Hydraulic Properties of Recycled Asphalt Pavement and Recycled Concrete Aggregate

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ABSTRACT

The saturated hydraulic conductivity (k_{sat}) and water characteristic curves (WCCs) of three recycled asphalt pavements (RAPs) and three recycled concrete aggregates (RCAs) were measured. The k_{sat} was determined using a constant-head, rigid-wall, 152-mm-diameter permeameter. The specimens were prepared at 95% of maximum dry density based on modified Proctor testing. The k_{sat} of the RAPs varied from 3.8×10^{-5} to 3.7×10^{-4} m/s and from 1.6×10^{-5} to 2.6×10^{-5} m/s for the RCAs. Hazen's equation (1911) tends to over predict k_{sat} for RAPs and RCAs. Hanging columns with large-scale testing cells (305-mm inner diameter and 76-mm height) fitted with air aspirators were used to determine the WCCs. The WCC of each recycled material was fitted using the Fredlund and Xing (1994) model because this model is used in the Mechanistic-Empirical Pavement Design Guide (MEPDG). A hanging column test can measure suction lower than 1 kPa with high accuracy ($\pm$0.02 kPa). The slopes of the WCCs of RAPs were steeper than those of RCAs, although RAPs have higher densities. Compared to Rahardjo et al. (2010), RAPs and RCAs used in this study provided higher air entry suction because the specimens were prepared at higher, compacted density to replicate field conditions. To develop a WCC for RAPs and RCAs over a larger range of suctions, a device such as a pressure plate extractor is recommended.

INTRODUCTION

The use of recycled material as a base course in pavement construction has widely increased over recent decades. Use of recycled material can reduce global warming potential, energy consumption, and hazardous waste generation (Lee et al., 2010). The use of recycled material can also provide cost and time savings because the material is generated and reincorporated on site (Bennert et al., 2000).

Among recycled materials, recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA) are commonly used for pavement construction (FHWA, 2008). RAP is a coarse granular material derived from crushing existing asphalt surfaces. RCA is an aggregate obtained from demolition of concrete structures such as roads, runways, and buildings (Guthrie et al., 2007; FHWA, 2008). Studies have confirmed that recycled materials can provide high strength and durability, either as a mixture or as a complete replacement for conventional aggregate (Blankenagel and Guthrie, 2006). However, the hydraulic properties of RAPs and RCAs, which affect long-term performance of base course (Cedergren, 1988), have not been thoroughly investigated.

The important hydraulic properties of base course include saturated hydraulic conductivity (k_{sat}) and the water characteristic curve (WCC). The Mechanistic-Empirical Pavement Design Guide (MEPDG) requires k_{sat} as an input for drainage design and the WCC for adjusting the modulus for base and subgrade for structural pavement design (NCHRP, 2004). However, the WCCs of RAP and RCA (typically, coarse aggregate) are difficult to obtain directly because the water content of coarse aggregate can change rapidly at low suction (< 1 kPa), and few methods measure suction, ψ, accurately for $\psi < 1$ kPa (Li et al., 2009). To accurately characterize the hydraulic properties of large aggregate, specimens should be prepared at field density, and large enough to represent field compaction condition. ASTM D2434-68 recommends that the minimum diameter of a specimen cylinder for granular material should be approximately 8 times of the maximum aggregate size for hydraulic conductivity test.

This study investigated the k_{sat} of three compacted RAPs and three RCAs used as base course with constant-head, rigid-wall, compaction-mold permeameters. The WCCs were measured by hanging columns with large-scale testing cells (304-mm inner diameter and 76-mm height). The WCC of each recycled material was fit using the Fredlund and Xing (1994) model because this model is used in the Mechanistic-Empirical Pavement Design Guide (MEPDG). The hydraulic properties of RAP and RCA measured in this study are compared to results from the literature for similarly graded, coarse aggregate.

Hydraulic properties of coarse granular material

Saturated hydraulic conductivity

Saturated hydraulic conductivity (k_{sat}) is the property that defines the ability of water to flow through saturated soil. The k_{sat} of granular material is mainly influenced by particle size and grain size distribution. Various empirical relationships have been proposed to predict k_{sat} of coarse-grained soil (e.g., Hazen, 1911; Kenny et al., 1984; Sherard et al., 1984). Hazen (1991) proposed the relationship between k_{sat} and effective diameter (D_{10}) for uniformly graded, loose sand as:

$$k_{sat} = 0.01 c_1 D_{10}^2 \qquad (1)$$

where the unit of k_{sat} is m/s, c_1 is a constant related to particle shape (0.4 to 1.2), and D_{10} is the 10th percentile for particle size in units of mm.

Water characteristic curve

A WCC describes the relationship between water content or degree of saturation and ψ, where $\psi = u_a - u_w$ (u_a is pore air pressure and u_w is pore water pressure). The ψ corresponding to the intersection of the two sloping lines at low suction of the WCC is defined as the air-entry suction (ψ_a) (Fredlund and Rahardjo, 1993). Although the drying path and wetting path of the WCC might be different due to hysteresis, measurement of the wetting path is difficult and only the drying curve is typically measured, especially for granular material (Hillel, 1980).

Numerous fitting equations have been proposed to describe the WCC (e.g., Brooks and Corey, 1964; van Genuchten, 1980; Fredlund and Xing, 1994). Among those models, the Fredlund and Xing equation provides a sigmoid curve suitable for different type of soil for matric suction from 0 to 1 GPa. The model requires four fitting parameters as defined by:

$$\theta = C(\psi)\frac{\theta_s}{\left\{ln\left[e+(\psi/a_f)^{b_f}\right]\right\}^{c_f}} \qquad (2)$$

$$C(\psi) = \left[1 - \frac{ln\left(1+\frac{\psi}{h_{rf}}\right)}{ln\left(1+\frac{1\,000\,000}{h_{rf}}\right)}\right] \qquad (3)$$

where θ is volumetric water content, θ_s is saturated volumetric water content, ψ is suction in kPa, and a_f, b_f, c_f and h_{rf} are fitting parameters. $C(\psi)$ is the adjusting function used to force θ to zero at 1 GPa.

MATERIALS

Three RAPs and three RCAs were collected from different states across the US (Bozyurt, 2011). The RAPs and RCAs were named according to the source state. Index tests were conducted on each recycled material. Grain size distribution and classification were determined according to ASTM D422. Specific gravity (G_s) and percent absorption were determined per AASHTO T85. Compaction tests were conducted using modified Proctor effort according to ASTM D1557.

Results of index tests on the RAPs and RCAs are summarized in Table 1. The RAPs and RCAs are broadly graded, including classifications of SM, SP, SW, and

GM according to the Unified Soil Classification System (USCS). The G_s of RAPs are lower than conventional aggregates because RAPs are comprised of asphalt, which has low G_s. The grain size distributions of the tested materials are presented in Figure 1. RAPs have a lower percentage of fines than RCAs. RAPs are hydrophobic materials, while RCAs are hydrophilic materials (Rahardjo et al., 2010). Thus, percent absorption tends to be higher in RAPs as compared to RCAs. Percent absorption of RAPs ranged between 1.5 and 3.0, while RCAs had percent absorption ranging from 5.0 to 5.8. Compaction curves for RAPs and RCAs are presented in Figure 2. Both RAP and RCA are sensitive to the molding water content. RAP has higher maximum density than RCA and lower optimum water content.

Table 1. Properties of RAPs and RCAs

Properties	RAP			RCA		
	Colorado	New Jersey	Wisconsin	Colorado	California	MnROAD
USCS designation	SP	GW	SP	SM	SW	SP
Specific gravity, G_s	2.40	2.49	2.46	2.63	2.63	2.71
Maximum dry unit weight (kN/m^3)	20.6	20.3	20.2	18.9	19.8	19.7
Optimum water content (%)	5.7	6.4	7.7	9.3	10.9	11.2
Percent fines	0.7	0.7	0.5	12.82	3.05	2.32
Percent absorption	3.0	2.1	1.5	5.8	5.0	5.0

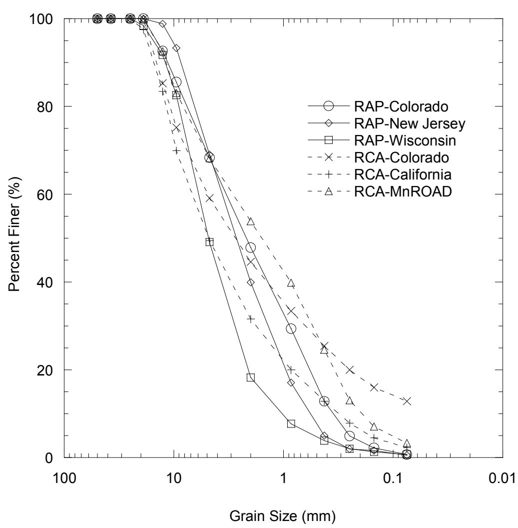

Figure 1. Grain size distributions

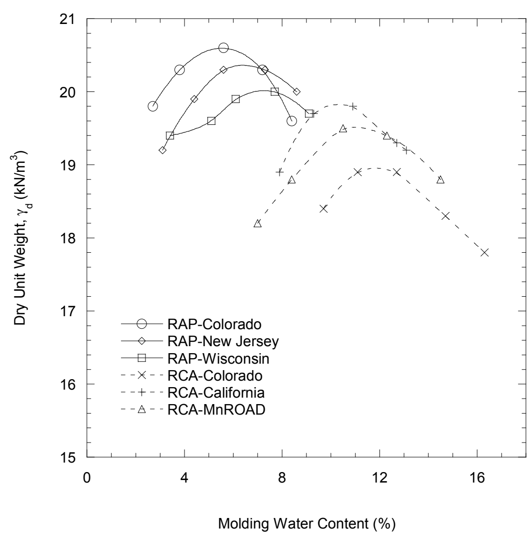

Figure 2. Modified Proctor compaction curves

METHODS

Hydraulic conductivity measurement

Hydraulic conductivity was conducted following ASTM D5856, measurement of hydraulic conductivity of porous material using a rigid-wall, compaction-mold permeameter. The specimens were compacted in 152-mm-diameter compaction molds at 95% of the maximum dry density as shown in Table 1. Tap water was used for all tests. The flow rate of an empty cell was checked for compliance in head loss. If the flow rate of an empty cell is lower than 10 times the flow rate of the cell with the specimen, the head loss from the specimens can be considered to be negligible (Daniel, 1994). The head was kept constant with a Marriott bottle. The hydraulic gradients were less than 5 because a high hydraulic gradient can wash fines from the sample. The ratio of outflow to inflow was measured to confirm saturation of the specimens.

WCC measurement using large-scale hanging column test

A hanging column test combined with an air aspirator was used to determine the WCCs for the RAPs and RCAs. Figure 3 presents the schematic of the hanging column test. The test equipment includes four main parts: testing cell, outflow column, manometer, and the hanging column. The hanging column test can measure the WCC precisely at ψ < 1 kPa with high accuracy ($\pm$0.02 kPa; i.e., ≅ 2-mm height of water). The lowest ψ which can be measured with this setup is 0.05 kPa. The highest ψ for the hanging column test is approximately 80 kPa due to the limitation of water cavitation. However, ceiling height also limits the ψ applied, or 25 kPa in this study. Suction higher than 25 kPa was supplied to the specimens using an air aspirator.

Testing followed ASTM D6836 method A. Large-scale cylinder specimens of 305-mm inner diameter and 76-mm height were prepared to simulate a base course layer in the field (Figure 4). A 1-bar porous ceramic plate was used in the testing cell. Rubber gaskets were installed to prevent air flow intrusion.

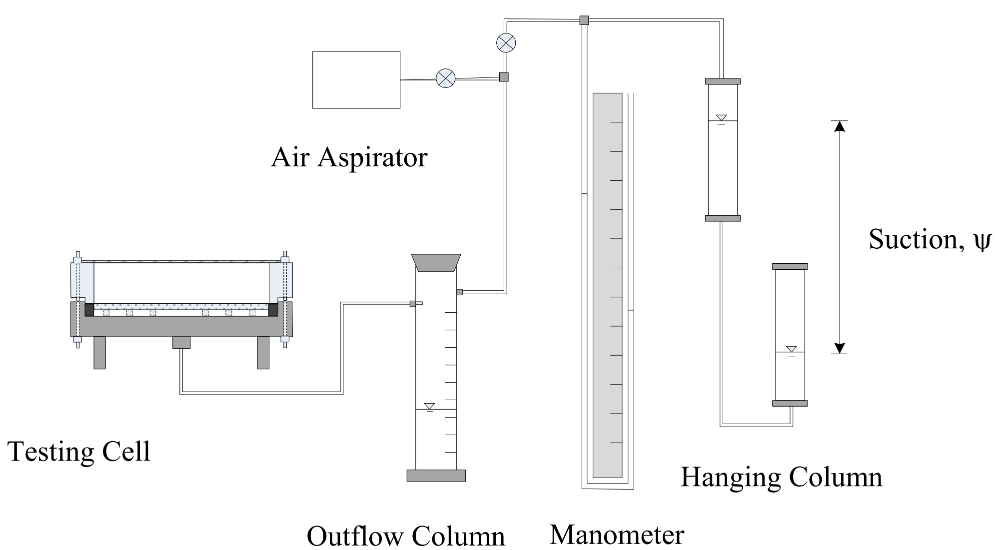

Figure 3. Schematic of hanging column apparatus

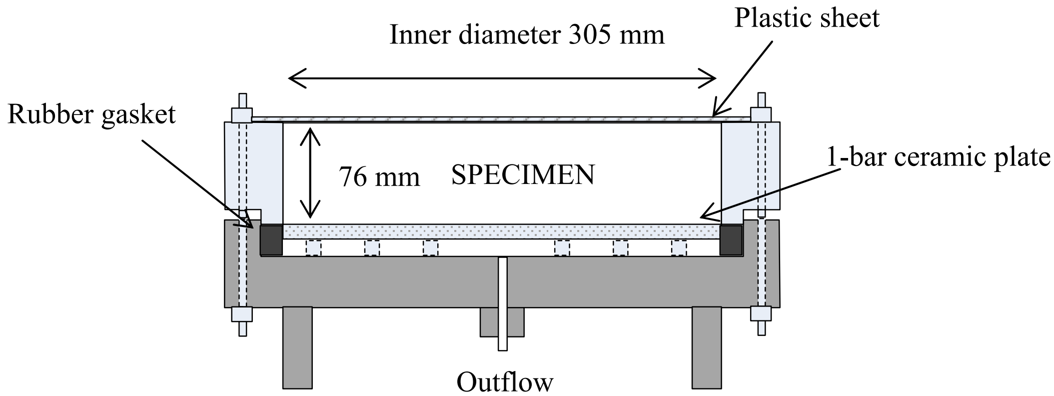

Figure 4. Schematic of large-scale testing cell

The specimens were prepared at θ_s calculated from the desired dry unit weight and measured G_s. Specimens were compacted in the testing cell to 95% of maximum dry density. A shaking table was used during compaction to ensure the specimen reached the target density. De-aired, distilled water was used for specimen preparation.

RESULTS

Average k_{sat} determined from five replicate tests are summarized in Table 2. The average k_{sat} of the RAPs ranged between 3.8x10^{-5} to 3.7x10^{-4} m/s, while k_{sat} of the RCAs ranged between 1.6x10^{-5} and 2.6x10^{-5} m/s. A statistical chart presenting the maximum and minimum values, and the percentiles at 75, 50 (median), and 25 for k_{sat} is depicted in Figure 5. The measured k_{sat} varied within a narrow range (maximum k_{sat}/minimum k_{sat} <2) for each replicate test for RAP and RCA, which indicates consistency of method. Figure 6 presents the relationship between effective diameter (D_{10}) and k_{sat} for the recycled materials. Increasing D_{10} tends to increase k_{sat} for RAPs, but does not show significantly increasing k_{sat} for RCAs. The Hazen (1911) prediction for k_{sat} (Eqn. (1)) was developed by using c_1 = 0.4 and 1.2 for the lower and upper bounds, respectively. RAPs and RCAs have lower k_{sat} for the same D_{10}. In comparison to the loose, uniformly graded aggregate for which the Hazen empirical equation was developed, the recycled materials of this study are compacted and more broadly graded; thus, this widely used predictor of k_{sat} is not applicable for these recycled materials.

Table 2 Average (k_{sat}) of RAPs and RCAs

Description	RAP			RCA		
	Colorado	New Jersey	Wisconsin	Colorado	California	MnROAD
D_{10} (mm)	0.35	1.00	0.56	0.073	0.31	0.08
Measured k_{sat} (m/s)	3.8x10^{-5}	3.7x10^{-4}	5.2x10^{-5}	1.6x10^{-5}	1.9x10^{-5}	1.8x10^{-5}

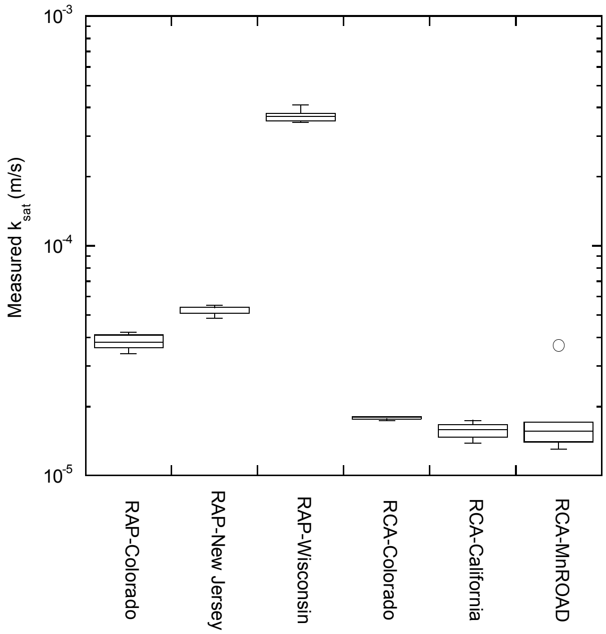

Figure 5. Statistical chart for k_{sat} of RAPs and RCAs

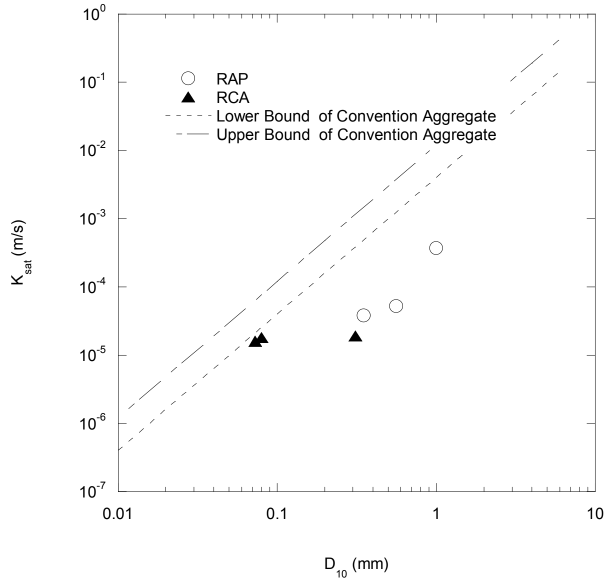

Figure 6. K_{sat} versus D_{10} forRAPs and RCA

The hanging column test combined with an air aspirator used in this study measured suction between 0.05 and 75 kPa for RAP and RCA, with high accuracy for low suction measurements ($\pm$0.02 kPa). Measured WCCs of the RAPs and RCAs are presented as Figure 7. The ψ_a of the RAPs range from 0.1 to 1.1 kPa, and from 0.5 to 3.0 kPa for the RCAs. The slope at the desorption part of the WCC is greater for the RAPs in comparison to the RCAs. Residual water content (θ_r) represents the water content at the dry state of the WCC for which an increase in ψ does not correspond to an appreciable change in θ. The θ_r of RAPs was obtained for RAP-New Jersey and RAP-Wisconsin. However, the θ_r of RAP-Colorado and the RCAs were indeterminate in this study. Extending the ψ measurement to a higher range (> 80 kPa) from another test method (e.g., pressure plate extractor) is recommended if a full-range WCC of RAP and RCAs is desired or necessary.

The data from each measured WCC was fit to the Fredlund and Xing (1994) model as presented by Eqns (2) and (3) using least square methodology. As shown in Figure 7, the Fredlund and Xing model provides good fits for the recycled materials evaluated in this study. The a_f parameter might be related to ψ_a of the WCC, while the b_f and c_f parameters influence the slope of WCC at low and high ψ, respectively. The higher the b_f, the greater the slope on the desorption portion. The h_{rf} parameter used to adjust θ became zero at 1 GPa. The fitting parameters for the Fredlund and Xing model are summarized in Table 3.

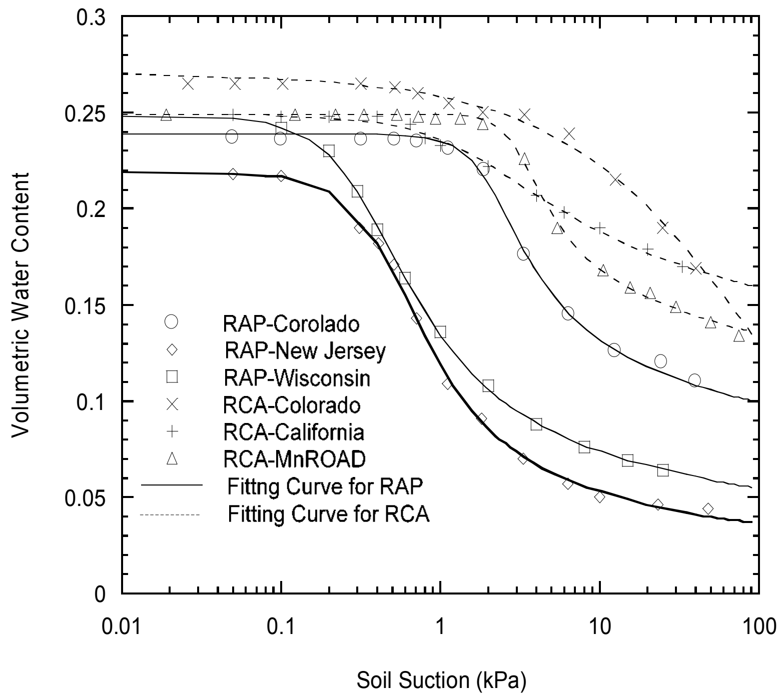

Figure 7. Measured WCC data fitted to Fredlund and Xing (1994) model

Table 3 WCC parameters for RAPs and RCAs

Description	Symbol	RAP			RCA		
		Colorado	New Jersey	Wisconsin	Colorado	California	MnROAD
Saturated θ, Porosity	θ_s, n	0.24	0.22	0.25	0.27	0.25	0.25
Air Entry Suction, kPa	ψ_a	1.1	0.2	0.1	3.0	0.5	1.7
Fredlund and Xing fitting parameters							
Best fit	a_f(kPa)	1.8	0.4	0.3	4.1	1.4	2.8
	b_f	3.5	2.4	2.1	1.2	1.2	4.7
	c_f	0.3	0.7	0.6	0.4	0.2	0.2
	h_{rf}(kPa)	97	97	100	6197	5596	6047

Table 4 Comparison of ψ_a of RAPs and RCAs to reference data

Materials	USCS Classification	Dry Density (Mg/m^3)	ψ_a (kPa)	Reference
RAPs RCAs	GW, SP SP, SP, SM	1.94-1.97 1.83-1.92	0.1-1.1 0.5-3.0	This study
RAPs RCAs	GP, SP GP, SP	1.53-1.67 1.55-1.71	0.01-0.03 0.042-22	Rahardjo et al. (2010)

Air-entry suctions for RAPs and RCAs from this study were compared to those from Rahardjo et al. (2010) in Table 4. The ψ_a of the RAPs and RCAs measured in this study are greater than those of RAPs and RCAs conducted by Rahardjo (2010). The RAPs and RCAs used in this study were compacted to realistic field conditions and thus have higher density than the comparable reference data.

SUMMARY AND CONCLUSIONS

This study presents the hydraulic properties (k_{sat} and WCC) of compacted RAPs and RCAs obtained from different states across the USA that have been used as base course for highway construction. The k_{sat} of the RAPs ranged from 3.8×10^{-5} to 3.7×10^{-4} m/s and from 1.6×10^{-5} to 2.6×10^{-5} m/s for the RCAs. The k_{sat} was proportional to the effective diameter (D_{10}) for RAPs, but does not provide a strong relationship for RCAs. Hazen's (1911) equation for conventional aggregate tends to over predict k_{sat} for both RAPs and RCAs.

A hanging column test combined with an air aspirator can generate suction between 0.05 and 75 kPa for a recycled base, providing high accuracy for low suction measurements ($\pm$0.02 kPa). Fredlund and Xing's (1994) equation provides a good fit for the WCCs of RAPs and RCAs. Compared to Rahardjo et al. (2010), RAPs and RCAs used in this study provided higher ψ_a because the specimens were prepared at higher, compacted density. Extension of ψ measurements using devices such as a pressure plate extractor or sensors would be recommended if the full-range WCC for RAPs and RCAs is desired.

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