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TECHNICAL NOTE

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Soil–Water Characteristic Curve and Permeability Function of Recycled Concrete Aggregates Coated with Oil or Wax

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Reference

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ABSTRACT

Recycled concrete aggregate (RCA) is known to be a hydrophilic material. An attempt has been made to convert RCA into a hydrophobic material by coating it separately with oil or wax. Both oil and wax are known to increase the hydrophobicity of soil. Although the soil–water characteristic curve (SWCC) and permeability function of coarse-grained aggregates have been investigated, the effect of the introduction of hydrophobicity (coating it with oil or wax) into the coarse aggregates to their SWCC and permeability function has not been fully understood. The SWCC indicates that coating RCA with oil or wax modifies the drying and wetting curves as compared with RCA without any coating. The air-entry values and water-entry values are also modified upon coating. RCAs coated with oil or wax were found to prevent ingress of water during the wetting test for SWCC. The permeability function of RCAs is also modified.

Keywords

recycled concrete aggregate, soil–water characteristic curve, permeability function, oil, wax, hydrophobicity

Introduction

The National Environmental Agency Singapore aims to work toward “zero landfill” requirements, and the Building and Construction Authority has been working closely with industries to promote and adopt the use of recycled materials in construction to achieve environmental sustainability (Lang 2005; Building & Construction Authority 2012).

Limited studies have been conducted on the determination of the water characteristic curve (WCC) of recycled coarse aggregates (RCAs) (Rahardjo, Vilayvong, and Leong 2011; Rahardjo et al. 2013). Rahardjo, Vilayvong, and Leong (2011) studied the WCC of RCAs and reclaimed asphalt pavement (RAP) by using the Tempe cell. The results showed that the recycled materials with high gravel content have air-entry values (AEV) below 1.0 kPa and a steep WCC. The WCC and saturated coefficient of permeability were incorporated into a statistical model to indirectly predict the permeability function of the recycled materials.

Another study by Rahardjo et al. (2013) on fine and coarse RCAs and RAPs observed that the recycled materials have similar characteristics as natural aggregates under saturated and unsaturated conditions. The fine RCA and RAP have smaller particle sizes, higher water-entry values, and lower permeability as compared with the coarse RCA and RAP. The predicted wetting WCCs are close to the experimental data of wetting WCC of recycled materials.

RCA is known to be a hydrophilic material (Edil, Tinjum, and Benson 2012). Hence, in this study, an attempt has been made to convert RCA into a hydrophobic material by coating it, separately, with oil or wax. Both oil and wax are known to increase the hydrophobicity of soil (Smith 1974; DeBano, Savage, and Hamilton 1976; Doerr, Shakesby, and Walsh 2000). Few researchers have artificially prepared water repellent grains by mixing-in or solvent-in hydrophobic agents (Subedi et al. 2012) such as polytetrafluorethylene (Dell’Avanzi et al. 2010), stearic acid 5 (Leelamanie, Karube, and Yoshida 2008; González-Peñaloza et al. 2013), oleic acid (Subedi et al. 2012), and dichloromethylsilane (Bachmann and McHale 2009).

The main objective of the study was to understand the unsaturated hydraulic properties (SWCC and permeability function) of RCA under the hydrophobic condition.

This article presents the characterization of RCA coated with oil and wax. The SWCCs were measured in the laboratory using a Tempe cell (large), and permeability functions were computed indirectly using the measured SWCC results.

Materials and Methods

MATERIAL PREPARATION

Recycled Concrete Aggregate

Coarse RCA used in this study was sourced from Samwoh Corporation Pte. Ltd., Singapore. The investigated recycled materials are produced by removing all unwanted plastic, timber, and steel contents (Rahardjo et al. 2013).

Oil

Sunflower oil was sourced from the local market in Singapore. This is a nonvolatile oil compressed from sunflower (Helianthus annuus) seeds. It was preferred because the ecotoxicity is very low and the resources are regenerated yearly (Ştefănescu et al. 2005),

FIG. 1 Photographs of RCA: (a) RCA (Uncoated), (b) RCA (Oil), and (c) RCA (Wax).

implying that it is safe for the environment. Further, this was the cheapest oil available in the local market.

Wax

The paraffin wax used in this study was sourced from EPChem International Pte. Ltd., Singapore. Being essentially an alkane material, it is stable, shows good resistance toward oxidation, and does not dissolve in water (International Group, Inc., 2014). The photographs of RCA (Uncoated) and RCA coated with oil and wax are shown in **Fig. 1**.

For coating RCA with oil, the aggregates were kept submerged in oil bath in a plastic tub for 24 hours. After 24 hours, the oil was decanted from the tub, and any excess oil on the surface of the RCA was removed by wiping lightly with tissue paper. This wiping of excess oil from the surface of the aggregates was done to ensure that it did not clog or interfere with the ceramic disk in the Tempe cell during the determination of the SWCC.

For preparing RCA coated with wax, the wax was heated in a steel container to 150°C (higher than its melting point at 104°C. RCA (in small quantity) that was preheated to 105°C was put in a steel strainer and dipped in the liquid wax for five minutes. After that, the strainer with RCA was removed and the excess wax was allowed to drip. When the dripping of wax ceased, RCA was transferred to another steel container for drying.

LABORATORY TESTS

Experimental works in the laboratory were carried out to obtain the index properties and engineering properties of RCA (**Table 1**). Grain-size analyses were carried out in accordance with ASTM D422-63 (Reapproved 2007), *Standard Test Method for Particle-Size Analysis of Soils*, and are shown in **Fig. 2**. Relative density tests were carried out to determine the minimum and the maximum dry densities of the RCA according to ASTM D4253-00 (2006), *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table.*

The SWCC tests of the RCAs were carried out using a Tempe cell (with a 1-bar standard ceramic plate) following the procedures described in ASTM D6836 (2008)-e2, *Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge*. The details of the tests under a drying process for the recycled crushed concrete are similar to those explained by Rahardjo, Vilayvong, and Leong (2011).

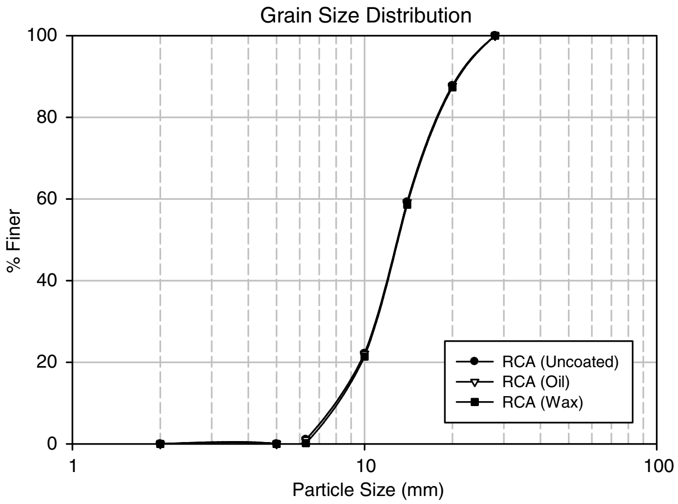
TABLE 1

Laboratory test results of RCA.

Properties	RCA (Uncoated)	RCA (Oil)	RCA (Wax)
Unified Soil Classification System (Group symbol)	GP	GP	GP
Group name	Poorly graded gravel	Poorly graded gravel	Poorly graded gravel
Specific gravity, G_s	2.64	2.62	2.61
Grain-size distribution			
D_{60}, mm	14.0	14.0	14.1
D_{30}, mm	12.1	12.1	12.2
D_{10}, mm	8.2	8.2	8.3
Coefficient of uniformity, C_u	1.707	1.707	1.699
Coefficient of curvature, C_c	1.275	1.275	1.272
Gravel content (> 4.75mm), %	99.4	100	100
Fines content (< 0.075mm), %	0	0	0
Relative Density Test Results			
Max. dry density, $\gamma_{d\ max}$, Mg/m^3	1.89	1.91	1.88
Min. dry density, $\gamma_{d\ min}$, Mg/m^3	1.25	1.26	1.245
Maximum void ratio, e_{max}	1.10	1.10	1.12
Minimum void ratio, e_{min}	0.39	0.39	0.40
Porosity correspond to e_{max}, n_{max}	0.52	0.52	0.52
Porosity correspond to e_{min}, n_{min}	0.28	0.28	0.28
Dry density of the specimens, ρ_{dry}, Mg/m^3 (80 % * max. dry density)	1.51	1.53	1.50
Void ratio of the specimens, e	0.75	0.74	0.73
Porosity of the specimen, n	0.43	0.42	0.43
Saturated permeability, k_s, m/s	0.075	0.078	0.080

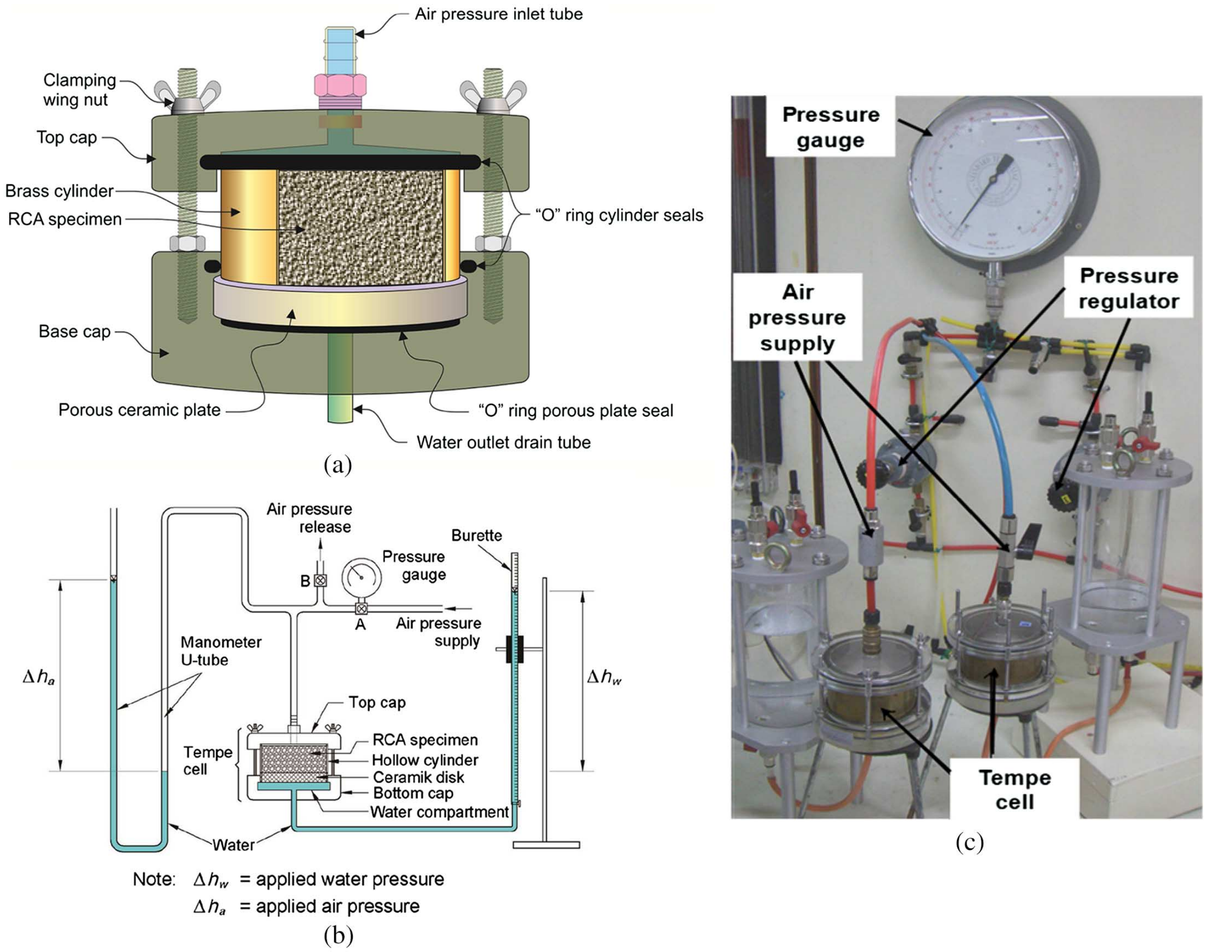
FIG. 2

Grain-size distribution curve of RCA (Uncoated), RCA (Oil), and RCA (Wax).



Based on the minimum and the maximum dry densities, RCA was placed in the Tempe cell and hand-compacted to achieve a density of 80 percent of the corresponding maximum dry density. The Tempe cell was used to measure the SWCC of coarse-grained RCA under three conditions: uncoated, coated with oil, and coated with wax. A zero

FIG. 3 Details of the Tempe cell: (a) line diagram of the Tempe cell, (b) sketch showing test setup, and (c) photograph of the Tempe cell and air pressure regulator assembly.



pore-water pressure was maintained at the bottom part of the specimen inside the Tempe cell, whereas air pressure was provided on top of the specimen. Details of the Tempe cell and the test setup are shown in **Fig. 3**.

A Tempe cell apparatus from SoilMoisture (Soilmoisture Equipment Corp., Santa Barbara, CA) was used to obtain the SWCC of the recycled materials in the matric suction range of 0–100 kPa (ASTM D6836-02, 2008). The Tempe cell consists of three parts: Top and base caps, hollow brass cylinder, and porous ceramic disk. The porous ceramic disk is a 1-bar (100 kPa) high-air-entry disk. O-rings are used to seal the joints to keep the cell airtight during the test. The brass cylinder of 88 mm in inner diameter and 60 mm in height was used for the tests (**Fig. 3a**).

The complete SWCC was obtained by following drying or wetting processes. Coarse-grained materials show a small AEV in the SWCC, and hence, they require the application of low matric suctions. However, applying low matric suctions to a specimen during desaturation (or drying process) is not easy. For low matric suction control (<10 kPa), the technique suggested by Rahardjo et al. (2013) was used because it can be implemented to apply matric suction as low as 0.001 kPa. For such low matric suction controls, modification to the air pressure system was made (Fig. 3b); regulator A is to regulate the air pressure supply and regulator B is to regulate the air release. A U-tube manometer was used to control water pressure head, and the readout from the head difference reflected the matric suction. Similar arrangements for applying low matric suctions in the Tempe cell have been reported by many researchers (Vanapalli, Garga, and Sedano 2007; Rahardjo, Vilayvong, and Leong 2011; Rahardjo et al. 2013). A photograph of the Tempe cell, air pressure regulator, and manometer is shown in Fig. 3c.

Before starting the test, the high air-entry ceramic disk was submerged in de-aired distilled water for saturation inside a vacuum desiccator for 24 hours. The compacted specimen inside the brass cylinder of Tempe cell was also saturated with de-aired distilled water. The compacted specimen was placed in the Tempe cell and weighed. The desired values of matric suction were controlled by regulating air pressure to the Tempe cell by means of the axis translation technique (Hilf 1956) while maintaining the pore-water pressure (u_w) at atmospheric pressure ($u_w = 0$). Therefore, the matric suction is equal to the air pressure applied. At the start of the test, 0.01 kPa of matric suction (1-mm water head difference in the U-tube manometer) was applied to the specimen. The water level outside the Tempe cell was kept at the same level as the top surface of the ceramic disk to ensure that the disk remained saturated during the test. The matric suction was applied until equilibrium was observed (i.e., the weight of the Tempe cell remained unchanged). This can be verified by plotting the weight of the Tempe cell with respect to time. The same procedure was applied for the next higher values of matric suction until there was no more reduction in the weight of the specimen. Finally, the specimen was removed from the Tempe cell and the remaining water content was measured by oven drying. The change in the mass of water at each applied matric suction was then back-calculated. A complete variation of volumetric water content with respect to matric suction was obtained by fitting the experimental data with the Fredlund and Xing (1994) equation.

The test for the determination of the SWCC under a wetting process was carried out after obtaining the drying curve of the SWCC. The air pressure was decreased from the last air pressure at the end of the drying process of the SWCC. Water then started to seep into the RCA. The air pressure was decreased according to the planned steps of matric suction decrement until a matric suction equal to 0.001 kPa was reached. At the end of the test for wetting SWCC, the water content of the RCA was determined. In this study, the permeability function was computed indirectly using the method explained in Fredlund and Rahardjo (1993). SWCC and saturated permeability were used in the computation.

Tokunaga and Sato (1975) and Sato and Tokunaga (1976) indicated that the representative elementary volume for bulk density, water content, and solute concentration is 5 cm or larger. The specimen size used in the Tempe cell in our test had a diameter and height larger than 5 cm; therefore, the specimen size can moderately accommodate the variation of density and water content in RCA. Further, several researchers (Rahardjo, Vilayvong, and Leong 2011; Rahardjo et al. 2013) have used a Tempe cell to study the WCC of coarse RCA.

However, even if there is a size effect in the SWCC of the RCAs obtained in the large size Tempe cell, the comparison of the SWCCs of RCA (uncoated), RCA (oil), and RCA (wax), which is the objective of this article, is still valid because the same size effect exists for all the tests. Also, other conditions of the tests remain the same. As such, the article focuses only on comparing the test results, which are discussed in the following section.

Results and Discussion

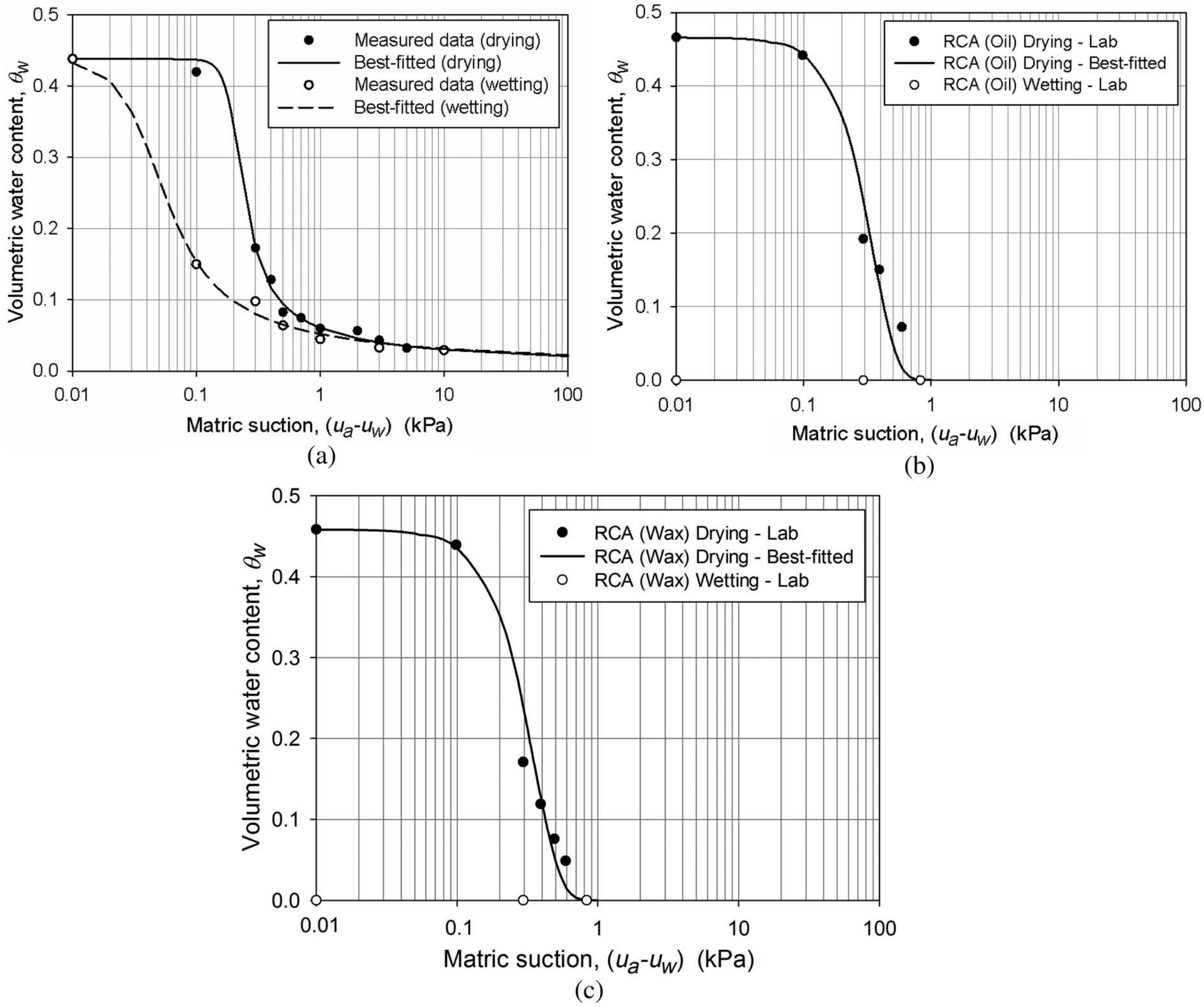
GRAIN-SIZE DISTRIBUTION OF RCA (UNCOATED), RCA (OIL), AND RCA (WAX)

The grain-size distributions and classifications of RCA (Uncoated), RCA (Oil), and RCA (Wax) were carried out in accordance with ASTM D6913-04, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*, and ASTM D2487-10, *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, respectively, and the results are shown in **Fig. 2** and **Table 1**.

SOIL–WATER CHARACTERISTIC CURVE (SWCC)

The soil–water characteristic curves of RCA (Uncoated), RCA (Oil), and RCA (Wax) are shown in **Fig. 4**. The SWCC of RCA (uncoated) follows different paths during drying and wetting processes. The water content during drying and wetting paths are different at a given matric suction. The water content at saturation is observed to be very close during

FIG. 4 Soil–water characteristic curves of RCAs: (a) RCA (Uncoated), (b) RCA (Oil), and (c) RCA (Wax).



(a)
(b)
(c)

drying and wetting. At a matric suction equal to zero, drying and wetting curves have about the same volumetric water content (0.43 and 0.42 for drying and wetting curves, respectively). Large pores between RCA grains minimize the volume of entrapped air. This condition caused the volumetric water content at a matric suction equal to zero in the wetting curve to become close to that in the drying curve.

Such different drying and wetting paths also indicate that the SWCCs of RCA are similar to those of natural aggregates. The difference in the drying and wetting water characteristic curve is referred to as hysteresis (Fredlund and Rahardjo 1993). The possible mechanisms that cause hysteresis in the SWCC can be the contact-angle effect (between air–water and solid particles) (Bear 1979), or the capillary theory of ink bottle effect (Fredlund and Rahardjo 1993).

However, the drying and wetting curves of RCA (Oil) and RCA (Wax) showed a different behavior as compared to RCA (Uncoated). The drying path of SWCC of both RCA (Oil) and RCA (Wax) reached a zero volumetric water content at a matric suction close to 1.0 kPa; RCA (Uncoated) reached a volumetric water content equal to 0.03 at a matric suction of 10 kPa.

In addition, no wetting curve could be obtained in case of RCA (Oil) and RCA (Wax) (**Fig. 4b** and **c**, respectively). The water content remained zero when the matric suction was reduced from 1.0 kPa to 0.01 kPa to obtain the wetting curve of the SWCC. A possible reason for such behavior might be that the coating of RCA with oil or wax, which changed its behavior from hydrophilic to hydrophobic, prevented any ingress of water in the macropores during the wetting phase. The coating might have also prevented water from entering the micropores of RCA.

The AEV of RCA (Uncoated) is recorded at 0.1 kPa. The same is recorded at 0.018 and 0.015 kPa for RCA (Oil) and RCA (Wax), respectively. With the increase in matric suction in the case of RCA (Uncoated), the reduction in volumetric water content is gradual, i.e., the slope of the drying curve is gentle. However, in cases of RCA (Oil) and RCA (Wax), the slope of the drying curve is very steep, implying a very fast reduction in volumetric water content. In other words, it can be said that the volumetric water content in the drying path of the RCA (Uncoated) is marginally higher than that of the RCA (Oil) and RCA (Wax) at the same matric suction up to the residual water content. Beyond that, the volumetric water content of the RCA (uncoated) is much higher than that of the RCA (Oil) and RCA (Wax). A possible reason for this may be that the coated RCAs are not able to hold water as they behave as hydrophobic materials and, hence, show a water repelling tendency. Additionally, some water is trapped in the pores of the RCA (Uncoated), showing a higher volumetric water content than RCA (Oil) and RCA (Wax), whose pores are devoid of water because of the coating on them.

Further, the water entry value in the case of the RCA (Uncoated) during wetting is recorded at 0.3 kPa. However, in the cases of RCA (Oil) and RCA (Wax), the same could not be recorded because the wetting curve could not be obtained. For a better comparison of the SWCCs of the three RCAs, i.e., RCA (Uncoated), RCA (Oil), and RCA (Wax), the drying and wetting curves of SWCCs are shown together in **Fig. 5**.

The experimental data of drying and wetting SWCCs of RCA (Uncoated), RCA (Oil), and RCA (Wax) were fitted using the Fredlund and Xing (1994) equation using the actual correction factor obtained. The hydraulic properties of RCA (Uncoated), RCA (Oil), and RCA (Wax) are shown in **Table 2**.

The experimental data of drying and wetting SWCCs were compared with the predicted drying and wetting SWCCs. **Table 2** shows that the R^2 values of RCA (Uncoated),

FIG. 5

SWCCs (drying and wetting) of RCA (Uncoated), RCA (Oil), and RCA (Wax).

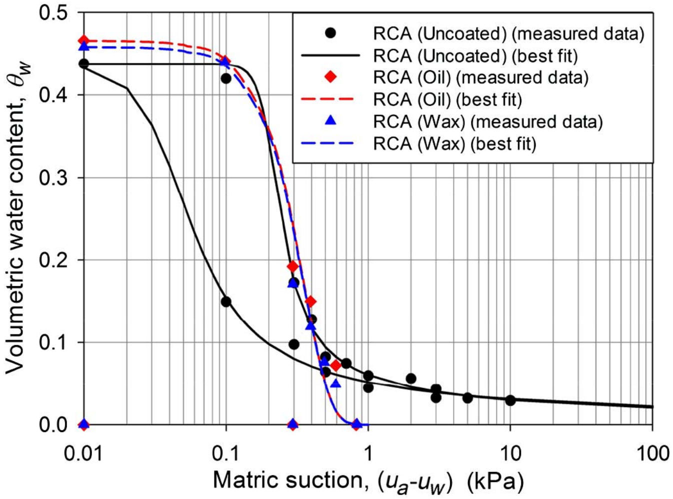


TABLE 2

Hydraulic properties of RCA (Uncoated), RCA (Oil), and RCA (Wax).

		RCA (Uncoated)		RCA (Oil)		RCA (Wax)	
Description	Symbol	Drying	Wetting	Drying	Wetting	Drying	Wetting
Saturated volumetric water content	θ_s	0.43	0.42	0.42	–	0.43	–
Air-entry value, kPa	*AEV*	0.1	–	0.018	–	0.015	–
Residual volumetric water content	θ_r	0.03	–	0.0	–	0.0	–
Water-entry value, kPa	*WEV*	–	0.3	–	–	–	–
Fredlund and Xing (1994) parameters for	*a*	0.20	0.036	4.36	–	4.31	–
fitting drying and wetting curves	*n*	7.33	2.68	2.34	–	2.36	–
	m	0.80	0.98	975.13	–	975.13	–
Coefficient of determination	R^2	0.9976	0.9960	0.9674	–	0.9999	–

RCA (Oil), and RCA (Wax) are close to 1, indicating a good performance of the Fredlund and Xing (1994) equation in estimating the drying and wetting SWCCs of RCA (Uncoated) as well as the drying curves SWCC of RCA (Oil) and RCA (Wax). The results presented in **Table 2** also show that RCA (Uncoated) has the highest AEV among the three materials, followed by RCA (Oil); RCA (Wax) has the lowest.

The saturated volumetric water content (**Table 2**) of the RCA (Untreated) is higher than its porosity (**Table 1**) because the RCA contained cement paste that could absorb more water during the saturation process relative to natural aggregates. This phenomenon was also observed by Limbachiya et al. (2004) who indicated that cement paste was porous and contributed to the additional water content during the saturation process of RCA.

Further, similar higher saturated volumetric water contents were also observed in RCA (Oil) and RCA (Wax), although their surfaces were coated with oil or wax, respectively, thus preventing the absorption of more water during the saturation process. However, this might be due to the fact that RCA was kept in oil or wax (molten) for a certain period of time, and this might have permitted the oil or wax to penetrate the micropores of RCA, thus showing a higher saturated water content than their porosity.

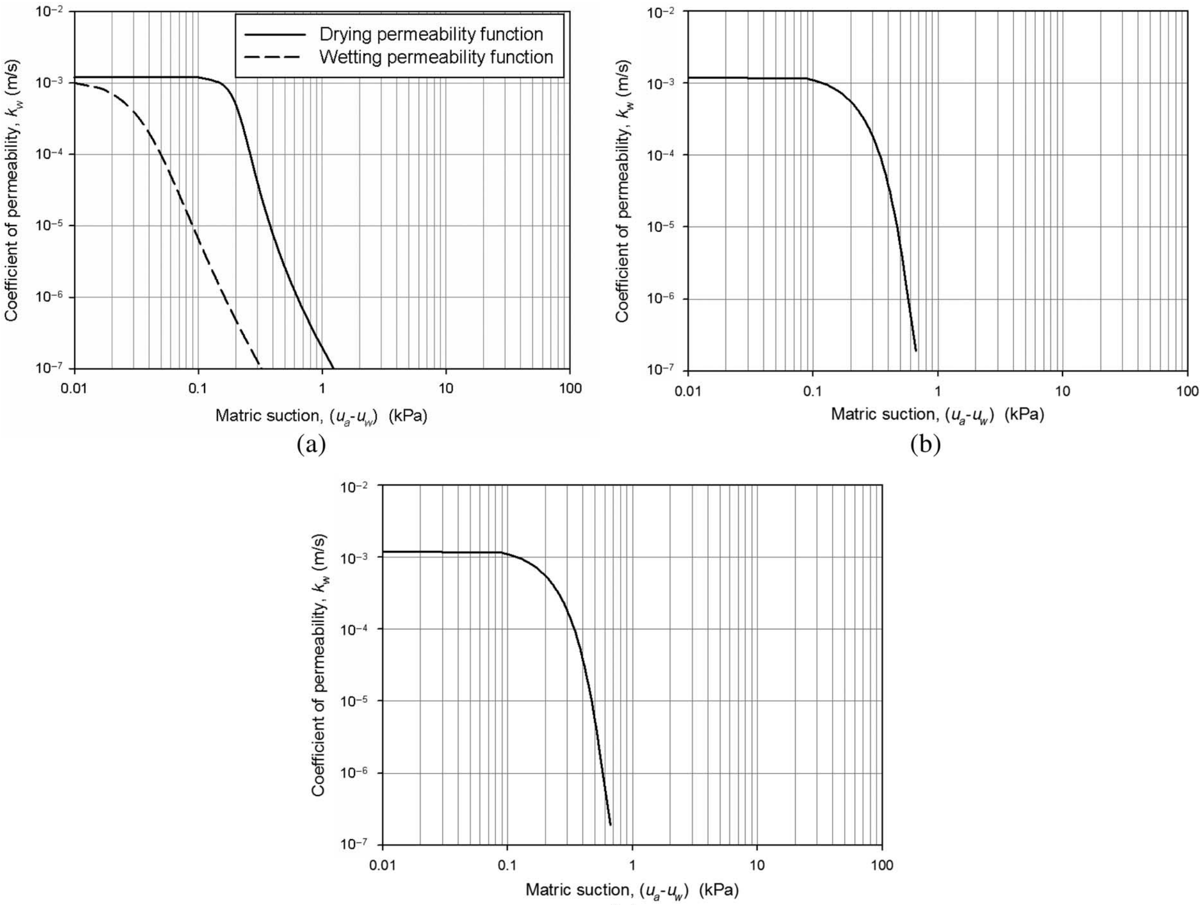
PERMEABILITY FUNCTION

The permeability function of RCA (Uncoated) during the drying and wetting processes is shown in Fig. 6a, and the permeability functions of RCA (Oil) and RCA (Wax) during the drying process only are shown in Fig. 6b and c, respectively. It is observed that the permeability of RCA (Uncoated) during the wetting process is lower than that during the drying process. Similar findings were reported by Rahardjo et al. (2013). The authors observed that this happened because of the higher air content during wetting, resulting in smaller available pore-volumes, thereby limiting the water flow within the pores of RCA.

The permeability functions of RCA (Oil) and RCA (Wax) during the drying process are very similar to each other. However, they are somewhat different from RCA (Untreated) as their slope is rather steep, implying that they become impervious at relatively lower matric suctions.

Further, the permeability functions of RCA (Oil) and RCA (Wax) could not be determined during the wetting process because no SWCC could be determined during this process. The test results of the hydraulic properties (SWCC and permeability function) of the RCA coated with oil or wax indicate that the coated RCA has become a hydrophobic material.

FIG. 6 Permeability function of RCA: (a) RCA (Uncoated), (b) RCA (Oil), and (c) RCA (Wax).



(a)

(b)

(c)

Applications and Environmental Effects

RCAs as capillary barrier materials have been studied and found to be feasible. As demonstrated by a number of scientific investigations (Stormont and Anderson 1999; Khire, Benson, and Bosscher 2000; Harnas et al. 2014), capillary barriers are an efficient type of sealing system that can be used as a final cover on landfills and remediation sites. Rahardjo, Krisdani, and Leong (2007) described a capillary barrier system (CBS) as a two-layer system (two sloping layers) of distinct hydraulic properties that is used as a cover system. A noncohesive fine-grained material is used in the upper layer, overlying a coarse-grained layer. The distinct hydraulic properties (i.e., SWCC and permeability function) between the fine-grained and coarse-grained layers prevent water infiltration into the soil below the CBS by utilizing the unsaturated soil mechanics principles. Under unsaturated conditions, the permeability of the coarse-grained layer is lower than the permeability of the fine-grained layer, limiting the downward movement of water through the capillary barrier effect. The infiltrated water is stored temporarily in the fine-grained layer and then removed by lateral drainage through the slope. As a result, the infiltrating water will not enter the coarse-grained layer because of its lower permeability relative to the fine-grained layer, protecting the underlying soil.

The study was intended to enhance the effectiveness of the coarse-grained layer in preventing water infiltration from the fine-grained layer by making the materials for the coarse-grained layer hydrophobic. In this case, the RCA, which was intended to be used as the material for the coarse-grained layer, was coated with oil or wax in order to make RCA hydrophobic. Because hydrophobic RCA can increase the contrast in the hydraulic conductivities of the two layers in a CBS, the resulting CBS can be expected to be more efficient than a traditional one. The use of the CBS as a slope cover system has been highlighted by Rahardjo (2015) and Rahardjo et al. (2012). Recently the CBS has also been incorporated as part of an earth retaining structure, as demonstrated in Rahardjo et al. (2018).

In this study, paraffin wax and cooking oil are used to coat RCA. The wax used is solid at room temperature, and if it enters soil, it will quickly be adsorbed to soil particles, it will be of low or no mobility, and it will not contaminate ground water (International Group, Inc., 2014).

It was reported by Smith (1974) that cooking oil that went to the land disposal showed no evidence for being toxic to decomposition systems.

Conclusions

The following conclusions are drawn based on the results:

(1) The AEV of RCA (Untreated) is the highest among all, followed by RCA (Oil). RCA (Wax) has the lowest AEV.
(2) RCA (Oil) and RCA (Wax) have no SWCC during the wetting process. This is most likely due to the hydrophobic nature of oil- or wax-coated RCA, which prevents ingress of water during the wetting process.
(3) The saturated permeability of RCA (Wax) is the highest, and the saturated permeability of RCA (Uncoated) is the lowest.

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