blends and the relationships between MC_p, the HD, and the DD were depicted in typical compaction plots.

Modified Oedometer Test

The compressibility of the blends was investigated following the ASTM-D2435/D2435M (ASTM 2011a) procedure with modifications made to the mold size and the compaction procedure to suit the particle size of samples of this research. Before sample preparation, the inner wall of the mold with a 150-mm diameter and a 120-mm height was lubricated using silicon grease to reduce friction during the loading steps. The base of the mold had 2-mm holes to allow drainage. A filter paper was used on the base, and the sample was placed into the mold in three layers and a total height of 75 mm to provide a diameter to height ratio of 2, as recommended by ASTM-D2435/D2435M (ASTM 2011a). Another filter paper was used on the top of the sample followed by the loading plate. The modified oedometer test setup is demonstrated in Fig. 4. The loading steps included 6, 12.5, 25, 50, 100, 200 kPa corresponding to the field stress levels for sewer pipes buried at depths of 3 to 4 m from the surface level. At each loading step, the

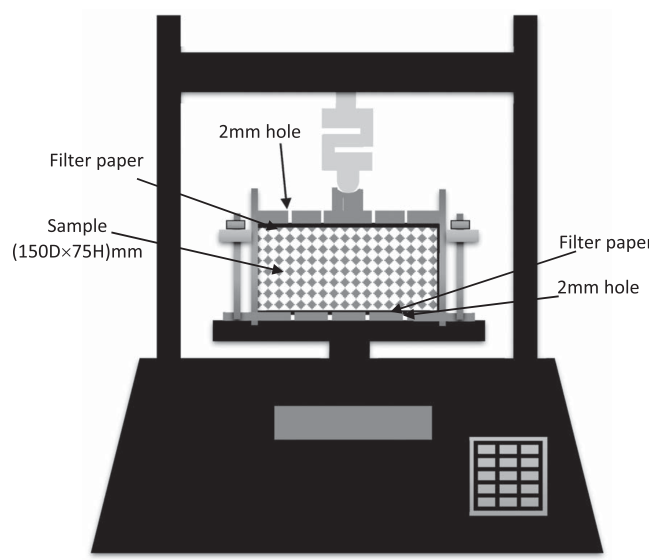

Fig. 4. Modified oedometer test setup.

settlement was recorded and monitored, and once no further settlement was achieved, the next loading step was applied. At the completion of the test, the weight of the sample and the moisture content were measured to calculate the final density [or void ratio (e)]. The test data were collected to plot the axial strain–axial stress (σ) and the $e - \log \sigma$ relationships.

Segregation Test

The segregation test to investigate the potential for the migration of finer particles was carried out by comparing the PSD of the whole blend before the segregation testing with the PSDs of three layers (top, middle, and bottom), after simulating the precipitation. As

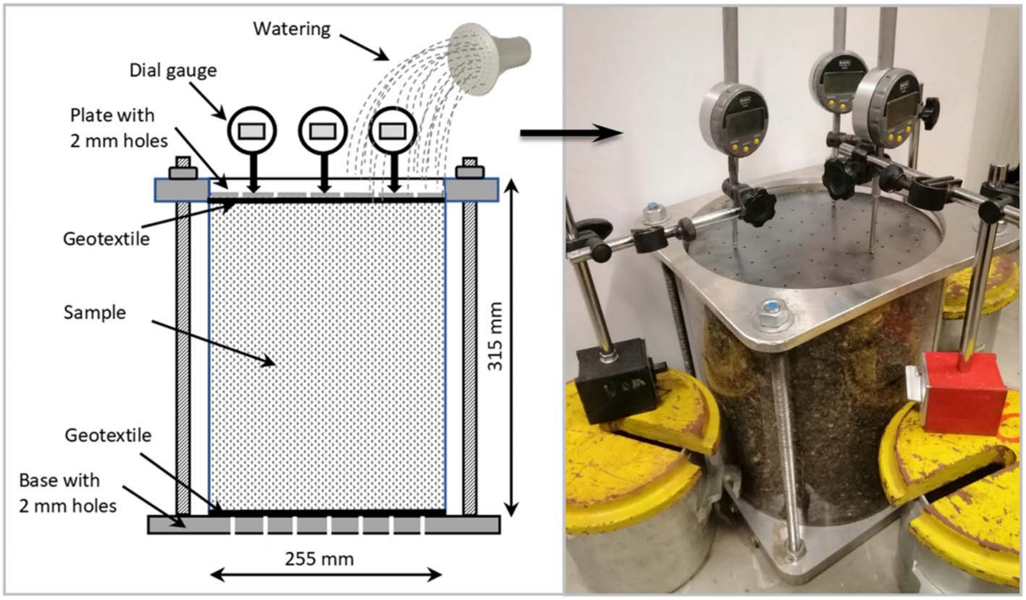

Fig. 5. Segregation test setup.

blends contained different materials and particle sizes, it was difficult to achieve a 100% homogenous blend. Thus, it was not appropriate to compare the pretest PSD of the blend with the PSD of each layer after testing. A practical approach was therefore proposed to prepare a blend that was as homogenous as possible. Using the target DD of each blend and the volume of the segregation test cylinder, the required amount of each individual material (RP, RG, and TDA) to fill the cylinder was calculated. Each individual type of recycled aggregate was split into three equal parts and mixed to form three identical samples of the blend. The three identical samples of the blend were next used to fill the test cylinder in three layers, resulting in a more homogenous blend.

In this study, a Perspex cylinder that is 255 mm in diameter and 315 mm in height was used for the segregation test as shown in Fig. 5. The base plate of the cylinder had 2-mm holes to allow drainage. A sheet of geotextile with 0.08 mm openings was placed on the base to prevent fine particles from passing through the 2-mm holes and also to prevent potential clogging of the holes. The three identical samples of each blend were next placed sequentially to fill a height of 300 mm and achieve the target density. The top level of each layer was marked on the Perspex cylinder to allow the separate collection of the three layers. Another sheet of geotextile was placed on the top of the sample for the uniform distribution of water. A steel plate with 2-mm diameter holes was placed on the geotextile, which imposed a negligible pressure of 0.17 kPa on the surface of the sample. The number of holes in the top steel plate was higher than that of the base plate to ensure that the flow rate was higher than the drainage rate, as is the case in the field during precipitation. Three dial gauges were set on the top of the steel plate to measure and monitor settlements due to watering. When no further settlement was observed, the process of adding water was stopped. In the current research, approximately 4 L of water was consumed in a duration of about 10 min until no further settlement was observed. The sample was then left to drain until it reached the field capacity. Based on several trial tests, carried out on the blends, the time required to reach the field capacity in this setup was about 45 min. At that stage, settlements shown on the dial gauges were recorded, and the average value was calculated. Next, the top, middle, and bottom layers were collected and placed in an oven set to 60°C for 48 h in three separate trays. After that, the posttest moisture content was calculated, and the PSD of each layer was obtained. Finally, the PSD of each layer was compared with the original PSD of the blend, and the potential for the migration of finer particles was investigated.

Results and Discussions

Environmental Assessment

EPA (2009) defines metal concentration thresholds to categorize materials as safe or hazardous industrial waste. The thresholds of the metal concentration for solid inert waste in terms of total concentration (TC) and Australian Standard Leaching Procedure (ASLP) are listed in Table 2. This table also presents the detailed leaching test results obtained for RG, RP, and TDA including the concentration of 15 metals in the leachates for two buffer solutions: one slightly acidic (pH = 5) and one alkaline (pH = 9.2). The values of TC and ASLP were compared with the metal concentration thresholds set by EPA (2009), and it was revealed that the TC and ASLP values of the three recycled materials were far below the solid inert waste threshold. Thereby, the environmental risks of using RG, RP, and TDA in backfilling sewer trenches in terms of metals leaching into the environment surrounding the trench backfilled with RG–RP–TDA mixtures were negligible.

Table 2 also lists acceptable concentrations for drinking water and hazardous waste designation according to EPA (1999). The EPA (1999) guideline suggests that a material is designated as a hazardous waste if any detected metal occurs at concentrations larger than 100 times the drinking water standard (Wartman et al. 2004). Accordingly, the ASLP values (in mg/L) of the RP, RG, and TDA used in this research were compared with the hazardous waste designation as presented in Table 2. The ASLP values were below the threshold of hazardous waste proving that the materials used in this research were not categorized as hazardous waste based on EPA (1999). Metals such as boron, molybdenum, nickel, and zinc do not cause any human risk or damage and as such are not listed in the US-EPA drinking water primary enforceable guideline (EPA 1999).

Table 2. Leaching test results obtained for RG, RP, and TDA along with the threshold values of TC and ASLP for different metals

Metals	Thresholds for solid inert waste[a] TC (mg/kg)	Thresholds for solid inert waste[a] ASLP (mg/L)	Drinking water standard[b] (mg/L)	Hazardous waste designation (mg/L)	TC_{RG} TC_{RP} TC_{TDA} (mg/kg)	$ASLP_{RG}$ $ASLP_{RP}$ $ASLP_{TDA}$ (pH = 5) (mg/L)	$ASLP_{RG}$ $ASLP_{RP}$ $ASLP_{TDA}$ (pH = 9.2) (mg/L)
Antimony	75	1	0.006	—	<7[c]	<0.15[c]	0.2 0.2 <0.15
Arsenic	500	0.35	0.05	5.0	<4[c]	<0.05[c]	<0.05[c]
Barium	6,250	35	2.0	100	18 39 1	0.2 0.2 0.03	0.1 0.03 0.03
Beryllium	100	0.5	0.004	—	<1[c]	<0.01[c]	<0.01[c]
Boron	15,000	15	—	—	<3[c]	<0.2[c]	—[c]
Cadmium	100	0.1	0.005	1.0	<0.4 1 <0.4	<0.01[c]	<0.01[c]
Chromium	500	2.5	0.1	5.0	8 12 <1	<0.01[c]	<0.01[c]
Copper	5,000	100	1.3	—	26 23 19	0.04 0.02 0.3	0.04 0.03 0.02
Lead	1,500	0.5	0.015	5	20 13 2	0.04 <0.03 <0.03	<0.03[c]
Mercury	75	0.05	0.002	0.2	<0.1[c]	—[c]	—[c]
Molybdenum	1,000	2.5	—	—	<1[c]	<0.03[c]	<0.03[c]
Nickel	3,000	1	—	—	14 3 <1	<0.02[c]	<0.02[c]
Selenium	50	0.5	0.05	1.0	<2[c]	<0.12[c]	<0.12[c]
Silver	180	5	0.05	5.0	<1[c]	<0.05[c]	<0.05[c]
Zinc	35,000	150	—	—	100 51 2,300	1 0.9 3	0.07 0.06 0.3
Tin	2.5	0.05	—	—	2 1 <1	<0.05[c]	<0.05[c]

[a]Data from EPA (2009).
[b]Data from EPA (1999).
[c]One value for TC or ASLP means that TC_{RG}, TC_{RP}, and TC_{TDA} or $ASLP_{RG}$, $ASLP_{RP}$, and $ASLP_{TDA}$ have the same value for all three materials.

Particle Size Distribution

The PSDs of the blends are presented in Fig. 6, together with the upper and lower gradation limits of Class 4 aggregates based on VicRoads (2013). The PSD curves showed that the blends fell within the Class 4 gradation on the coarse side (>2.36 mm); however, they were slightly outside the lower limit on the fine side (<2.36 mm).

Compaction Properties Using Different Techniques

This section provides results and discussions on different compaction procedures, including the standard Proctor (ASTM-D698, ASTM 2012), determination of maximum/minimum density (ASTM-D4254, ASTM 2016b; ASTM-D4253, ASTM 2016a), and SRT procedure.

The OMC and MDD based on the standard Proctor method for Blends 1, 2, 3, and 4 are shown in Fig. 7. The MDDs of Blends 1, 2, and 4 were close (13.6 kN/m^3 as an average); however, the MDD of Blend 3 was noticeably lower than the other blends. This could be attributed to the fact that Blend 3 had the lowest RG content with a relatively high specific gravity and the highest TDA content with a relatively low specific gravity. The maximum and minimum densities of each blend were determined to be (13.8 kN/m^3, 10.2 kN/m^3), (14.1 kN/m^3, 10.8 kN/m^3), (12.7 kN/m^3, 10.1 kN/m^3), and (15.0 kN/m^3, 10.5 kN/m^3) for Blends 1, 2, 3, and 4, respectively, as also presented in Table 3.

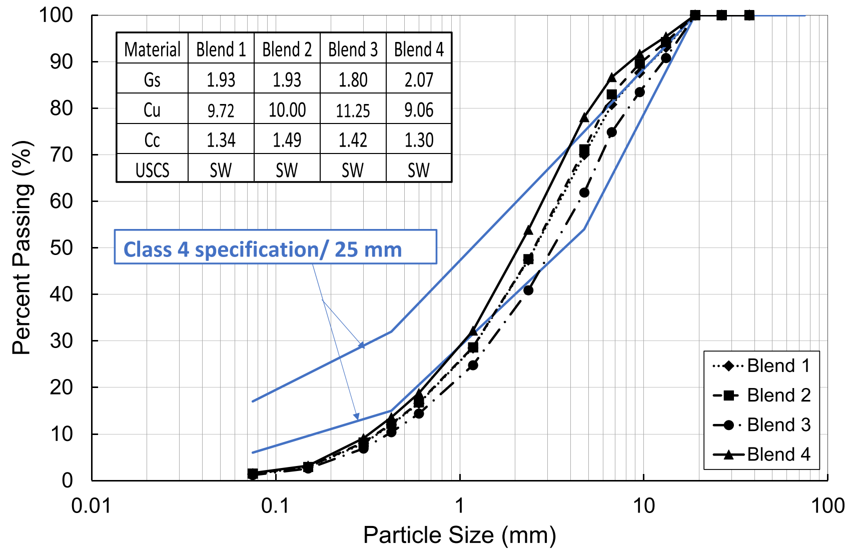

Fig. 6. PSD of the four blends.

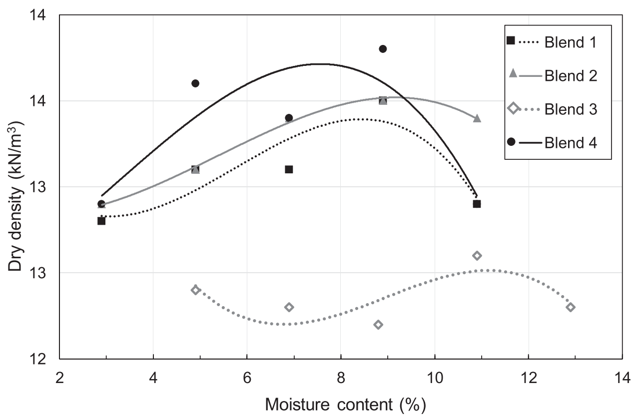

Fig. 7. Standard Proctor compaction results for Blends 1, 2, 3, and 4.

In the SRT procedure, initially recycled blends at the as-received moisture content of 2.3% were dropped from different heights to reach a DD corresponding to the RD ≥ 80%. Relative densities over 80% were reported to correlate with relative compactions greater than 95% (Look 2014), which is typically the minimum required density for fill earthworks. Granular soils with a RD greater than 80% fall in the category of dense to very dense soils that are known to have a lower risk of subsidence (Kimmerling 2002). Using the maximum and minimum densities and the density achieved through the standard Proctor and SRT procedures, the RD of each compacted sample was determined and is provided in Table 3.

Table 3 lists the MDDs obtained through the SRT procedure at MC_i of 2.3% (as-received) and the HD of 2,000 mm as 12.2, 11.5, 10.8, and 12.9 kN/m^3 for Blends 1, 2, 3, and 4, respectively. None of the relative densities reached the RD of 80% at the MC_i of 2.3%. Thus, a moisture content greater than typical as-received MCs was required to achieve the RD ≥ 80%.

The relationships between the DD and the post-test moisture content (MC_p) at different HDs were plotted for Blends 1, 2, 3, and 4 and are illustrated in Figs. 8–11, respectively. In these plots, the standard Proctor compaction curves are also presented for comparison. The data labels in Figs. 8–11 show the MC_i percentages, while the x axes correspond to the MC_p.

Figs. 8–11 show that for a constant HD, the value of DD increased as MC_p increased. For MC_is greater than 12% after dropping, the water drained from the sample and resulted in a MC_p between 9% and 12.7%. As an example, in one of the tests, a Blend 4 sample was prepared at a moisture content of 18% and dropped from the HD of 2,000 mm. It was left in the mold for 15 min until no further drainage occurred, and the MC_p was measured to be 9.7%. Therefore, once the MC_i became greater than 12%, the compaction curve moved toward the drier side of the plot, and, thus, the presence of two DDs for the same MC_p. The lower DD corresponded to the lower MC_i with no drainage ($MC_i = MC_p$), and the higher DD corresponded to the higher MC_i, which was reduced through drainage after compaction to reach the MC_p.

It is important to note that at a constant HD, for $MC_i > 12\%$ where drainage occurred after dropping, the corresponding MC_p was less than the MC_i where no drainage occurred after dropping ($MC_i = MC_p$). For example, in Fig. 11 at a HD of 2,000 mm and moisture content of 11.1%, no drainage occurred after dropping. However, at a moisture content of 18%, the water drained, reaching the moisture content of 9.7% (less than 11.1%). This was due to the fact that the total dry mass of the dropped particles for the sample with a moisture content of 11.1% was lower than that of the sample with 18% moisture content, resulting in a higher density for the sample with the MC_i of 18%. In other words, the void ratio of the blend with 11.1% moisture content was higher in which the water was kept in the voids. However, the water in the blend with 18% moisture content was forced to drain as the void ratio was lower, and, consequently, the resultant moisture content was less than 11.1%.

Figs. 8–11 also show that as the HD increased, at a constant MC, the DD increased, and as expected, the MC_p decreased as the HD increased. The increase in the HD from 1,500 to 2,000 mm led to an increase in the DD for blends with low MC_i. Once the MC_i became close to 15% or higher, the change in DD became negligible. For Blend 4, the change in the HD did not affect the DD even for low MC_i ranges.

The SRT compaction results revealed that the OMC and MDD in this method of compaction were achieved by dropping the samples from the HD of 2,000 mm at MC_is ≥ 15%. The OMC and MDD for Blends 1, 2, 3, and 4 were determined to be (18%, 13.0 kN/m^3), (15%, 13.5 kN/m^3), (15%, 11.3 kN/m^3), and (18%, 14.0 kN/m^3), respectively. The values of MC_p were 9.2, 9.7, 10.3, and 9.7 for Blends 1, 2, 3, and 4, respectively.

Table 3. Results obtained through the compaction procedures of this research

Compaction method	Parameter	Blend 1	Blend 2	Blend 3	Blend 4
Max/min density	Maximum density ASTM-D4253 (kN/m^3)	13.8	14.1	12.7	15.0
	Minimum density ASTM-D4254 (kN/m^3)	10.2	10.8	10.1	10.5
Standard Proctor (SP)	Estimated MDD (kN/m^3)	13.4	13.6	12.5	13.7
	Estimated OMC (%)	8.50	9.50	11.00	7.9
	Relative density (%)	91.5	88.0	93.7	77.8
Sand-raining technique (SRT)	MDD (kN/m^3) at MC$_i$ = 2.3% and HD = 2,000 mm	12.2	11.5	10.8	12.9
	Relative density (%)	62.8	26.1	31.5	62.0
	Estimated MDD (kN/m^3) at MC$_i$ and HD:	13.0	13.5	11.3	14.0
	HD (mm)	2,000	2,000	2,000	2,000
	MC$_i$ (%)	18.0	15.0	15.0	18.0
	MC$_p$ (%)	9.2	9.7	10.2	9.7
	Relative density (%)	82.5	85.5	52.0	83.3
	Percentage of (MDD$_{SRT}$/MDD$_{SP}$)	97.0	99.3	90.4	102.2

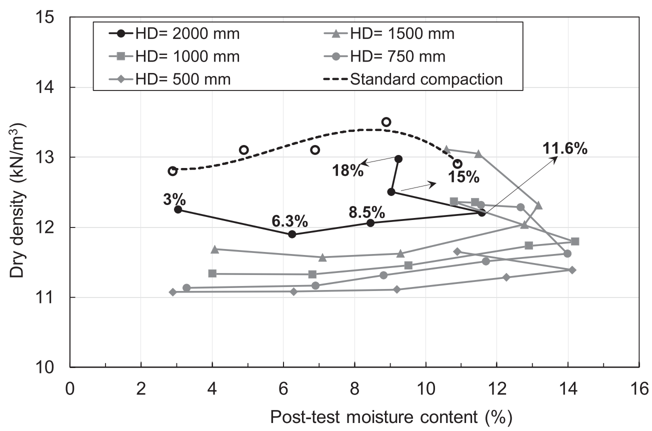

Fig. 8. Plot of DD versus MC at various HDs for Blend 1.

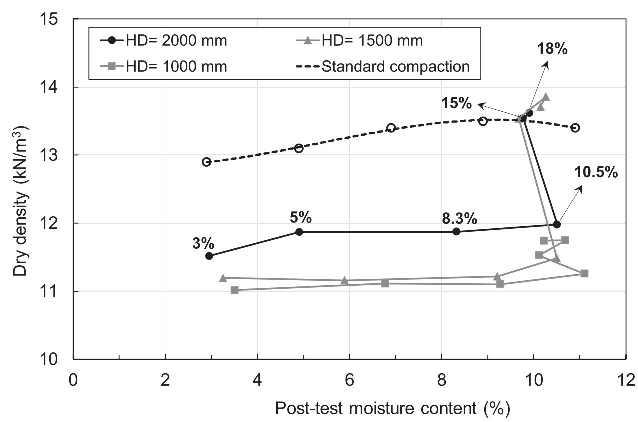

Fig. 9. Plot of DD versus MC at various HDs for Blend 2.

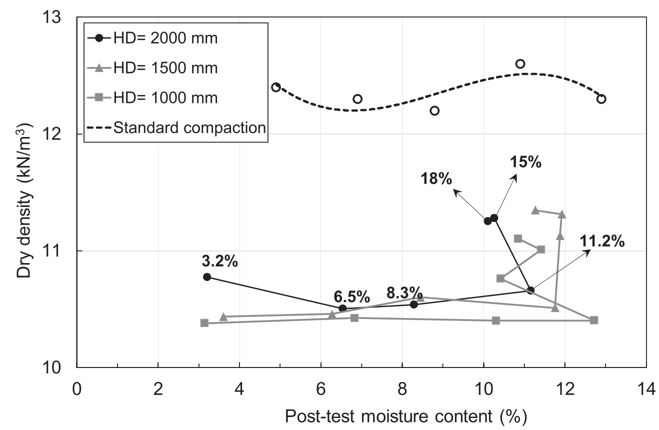

Fig. 10. Plot of DD versus MC at various HDs for Blend 3.

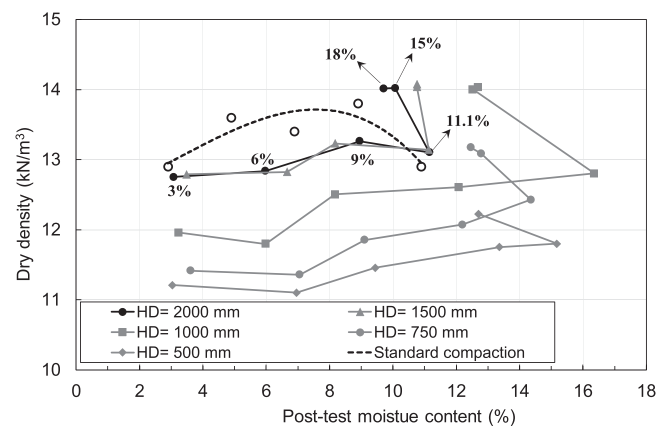

Fig. 11. Plot of DD versus MC at various HDs for Blend 4.

The dry densities obtained through the SRT compaction for Blends 1, 2, and 4 (Table 3) show that a density comparable to MDD of standard Proctor can be achieved at the HD of 2,000 mm. The relative densities with respect to maximum–minimum density test results (ASTM-D4254, ASTM 2016b; ASTM-D4253, ASTM 2016a) for Blends 1, 2, and 4 were 82.5%, 85.5%, and 83.5 (all >80%). The percentage ratio of MDD obtained from the SRT method to that achieved from the standard Proctor compaction (MDD$_{SRT}$/MDD$_{SP}$) were 97%, 99%, and 102.2% for Blends 1, 2, and 4, respectively. The RD of Blend 3 was 52%, which was significantly lower than other blends. Therefore, Blend 3 was deemed unsuitable for backfilling as it would not achieve the required density by only dropping from the top of the excavated trench without requiring an additional compactive effort. This lower RD of the backfilling material can lead to greater potential for postconstruction settlements.

Compressibility Properties

For further evaluation of the selected Blends 1, 2, and 4, the modified one-dimensional oedometer test was carried out to compare the stress–strain responses. The samples were prepared at the OMC and MDD achieved from the SRT compaction. Blends 1, 2, and 4 were prepared at the moisture contents equivalent to their MC_p being 9.2% for Blend 1 and 9.7% for Blends 2 and 4. The samples were placed into the mold in three layers to a total height of 75 mm to achieve dry densities of 13.0, 13.5, and 14.0 kN/m^3 for Blends 1, 2, and 4, respectively. Based on the modified oedometer results, the axial stress–strain relationship was plotted and is illustrated in Fig. 12. This figure shows that the total axial strains achieved in Blends 2 and 4 were lower than those of Blend 1 under the range of stresses applied from 6 to 200 kPa. Blends 2 and 4 were thus selected as the two superior blends to be further investigated. Blends 2 and 4 showed minor differences in axial strains and were selected as optimum mix designs due to their lower compressibility.

Discussion on the Selection of MCs for Construction Purposes

Results presented in the previous sections showed that in order to achieve the MDD in the SRT compaction, a MC_i of 15% or greater was required. Preparing blends with such high moisture contents, which are higher than the field capacity of the blends, may result

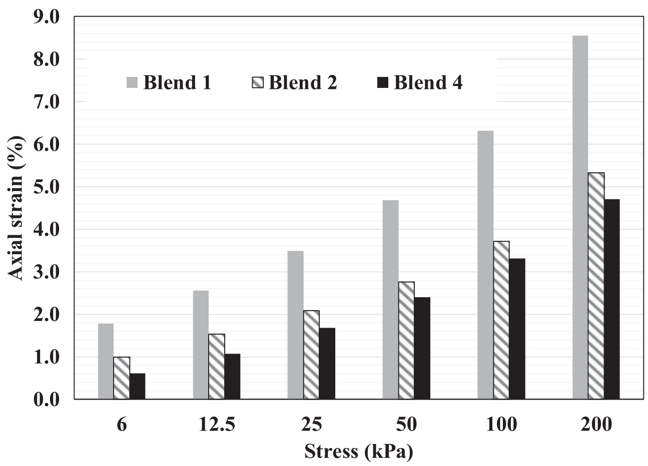

Fig. 12. Axial strain–stress relationships for Blends 1, 2, and 4 at the OMC and MDD.

in excess water ingress into the natural ground and potentially cause settlements or subsidence. On the other hand, considering Figs. 8–11, densities achieved through the SRT compaction showed that the blends may not achieve a satisfactory density if mixed with a moisture content close to their field capacity. Dropping Blends 2 and 4 prepared at the moisture content of about 9.7% from the height of 2 m resulted in dry densities of 12.0 and 13.3 kN/m^3, respectively, as shown in Figs. 9 and 11.

It should be noted that the density achieved through the SRT compaction is the loosest state of the densified blends. During the backfilling process, the surcharge of the upper layers results in further compaction of the bottom layers. In addition, the top layers of the backfilled area, where compaction quality control is possible, are typically further densified using typical conventional field techniques, such as compaction using the excavator compaction plate.

Fig. 13(a) demonstrates a schematic elevation view of a 4.5–5.5-m deep excavated trench to be backfilled with the high-quality crushed rock at the embedment zone (1 m), blends of RG, RP, and TDA at the recycled material backfill zone (3–4 m), and the site-won soils at the surface layer (0.5 m). Fig. 13(b) shows an excavated trench for sewer pipelines at Melbourne, Australia, where the 1-m embedment zone is backfilled with crushed rock. Fig. 13(c) shows an excavator compaction plate, densifying the surface layer that consists of site-won soils. Considering the preceding discussions, it is expected that the final density of the blends falls between the DD achieved at MC_i of 9.7% and those achieved at $MC_i \geq 15\%$. Therefore, further compressibility assessment was carried out on samples prepared at the moisture content of 9.7% and a density lower than the MDD achieved through SRT compaction.

Compressibility properties of Blend 2 were further assessed by preparing samples at (9.7%, 12.0 kN/m^3), (9.7%, 12.5 kN/m^3), and (9.7%, 13.0 kN/m^3) to be compared with a sample prepared at MDD of SRT (9.7%, 13.5 kN/m^3). In addition, Blend 4 was prepared at the moisture content of 9.7%, and the DD of 13.3 kN/m^3 was to be compared with a sample prepared at the moisture content of 9.7% and MDD of SRT (14.0 kN/m^3).

For Blend 2, the void ratio-log (σ) and axial strain–stress relationships were drawn as shown in Fig. 14. Fig. 14(a) shows that the initial void ratio increased as DD decreased. Nevertheless, the change in axial strains obtained due to imposed pressure up to 50 kPa was minor for blends prepared at the DD of 12.5, 13.0,

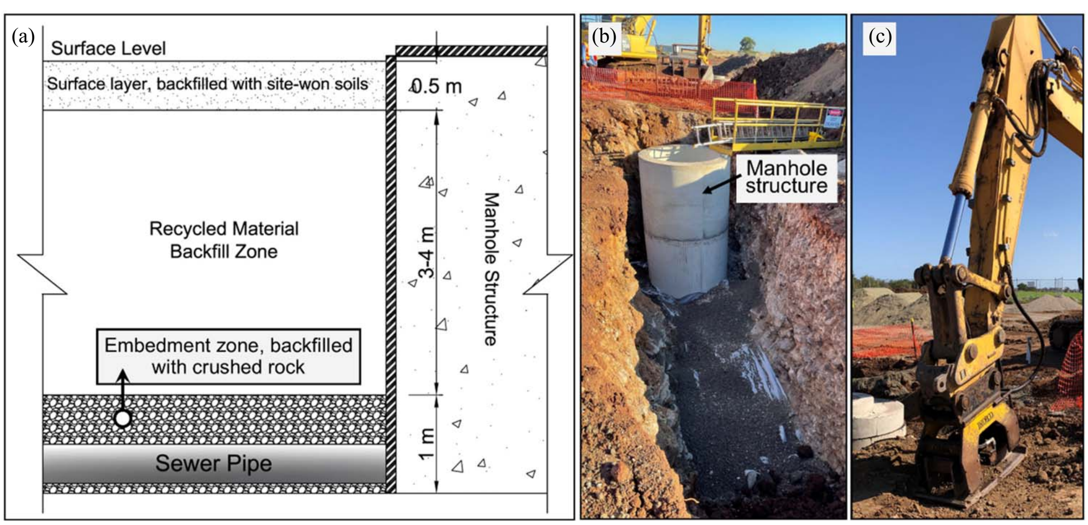

Fig. 13. Images of (a) proposed elevation view of an excavated trench; (b) an excavated trench for sewer pipelines in Melbourne, Australia; and (c) an excavator compaction plate. [Images (b and c) by Ehsan Yaghoubi.]

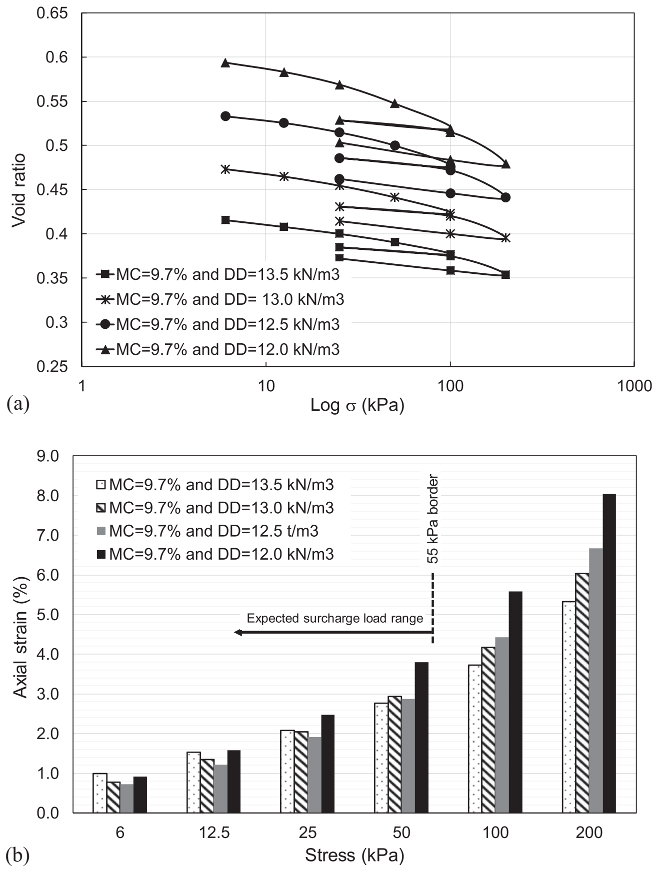

Fig. 14. Plots of (a) void ratio-log (σ); and (b) axial strain–stress relationship for Blend 2 at MC_p and $DD \leq MDD$.

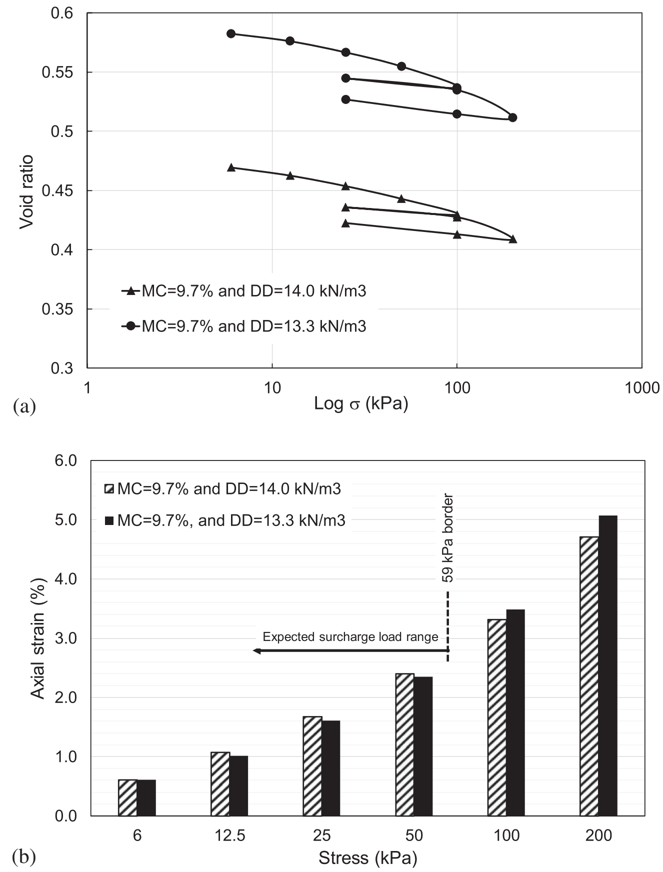

Fig. 15. Plots of (a) void ratio-log (σ); and (b) axial strain–stress relationship for Blend 4 at MC_p and $DD \leq MDD$.

and 13.5 kN/m^3 [Fig. 14(b)]. Assuming a maximum density of 14.1 kN/m^3 (ASTM-D4253, ASTM 2016a) and a depth of 4 m [as shown in Fig. 13(a)], the maximum surcharge at the bottom of the backfilled area is estimated to be 55 kPa. The axial strain obtained by loading Blend 2 samples prepared at the DD of 12.0 kN/m^3 was considerably higher than that of other blends [Fig. 14(b)]. As discussed previously, the surcharge from the top layer, together with additional compactive effort imposed by the excavator, is expected to increase the DD from 12.0 kN/m^3 to at least 12.5 kN/m^3. The axial strain shows a relatively small difference for Blend 2 samples prepared at the field capacity moisture content (9.7%), and dry densities of 12.5, 13.0, and 13.5 kN/m^3.

Fig. 15(a) shows the void ratio-log (σ) plot for Blend 4. In this plot, the sample prepared at the moisture content of 9.7% and the DD of 13.3 kN/m^3 started from a void ratio (0.59) higher than the void ratio of the sample prepared at the moisture content of 9.7% and DD of 14.0 kN/m^3 (0.47). Despite the difference in the initial void ratios, the change in the axial strain between the two Blend 4 samples under a pressure less than 100 kPa was relatively small [Fig. 15(b)]. The difference in axial strain between the loosest and densest state of the compacted Blend 4 was significant when subjected to a pressure greater than 100 kPa. By referring to Fig. 13, the bottom of the recycled material backfilled zone is at a depth of 4 m and assuming the maximum density of Blend 4 (15.0 kN/m^3), the maximum vertical stress due to the surcharge of the layers was calculated to be 59 kPa, which was significantly lower than 100 kPa. Consequently, despite achieving a lower density (13.3 kN/m^3) compared with the MDD of SRT compaction, it is expected that a negligible difference in axial strain be exhibited due to the sample being prepared at a moisture content lower than the OMC. It should be noted that due to the granular nature of the blends, a great proportion of the deformation is expected to occur during the construction and unlike clay, consolidation settlement is not expected.

Based on the preceding discussions, Blend 2 (MC = 9.7%, DD = 12.5 kN/m^3) and Blend 4 (MC = 9.7%, DD = 13.3 kN/m^3) were proposed as the optimum blends for backfilling of the excavated trenches.

Migration of Fines

To investigate the effect of sample moisture content and the HD on the amount of settlement achieved on the backfilled trench through precipitation, two different moisture contents and two different HDs were considered for testing. The first segregation test was carried out on Blends 2 and 4, prepared at the as-received moisture content of 2.3% and dropped from the height of 600 mm. This HD was found to be the typical height that excavator operators dump materials into the trench based on several random field observations. Consequently, at MC = 2.3% and HD = 600 mm, DDs of 11.0 and 11.2 kN/m^3 were achieved for Blends 2 and 4, respectively. In the second test, samples were prepared at MC = 9.7% and were dropped from a height of 2,000 mm, achieving the DDs of 12.5 and 13.3 kN/m^3 for Blends 2 and 4, respectively.

These results, as summarized in Table 4, indicated that a significant reduction of potential settlements was obtained due to an increase in the sample moisture content (from 2.3% to 9.7%) and the HD (from 600 to 2,000 mm). The total axial strain through the segregation testing decreased from 13.7% to 0.07% for Blend 2 and from 17.3% to 0.03% for Blend 4. The reason for this considerable strain reduction is that saturating the noncohesive sample

Table 4. Settlement and axial strain results of the segregation tests

Blend	MC (%)	DD (t/m^3)	HD (mm)	Ave settlement (mm)	Axial strain (%)	Field capacity (%)
2	2.3	1.10	600	41	13.7	8.2
	9.7	1.25	2,000	0.2	0.07	9.3
4	2.3	1.12	600	52	17.3	9.0
	9.7	1.33	2,000	0.08	0.03	9.5

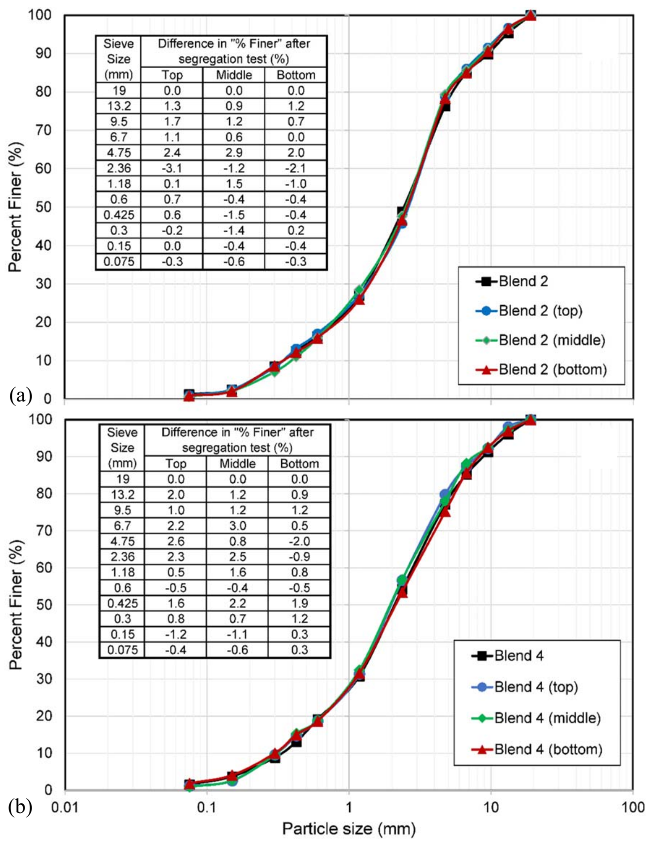

Fig. 16. Effect of the migration of fine particles on the PSD of (a) Blend 2; and (b) Blend 4.

with low moisture content and DD (thus, having large voids) can result in water carrying the finer particles into air voids in the direction of gravity. This leads to rearrangement of the particles toward more densification, and, hence, the sample exhibits higher settlements. The potential for such settlements decreases as the initial density and moisture content increase, mainly due to the presence of smaller and lower voids.

Axial strains achieved through the segregation tests on Blends 2 and 4 prepared at the moisture content of 9.7% were close to zero (0.07% and 0.03%, respectively). This can be explained using the findings of Tripathy et al. (2002) and Islam (2015), which showed that the OMC achieved in the standard Proctor compaction method produces an approximate degree of saturation of 85%. The segregation test samples were prepared at an MC of 9.7%, which was close to OMC obtained through the standard Proctor compaction for Blend 2 (9.5%) and higher than that of Blend 4 (7.9%). This meant that Blend 4 was prepared at an MC closer to the saturation condition, which led to the expectation that the ability to segregate was even less than that of Blend 2. At such a high degree of saturation, the surface tension on particles caused by moisture is expected to reduce the potential for the segregation of particles.

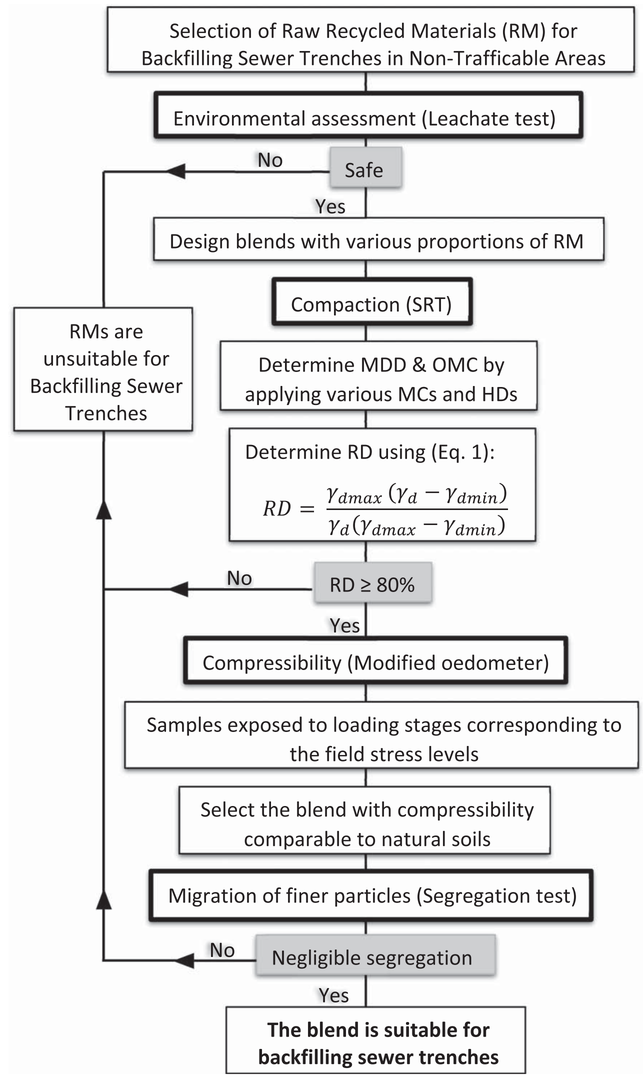

Fig. 17. Design chart for the selection of suitable blends of recycled aggregates.

At the end of the segregation testing, the sample was separated into three layers, namely top, middle, and bottom layers. These layers were dried in the drying oven at a temperature of 60°C for 48 h and the average moisture contents, which represented the field capacity, were measured as presented in Table 4. These moisture contents were close to post-test MCs obtained from the SRT procedure. For Blends 2 and 4 prepared at MC = 9.7%, each layer was sieved to investigate the migration of fine particles. Fig. 16 shows the PSD of the top, middle, and bottom portions of the segregation test on Blend 2 and 4 samples in comparison with the PSD of the pre-test Blend 2 and 4 samples. The difference between the PSDs presented in Fig. 16 is no greater than 3% for any of the sieve sizes, showing that a negligible migration of fines (if any) occurred. This was expected as no considerable settlement was recorded after simulating the precipitation.

To investigate the potential for longer-term settlement, the segregation test was repeated for Blends 2 and 4 prepared at the moisture content of 9.7% and DDs of 12.5 and 13.3 kN/m^3, respectively. This time, samples were left for a month inside the test cylinder, and the settlements were monitored. During this time, the test setup was sealed using cellophane sheets to minimize the evaporation of water. At the end of the month, no further settlement was recorded after the first 1 h from the start of the test, showing that a negligible longer-term settlement was to be expected.

Proposed Chart for Determining the Optimum Mix Design

The procedure to select a blend of recycled materials comprising RG, RP, and TDA that are environmentally safe, exhibit self-compacting properties and show suitable mechanical characteristics for backfilling sewer pipeline trenches in nontrafficable areas is demonstrated in Fig. 17. The procedure can be summarized in the following steps:

(1) Evaluate the potential environmental hazards of the individual recycled materials by conducting leachate tests. If the test results meet the requirements that the recycled materials can safely be used as fill materials, a series of blends including different proportions of recycled materials can be prepared.
(2) Compact the prepared blends using the SRT at various moisture contents and HDs to determine the OMC and the MDD.
(3) Determine the RD for each blend by using the MDD achieved by the SRT, plus maximum and minimum densities obtained following the ASTM-D4254 (ASTM 2016b) and ASTM-D4253 (ASTM 2016a) procedures.
(4) Accept blends that achieved the RD ≥ 80%, to be further assessed for compressibility.
(5) The compressibility of the accepted blends is assessed by carrying out the modified oedometer test with stress levels adopted based on the estimated overburden pressure over the pipeline. The blends that exhibit low compressibility are accepted to be further assessed for the potential of the migration of finer particles.
(6) The potential for the migration of finer particles is investigated through the segregation test. An inconsiderable segregation value (up to 3% difference in fines for each sieve size in the PSD results) indicates that the blend accepted in Step 5 can be considered as the optimum blend and suitable for backfilling sewer pipe trenches in nontrafficable areas.

Conclusions

Blends of recycled materials including RG, RP, and TDA were experimentally studied to investigate the feasibility of replacing conventional backfill material with these alternative blends. In addition to environmental testing, three application-specific testing procedures were used including the SRT, modified oedometer test, and segregation test. These testing schemes were developed or modified to simulate the backfilling process of excavated trenches, stress–strain behavior under potential loading conditions, and potential settlement and migration of fines as a result of rain events, respectively. The following conclusions were made based on this study:

(1) The environmental risks of using RG, RP, and TDA in backfilling sewer trenches in terms of metals leaching into the soil, water streams, the groundwater were negligible.
(2) The DD achieved by the SRT compaction increased as the moisture content and the HD increased with decreased tire content decreased.
(3) The MDD was achieved when a blend was prepared at a moisture content ≥ 15% and by dropping the blends from a height of 2,000 mm.
(4) For the same post-test moisture content, two dry densities were achieved through the SRT compaction. The greater of the two belonged to the samples prepared with MC_i obtained through the SRT compaction approached the corresponding values obtained from the standard Proctor compaction. In both compaction methods, relative densities greater than 80% were achieved, which is known to offer a lower risk of subsidence in backfilled trenches.
(5) Blends 2 and 4 were deemed suitable for backfilling of trenches located in nontrafficable areas, exhibiting less compressibility response and achieving greater RD.
(6) By simulating the precipitation, in Blends 2 and 4, a negligible potential for the migration of finer particles and associated long-term settlements was observed.

The following approach is proposed for the construction of trial sites for practical evaluations and real-life feasibility investigations:

(1) Production of the mixtures: in smaller-scale applications, the three raw recycled materials can be placed in a commercially available large steel waste disposal bin. An excavator bucket with known volume can be used to add the volumetric proportions required. The predetermined amount of water can be added using a water truck equipped with discharge gauges. The raw materials, with water added, can next be mixed using a smaller excavator bucket inside the large bin until a uniform mixture is observed. In larger-scale projects, the mixing procedure can be undertaken in a typical batching plant.
(2) Trench backfilling procedure: the batched mixture can be loaded using an excavator. Next, the excavator bucket can be positioned over the trench alignment and raised as high as practical with the contents dumped into the trench from a height of at least 2 m. Guidance and supervision is required at the final placement stages, to ensure that the mixture is dropped from as high as possible to maintain the 2-m drop height.

This research aimed to propose a testing methodology for determining the mix design of blends of 100% recycled materials that are suitable for backfilling deep sewer trenches in nontrafficable areas where quality control and traditional compaction methods are challenging. The outcomes of this research are expected to promote sustainable construction approaches and the utilization of recycled geomaterials in geotechnical projects.

The construction and instrumentation of a full-scale site has been completed as part of the next stage of this study where monitoring of settlements and moisture variations is being undertaken.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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References

Al-Taie, A., M. Disfani, R. Evans, and A. Arulrajah. 2020. "Effect of swell–shrink cycles on volumetric behavior of compacted expansive clay stabilized using lime." *Int. J. Geomech.* 20 (11): 04020212. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001863.

AS (Australia Standards). 1997. *Wastes, sediments and contaminated soils—Preparation of leachates—Bottle leaching procedures*. AS4439. Sydney, Australia: AS.
ASTM. 2012. *Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))*. ASTM-D698. West Conshohocken, PA: ASTM.
ASTM. 2010. *Standard test methods for specific gravity of soil solids by water pycnometer*. ASTM-D854. West Conshohocken, PA: ASTM.
ASTM. 2011a. *Standard test method for one-dimensional consolidation properties of soils using incremental loading*. ASTM-D2435/D2435M. West Conshohocken, PA: ASTM.
ASTM. 2011b. *Standard practice for classification of soils for engineering purposes (unified soil classification system)*. ASTM-D2487. West Conshohocken, PA: ASTM.
ASTM. 2016a. *Standard test methods for maximum index density and unit weight of soils using a vibratory table*. ASTM-D4253. West Conshohocken, PA: ASTM.
ASTM. 2016b. *Standard test methods for minimum index density and unit weight of soils and calculation of relative density*. ASTM-D4254. West Conshohocken, PA: ASTM.
BOEBC (Board of Education of British Columbia). 2016. "Operations policy and planning Committee Meeting on January." Accessed April 12, 2021. https://www.sd61.bc.ca/board-of-education/meetings/.
Davies, J. P., B. A. Clarke, J. T. Whiter, and R. J. Cunningham. 2001. "Factors influencing the structural deterioration and collapse of rigid sewer pipes." *Urban Water* 3 (1–2): 73–89. https://doi.org/10.1016/S1462-0758(01)00017-6.
EPA. 1999. *National primary drinking water standards*. EPA-F-94-001. Washington, DC: EPA.
EPA. 2009. *Solid industrial waste hazard categorisation and management*. Industrial Waste Resource Guidelines. Publication No. IWRG 631. Melbourne, VIC, Australia: EPA.
Fauzi, A., Z. Djauhari, and U. J. Fauzi. 2016. "Soil engineering properties improvement by utilization of cut waste plastic and crushed waste glass as additive." *Int. J. Eng. Technol.* 8 (1): 15–18. https://doi.org/10.7763/IJET.2016.V8.851.
Gade, V. K., and S. M. Dasaka. 2016. "Development of a mechanized traveling pluviator to prepare reconstituted uniform sand specimens." *J. Mater. Civ. Eng.* 28 (2): 04015117. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001396.
Gajjar, P., K. van der Vaart, A. R. Thornton, C. G. Johnson, C. Ancey, and J. M. N. T. Gray. 2016. "Asymmetric breaking size-segregation waves in dense granular free-surface flows." *J. Fluid Mech.* 794: 460–505. https://doi.org/10.1017/jfm.2016.170.
Gillemot, K. A., E. Somfai, and T. Börzsönyi. 2017. "Shear-driven segregation of dry granular materials with different friction coefficients." *Soft Matter* 13 (2): 415–420. https://doi.org/10.1039/C6SM01946C.
Harvey, R. R., and E. A. McBean. 2014. "Comparing the utility of decision trees and support vector machines when planning inspections of linear sewer infrastructure." *J. Hydroinf.* 16 (6): 1265–1279. https://doi.org/10.2166/hydro.2014.007.
Imteaz, M. A., A. Arulrajah, S. Horpibulsuk, and A. Ahsan. 2018. "Environmental suitability and carbon footprint savings of recycled tyre crumbs for road applications." *Int. J. Environ. Res.* 12 (5): 693–702. https://doi.org/10.1007/s41742-018-0126-7.
Islam, M. 2015. "A study of volumetric behaviour of compacted clayey soils in the void ratio, moisture ratio and net stress space." Thesis, Monash Univ., Faculty of Engineering, Dept. of Civil Engineering.
Karunarathne, A. N. 2016. "Investigation of expansive soil for design of light residential footings in Melbourne." Ph.D. thesis, Dept. of Civil and Construction Engineering, Swinburne Univ. of Technology.
Kimmerling, R. E. 2002. *Geotechnical engineering circular No. 6 shallow foundations*. FHWA-SA-02-054. Washington, DC: Federal Highway Administration. Office of Bridge Technology.
Li, J., J. Zou, P. Bayetto, and N. Barker. 2016. "Shrink-swell index database for Melbourne." *Aust. Geomech. J.* 51 (3): 61–76.
Lindsey, T. C. 2011. "Sustainable principles: Common values for achieving sustainability." *J. Cleaner Prod.* 19 (5): 561–565. https://doi.org/10.1016/j.jclepro.2010.10.014.
Look, B. G. 2014. *Handbook of geotechnical investigation and design tables*. Boca Raton, FL: CRC Press.
MRWA (Melbourne Water Retail Agencies). 2013. *Backfill specification-specification 04-03.2*. Melbourne, VIC, Australia: MRWA.
NWC (National-Water-Commission). 2011. *Urban water in Australia: Future directions*. Canberra, Australia: ACT.
Qi, Y., B. Indraratna, and M. R. Coop. 2019. "Predicted behavior of saturated granular waste blended with rubber crumbs." *Int. J. Geomech.* 19 (8): 04019079. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001440.
Rajeev, P., and J. Kodikara. 2011. "Numerical analysis of an experimental pipe buried in swelling soil." *Comput. Geotech.* 38 (7): 897–904. https://doi.org/10.1016/j.compgeo.2011.06.005.
Rodriguez, N. M., and P. V. Lade. 2013. "True triaxial tests on cross-anisotropic deposits of fine Nevada sand." *Int. J. Geomech.* 13 (6): 779–793. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000282.
Tabaroei, A., S. Abrishami, and E. S. Hosseininia. 2017. "Comparison between two different pluviation setups of sand specimens." *J. Mater. Civ. Eng.* 29 (10): 04017157. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001985.
Thyagaraj, T., S. R. Thomas, and A. P. Das. 2017. "Physico-chemical effects on shrinkage behavior of compacted expansive clay." *Int. J. Geomech.* 17 (2): 06016013. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000698.
Tripathy, S., K. S. Subba Rao, and D. G. Fredlund. 2002. "Water content - Void ratio swell-shrink paths of compacted expansive soils." *Can. Geotech. J.* 39 (4): 938–959. https://doi.org/10.1139/t02-022.
van der Vaart, K., P. Gajjar, G. Epely-Chauvin, N. Andreini, J. M. N. T. Gray, and C. Ancey. 2015. "Underlying asymmetry within particle size segregation." *Phys. Rev. Lett.* 114 (23): 238001. https://doi.org/10.1103/PhysRevLett.114.238001.
VicRoads. 2013. *Section 815: Cementitious treated crushed rock for pavement subbase*. Kew, VIC, Australia: VicRoads.
WADER (Western Australia Department of Environment Regulation). 2015. *Background paper on the use of leaching tests for assessing the disposal and re-use of waste-derived materials*. Perth, Australia: WADER.
Wang, C., A. Deng, and A. Taheri. 2018. "Digital image processing on segregation of rubber sand mixture." *Int. J. Geomech.* 18 (10): 04018138. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001269.
Wartman, J., D. G. Grubb, and A. S. M. Nasim. 2004. "Select engineering characteristics of crushed glass." *J. Mater. Civ. Eng.* 16 (6): 526–539. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:6(526).
Yaghoubi, E., M. Yaghoubi, M. Guerrieri, and N. Sudarsanan. 2021. "Improving expansive clay subgrades using recycled glass: Resilient modulus characteristics and pavement performance." *Constr. Build. Mater.* 302: 124384. https://doi.org/10.1016/j.conbuildmat.2021.124384.

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