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Effects of vegetation type on water infiltration in a three-layer cover system using recycled concrete*

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Abstract: To promote environmental sustainability, recycled construction concrete is suggested for civil infrastructure works. The aim of this study was to investigate the effects of vegetation type on water infiltration under extreme rainfall conditions in a proposed three-layer landfill cover system containing recycled concrete. Three soil columns, namely bare, covered with shrub (*Schefflera arboricola*), and covered with grass (*Cynodon dactylon*), were subjected to ponding tests. Each column was compacted with a bottom layer of silty soil, an intermediate layer of coarse recycled concrete aggregate, and an upper layer of fine recycled concrete aggregate. Water breakthrough occurred only in the bare cover system after 48 h of ponding, equivalent to a rainfall return period of greater than 1000 years in Hong Kong. Under the vegetated covers, suction maintained in the bottom silty soil layer was higher than under the bare cover by 49–52 kPa and hence no percolation was observed after 48 h of ponding. Comparing the two vegetated cover systems, suction maintained under the shrub cover was 2–12 kPa higher (2%–8% lower volumetric water content) than that under the grassed cover in the layers of recycled concrete. This implies that shrub cover can be more effective than grass cover in reducing water infiltration in humid climates.

Key words: Recycled concrete; Soil suction; Three-layer landfill cover; Vegetation; Water content
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1 Introduction

Landfilling is a simple and cost-effective method to dispose of municipal solid waste. To reduce water infiltration and percolation, a permanent cover is needed (Moon et al., 2008; Barnswell and Dwyer, 2012). In recent years, a two-layer cover with capillary barrier effects (CCBE) has become a popular alternative to conventional compacted clay covers in arid and semi-arid areas (Ross, 1990; McCartney and Zornberg, 2010; Rahardjo et al., 2012; Zhang et al., 2016). The two soil layers, namely a fine-grained soil layer over a coarse-grained soil layer, have contrasting permeability and water retention capacity. To improve the effectiveness of CCBE in humid regions, Ng et al. (2016d) proposed a new all-weather three-layer landfill cover system including a clay layer below the traditional two-layer CCBE, which can minimize percolation effectively.

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To achieve cost savings and environmental sustainability, recycling of construction waste has become increasingly popular in these years (EPD, 2003). Compared with other materials (such as virgin aggregates), recycled concrete aggregates (RCAs) have lower water entry values (Harnas et al., 2016). RCAs are also coarser, more porous, and rougher than natural aggregates. Hence, RCAs have a saturated water content 3–5 times higher and a density 3%–10% lower than those of natural aggregates (Ramaswamy et al., 1983; Limbachiya et al., 2004; Rahardjo et al., 2011). The water permeability of compacted RCAs might also decrease over time due to self-cementing (Poon et al., 2006). The self-cementing effect of RCAs can be affected by the age, grade, and amount of cementitious materials used in the original concrete. As RCAs have hydraulic properties similar to those of natural soils under saturated and unsaturated conditions (Rahardjo et al., 2013b), they also have the potential to be used as cover materials for landfills.

For aesthetic and ecological reasons, plants are commonly grown on landfill covers (Wan et al., 2016). Plants can also remove moisture from soils to the atmosphere via evapo-transpiration (ET), resulting in a reduction of soil water content and water permeability (Hauser et al., 2001; Ng and Menzies, 2007; Barnswell and Dwyer, 2011; Ng et al., 2016a, 2016b, 2016c). According to the unsaturated permeability function, low water content (i.e. high soil suction) corresponds to low water permeability (van Dijk, 2018). As the air in soil pores is non-conductive of water, ET will lead to a reduction in water content and hence a reduction in the available water flow paths, resulting in increased tortuosity of water paths and reduced water permeability (Ng and Menzies, 2007). ET effects can be highly dependent on plant type (Pollen-Bankhead and Simon, 2010; Leung et al., 2015a; Ni et al., 2017, 2018). Single-layer landfill covers with plants have been shown to reduce infiltration effectively in arid and semi-arid regions (Albright et al., 2004), but the effects of plant type on the performance of layered covers (i.e. three-layer covers) in humid regions are still not well understood.

The main objective of this study was to investigate the effects of plant type on water infiltration in a three-layer landfill cover system constructed with recycled concrete in a humid climate.

2 Materials and methods

2.1 Test setup and instrumentation

Three columns were constructed, each with an inner diameter of 300 mm and a height of 1500 mm (Fig. 1). Each column was made of transparent acrylic, which allowed the observation of plant root growth. From the bottom to the top of each column, the thicknesses of layers of completely decomposed volcanic rocks (CDV), coarse recycled concrete aggregate (CRC), and fine recycled concrete aggregate (FRC) were 300, 200, and 400 mm (Figs. 1 and 2), respectively. The selection of such combinations and depths of individual layers was based on the experiments of Ng et al. (2015, 2016d), who used artificial soils as cover materials. They demonstrated that these depths of individual layers were the minimum required to minimize water percolation and gas emission effectively.

As recycled concrete is not favorable for plant growth, a vegetation soil layer (i.e. completely decomposed granite (CDG)) with a thickness of 300 mm was placed on the top of the three-layer cover system as recommended by the Geotechnical Engineering Office of the Government of the Hong Kong Special Administrative Region, China (GEO, 2011). A drainage hole with a diameter of 5 mm was made at the bottom of each column to collect any percolating water in a graduated flask during testing. Each soil column was equipped with a constant-head water supply system for the ponding test. The system consisted of a water storage tank (Mariotte's bottle) and a plastic tube connecting the soil column and water storage tank (Fig. 1).

All columns were placed in the geotechnical laboratory of Harbin Institute of Technology, Shenzhen, China. The daily temperature and humidity in the room were maintained ~26 °C and ~55%, respectively. An array of soil moisture probes (EC-5, Decagon Devices, Inc., USA) was installed along the column depth to measure the volumetric water content (VWC). The measurement range of the soil moisture probes was from 0 to 100%. Each moisture probe was calibrated in the laboratory and the accuracy was ±2% of VWC. The instrument depths were 50, 150, 400, 600, 800, and 1000 mm. To check the VWC response during testing, another vertical array of miniature-tip tensiometers (2100F, Soil Moisture

Equipment Cooperation, USA) was installed at the same depths as the soil moisture probes. The measurement range of each tensiometer was from 0 to 90 kPa and the accuracy was ±1 kPa (Soilmoisture Equipment Corporation, 2009).

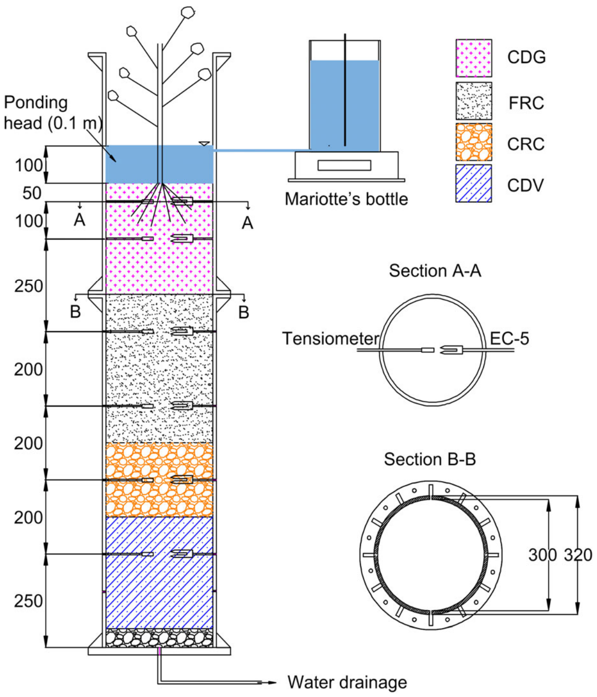

Fig. 1 Schematic diagram of a typical soil column test (unit: mm)

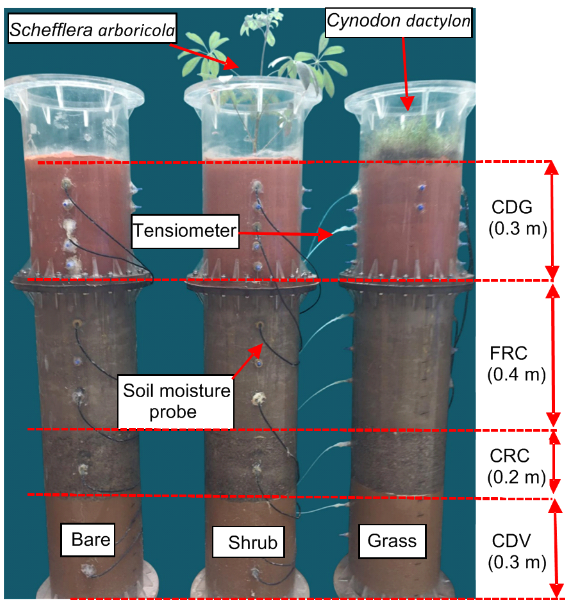

Fig. 2 Overview of the three soil columns

2.2 Soil type and selected plant species

The properties of the cover materials used in this study are presented in Table 1. The particle data were obtained from a sieve analysis described in ASTM D422 standard (ASTM, 2007). Specific gravity tests were performed based on the ASTM D854 standard test method (ASTM, 2010a). Atterberg limit tests were conducted in accordance with ASTM D4318 (ASTM, 2010b). The compaction curves for the CDG, FRC, and CDV were determined following ASTM D698 (ASTM, 2012). The saturated permeability (k_s) of compacted FRC and CDV was measured using a flexible wall permeameter according to ASTM D5084 (ASTM, 2010c), whereas k_s of CRC was tested by the constant-head method as described in ASTM D2434 (ASTM, 2006). According to the unified soil classification system (USCS) (ASTM, 2011), CDG, FRC, CRC, and CDV were classified as silty sand (SM), well-graded sand (SW), poorly graded gravel (GP), and silt (ML), respectively.

The saturated permeability of the CDG, FRC, CRC, and CDV layers was 1.7×10^{-7}, 6.6×10^{-5}, 2.5×10^{-1}, and 2.2×10^{-9} m/s, respectively.

The drying and wetting soil water characteristic curves (SWCCs) of the CDG, FRC, and CDV layers were measured using a modified pressure plate apparatus with an air-entry pressure of 500 kPa (Ng and Pang, 2000). The axis translation technique was applied in the measurements. A hanging column apparatus was used to obtain the drying and wetting path SWCC of CRC (ASTM, 2016).

Table 2 shows the criteria for the fine-grained and coarse-grained materials used in the CCBE. The fine and coarse RCAs (FRC and CRC) used in this study met the recommended values for CCBE cover materials suggested by Rahardjo et al. (2006, 2007, 2013a).

The CDV, CRC, FRC, and CDG layers were compacted successively from the bottom to the top in each soil column. The CDG, FRC, and CDV layers were compacted to a degree of compaction (DOC) of 95% at an optimum moisture content by following the procedures described by ASTM (2012), whereas the CRC layer (containing only gravel) was compacted to a DOC of 95% in a dry state. A DOC of 95% is commonly used for landfill-covers and man-made slope designs against rainfall infiltration in Hong Kong (GCO, 2000). The species selected for this study, namely *Schefflera arboricola* and *Cynodon dactylon*, can survive well under such a high level of compaction (Ni et al., 2017). Based on the instantaneous profile method (Ng and Leung, 2012), the coefficient of permeability of the soils in each column was determined by the measured VWC and soil suction. The deduced average coefficient of permeability of the top soil, FRC, CRC, and CDV layers under near saturation conditions was 1.6×10^{-7}, 5.3×10^{-5}, 2.0×10^{-1}, and 1.7×10^{-9} m/s, respectively. For each layer, the differences in average water permeability among the three columns were less than 5%.

One shrub species, *Schefflera arboricola*, and one grass species, *Cynodon dactylon* (commonly known as Bermuda grass), were selected for testing in this study (Fig. 2). Before transplantation, a one-year-old shrub with a shoot length of ~370 mm and a root depth of ~140 mm was provided by the supplier in Shenzhen. Grass turf with an average shoot length of 50 mm and a root depth of 20 mm was grown from grass seed at a nursery. After completion of soil compaction, the shrub was transplanted into the top vegetation soil layer at the centre of the soil column. When transplanting grass turf, the surface soil was scarified to ensure good contact between the grass roots and the soil.

2.3 Test procedures

Before the start of the ponding test, the plants in the two columns were grown on for four months, which was considered sufficient for root establishment in the surrounding soil (Ng et al., 2016a; Ni et al., 2017).

During this 4-month growth period after transplantation (i.e. 120 d), each column, including the bare column, was irrigated regularly with a constant amount of water of 200 mL/d (2.83 mm/d), based on the annual rainfall data for Shenzhen between January and April (from the Meteorological Bureau of Shenzhen Municipality), when the tests were conducted. Between irrigation events, all columns went subjected to the same natural drying processes.

After four months of plant growth and one day of drying, all three soil columns were subjected to an infiltration test under a constant ponding head of 100 mm for 48 h (equivalent to more than a 1000-year return period in Hong Kong) (Ng et al., 2016d). Variations in VWC and suction were monitored continuously throughout the ponding test. Any basal percolation was also recorded during the test period.

Table 1 Index properties of soil

Index property	Description			
	CDG	FRC	CRC**	CDV
Particle-size distribution				
Gravel content (>2 mm) (%)	0.00	0.00	100.00	0.00
Sand content (≤2 mm) (%)	74.00	94.00	0.00	40.00
Silt content (≤63 μm) (%)	16.00	6.00	0.00	58.00
Clay content (≤2 μm) (%)	10.00	0.00	0.00	2.00
Specific gravity	2.60	2.45	2.45	2.65
Atterberg limit				
Liquid limit (%)	36.3			40.0
Plastic limit (%)	24.1			27.0
Plasticity index (%)	12.2			13.0
USCS*	SM	SW	GP	ML
Standard compaction test				
Maximum dry density (kg/m^3)	1660	1670	1570	1550
Optimum moisture content (%)	19	11		25
Saturated permeability (m/s)	1.7×10^{-7}	6.6×10^{-5}	2.5×10^{-1}	2.2×10^{-9}
Soil water retention				
Air entry value (kPa)	3	4	0.85	10
Water entry value (kPa)	95	90	2.00	200

*ASTM (2011); **CRC (contained only gravel) was compacted at dry state

Table 2 A list of criteria for CCBE

Parameter	Value	Recommended value
Water-entry value of coarse-grained layer (kPa)	0.85	<1 (Rahardjo et al., 2006)
Water-entry value ratio of fine-grained layers and coarse-grained layers	45.0	>10 (Rahardjo et al., 2006)
Saturated permeability of fine-grained layer (m/s)	6.6×10^{-5}	$>1\times10^{-5}$ (Rahardjo et al., 2007)

3 Results and discussion

3.1 Distribution of volumetric water content profile

Fig. 3 shows the measured VWC profile before and after 48 h of ponding. Before ponding, the VWC was distributed nonlinearly throughout the depth. At a depth of 50 mm, there was almost no difference in VWC among the three covers. This is because of regular irrigation near the ground surface during plant growth. Below the root zone, the VWC in the FRC layers of the vegetated covers was 2%–8% lower than that of the bare cover. Water uptake by roots can extend the zone of influence of the VWC to more than four times the root depth (Ng et al., 2016c). Hence, a lower VWC was maintained further below the root zone. At a depth of 100–600 mm the VWC was 2%–6% lower with shrub cover than with grass cover. The shrubs had deeper roots (~200 mm) than the grass (~40 mm), resulting in higher root water uptake ability and hence lower VWC.

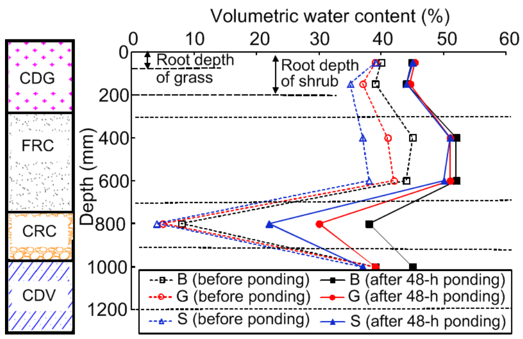

Fig. 3 Volumetric water content distributions before and after ponding in different vegetated columns

B: bare cover column; G: grass cover column; S: shrub cover column

After 48 h of ponding (equivalent to more than a 1000-year rainfall return period), the VWC in the CDG and FRC layers of all covers increased to close to saturation (i.e. 45% for CDG and 52.5% for FRC). The degree of saturation in the CDG and FRC layers after 48 h of ponding was 98.9% and 98.0%, respectively. The VWC in the CRC layer increased from 4%–8% to 22%–38%, indicating water breakthrough in the traditional two-layer CCBE. This means the traditional two-layer CCBE can restrict the downward flow of water only temporarily, as also demonstrated by Ng et al. (2016d). The VWC in vegetated columns was 6%–14% lower in the CRC and CDV layers than under bare cover. There was no change in the VWC in the bottom CDV layer in vegetated columns. Moreover, in the CRC and CDV layers the VWC under the shrub cover was 2%–5% lower than under the grass cover, indicating less water infiltration under the shrub cover. When water was ponded on the soil surfaces, the higher initial suction in the vegetated columns caused lower unsaturated permeability. In addition, occupancy of soil pore space by plant roots blocks channels for water flow during infiltration (Leung et al., 2015b; Ng et al., 2016b). This resulted in less water infiltration under vegetated covers and hence a lower VWC was retained. This is consistent with the results of Leung et al. (2015b) and Ng et al. (2014), who investigated the same plant species in a single soil layer.

After 48 h of water ponding, percolation was observed only under the bare cover, with a total of 35 g of water, which was equivalent to 0.5 mm of water depth in the column. These findings differ from those of Ng et al. (2016d), who found no percolation in a three-layer cover system under a rainfall return period greater than 1000 years. This is because the saturated permeability of FRC and CRC materials in this study (6.6×10^{-5} and 2.5×10^{-1} m/s, respectively) was one to two orders of magnitude higher than that of the artificial silt and sand used by Ng et al. (2016d). In this study, no percolation was observed under the covers with shrub or grass. This is consistent with no change of VWC at the instrumented locations in the bottom CDV layer during the ponding test.

3.2 Observed distribution of suction profile

Fig. 4 shows the suction distribution profiles of the bare and vegetated covers. Before ponding, suction in the top layer was lower than at deeper depths. There was almost no difference in suction at the shallow depth (0–150 mm) among three covers. Suction near the ground surface always decreased to zero after daily irrigation, where vegetation effects on soil suction might be neglected. However, suction below the root zone (i.e. ~200 mm) before ponding varied significantly, especially in the FRC layer. Suction under vegetated covers was up to 95% higher than under bare cover. This is mainly due to ET during plant growth. Compared with grass, shrub induced an additional 25%–30% suction in the FRC and CRC layers, which is consistent with the VWC results in Fig. 3.

Based on the instantaneous profile method (Ng and Leung, 2012), the water permeability of different materials in the three columns after 48 h of ponding was determined using the measured VWCs and soil suctions. The results are shown in Fig. 5. There was almost no difference in water permeability in the top CDG and FRC layers since they had similar degrees of saturation or suction (Figs. 3 and 4). In contrast, the water permeability in the CRC in the column covered by shrub was about two orders of magnitude lower than that in the column covered by grass, which in turn was about two orders of magnitude lower than that in the column covered by bare soil. In the bottom CDV layer, the water permeability was less than 1×10^{-9} m/s in all three columns, but lowest in the column covered with shrub. The water permeability in each column was consistent with its corresponding VWC (Fig. 3) and suction (Fig. 4) distributions. The water permeability measurements in each column show that the two vegetated three-layer cover systems using construction wastes could be used as effective landfill covers to minimize rainfall infiltration.

Ng et al. (2013) investigated the same grass species in a single soil layer of the same type as used in this study. They found that after drying for 7 d from the same saturated conditions, induced suction within the root zone of the grass-covered soil was almost 3 times greater than that in the bare soil (Fig. 6). The depth of the suction effect can be more than 3.5 times the root depth. Induced higher suction by plant roots was also observed by Garg et al. (2015) who investigated a tree species in the same soil as the top soil in this study. It is evident that the plants are indeed pulling more water than the bare soil due to an increase in ET.

After 48 h of ponding, suction in the top CDG and FRC layers decreased almost to zero. As indicated by the decrease in soil suction, water penetrated into the CRC layers in all three covers. This demonstrated again that the traditional two-layer CCBE was no longer effective after 48 h of ponding. For the bare cover, suction in the bottom layer of CDV decreased from 52 kPa to 3 kPa during ponding. However, for the vegetated covers, a large amount of suction (52 kPa for the grass and 57 kPa for the shrub cover) was still maintained in the bottom layer of CDV. Comparing the two vegetated cover systems, the suction maintained in the FRC, CRC, and bottom CDV layers under the cover with shrub was higher than that under the cover with grass by 2–6 kPa, 6 kPa, and 5 kPa, respectively (Fig. 4).

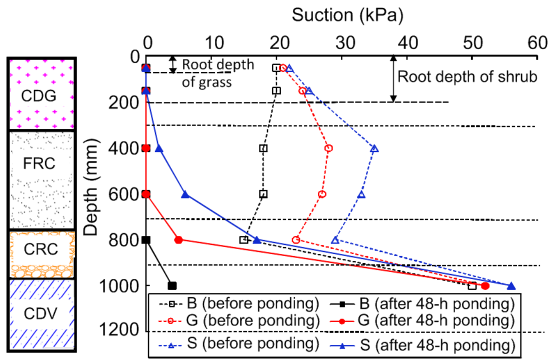

Fig. 4 Suction distributions before and after ponding

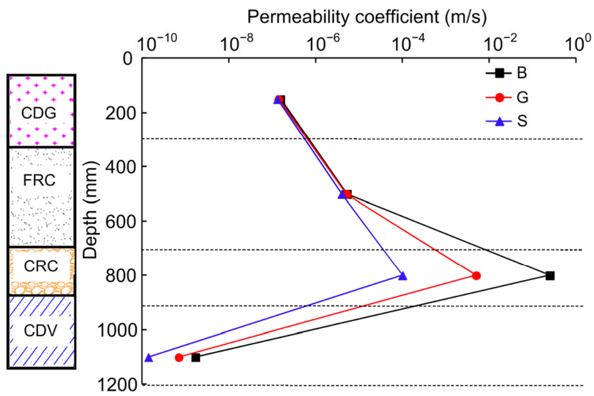

Fig. 5 Measured distributions of soil water permeability in bare and vegetated columns after 48-h ponding

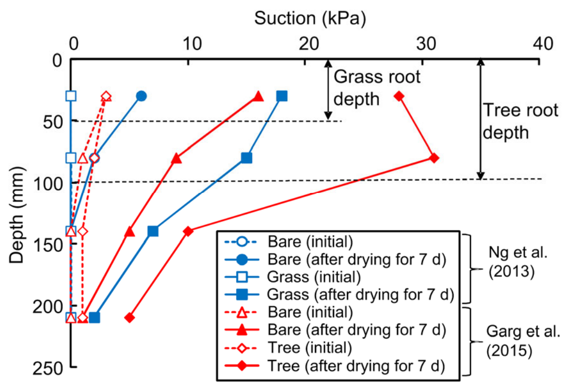

Fig. 6 Comparisons of suction response among bare, grass-covered, and tree-covered soil during drying (Ng et al., 2013; Garg et al., 2015)

After ponding, the suction maintained below the root zone in the vegetated covers was higher than that under the bare cover. Similar results were found by Ng et al. (2013, 2016c) in a single layer soil vegetated with a single tree or grass plant (Fig. 7). In their tests, suction was induced before ponding by natural drying from nearly-saturated conditions. After ponding, suction was maintained at a depth of 80 mm in the tree- and grass-covered soil columns. Suction was 155% higher under tree cover and 40% higher under grass cover than under bare soil.

Comparing the VWC and suction measurements in Figs. 3 and 4, the consistent results show that the shrub was more effective than the grass in maintaining a low water content (high suction) and hence reducing water infiltration in the three-layer cover with recycled concrete.

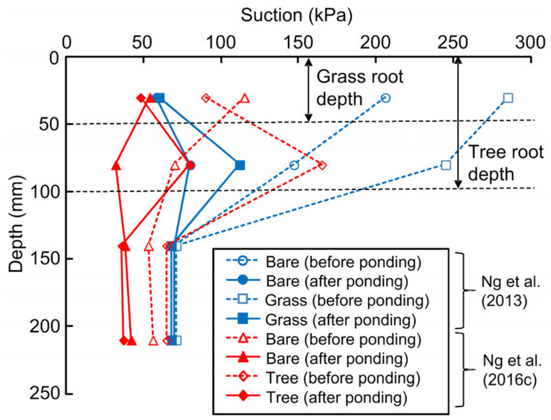

Fig. 7 Measured suction distributions in the single layer soils vegetated with grass and tree before and after ponding (Ng et al., 2013, 2016c)

4 Conclusions

This study explored the effects of vegetation type (i.e. shrub and grass) on water infiltration in a three-layer landfill cover system using recycled concrete. Based on the results, the following conclusions may be drawn:

1. During ET before ponding, the VWC in the fine recycled concrete layer of the vegetated three-layer system was generally lower than that of bare cover. Moreover, the water content under the shrub cover was even lower than that under the grass cover. This is because shrubs have deeper roots and a larger zone of influence on root water uptake than grass species.

2. After 48 h of ponding, equivalent to a rainfall return period of greater than 1000 years in Hong Kong, percolation was observed only under the bare cover. For the vegetated cover systems, even though capillary effects in the upper two layers were not effective, higher suction was maintained in the bottom layer than in the bare cover column. As expected, water permeability was lower in the vegetated columns, which prevented percolation.

3. Compared with the grassed cover, the cover with the shrub maintained a lower VWC and hence a higher suction in the layers. This implies that shrubs are more effective in reducing water infiltration in three-layer landfill covers in humid climates.

4. The vegetated three-layer landfill cover with recycled concrete satisfactorily minimized water infiltration under extreme rainfall conditions. This is therefore a promising alternative cover system for landfills. Note that these conclusions are based on a study carried out under specific conditions. Readers should be cautious about extending them to general use.

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中文概要

题　目：植物种类对由建筑垃圾构筑而成的三层土覆盖层系统防渗特性的影响研究

目　的：为提高资源重复利用率，建筑垃圾常常被回收、粉碎并重新应用在土木工程建设中。本文旨在将回收建筑垃圾骨料应用于三层土覆盖层系统，并研究植物对其防渗特性的影响。

创新点：1. 提出一种由建筑垃圾构筑而成的三层土覆盖层系统；2. 对比灌木、草以及裸土 3 种工况下该覆盖层的防渗特性。

方　法：1. 采用一维土柱渗透试验研究由建筑垃圾构筑而成的三层土覆盖层系统的防渗特性。2. 分别模拟灌木、草和裸土 3 种植被覆盖情况。3. 移栽植物并养护，而后进行降雨试验，对比 3 种植被覆盖层的吸力响应及水分渗入。

结　论：1. 在干旱条件下，蒸腾作用的大小顺序为：灌木>草>裸土，因为植物可以将更多的水分从覆盖层中释放到大气中；2. 在极端降雨条件下，相比裸土覆盖层，植被覆盖层可以更好地保持吸力并阻止渗滤液的产生，且灌木比草效果更佳；3. 在极端降雨条件下，由建筑垃圾构筑而成的植被型三层土覆盖系统是一种理想覆盖层，可以在湿润地区有效防止雨水下渗而进入垃圾体。

关键词：回收骨料；吸力；三层土覆盖系统；植物种类；土壤含水率