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Effects of stress history on compressibility characteristics of undisturbed landfill waste material

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ABSTRACT

An extensive set of experiments were conducted in this study to evaluate the impacts of different levels of loading and unloading on compressibility characteristics of landfill waste materials. To achieve this purpose, a large undisturbed waste sample with a diameter of 250 mm was collected from a landfill site, in Sydney. The collected sample was composed of mainly construction waste, decayed organic material, wood, metal, plastic, glass, paper, and cardboard. A large diameter Rowe cell setup was utilised to saturate the undisturbed sample followed by multi-stage unloading and reloading consolidation and creep tests, lasting approximately 330 days. The testing data on the landfill waste were used to determine the compression and recompression indices, as well as the coefficient of consolidation and creep index. These experimental results demonstrate that the compressibility parameters of the collected landfill material significantly depend on the loading history, and in particular, the over consolidation ratio. The findings revealed that the stress history of the waste material has a significant effect on the primary settlement and its rate as well as the long-term creep rate. Thus, it is inferred that the application of the preloading method can improve the compressibility parameters and significantly reduce the post-construction consolidation and creep settlement of landfills.

1. Introduction

The management of waste is probably one of the most crucial aspects of maintaining a healthy and sustainable environment. In order to achieve sustainability in the field of civil engineering, it is critical to point out that there are two principal approaches to this issue that can be considered. A first approach is to study the engineering behaviour of recycled aggregates to determine whether it would be feasible to reuse these aggregates in future projects. Another approach is the redevelopment of abandoned landfill sites.

Demolition waste material has been extensively researched as a recycling material for aggregates and construction materials. For example, the engineering behaviour of recycled concrete aggregates has been extensively studied [1–3]. A similar study investigated the possibility of reusing asphalt aggregates (demolished material) in transportation infrastructures [4]. Despite significant findings and ongoing efforts on reusing waste material, landfills remain the most common method for managing waste. For example, in Australia alone, there are more than 2800 regulated and unregulated landfill sites [5]. In recent decades, urban growth and metropolitan area expansion have resulted in many closed landfill sites located in or adjacent to cities. Indeed, there are numerous environmental and engineering challenges for construction over closed landfill sites, such as overall stability, non-uniform and excessive settlement, landfill failure, generation of toxic greenhouse gases (i.e. methane), contaminating leachate generation, and contamination of surrounding sites and water [6–9]. In the greater Sydney area alone, there are several transportation infrastructure megaprojects, which are being built over closed landfill sites, such as the Sydney Gateway interchange, Westconnex - St Peters interchange and Moorebank intermodal terminal.

Researchers in recent decades have studied various engineering and mechanical aspects of landfills. Since landfill waste materials may include significant voids, many researchers have extensively studied spatial variations of unit weight of landfill materials for various types of landfills via in-situ measurements [10–14]. The geotechnical behaviour of waste material and mechanisms of landfill settlement and the factors affecting settlement rates and magnitude were studied experimentally and numerically in many research studies [15–20]. Nonetheless, a more in-depth understanding of landfill short-term and long-term

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List of symbols

C_k	permeability change index
C_v	coefficient of consolidation
C_α	creep coefficient
e	void ratio of the soil
e_0	Initial void ratio
G_s	specific gravity
IVC	infinite volume controllers
k	coefficient of permeability
m_v	coefficient of volume compressibility
OCR	over-consolidation ratio
PVC	Pressure-volume controllers
v_0	initial specific volume $= 1 + e_0$
ω	water content
α	material constant value in Eq. (1)
β	material constant value in Eq. (3)
$\sigma_c^{'}$	pre-consolidation pressure
ψ/v_0	creep index
λ/v_0	compression index
κ/v_0	recompression index
ε_z	vertical strain $= \Delta H/H$

compressibility characteristics and utilising practical approaches for controlling and minimising settlement are necessary. Moreover, several past investigations assessed the effects of waste composition, confining pressure, sample disturbance, particle size, unit weight and biodegradation rate on mechanical characteristics of landfill materials, such as shear strength parameters [15,21–26].

One of the key challenges of constructing infrastructure on top of closed landfill sites is how to deal with a large settlement, which may continue over many years measured in decades. Numerous researchers [27–29] reported that extensive differential settlements were experienced by landfills subjected to surcharge, which could cause cracks on the landfill covering system. Indeed, a range of ground improvement techniques such as dynamic compaction, concrete injected columns, compaction using large impact roller, stone columns and surcharge preloading can be used for reducing and controlling post-construction settlement of structures built on closed landfill sites [30–35]. For instance, Mukherjee and Mishra [36] conducted a research on the effect of sand bentonite-glass fibre composite for landfill construction and discovered that the addition of fibres can enhance mechanical properties of this composite material.

Among the existing ground improvement techniques, surcharge preloading is known as one of the most common, economical and effective ground improvement techniques to reduce post-construction settlement of structures and improve bearing capacity of foundations on the weak ground [37–44]. In principle, when the applied surcharge on porous material exceeds the pre-consolidation pressure, pores compress notably, leading to improved shear strength and reduced compressibility of the ground. Thus, preloading would result in reduced primary and secondary settlements. Furthermore, in comparison to many other ground improvement techniques, utilising the preloading method on the landfill would have minimal impacts on the landfill liner and covering system since there would be no physical intrusion through the landfill in this technique. Few previous studies investigated the impact of preloading on improving landfill characteristics [45–47]. El-Sherbiny, et al. [45] evaluated the effect of preloading on the compressibility of the municipal solid waste and demolition waste material in a roadway project, while Al-Yaqout and Hamoda [46] conducted field studies to assess the response of organic waste landfills to preloading. Moreover, the study conducted by Lewis et al. [47], used 12 years of post-construction settlement monitoring data to compare effectiveness of dynamic compaction with preloading for landfill improvement.

Several researchers conducted one-dimensional consolidation/compression tests on disturbed or reconstituted landfill material to assess compressibility characteristics of collected waste [17,48–51]. In particular, Zekkos, et al. [49] investigated the response of large-scale reconstituted landfill material to compression from five different landfill sites at the site moisture condition. They concluded that waste composition and dry unit weight had significant effects on compressibility characteristics of landfill material. The study by Chen, et al. [52] estimated and reported the secondary compression of landfills as well as developed a numerical model and experimental apparatus to measure the settlement of waste samples. Besides, Fei and Zekkos [51] studied the influencing factors on the secondary compression of municipal solid waste (MSW) in the laboratory via bioreactor simulators. They assessed the impact of external vertical load, waste composition, total unit weight, and simulator size on long-term settlement response of MSW.

Moreover, the effects of test scale, stress level, waste segregation, and waste decomposition on the immediate compression and creep settlement of municipal solid waste were evaluated by Bareither, et al. [17] and Karimpour-Fard and Machado [53] conducted large-scale oedometer and triaxial tests on collected landfill material on the site moisture condition, which was partially saturated. They observed that due to significant mass loss as a result of biodegradation, the long-term compression parameters were significantly larger than the corresponding short-term parameters. They also reported that the obtained compressibility parameters from laboratory tests, which are generally short (often measured in weeks), were less than the corresponding values from long-term field measurements utilising installed benchmarks at the landfill sites (often measured in years). It should be noted that the vast majority of previous research studies, which investigated mechanical properties of landfill materials, were conducted on reconstituted samples [13,23,48,49,54,55]. However, many research studies reported that compressibility parameters of granular materials are significantly altered by sample disturbance, and thus samples reconstituted to the same density as in-situ yet does not represent the real parameters of the material, obtained from undisturbed sample or field testing [56–59]. Therefore, further studies on the compressibility characteristics of undisturbed landfill samples taken from site are deemed essential.

The aim of this study was to experimentally investigate the impacts of different loading and unloading conditions on the compressibility parameters of an undisturbed landfill sample. A large 250 mm diameter Rowe cell consolidation test was performed on waste material collected from a landfill site in Sydney, Australia. In this study, to assess consolidation and creep settlement characteristics of landfill waste material, an undisturbed waste sample was collected via a 250 mm diameter sampling tube from a closed landfill site in Sydney. Then using a 250 mm diameter hydraulic consolidation setup (Rowe cell), a series of incremental loading, unloading and reloading tests were conducted on the specimen. The multi-stage loading compression test was conducted on a 131 mm thick cylindrical landfill waste sample in order to determine the compression and recompression indices, as well as coefficient of consolidation and creep index. This study divided the consolidation test into four stages: initial loading, first unloading, reloading and second unloading. The specimen underwent a number of complementary tests, such as measurement of moisture content and organic content, particle size distribution, and composition determination. Since the creep settlement was recorded at each stage of the consolidation test, the total duration of these tests was nearly one year. The objectives of this research are: (i) determining waste composition and geotechnical properties through laboratory testing of the undisturbed specimen, (ii) evaluating the effects of stress history on compression and creep indices (saturated conditions), and (iii) providing experimental evidence regarding the use of preloading techniques to minimize post-construction deformations of landfill sites.

The planned laboratory experiments will help to address the gap in understanding how loading conditions affect the compressibility and creep behaviour of real heterogeneous solid waste samples collected from a closed landfill site. The results can provide guidance on improvement methods for closed landfill sites undergoing redevelopment.

2. Materials and experimental plan

The testing program involved three main stages: 1) collecting a large undisturbed waste sample from the closed landfill site using a custom-made Shelby tube, 2) laboratory characterisation of the waste composition and properties through visual inspection, sieving, and direct measurements, and 3) loading the undisturbed specimen in a large Rowe cell to conduct incremental consolidation and creep tests in the saturated conditions. The waste sample was subjected to staged loading up to 800 kPa and unloading cycles to evaluate the effects of stress history (preloading) on compressibility parameters. The custom-fabricated Shelby tube allowed minimally disturbed sampling of the heterogeneous waste material. Laboratory testing provided physical characterisation and stratification of the specimen. The programmed Rowe cell tests then assessed the waste's compression and creep characteristics under different loading conditions and over-consolidation ratios (OCR). Details of these testing methods are provided in the following sections.

2.1. Undisturbed landfill sample collection

The required landfill material sample was collected from a closed uncontrolled landfill site in Sydney (-33.865143, 151.209900), NSW Australia that was operational for 19 years from 1984 until closure and capping in 2003. The undisturbed sample was obtained from a depth of 3 m in an area containing mixed wood, plastic, construction and demolition waste materials. Over the 19-year span, the site had disposed mostly non-putrescible wastes such as soil, concrete, wood, metals, plastics, masonry rubble and other construction debris.

A special large-diameter custom-made steel U250 Shelby tube with a height of 200 mm, an internal diameter of 250 mm and a wall thickness of 12 mm was designed and manufactured for collecting an undisturbed sample from this landfill. The inner diameter of the Shelby tube was selected precisely equal to the diameter of consolidation Rowe cell setup available in the laboratory to ensure the sample could simply be extruded into the Rowe cell without a need for trimming since trimming could disturb landfill samples. Shelby tube edges were tapered with an angle of 30° for easier penetration into the landfill, as shown in Fig. 1. It should be noted that the 12 mm thickness of the Shelby tube wall was designed and deemed essential to ensure it would not buckle while penetrating the landfill waste with large particles. The sharp edge of the corer minimised disturbance caused by pushing it into the ground. In this study, tube edges were sharpened and reduced to 3 mm for better penetration. Considering the inner diameter of 250 mm, the sample disturbance ratio was estimated to be 2.4%, which was significantly less than the 10% limit recommended by Hvorslev [60].

To characterise the overall subsurface profile, sonic drilling was conducted at multiple locations across the site and more than 90 m of core samples were retrieved from three boreholes for analysis. Fig. 2 displays the variation in total unit weight, dry unit weight, and moisture content with depth from the collected sonic drilling samples from three boreholes (BH1, BH2, BH3) and three test pits (TP1, TP2, TP3). The undisturbed specimen for this study was collected from near the bottom of TP1 at a depth of 3 m. The observed variability is likely due to the heterogeneous nature of the loosely dumped waste fill. The mean total unit weight is in the range of 13–17 kN/m^3, while the mean dry unit weight is in the range of 8–12 kN/m^3. The mean moisture content varies between 20% and 50% along the depth. These in-situ unit weight measurements provide baseline values representative of the site's conditions prior to subsequent laboratory testing.

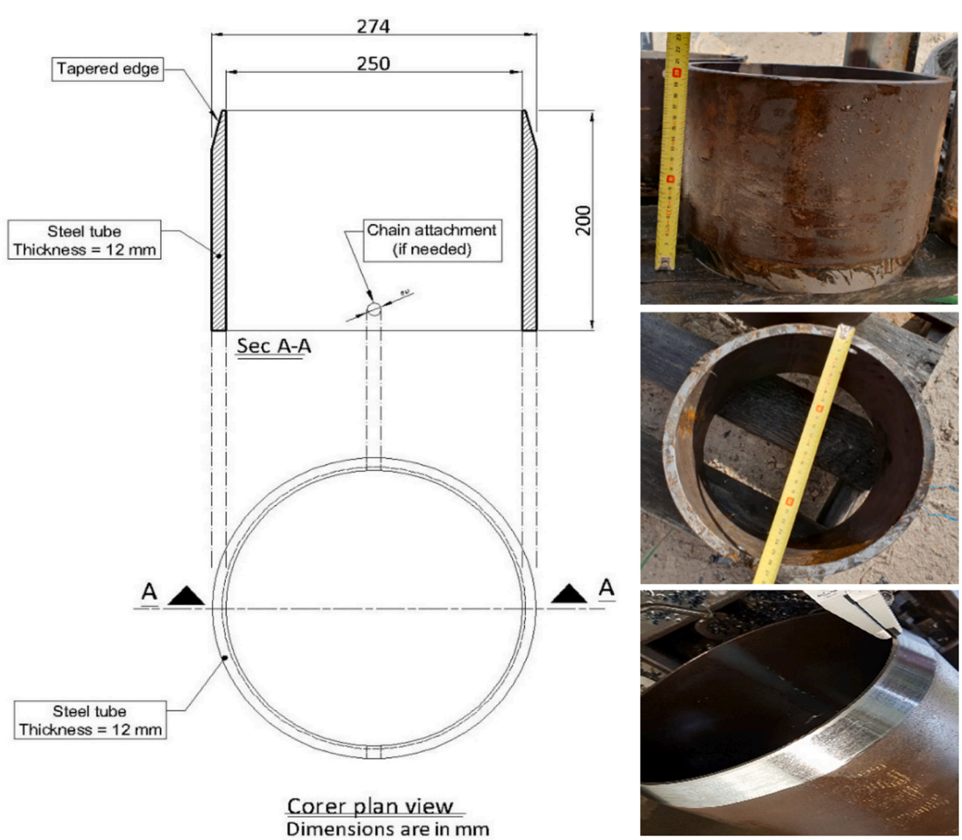


Fig. 1. Schematic diagram and pictures of designed push tubes.

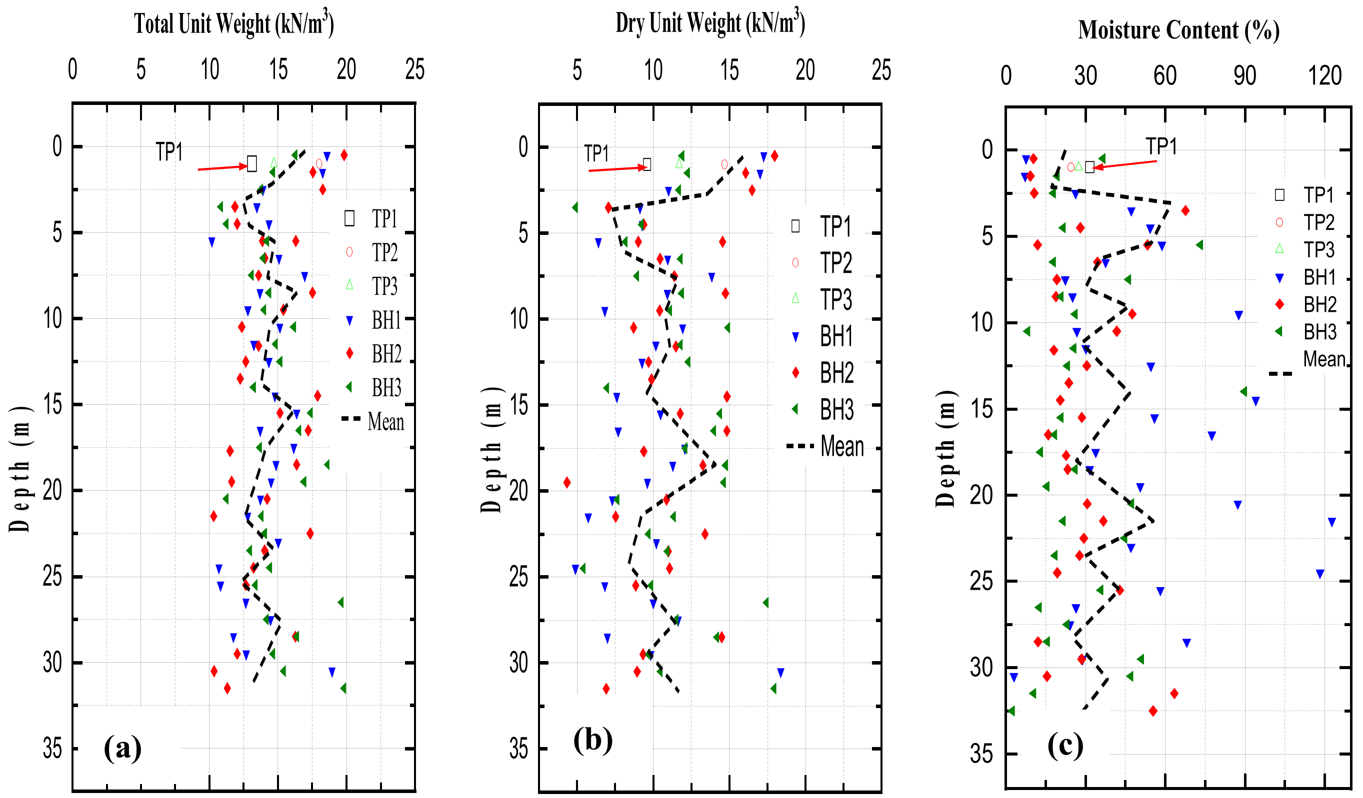


Fig. 2. Landfill properties profile with depth, (a) total unit weight, (b) dry unit weight and (c) moisture content.

After removing the covering layer of the landfill (two meters of sandy soil), in order to penetrate deeper and find intact waste sample, a 1 m deep test pit was excavated and from the bottom of the test pit, an undisturbed sample was collected. Fig. 3 illustrates the different stages of undisturbed sample collection from the landfill site. This large custom-made Shelby tube was advanced into the landfill using hydraulic push equipment. The large diameter and selected wall thickness of the tube minimised sampling disturbances, while the inner diameter of the tube matching the Rowe cell diameter enabled direct testing of the extracted undisturbed specimen. The hydraulic system of 145 CR-9 Hyundai

Fig. 3. Site sampling, (a) removing sandy cover layer, (b) test pits excavation, (c) driven push tube in landfill, and (d) wrapping and transferring to the UTS Geotechnology Laboratory.

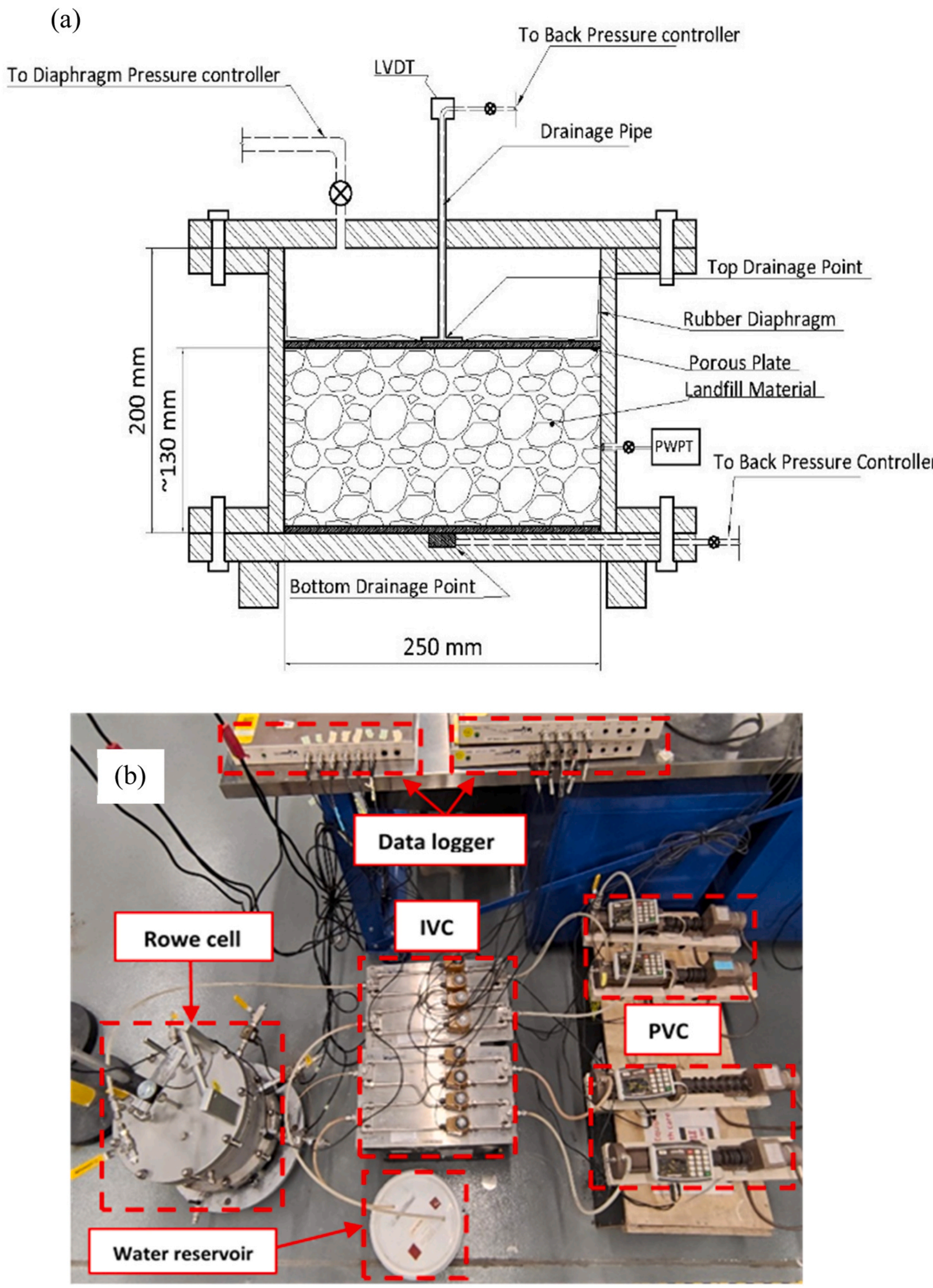
excavator was used to push the Shelby tubes into the base of the test pit. Careful sample extraction and sealing preserved the natural state and moisture content prior to laboratory testing. Surrounding waste material was dug out and then the filled Shelby tube was removed smoothly. Then heavy-duty plastic caps were placed on both ends of the tube and the sample was fully sealed by plastic wrap to maintain the site moisture condition, and then transferred to the UTS Geotechnology Laboratory for testing.

2.2. Testing program

2.2.1. Large diameter rowe cell setup

The large diameter consolidation Rowe cell introduced by Rowe and Barden [61], was used to conduct the staged loading tests on the undisturbed waste sample. The hydraulic Rowe cell applies vertical pressure through a flexible diaphragm filled with water. The cylindrical cell had the internal diameter of 250 mm and height of 200 mm. These dimensions allowed direct in-situ testing of the collected sample which had the diameter of 250 mm.

As shown in Fig. 4, this Rowe cell was equipped with pore pressure transducers at the middle height, axial displacement transducer (LVDT), pressure controllers and back pressure saturation system. In the adopted test setup, two-way drainage condition allowing free water drainage subjected to back pressure from top and bottom boundaries was maintained to accelerate the consolidation process, and brass porous plates were utilised to maintain uniform drainage boundaries. Comparable



* IVC is the Infinite Volume Controller (plate)
** PVC is the pressure/volume controllers

Fig. 4. 250 mm consolidation Rowe cell setup, (a) schematic Rowe cell setup diagram, and (b) actual setup in the UTS Geotechnology Laboratory.

Rowe cell configurations (various sizes) were used in numerous other studies for long-term compression testing of different geomaterials [62–65].

For creating the required vertical stress applied on top of the sample, the pressure-volume controllers (PVC) were used to pump water behind the convoluted flexible rubber diaphragm. At the same time, the pore water pressure variations were monitored and recorded using a pore water pressure transducer (PWPT) installed near the middle of sample on the sidewall. Referring to Fig. 4, since the landfill waste sample could experience significant volume changes over time, two sets of Infinite Volume Controllers (IVC) were used to maintain the vertical stresses and back pressures uninterruptedly. Indeed, two sets of pressure-volume controllers were paired with two infinite volume controllers for stress and backpressure applications, and when one controller reached the volume supply limit, the other controller could kick in and allow continuous supply of water and testing.

Since the internal diameter of the Shelby tube matched the diameter of the Rowe cell, the undisturbed sample could be directly extruded into the Rowe cell and ends of the sample were trimmed to create flat surfaces. Then, the top porous plate was placed on extruded sample, which was trimmed to 131 mm height, followed by placing the rubber diaphragm and lid and sealing the system via O-rings and 18 bolts. Fig. 4 displays details of the 250 mm Rowe cell consolidation setup used in this study.

In order to saturate the sample, distilled and de-aired water was pumped into the sample via the backpressure lines attached to the top and bottom of the sample. During the saturation process, the applied effective vertical stress was maintained constant at 10 kPa, while to achieve the required level of saturation, the back pressure was gradually increased from 20 kPa to 530 kPa, where B-value in excess of 0.90 was reached after 42 days. It should be noted that the Skempton's B parameter was defined as the ratio of the increase of the excess pore water pressure to the applied stress increment [66].

After completing the saturation stage, the specimen was subjected to compression, while allowing drainage of water from top and bottom of the sample via porous plates (i.e. two-way drainage). The testing plan included incremental initial loading, first unloading, reloading and second unloading, with the initial loading from effective pressure of 20 kPa to 400 kPa in four steps (i.e. 20, 50, 100, 200, 400 kPa), followed by incremental unloading back to 20 kPa, and then incremental reloading to 800 kPa in 5 steps (i.e. 20, 50, 100, 200, 400, 800 kPa) followed by incremental unloading to 20 kPa. During each loading increment, the effective pressure (i.e. vertical stress minus backpressure) remained constant for up to 40 days per increment to ensure significant creep deformation could occur following the primary consolidation of saturated landfill material. It should be noted that throughout this test, the backpressure was maintained at 530 kPa. Table 1 summarises the loading stages adopted in this study.

In terms of the setup and the test sequence, the specimen was extracted from the Shelby tube and trimmed to a height of 131 mm. This trimmed specimen was then placed directly into the Rowe cell. The upper cell chamber was filled with water and back pressure applied to saturate the specimen through the porous plates. Saturation was commenced and monitored until a Skempton's pore pressure B-value exceeding 0.90 was achieved to ensure saturation had occurred. At this point, the programmed consolidation testing began, with the sample being subjected to precisely controlled incremental loading steps up to maximum vertical stress of 400 kPa followed by staged unloading cycles back down to 20 kPa and incremental reloading to 800 kPa. At each loading increment, once primary consolidation was deemed complete based on pore pressure dissipation, creep tests were carried out to characterise the continual deformation behaviour. These constant load creep stages continued for extended durations to capture long-term secondary compression characteristics. In this manner, a comprehensive set of multi-staged consolidation and creep tests were performed enabling evaluation of stress history impacts on the intrinsic compressibility properties.

2.2.2. Complementary tests

In order to determine the moisture content and the organic content, the sample was tested in accordance with ASTM D 2974–87 [69]. Before starting the consolidation test, a representative sample of the specimen was collected to determine the initial moisture content. The organic content was also determined using this oven-dried material. The total and dry unit weights of the undisturbed landfill specimen were calculated by subtracting the weight of the Rowe cell fill with the undisturbed specimen from the weight of the empty Rowe cell.

After completion of the second unloading stage, the landfill material was taken out of the Rowe cell for conducting complementary tests, including the particle size distribution of material, waste composition and measuring the waste specific gravity (G_s).

Table 1
Specimen height and void ratio variation at different loading stages.

Stage	Effective pressure (kPa)	H_i (mm)	ΔH (mm)	e_i *	e_1 **	Vertical strain, ε_z(%) ***	Loading duration (days)
Saturation	10	131.00	9.05	1.23	1.08	6.91	21
	20	121.95	2.76	1.08	1.03	2.74	21
Initial Loading	50	119.19	3.57	1.03	0.97	12	6
	100	115.62	7.11	0.97	0.85	17.9	15
	200	108.51	5.88	0.85	0.75	22.95	31
	400	102.63	6.61	0.75	0.64	28.46	37
First Unloading	400–100	96.02	-2.19	0.64	0.67	26.79	7
	100–20	98.21	-2.04	0.67	0.71	25.61	9
Reloading	50	100.25	0.10	0.71	0.71	25.61	7
	100	100.15	1.06	0.71	0.69	25.81	44
	200	99.09	1.28	0.69	0.67	26.88	35
	400	97.81	1.94	0.67	0.63	28.44	28
	800	95.87	5.32	0.63	0.54	32.97	37
Second Unloading	800–400	90.55	-0.53	0.54	0.55	30.42	7
	400–100	91.08	-1.96	0.55	0.58	28.93	7
	100–20	93.04	-1.53	0.58	0.61	28.09	8

* e_i is the void ratio at the start of each step
** e_1 is the void ratio at the end of each step
*** ε_z is the vertical strain at the end of each step

3. Results and discussion

3.1. Physical characteristics

Since landfill waste is made up of many different types of materials, it is important to find out their types and quantities. In other words, waste composition greatly influences landfill engineering properties [22,67]. In this study, after all stages of the consolidation test were completed, the specimen was dried and sieved, similar to the procedure reported by Bareither, et al. [68]. Referring to Fig. 5(a), approximately 62% of the collected waste material (by weight) was construction waste such as stone, concrete, brick, and soil. The remainder of the waste sample was identified as wood pieces, plastic, glass, metal, fabric, and soil-like materials. As displayed in Fig. 5(c), collected waste material on each sieve was sorted visually and separated by hand picking. The largest particle in the collected undisturbed sample measured 52 mm in diameter. Particle size distribution of the landfill waste material (Fig. 5b) indicates over 70% of particles being larger than 1 mm, while a considerable 12.5% of particles are finer than 0.425 mm with 3.6% of materials being finer than 0.075 mm (passing sieve #200). Moreover, visual inspection revealed likely clay-sized particles adhered to the surfaces of the larger waste components, though unquantified.

Fig. 5(d) displays microscopic images of key landfill components acquired via an Olympus BX41 digital microscope at 10x magnification. A 50 μm scale is displayed for size reference. The visible materials present are fragments of wood, paper and fabric embedded within a fine-grain soil. The wood piece exhibits a tubular structure, indicating capacity for moisture absorption. In contrast, the paper shred reveals tightly packed cellulose fibres with some void space in between. Another image shows the woven pattern of the fabric shard and soil grains attached to it. The highly porous organic matter and soils with clay would facilitate retention of moisture. The presence of flexible materials like fabric could also contribute to compressibility.

Initial moisture content and organic content of the collected sample were measured to be $\omega = 55.4\%$ and $OC = 30\%$, respectively. The total and dry unit weights of the collected undisturbed sample were measured to be 14.7 kN/m^3 and 9.5 kN/m^3, respectively, which is within the ranges reported for TP1 (Fig. 2). Since the collected waste was non-uniform with some large particles, a customised technique inspired by Yesiller, et al. [70], was adopted for measuring G_s. A large size Erlenmeyer flask with distilled and de-aired water was used to measure the average specific gravity (G_s) of the waste material. Four samples were picked and tested from the waste specimen and the average specific gravity was determined to be $G_s =$ 2.12. Based on the measured initial moisture content, unit weight and specific gravity, the initial void ratio of the collected sample was determined to be $e_0 = 1.23$.

3.2. Coefficient of consolidation and hydraulic conductivity

The adopted initial loading, first unloading, reloading and second unloading stages and corresponding sample height, void ratio and loading duration are summarised in Table 1. It should be noted that during the saturation stage, which took about 42 days, where effective vertical stress of 20 kPa was achieved (i.e. corresponding to cell pressure of 550 kPa and backpressure of 530 kPa), the sample height was reduced by about 10 mm.

Fig. 6 displays the variation of the vertical strain experienced by the sample during different stages of the initial loading, first unloading, reloading and second unloading with time. Following the saturation stage, multi-stage, stress-control consolidation tests were conducted on the undisturbed landfill specimen. The entire testing duration was 330 days since at each step after the consolidation stage creep test on waste material was conducted. It could be observed that the sample lost nearly 40 mm of its initial height (i.e. vertical strain of 30%) when the sample was loaded from its initial state to the final vertical stress of 800 kPa via loading-unloading-reloading cycles.

As mentioned earlier, this Rowe cell was equipped with a pore water pressure transducer (PWPT) on the sidewall and the variation of PWP was recorded for all steps and stages of the test as illustrated in Fig. 7. Indeed, the rather low hydraulic conductivity of landfill material resulted in slow dissipation of the excess pore water pressure with time.

3.2.1. Coefficient of consolidation

Rowe cell consolidation test data were used to calculate the coefficient of consolidation. Although in the simplified engineering analysis, it may be assumed that the coefficient of consolidation (C_v) remains unchanged, it varies with applied consolidation pressure and is not a material constant [71]. The Chan (2003) least-squares approach was employed to determine the coefficient of consolidation based on the results of consolidation settlement reported in Fig. 9. The least-squares approach was used to determine the coefficient of consolidation, which resulted in the best-fitted variations of the primary consolidation settlement with time at each stage of loading. Table 2 summarises the determined coefficients of consolidation for undisturbed landfill material during the initial loading and reloading stages. It is observed that the value of C_v increased with the effective pressure. In other words, C_v increased in both normally consolidated and over consolidated conditions, when the applied effective stress was raised.

Furthermore, referring to Fig. 8, it is observed that the coefficient of consolidation increased significantly when the sample was preloaded with increasing over consolidation ratio (OCR). Referring to the consolidation data reported in Table 2 and Fig. 8, the following simplified equation is recommended to obtain the variations of $C_{v(OC)}/C_{v(NC)}$ with OCR for the landfill waste material used in this study:

$$\frac{C_{v(OC)}}{C_{v(NC)}} = 1 + \alpha.(OCR.(\ln OCR)) \tag{1}$$

Where, $C_{v(OC)}$ and $C_{v(NC)}$ are coefficients of consolidation for over consolidated and normally consolidated landfill material, respectively, OCR is the over consolidation ratio and α is a material constant value, determined to be 0.577 in this study. According to Eq. (1), a higher over consolidation ratio yields a higher coefficient of consolidation ratio for landfill material. The results summarised in Table 2 indicate that, when $OCR = 1$, the C_v value varies in the range of 4.7 m^2/yr – 12.1 m^2/yr, whereas in over-consolidated states ($OCR = 2$ *to* 8), the C_v varies in the range of 27.1 m^2/yr - 50.4 m^2/yr, which illustrates the significant impact of stress history on the coefficient of consolidation, required for the preloading design.

3.2.2. Hydraulic conductivity

In soil media, permeability is known to be impacted by the void ratio, and Eq. (2) proposed by Taylor [72] describes the relationship between permeability and void ratio for granular Soils with significant fines or fine grained soils:

$$\log k = \log k_{ref} - \frac{(e_{ref} - e)}{C_k} \tag{2}$$

where, C_k is the permeability change index and k_{ref} is the reference permeability corresponding to the reference void ratio (e_{ref}). This logarithmic relationship has been widely applied in geomechanics to estimate the permeability-void ratio relationship for granular materials with fine content (e.g. [73,74]).

The evaluated correlations between the coefficient of permeability (k) and the void ratio (e) presented in Fig. 9 for varying void ratios indicated a coefficient of determination of $R^2 = 0.81$, validating the suitability of this relationship for the adopted landfill waste material and comparable to the values reported in the literature for geomaterials [73, 75].

Yang, et al. [11] stated that the leachate distribution in a landfill is controlled by its hydraulic conductivity. It means that the landfill permeability coefficient has significant effects on overall stability of

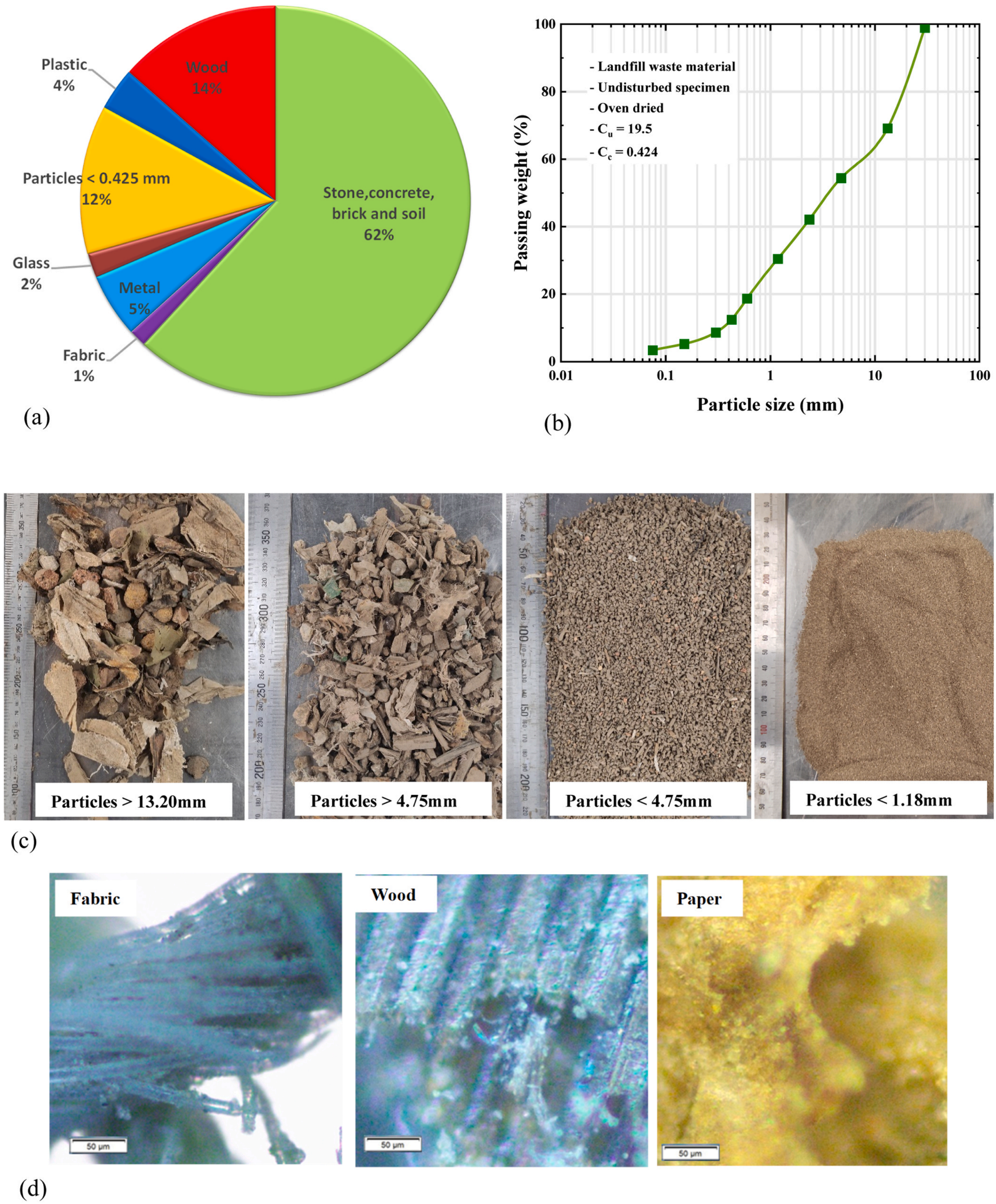


Fig. 5. Different components and particle sizes of undisturbed landfill sample, (a) waste material composition (by weight), (b) particle size distribution curve, (c) displaying the dried and sieved waste components, which include soil, stone, wood, plastic, debris, and other waste materials and (d) microscopic images of different waste material components.

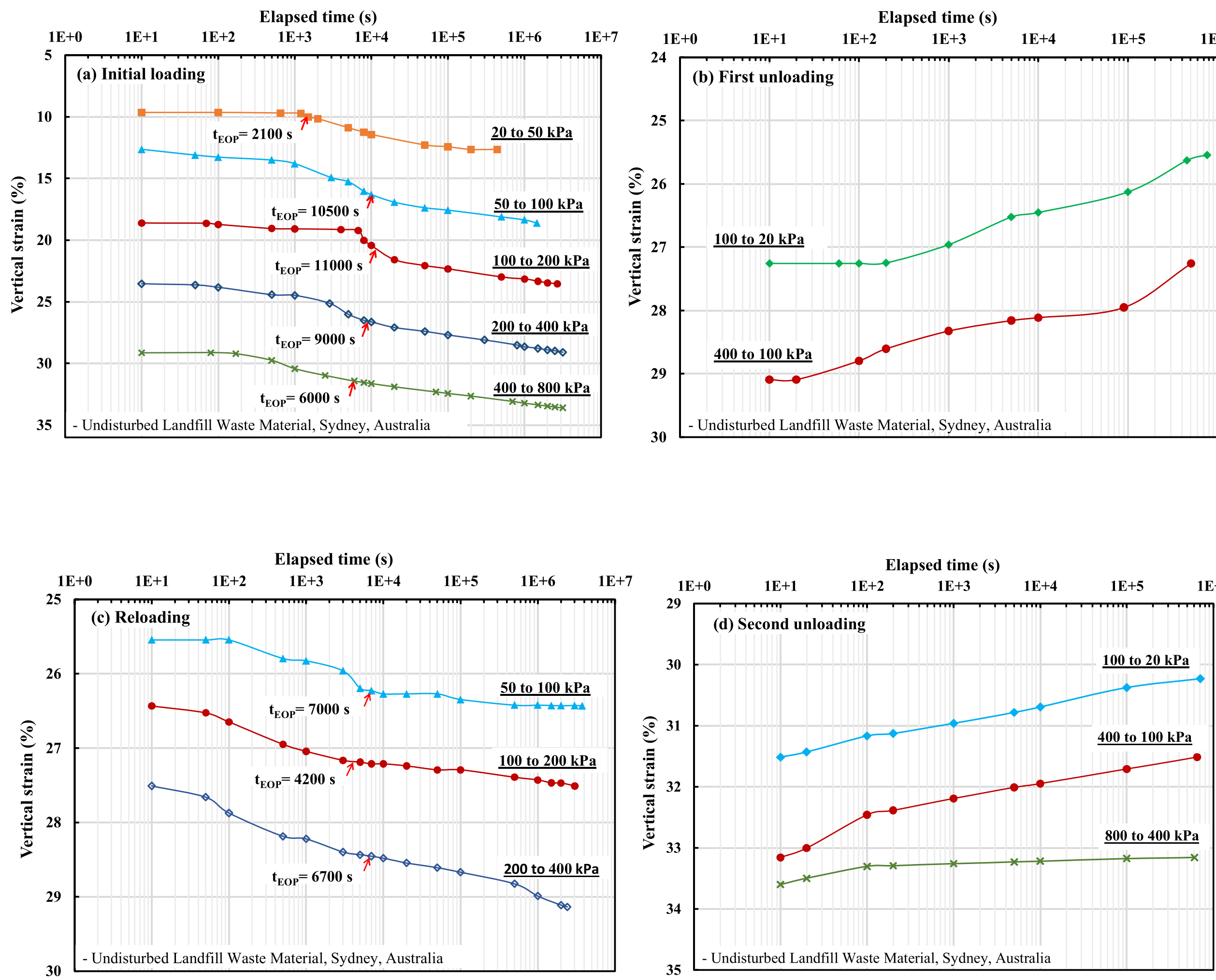


Fig. 6. Vertical strain variation by time, (a) initial loading, (b) first unloading, (c) reloading, and (d) second unloading.

landfill site. Furthermore, permeability coefficient of landfill waste is highly dependent on landfill composition, especially organic waste content. Similar to the other porous media, the permeability coefficient of landfill waste material is also correlated to its void ratio. Based on the calculated C_v and the corresponding coefficient of volume compressibility (m_v), the coefficient of hydraulic conductivity (k) can be calculated via

$k = C_v.\ \ m_v.\ \ \gamma_w$ following Terzaghi's one-dimensional consolidation theory, where γ_w is water unit weight.

As illustrated in Fig. 9, the coefficient of permeability varies in the range of 3.73×10^{-10} m/s to 3.45×10^{-9} m/s for this undisturbed landfill specimen. According to Xie, et al. [76] these low permeability values of landfill, could be attributed to the swelling of organic materials and impermeable plastic fragment in waste. It is evident that, there is a clear correlation between k and e, where higher values of e correspond to higher k values. By comparing the results report in this study with exiting literature [77,78], it can be noted that the hydraulic conductivity of the collected waste material is comparable with fine grain soils such as silty clay or clayey sands.

3.3. Compressibility indices and creep coefficient

3.3.1. Compression and recompression indices

In addition to the pre-consolidation pressure (or over consolidation ratio) of the collected sample, compressibility indices were also measured. As illustrated in Fig. 10, effective vertical stresses at the end of primary consolidation and the corresponding vertical strains were plotted for all loading stages, including initial loading (20 kPa to 400 kPa), first unloading (400 kPa to 20 kPa), reloading (20 kPa to 800 kPa) and second unloading (800 kPa to 20 kPa) stages. The Casagrande technique [79] was employed to determine the pre-consolidation pressure, $\sigma_c^{'} = 62$ kPa. Referring Fig. 10, the slope of the best fitted lines at the initial loading stage which is known as compression index (λ/ν_0) was determined to be 0.072 and slope at reloading stage which is referred to as recompression index (κ/ν_0) was determined to be 0.012. It is worth noting that the measured compression index (c_c) was equal to 0.356 while the measured recompression index (c_r) was 0.063.

3.3.2. Creep index of undisturbed landfill specimen

When soils become over-consolidated (e.g. by removing the surcharge), it experiences less creep settlement compared to its counterpart at normally consolidated state. Preloading is a technique widely used to reduce the long-term secondary settlement of soil induced by creep. As a result of adding a temporary surcharge and removing it in due course, the stress history of the soil changes impacting the long-term creep deformations. Past experimental studies [78,80–83] showed that preloading and increasing the level of over-consolidation of the soil as a result of loading and unloading could significantly reduce the creep settlement. In this study, to determine the creep compression rate at different loading levels, the applied stresses were maintained for

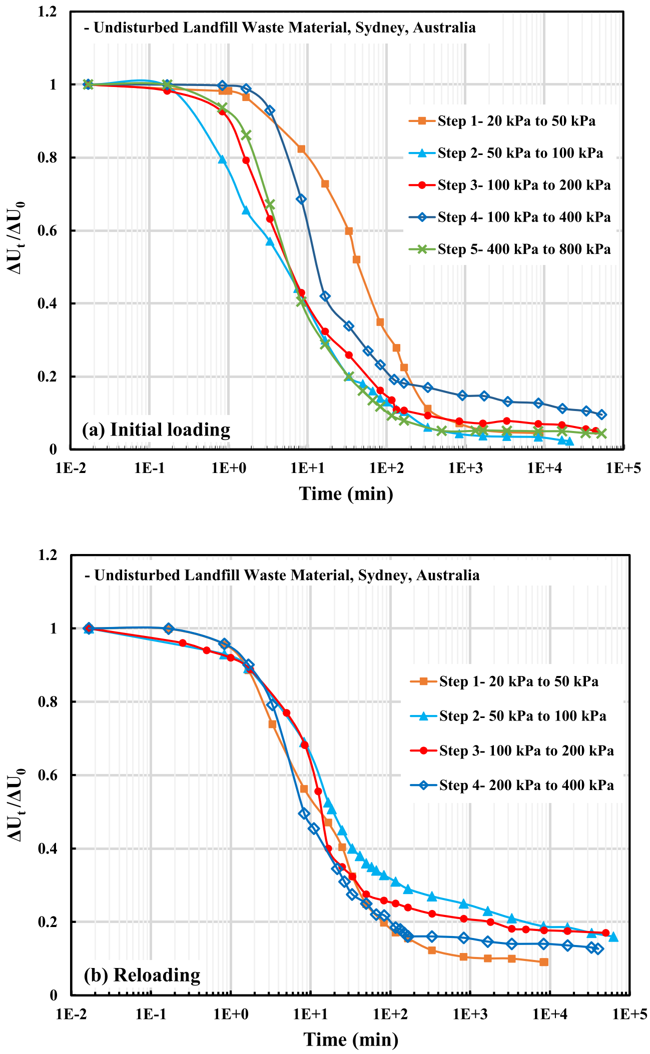


Fig. 7. Ratio of excess pore water pressure dissipation ($\Delta U_t/\Delta U_0$) by time, (a) initial loading and (b) reloading.

Table 2
Variation of coefficient of consolidation with loading stages and over-consolidation ratios (OCR).

Stage	Effective stress (kPa)	OCR	C_v (m^2/yr)
Initial loading	50	1.2	4.72
	100	1	7.69
	200	1	8.55
	400	1	8.37
	800	1	10.90
Reloading	50	8	50.45
	100	4	30.60
	200	2	27.00
	400	1	12.12

extended duration after end of primary consolidation. Indeed, once the excess pore water pressure, measured near middle of the sample, dropped below 1 kPa, end of primary consolidation (EOP) was presumed to be reached. The creep index (ψ/ν_0) introduced by Yin and Graham [84] was computed by finding the slope of the creep strain (vertical strain, ε_z) versus logarithm of time graphs as displayed in Fig. 11. It should be noted that $\psi/\nu_0 = \ln(10)C_\alpha/\nu_0$, where C_α/ν_0 is the conventional creep coefficient measured in decadic logarithm time scale, and $\nu_0(\text{initial specific volume}) = 1 + e_0 = 2.23$. Moreover, each creep increment (stage) was continued under the applied stress increment for

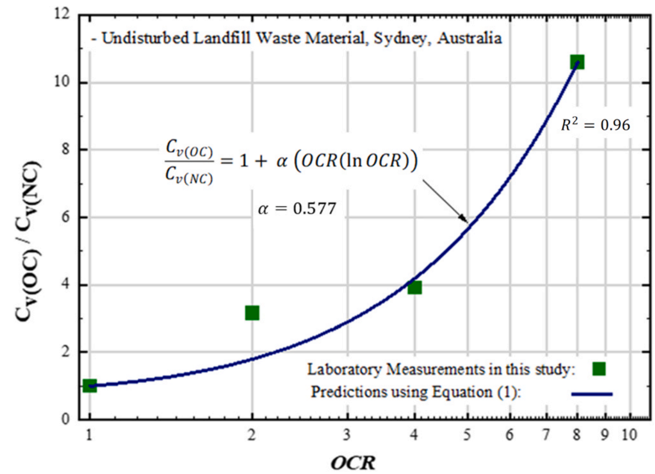


Fig. 8. Variations of coefficient of consolidation ratio $C_{v(OC)}/C_{v(NC)}$ with over consolidation ratio.

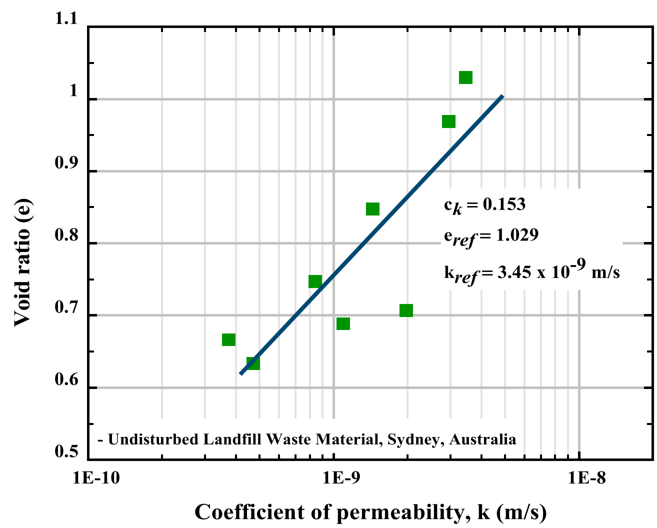


Fig. 9. Variations of coefficient of permeability with the void ration of the waste sample determined from consolidation test data.

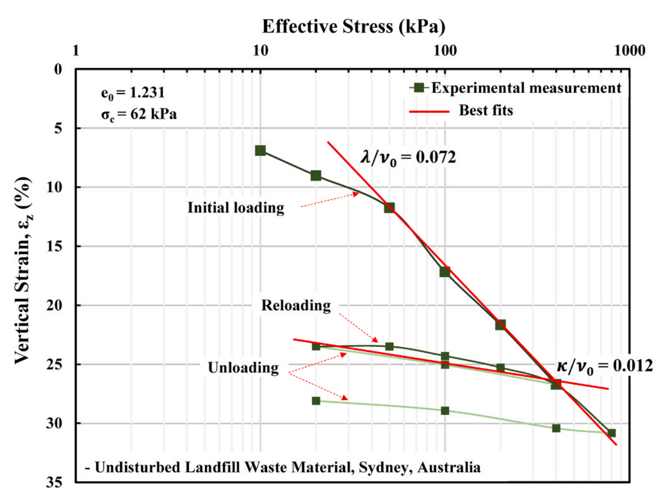


Fig. 10. Variations vertical strain and effective stress at the end of consolidation for different loading, unloading and reloading stages.

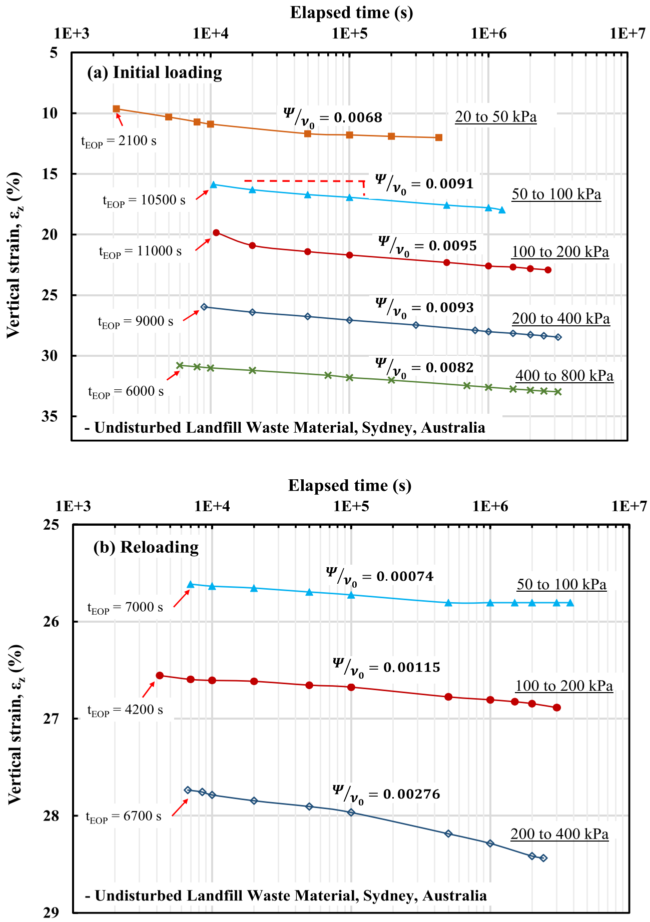


Fig. 11. Secondary settlement of landfill material, (a) initial loading, and (b) reloading stages.

at least two logarithmic cycles of time after end of primary consolidation (EOP).

In Fig. 12, the creep index ratio ($\frac{\psi/v_0(OC)}{\psi/v_0(NC)}$) has been plotted against *OCR* obtained from the extended creep tests conducted on the collected undisturbed landfill waste. Referring to the test results reported in Fig. 12, Eq. (3) was proposed as an empirical relationship between the creep ratio ($\frac{\psi/v_0(OC)}{\psi/v_0(NC)}$) and *OCR*:

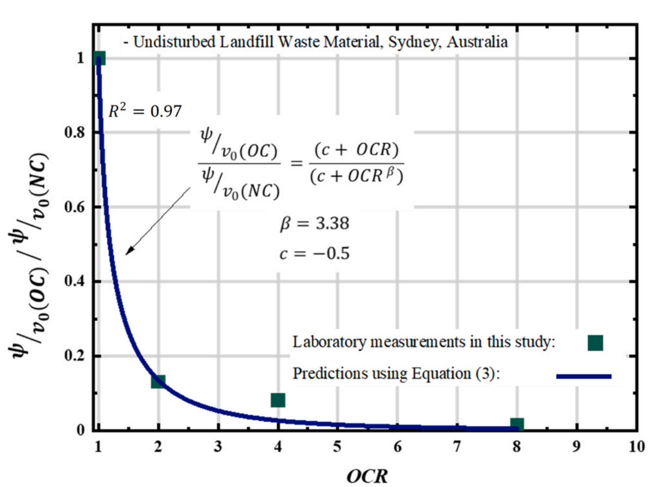


Fig. 12. Variations of creep index with overconsolidation ratio (OCR).

$$\frac{\psi/v_0(OC)}{\psi/v_0(NC)} = \frac{(c + OCR)}{(c + OCR^{\beta})} \tag{3}$$

In this equation, $\psi/v_0(NC)$ and $\psi/v_0(OC)$ represent creep indices in normally consolidated and over-consolidated states, respectively. Model parameters, β and *c* can be determined from creep test data, which were found to be 3.38 and −0.50, respectively for the landfill waste material attested in this study. It is evident that while the *OCR* was rising, the creep ratio ($\frac{\psi/v_0(OC)}{\psi/v_0(NC)}$) for landfill material decreased steadily, representing the fact that preloading techniques could lead to a significant reduction in the creep settlement.

Referring to Figs. 11(a) and 12, it can be noted that the compression index (λ/v_0) and creep index (ψ/v_0) values in normally consolidated state (initial loading) of waste material were in the range of 0.072 and 0.0068 – 0.0095 (the average value is equal to 0.00858), respectively, which are in agreement with the reported values in the literature for waste material [49,85–87]. During reloading stage (i.e. $OCR = 2 – 8$), the recompression index (κ/v_0) was measured to be 0.012, well less than compression index λ/v_0 as expected ($\lambda/\kappa = 6$). In addition, reviewing the creep settlement data in the reloading stage while waste material was over consolidated, indicated a considerable reduction in the creep rate compared to the normally consolidated state of the waste as in the initial loading stage. Referring to Fig. 11, ψ/v_0 of over consolidated waste ($OCR = 2 – 8$) varied in the range of 0.00074 – 0.00276, which shows more than 85% reduction compared to the corresponding value sin the normally consolidated range (i.e. 0.0068 – 0.0095).

A sensible understanding of the primary and secondary settlement behaviour of normally consolidated and over-consolidated landfill waste material was provided by this long-term consolidation and creep tests on the undisturbed waste specimen. Based on experimental results of this study, it is evident that preloading landfill sites could significantly reduce both the primary and creep settlements. Referring to Eq. (3) and Fig. 12, when landfill waste material becomes over-consolidated as a result of application of surcharge (i.e. preloading technique), the creep index could reduce significantly. Thus, preloading would be a feasible ground improvement technique for closed landfill sites for reconstruction projects, especially if sufficient site investigation and material testing are carried out to establish the design parameters.

4. Conclusions

In this study, a 250 mm Rowe cell consolidation apparatus was adopted to study the primary consolidation settlement and creep of landfill material. For fulfilling this purpose, an undisturbed sample was collected from the closed landfill site in Sydney. Initial moisture content and the total unit weight of the sample were measured to be 55.4% and 14.7 kN/m^3, respectively. The specific gravity (G_s) of this waste sample was measured to be 2.12, which consists of decayed organic material, demolition waste, wood, soil, plastics, fabrics, metal, glass and fine particles, and the initial void ratio of the collected sample was determined to be $e_0 = 1.231$ (i.e. initial specific volume $v_0 = 2.231$). This undisturbed collected sample was subjected to an array of long-term consolidation and creep tests for about 330 days, which included initial loading (up to 400 kPa), first unloading, reloading (up to 800 kPa) and second unloading stages. Landfill compressibility coefficients were obtained in normally consolidated and over-consolidated stress states, while the coefficient of consolidation and hydraulic conductivity were also determined. The compression and recompression (swelling) indices were determined to be $\lambda/v_0 = 0.072$ and $\kappa/v_0 = 0.012$ (i.e. $\lambda/\kappa = 6$), respectively, while the consolidation test results indicated a pre-consolidation pressure of $\sigma_c = 62$ kPa for the collected sample.

In addition, the coefficient of permeability of the collected waste was determined to be in the range of 3.73×10^{-10} m/s to 3.45×10^{-9}, for the range of stresses applied in this study. It is shown that the permeability increased as the void ratio increased comparable to geomaterials with significant fine content. Indeed, the low permeability could be attributed to the presence of fine particles and also plastics and swollen organic material. Moreover, an empirical equation (Eq. (1)) has been proposed for the relationship between the coefficient of consolidation and the over-consolidation ratio. The test results showed that the coefficient of consolidation (C_v) of waste sample increased significantly as the over-consolidation ratio (*OCR*) of the sample increased. Parameters obtained from the laboratory testing provided indicative values for the compressibility and hydraulic conductivity of the collected undisturbed landfill sample.

In order to capture creep deformation characteristics of the waste material, constant stress creep tests were conducted during initial loading and reloading phases. As a result, creep index (ψ/v_0) for the normally consolidated state of the sample ($OCR = 1$) was measured to be in the range of 0.0068 – 0.0095, whereas creep index (ψ/v_0) for the over-consolidated state ($OCR = 2 - 8$) was determined to be in the range of 0.0007 – 0.0027. Using the obtained results, an empirical relationship reported in Eq. (3) was developed, which demonstrates the relationship between over-consolidation ratio (*OCR*) and creep index (ψ/v_0). Results of this experimental research proved that application of preloading technique, as a ground improvement method for closed landfill sites, can significantly reduce the post-construction settlement of the waste including creep deformations.

The present study shows that collecting undisturbed samples from landfills and conducting consolidation tests under full saturation conditions are feasible and effective methods to obtain the required landfill parameters, required for settlement predictions for redevelopment projects. In addition, the preloading technique has proven to be useful in landfill redevelopment projects to reduce the post-construction settlement of landfills. It should be noted that due to diversity of landfill types and highly variable composition, assumptive mechanical and physical engineering parameters for design of new structures on landfill sites can be highly uncertain and unreliable and it is strongly recommended to practicing engineers to conduct site specific investigation and testing similar to this study to obtain the required materials properties for more reliable design and construction.

The results provide supporting evidence for the effectiveness of preloading as a ground improvement approach for closed landfill sites undergoing redevelopment. Key findings of this study were the systematically lower compressibility parameters and creep rates measured when the landfill sample was in an over consolidated state compared to normally consolidated state for a given applied stress level. As shown in Figs. 10 and 12, the over consolidated specimen exhibited both reduced compression index and creep index compared to the normally consolidated specimen for the same stress level, which compared well with observed patterns for natural soils. Indeed, the Rowe cell compression testing results aligned with principles of preloading and stress history effects in soil mechanics. The observed experimental trends provide evidence that preloading could improve the compressibility characteristics of landfill wastes in a similar manner as for soft soils.

CRediT authorship contribution statement

Hossein Haddad: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Behzad Fatahi:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hadi Khabbaz:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Formal analysis. **Jeff Hsi:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Idy Li:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Behzad Fatahi reports financial support was provided by CIMIC Group Ltd.

Data availability

Data will be made available on request.

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