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2018

Rahardjo, H., Gofar, N., & Satyanaga, A. (2018). Effect of concrete waste particles on infiltration characteristics of soil. *Environmental Earth Sciences*, 77(9),347-.
doi:10.1007/s12665-018-7530-3

<https://hdl.handle.net/10356/102631>

<https://doi.org/10.1007/s12665-018-7530-3>

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Effect of Concrete Waste Particles on Infiltration Characteristics of Soil

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ABSTRACT:

Demolition of old buildings to create space for new development resulted in the near surface soil (topsoil) to be mixed with particles derived mostly from concrete wastes. This condition could affect the infiltration capacity and surface runoff, therefore storm-water management of the area. This paper presents results of study on the effect of concrete waste particles on the hydraulic properties and infiltration capacity of the topsoil. Laboratory tests were performed to compare the hydraulic properties of the topsoil and the mixture of topsoil and concrete particles. Laboratory infiltration column test was performed on the mixture to evaluate its infiltration capacity. Results from the laboratory tests indicated that the presence of particles from concrete waste decreased the water holding capacity and the permeability, thereby the infiltration capacity of the ground surface. The results were supported by numerical analysis performed using the same material and boundary conditions as the column test. Parametric study was performed on both the topsoil and the mixture in order to extend the results of infiltration test to different materials under different ranges of rainfall intensity. The parametric study showed that the presence of concrete particles increased the run-off and the effect increased as the rainfall intensity increased. Therefore, the increase in runoff coefficient should be considered for the storm-water management when the near surface soil is mixed with concrete waste.

KEYWORDS: Demolition waste; topsoil; water retention; permeability; infiltration capacity; surface run-off.

1. INTRODUCTION

Construction and demolition activities to create space for new buildings are unavoidable part of development of urban area. The demolition of old buildings and other infrastructures generated waste on land surface. Three types of material are derived from construction and demolition waste of buildings: crushed concrete; crushed masonry and mixed demolition debris (Cardoso et al., 2016). While the larger particles are moved to landfill or recycling plant, the smaller particles and debris are left and naturally mixed with soil near ground surface. The

ground surface is usually ploughed and compacted to prepare the land for new development. Previous study on the effect of demolition waste on the compaction properties and unconfined compressive strength of clay (Cabalar et al., 2016) showed that the addition of waste particles increases the dry unit weight and decreases the optimum water content of clay while the unconfined compressive strength increased quite significantly with addition of concrete particles. The mixture of topsoil with particles from demolition waste and the subsequent compaction process also affect the infiltration capacity, thus increasing the run-off coefficient of the area when subjected to rainfall precipitation (Shi et al, 2007). Based on their study, Shi et al. (2007) showed that the imperviousness of land surface is not only influenced by changing in land use, but also by changing in soil texture, initial soil moisture, and rainfall intensity.

In unsaturated soil, the infiltration capacity of the soil is controlled by rainfall intensity and initial moisture content or antecedent rainfall as well as the infiltration characteristics of the soil (Rahimi et al., 2011). The infiltration characteristics of the soil are defined by the hydraulic properties of the soil i.e. water retention capacity and rate of water movement through the soil. The infiltration characteristic of soil is controlled by hydraulic properties of the soil i.e. water retention capacity and rate of water movement through the soil. The water retention capacity of soil is usually presented as soil-water characteristic curve (SWCC) while the movement of water through soil is related to the coefficient of water permeability of the soil (Fredlund and Rahardjo, 1993), The SWCC is characterized by several parameters i.e. air entry value (AEV), water entry value (WEV) and the slopes of drying and wetting curves. The AEV is the matric suction at which water starts to drain from large pores and desaturation occurs rapidly. On the other hand, WEV is the matric suction at which water starts to enter the porosity of the soil from dry condition. The slopes of the drying and wetting curves represent the rate of desaturation and saturation process respectively. The rate of desaturation is controlled by residual suction and coefficient of permeability while the rate of saturation was controlled by WEV (Fredlund and Rahardjo, 1993).

The infiltration properties of soil can be investigated by means of soil column apparatus. Many researchers has adopted the method effectively in their study of water infiltration behaviour in homogeneous as well as multi layered soil (e.g. Doscher et al. 1998; Yang et al., 2004, 2006; Lee et al. 2011). Doscher et al. (1998) demonstrated a straightforward method to present water movement in soil column using tensiometer and time domain reflectometry (TDR). The effects of hysteresis were observed when plotting the water content against negative pore-water pressure (suction). Yang et al (2004) demonstrated that the apparatus proved to be effective for infiltration study and for estimation of hydraulic properties of soil i.e. SWCC and saturated permeability.

Furthermore, [Lee et al. \(2011\)](#) confirmed that the simpler soil column experiment give an equally good result to quantify the suction variations in single-layered homogenous soil when compared with two dimensional model.

The effect of concrete waste particles on the infiltration capacity of the surface soil has not been studied previously. This paper presents the results of experimental study on infiltration of rainwater in the topsoil mixed with concrete particle derived from demolition waste. Laboratory tests were carried out following relevant ASTM standards to establish the water retention ability and the permeability function of both topsoil and mixture of topsoil and the concrete particles (subsequently referred as Topsoil and Mixture). The study adopted the soil column apparatus and procedure presented by [Yang et al. \(2004\)](#) with modification on the diameter of the column. Larger diameter column was fabricated and used in this study to accommodate the size of concrete waste particles. The soil infiltration column test comprised several stages i.e. preparation of the material and instrumentation, upward saturation, draw-down, rainfall infiltration and drying. Since the time required to perform the infiltration test was quite long (about two months), the soil column test was only performed on one mixture composition i.e. 50% concrete waste particle and 50% topsoil by dry weight and one rainfall pattern i.e. 14.5 mm/h for 12 h. The long testing time was required due to the low permeability of the mixture. The evaluation of the results from the infiltration column test was carried out using the results from numerical analyses which is commonly performed by many researchers in geotechnical engineering (e.g. [Indrawan et al., 2007](#); [Yang et al., 2006](#); [Iryo and Rowe, 2004](#)). Numerical analysis of infiltration test was performed in this study using the same material (Mixture) and boundary conditions as the laboratory infiltration test to serve as the baseline case. Similar analysis were carried out using Topsoil as the soil column material to evaluate the effect of concrete waste on water infiltration into Topsoil. A parametric study was carried out to extend the results of the numerical analyses on both Mixture and Topsoil for different rainfall intensities.

2. EXPERIMENTAL PROGRAM AND PARAMETRIC STUDY

2.1 Material Properties

Materials used in this study were surface soil (topsoil) and concrete waste particles which contained crushed stone and cement. The particle size distributions of the materials were obtained following [ASTM D422-63 \(2007\)](#) and [ASTM D1140-00 \(2006\)](#) are shown in [Figure 1](#). The shape of concrete particles used in this study was random with an equivalent diameter of about 5 to 30 mm. Water absorption of the aggregates was tested following [ASTM C127-15 \(2015\)](#) and the result showed that the water absorption of RCA was 6.6%. Mixtures of 50% concrete aggregate and 50% topsoil by dry weight were selected for this study. This composition was designed based on

the porosity of the concrete and the maximum compaction to be achieved if all voids were with topsoil. The mixture was prepared at a dry density of 1.53 Mg/m^3 and a gravimetric water content of 7.8% (volumetric water content 12%) which represents 90% of compaction level. The resulting porosity of the mixture was 0.39. High level of compaction could be achieved for this mixture because, unlike natural aggregate, the concrete waste aggregate is weak, thus can break into smaller particles (Cardoso et al, 2016). The properties of the mixture and its components materials are shown in Table 1.

The SWCCs of the materials used in this study were obtained using Tempe Cell and Pressure plate following ASTM D6836-02 (2002). Only a few data in the lower suction range ($<1500 \text{ kPa}$) were obtained from laboratory test, thus Fredlund and Xing (1994) fitting equation with $C(\psi)=1$ was used to construct the drying curve (Leong and Rahardjo, 1997a). The SWCC tests were performed following drying path. However, the soil experiences wetting and drying process due to climatic changes, thus the hydraulic properties of the soil in wetting path is important for the analysis of rainfall infiltration through the soil. The wetting and drying curves serve as boundary of scanning curves of SWCC. The wetting curves was constructed using Pham et al (2005) fitting equation which was developed based on Feng and Fredlund (1999) equation for drying curve. The fitting curve required determination of the ratio between the slope of the boundary drying curve and the slope of boundary wetting curve (R_{SL}) and the distance between the inflection points at the drying and wetting curves respectively (D_{SL}). The selection of R_{SL} and D_{SL} values for the mixture used in this study was aided by the results of soil column experiment during upward saturation (UF) and rapid drawdown (DD). The SWCC drying and wetting curves of Mixture as compared to those of Topsoil are presented in Figure 2a. Figure 2b shows the SWCC drying and wetting curves of Mixture together with data obtained from infiltration column test. The air entry value (ψ_a) and other characteristic values from SWCC drying curves were calculated using Zhai and Rahardjo (2012) equations. These values, together with the fitting coefficients used in Fredlund and Xing (1994) drying curve as well as Pham et al (2005) wetting curve are summarized in Table 2.

Coefficients of saturated permeability of both Topsoil and Mixture were tested using a flexible wall permeameter in triaxial cell following ASTM D5084-10 (2010). In addition, the coefficient of saturated permeability of the mixture was also estimated from the upward saturation stage in soil column test. For concrete particles, the coefficient of saturated permeability was tested using a constant head test (ASTM D2434-2006) whereby the concrete particles were placed and compacted inside a box of size $0.3 \times 0.3 \times 0.3 \text{ m}$. The test results are shown in Table 2. Generally, the permeability of soil remains relatively constant at matric suctions below air entry value but starts to decrease significantly at matric suctions beyond the air entry value. The permeability

function of the mixture was determined from the saturated permeability and SWCC of the mixture using the statistical model proposed by Childs and Collis-George (1955). The calculated permeability function was best fitted using Leong and Rahardjo equation (Leong and Rahardjo, 1997b). The p parameters of both Topsoil and Mixture were presented in Table 2. The permeability function of Mixture and Topsoil used in this study are shown in Figure 3.

2.2 Soil Column Apparatus

The soil column apparatus designed for this study comprised three major components: the acrylic cylinder, the water flow system, and the measurement system. The biggest particle used in this study was 30 mm, while ASTM D2434-68 (2006) requires that the minimum diameter of cylinder for permeability study is seven times the maximum particle size. Thus, the inner diameter of the soil column used in this study was 300mm. Method presented in Yang et al. (2004) was adopted in this study. The column and locations of instrumentations are shown in Figure 4.

The acrylic cylinder was 5 mm in thickness. It consisted of a 1.050 m-high main cylinder for holding the soil mixture with a 0.225 m-high extension. The two parts were connected by eight bolts through 25 mm-thick flanges. An O-ring in a groove was coated with silicon grease and placed in between the two plates to provide good seal. The main cylinder was supported by four acrylic stiffeners and a 25 mm-thick bottom plate. The bottom plate was connected to a stainless-steel base plate by eight bolts. The stainless-steel base plate had two drain outlets and was supported by four steel rods with adjustable height.

The water flow system comprised water inflow and outflow control systems. The inflow control consisted of a rainfall simulator and a water pump connected to a main water supply. The rainfall simulator was a Wilson misting nozzle (AD 15 series) with aperture opening of 0.15 mm connected to the water pump by a pipe. The pump generated pressures to control the intensity of water sprayed by the rainfall simulator during the test. The range of rainfall intensity which can be applied in this infiltration column was between 14.5 mm/h and 36.51 mm/h. Water percolated down through the soil column and was drained into a constant head tank by an outlet at the base plate. The overflow from the constant head tank was directed to a container placed on a load cell (electronic weighing balance) to quantify the amount and the rate of discharge.

The measuring devices installed in the column were tensiometer-transducer system, time domain reflectometer (TDR) and data acquisition system. The column was fabricated with nine threaded holes for the installation of tensiometer tube and nine holders with three holes to support the TDR needles. The vertical interval between two connections was 0.1 m. O-ring with silicon grease was placed in a groove provided at each connection to prevent

leakage. The tensiometer-transducer system consisted of four small tip tensiometers model 2100F (Soil-moisture Equipment Corporation, USA) connected to four transducers model GT3-15 (ICT international Pty Ltd). The high air-entry ceramic tip used in this study had an air-entry value of 100 kPa. Thus; the range of pore-water pressure (PWP) measurement was -100 to 100 kPa. The soil moisture sensor was MP306 (ICT International Pty Ltd, Australia) with three in-plane stainless steel needles. The moisture sensor adopted standing wave principle to determine the changes in volumetric water content (VWC) based on the changes in the dielectric constant of the soil. The moisture sensor can provide measurement of VWC with an accuracy of $\pm 0.01\%$. The tensiometers and the moisture sensors were calibrated prior to the test.

The instrumentations were connected to a data acquisition system (DAS). Changes in the PWP and VWC were recorded continuously. The DAS was made up of a personal computer (PC), a data logger for soil moisture sensor referred to as Soil Moisture Meter (SMM) and a data logger for the tensiometer-transducer system referred to as Soil Tension Meter (STM).

After the soil column apparatus was set up, gravels with an average size of 5mm, wrapped with a highly permeable geo-textile were placed evenly at the bottom of the soil column to avoid turbulent discharge. The soil mixture was then placed and compacted in nine layers of 100 mm until the final height of the soil column was 900 mm. The ceramic tips of the tensiometer were buried and the soil moisture sensor needles were inserted at four elevations (i.e. 0.07 m, 0.37 m, 0.57 m and 0.87 m from the base) during the placement and compaction of the soil layer.

2.3 Infiltration Test Program

The PWP readings in the soil column were usually inconsistent after the compaction process. Therefore, upward flow (UF) and rapid drawdown tests (DD) were carried out to create a hydrostatic condition throughout the column before the rainfall tests. The UF test was aimed to saturate the soil column (removing the entrapped air) and to assess the saturated coefficient of permeability of the mixture. The test was conducted until a steady-state upward flow condition was achieved. Afterwards, the valve at the bottom of the column was closed. The DD test was conducted by lowering the water table from the top of the column to the base of the column to achieve an initial condition for rainfall test. The water table was maintained at the bottom of the column during the rainfall test. Once the pore-water pressures became stabilized after the UF and DD tests, the mixtures were subjected to a rainfall intensity. The soil column tests were performed on the mixture subjected to a rainfall intensity of 14.5 mm/h (equivalent to 4×10^{-6} m/s) for 12 hours. This rainfall intensity was used in the column test due to the limited capacity of the rainfall simulator available at the time of study. Ponding was expected to occur since the rainfall

intensity is one order of magnitude higher than the saturated coefficient of permeability of the mixture. The ponded water was collected above the soil surface in the extended cylinder (Figure 4) to simulate runoff. The height of the extended cylinder above the soil surface was 200 mm, thus the duration of the rainfall was adjusted such that there would be no overflow from the extended cylinder. The rainfall was allowed to infiltrate into the soil column and to discharge through a drainage provided at the base of the soil column. PWP, VWC and cumulative discharge were recorded at time intervals of 10 minutes during and after rain stopped.

2.4 Parametric Study

A parametric study was performed numerically using the saturated/unsaturated seepage finite element code SEEP/W (GeoSlope International 2012) to evaluate the results of laboratory infiltration test. The dimensions and finite element mesh adopted in the modelling of the soil column infiltration test are shown in Figure 5a. The analysis was carried out with similar boundary conditions as used in the soil column test. Rainfall was assigned at the top of the column while the bottom of the column was set at atmospheric pressure. Similarly, the initial condition of the numerical analysis was set using a spatial function based on the initial matric suctions obtained from tensiometer readings after the drawdown process in the column test (Figure 5b). Other boundary conditions included zero pressure ($H=0$) at the bottom of the soil column and zero flux ($Q=0$) at both sides of column, to ensure the water flows to occur in the vertical direction only during the simulation of the soil column test. Ponding was allowed on the surface of soil column to allow for generation of positive pore water pressure. Wetting SWCC shown in Figure 2a and the saturated coefficient of permeability, k_s obtained from the upward saturation stage in the soil column test (4.33×10^{-6} m/s) were used as the input for the numerical model.

As the baseline case, the numerical model was first calibrated with the results of laboratory infiltration column test. The rainfall pattern used in the infiltration test was assigned on the surface of the numerical model. The results in terms of PWP, VWC as well as the water balance were matched with the results from the laboratory infiltration test. Then, the parametric study was carried out to evaluate the effect of rainfall pattern on the infiltration characteristics of Mixture. The rainfall intensity used in the infiltration column test and the baseline case was about ten times the coefficient of saturated permeability of Mixture ($q/k_s \approx 10$). Then, the parametric study was performed for the rainfall intensities and durations as shown in Table 3. The same rainfall intensities were also applied on the numerical model using Topsoil as the material for soil column. Therefore, the effect of concrete waste on the runoff coefficient of the area could be evaluated based on the comparison of the performance of Topsoil and Mixture.

3. RESULTS AND DISCUSSION

3.1 Water Retention and Permeability

The SWCC curves shown in Figure 2a indicates that addition of concrete particles to topsoil decreased the saturated volumetric water content (θ_s) and the air entry value (ψ_a). The lower ψ_a demonstrated that Mixture started to de-saturate at lower suction as compared to Topsoil. The results agree with the study by Rahardjo et al. (2008) on the mixture of 50% topsoil with 50% granite chips which suggested that the θ_r of the mixture is lower than the θ_r of the topsoil. Based on the hysteresis of the drying and wetting curves, the presence of concrete particles and the compaction process decreased the water retention capacity of the topsoil. Observation of Figure 2a indicated that, based on the porosity of the soil and the range of volumetric water content in the transition zone of the SWCC curves, the presence of concrete particles reduced the water storage capacity of the topsoil by 45%. In term of field capacity, i.e. the amount of water remaining in soil a few days after wetting and drainage is negligible or at matric suction of 33 kPa (Kirkham, 2014), the field capacity of the mixture was 29%. Thus, there was a reduction of 15% from the field capacity of topsoil (44%).

Results presented in Table 1 show that the saturated permeability of Mixture (4.33×10^{-7} m/s) was less than that of Topsoil (1.24×10^{-6} m/s). Since both the saturated coefficient of permeability and the SWCC of Mixture are lower than those of Topsoil, the permeability function of Mixture is always lower than that of Topsoil (Figure 3). Hence, the rate of water percolation in Mixture is expected to be slower than that in Topsoil. The result is in contrast to Rahardjo et al (2008) research on the effect of natural aggregate which showed that the addition of natural aggregate increased the coefficient of saturated permeability of the mixture. However, Cardoso et al (2016) explained that it is possible that a layer containing concrete aggregate to have lower permeability because, unlike natural aggregate, fine particles could be generated during compaction of mixture of topsoil and concrete waste particles. The fine particles filled in the macro pores formed in the mixture and increased the compaction level. Note that the mixtures were prepared at relative density of 90% for SWCC test, saturated permeability test and the soil column experiment.

3.2 Results of Soil Column Test

Results of the soil column tests indicated that the PWP increased steadily during rainfall and the maximum PWP was achieved at the end of rainfall (Figure 6). PWP redistribution in the mixture was slow after rainfall due to low coefficient of permeability. The PWP at the bottom remained zero because the water was drained effectively through the outlet. Positive PWP was observed for some time by T1 due to ponding because the rainfall

rate was higher than the coefficient of saturated permeability of the soil. The top part of soil column remained saturated for 1 day after rainfall. The test was stopped after the PWP and VWC reached equilibrium conditions (4 days). The VWC variations with time are shown in Figure 7. The figure illustrates that soil moisture sensors S1 recorded an increase of VWC immediately after the rainfall started while responses of S2 and S3 were delayed by about 12 and 30 h, respectively. The VWC recorded by S2 and S3 increased to a certain value and became relatively constant after the rainfall stopped. The VWC recorded by S1 decreased about 1.5 h after the rainfall stopped. Readings of soil moisture sensor S4 were relatively constant because it was close to the bottom of soil column.

Experimental points during and after rainfall plotted against the drying and wetting SWCC curve of the mixture are shown in Figure 2b. Because the height of soil column was 0.9 m, the theoretical range of PWP in the soil column was between -9 kPa and 0 kPa. The saturated volumetric water content of the mixture was 39%, while the initial volumetric water content was 12% (initial gravimetric water content during preparation of the mixture was 7.8%). The final VWC recorded by S1 was close to the saturated VWC (0.39), while S2 recorded VWC of 0.32 and S3 and S4 recorded VWC of 0.28. The average VWC throughout the soil column (S1, S2, S3 and S4) was 0.32, thus the mixture in the soil column did not reach fully saturated condition. Considering the average initial VWC of the mixture before rainfall test, the amount of rainwater absorbed by the mixture was equivalent to 75mm of rainfall.

Figure 8 shows the water balance graph i.e. the variation of the amount of rainwater discharged from the soil column, stored in the mixture and became run-off. There was a 2.5 hr delay before the rainwater was discharge from the bottom soil column. Discharge rate indicates that the rate of infiltration into soil mixture was very small as compared to the rate of rainfall causing ponding on the surface. In the soil column test, this condition continues for a long time until all water seeped into the mixture. Based on the ratio of amount of infiltration to the amount of rainfall and the amount of water absorbed by Mixture, it could be calculated that the cumulative infiltration after 12 hr rainfall was only about 50.7%. The soil column test indicated that the water continuously seeped into the soil that after 48 hr, the cumulative infiltration reached 80.8%.

3.3 Results of Parametric Study

Results of numerical analysis, using the same boundary conditions as used in the soil column test, are presented in Figures 6, 7 and 8 in terms of PWP, VWC and water balance, respectively. The figures indicate that the results are comparable and could be used as the baseline for the parametric study. Figure 8 showed that the surface runoff on Mixture at the end of rainfall (12h) was 53%, but decreased to 40% after 24 h and decreased to

6% after 48 h. The numerical analysis gave almost a similar amount of run-off as obtained from the soil column test for 12 h and 24 h after rainfall started. However, at 48h after rainfall started, the numerical analysis showed higher amount of discharge as compared to the results of laboratory infiltration test. The numerical analysis indicated that the cumulative infiltration into Mixture 48 h after rainfall started was 95.4% as compared to the cumulative infiltration obtained from laboratory infiltration test (80.8%).

As mentioned earlier, numerical analysis was then performed on Topsoil to derive a comparison on the effect of concrete waste on the runoff coefficient under the same rainfall intensity. Figure 9 shows the effect of concrete waste particles on the run-off coefficient of the Topsoil. For Topsoil, the rainfall intensity of 14.5 mm/h for 12 h only generated 26% runoff and the rainfall was totally infiltrated to the soil 16 h after the rainfall started. Furthermore, evaluation of Figure 9 shows that Mixture can only store 66% of the water that can be stored in the same volume of Topsoil.

Furthermore, the parametric study was performed for different rainfall intensities as shown in Table 3. The results of this parametric study shows that the effect of concrete waste on the infiltration capacity of ground surface was dependent on the rainfall intensity. Figure 10a shows the effect of different rainfall intensities on the runoff from the Mixture at $t = 12$ h, 24 h and 48 h since the beginning of rainfall. The lower the rainfall intensity, the more water infiltrated into the soil, resulting in less run-off. The amount of water infiltrated into the Mixture is less than the one infiltrated into the Topsoil due to the lower permeability of the Mixture as compared to the Topsoil. Figure 10b shows that the amount of infiltration into soil layers was also affected by elapsed time since the rainfall stopped. The rate of rainfall infiltration into the soil increases slightly with time. The ratio between the rainfall intensity (q) and the coefficient of saturated permeability of the soil (k_s) also governed the volume of the water infiltrated into the soil layers. Figure 10b indicated that the rainfall intensity of less than or equal to 14.5 mm/h, applied on the surface of Topsoil, generate only a small runoff during the application of rainfall. However, the same rainfall intensity pattern produced quite a significant runoff on top of the Mixture and the ponded water stayed up to 51h. Zero runoff was only achieved on the surface of Mixture when the rainfall intensity was decreased to 1.45 mm/h. Note that the coefficient of saturated permeability of Topsoil was almost ten times that of Mixture (Table 1). The results of parametric study implies that rainfall with intensity ratio (q/k_s) of less than 5 could be absorbed into and drained out from either the Topsoil or Mixture.

4. CONCLUSIONS

Hydraulic properties and water infiltration behaviour through topsoil mixed with particles from concrete waste (Mixture) was studied using soil column apparatus. Based on SWCC, the presence of concrete particles

from demolition waste decreased the infiltration capacity of the soil. The porosity of the topsoil decreased by 27% from 0.52 to 0.39. Based on the SWCC drying and wetting curves, the water storage capacity of the soil was estimated to decrease by 44%. Observation on the field capacity implies that the mixture can hold only 65% water near the ground surface as compared to the original soil. Besides the low water holding capacity, the mixture also has lower coefficient of water permeability than the topsoil because compaction process generates finer concrete particles in the mixture. The results of soil column test showed that the cumulative infiltration after 12 hr rainfall was about 50.7% while after 48 h, the cumulative infiltration reached only 80.8%.

Numerical analyses performed on similar initial and boundary conditions as used in the soil column test showed comparable results, indicating that there was a significant increase in the surface runoff when the topsoil was mixed with concrete waste particles because the mixture has lower water storage and coefficient of saturated permeability. The Mixture can only store 66% of the water that can be stored in the same volume of Topsoil. These results agree with the analysis based on SWCC. The effect of concrete waste particles increased as the rainfall intensity increased. Rainfall intensity ratio to the saturated permeability (q/k_s) plays an important role on the amount of surface run-off. The rainfall intensity higher than five times the coefficient of saturated permeability of surface soil could generate significant runoff on ground surface. This study implies that concrete waste particles left on the ground surface after demolition cause more runoff to surface drain which should be considered for storm-water management of the area.

ACKNOWLEDGEMENTS

The authors acknowledge former Master student Yusi Zhu for performing the soil column test and other laboratory tests.

REFERENCES

- ASTM C127-15 (2015) Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, ASTM International, West Conshohocken, PA.
- ASTM D422-63. (2007) Standard Test Method for Particle-Size Analysis of Soils, ASTM International, West Conshohocken, PA.
- ASTM D1140-00. (2006) Standard Test Methods for Amount of Material in Soils Finer than the No. 200 (75- μ m) Sieve, ASTM International, West Conshohocken, PA.
- ASTM D6836-02. (2002) 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, ASTM International, West Conshohocken, PA.
- ASTM D2434-68 (2006). Standard Test Method for Permeability of Granular Soils (Constant Head) ASTM International, West Conshohocken, PA.

- BCA-SIA, (2008) Sustainable Architecture. Publication 2008, Issue 1. BCA Academy of Built Environment, Singapore.
- Cabalar, A.F., Abdulnafa, M.D. & Karabash, Z. (2016) Influences of various construction and demolition materials on the behavior of a clay. *Environ Earth Sci* (2016) 75: 841.
- Cardoso, R., Silva, R.V., de Brito, J., Dhir, R. (2016) Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review. *Waste Management* 49, 131–145.
- Doscher, C. Hamlett, J.M. and Duffy C.J. (1998) Soil Column to Demonstrate Soil–Water Movement”, *J. Nat. Resour. Life Sci. Educ.* 27: 30–34
- Feng, M. and Fredlund, D.G. (1999) Hysteretic Influence Associated with Thermal Conductivity Sensor measurements. *Proceedings of the 52nd Canadian Geotechnical Conference, Montreal*, p. 651–657.
- Fredlund, D.G., Xing, A. and Huang, S. 1994. Predicting the Permeability Function for Unsaturated Soils Using the Soil-Water Character Curve. *Canadian Geotechnical Journal*. 31(3): 533-546
- Fredlund, D.G. and Xing, A., (1994) Equations for the Soil-Water Characteristic Curve. *Canadian Geotechnical Journal*. 31(3):521-532.
- Fredlund, D.G. and Rahardjo, H. (1993) *Soil Mechanics for Unsaturated Soils*. New York: John Wiley & Sons, Inc., pp. 517.
- Indrawan, I.G.B., Rahardjo H. and Leong E.C. (2007) Drying and Wetting Characteristics of a Two-Layer Soil Column. *Canadian Geotechnical Journal*. 44:20-32.
- Iryo, T. and Rowe, R.K. (2004). Numerical Study of Infiltration into a Soil Geotextile Column”. *Geosynthetics International*. 11(2):377–389.
- Kirkham, M.B. (2014) *Principles of soil and plant water relations* (2nd ed.) Elsevier. Burlington. p. 153-170
- Lee, M.L., Gofar, N. and Kassim, A. (2011) Performances of two instrumented laboratory models for the study of rainfall infiltration into unsaturated soils. *Engineering Geology*. 117(1-2):78-89.
- Leong, E. C. and Rahardjo, H. (1997a). Review of Soil Water Characteristic Equations. *Journal of Geotechnical and Geoenvironmental Engineering*. 123(12), 1106-1117.
- Leong, E. C. and Rahardjo, H. (1997b) Permeability Functions for Unsaturated Soils. *Journal of Geotechnical and Geoenvironmental Engineering*. 123(12), 1118-1126.
- Pham, H.Q., Fredlund, D.G. and Barbour, S.L. (2005) A study of hysteresis models for soil water characteristic curves. *Canadian Geotechnical Journal* 42(6): 1548-1568
- Rahardjo, H., Satyanaga, A. Leong E.C. and Wang, J.Y. (2013) Unsaturated Properties of Recycled Materials. *Engineering Geology*. 161(1-2):44-54
- Rahardjo, H., Vilayvong K. and Leong, E.C. (2011) Water Characteristic Curves of Recycled Materials. *Geotechnical Testing Journal. ASTM International*. 34(1): 1-8. Paper ID GTJ103177
- Rahardjo, H., Indrawan, I.G.B. Leong E.C. and Yong, W.K. (2008) Effects of Coarse-Grained Material on Hydraulic Properties and Shear Strength of Top Soil. *Engineering Geology*. 101(3-4):165-173
- Rahimi, A., H. Rahardjo and E.C. Leong. (2011) Effect of Antecedent Rainfall Patterns on Rainfall Induced Slope Failure. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 137 (5): 483-491.
- Shi, P.J., Yuan, Y., Zheng, J., Wang, J.A., Ge, Y. and Qiu, GY. (2007) The effect of land use/cover change on surface runoff in Shenzhen region, China. *Catena* 69: 31 – 35.

- 373 Yang, H., Rahardjo, H. Wibawa, B. and Leong, E.C. (2004) A Soil Column Apparatus for Laboratory
374 Infiltration Study. Geotechnical Testing Journal. ASTM International. 27(4):347 – 355. Paper ID
375 GTJ11549
- 376 Yang, H., Rahardjo, H., and Leong, E.C (2006) Behaviour of Unsaturated Layered Soil Columns during
377 Infiltration. ASCE Journal of Hydrologic Engineering. 11 (4): 329-337.
- 378 Zhai, Q. and Rahardjo, H. (2012) Determination of Soil-Water Characteristic Curve Variables. Computer and
379 Geotechnics. 42: 37-43.

Table 1: Summary of basic properties of Mixture and its constituent materials

Properties	Topsoil	Concrete particles	Mixture
USCS classification (ASTM D2487-11 (2011))	CL (Low plasticity Clay)	GP (Poorly Graded Gravel)	GC (Gravel with Clay)
Specific gravity, G_s ASTM D 854-06 (2006)	2.47	2.43	2.46
Porosity (n)	0.528	0.521	0.387
Gravel (>4.75mm) (%)	0	97.9	49.8
Sand (0.075~4.75mm (%))	53.6	2.1	27.1
Silt (0.005~0.075mm) (%)	7.3	0	3.6
Clay (<0.005mm) (%)	39.1	0	19.5
Max dry density, ρ_{dmax} (Mg/m ³)	1.46	1.57	1.71
Optimum water content (%)	22.50	-	14.70
Dry density at preparation (Mg/m ³)	1.18	1.25	1.53
Relative density (%)	80	80	90
Saturated permeability, k_s (m/s)	1.24×10^{-6} (triaxial test)	7.5×10^{-3} (constant head test)	2.91×10^{-7} (triaxial test) 4.33×10^{-7} (soil column test)

Table 2 Characteristic values derived from SWCC curves and permeability function

Properties	Symbol	Topsoil	Mixture
Saturated volumetric water content	θ_s	0.52	0.39
Air-entry value (AEV, kPa)	ψ_a	17	5
Residual matric suction (kPa)	ψ_r	846	455
Residual volumetric water content	θ_r	0.03	0.11
Slope of SWCC drying curve	m	0.229	0.112
Water entry value (WEV, kPa)	ψ_b	20	15
Slope of SWCC wetting curve	m_w	0.44	0.240
Fredlund & Xing (1994) parameters for predicting drying curve	a	59.78	15.77
	n	1.20	1.21
	m	0.89	0.57
	b_w	16.76	4.38
Pham et al (2005) parameters for predicting wetting curve	c_w	0.03	0.11
	d_w	1.71	1.85
	DSL	1.65	1.5
	RSL	0.50	0.5
Leong & Rahardjo p parameter for predicting permeability function	p	14	12

Table 3 Rainfall intensity and rainfall duration used in the parametric study

Rainfall Pattern	Intensity	Duration	Comment
1	22 mm/h (6×10^{-6} m/s)	12 h	$q/k_s = 15$
2	14.5 mm/h (4×10^{-6} m/s)	12 h	Baseline case, $q/k_s = 10$
3	7.2 mm/h (2×10^{-6} m/s)	12 h	$q/k_s = 5$
4	1.45 mm/h (4×10^{-7} m/s)	12 h	$q/k_s = 1$
5	0.72 mm/h (2×10^{-7} m/s)	12 h	$q/k_s = 0.5$

Note: k_s of mixture = 4.33×10^{-7} m/s

FIGURE CAPTION

- Figure 1. Particle size distributions of Topsoil, Concrete particles and Mixture
- Figure 2. Drying and wetting SWCC of Topsoil and Mixture
- Figure 3. Permeability functions of Topsoil and Mixture
- Figure 4. Infiltration column set up with location of instrumentations
- Figure 5. Finite element mesh, boundary conditions and initial condition adopted in numerical analysis
- Figure 6. Pore-water pressure variation with depth
- Figure 7. Volumetric water content variation with time
- Figure 8. Water balance graph
- Figure 9. Comparison of water balance between the Mixture and Topsoil
- Figure 10. Effect of rainfall intensity on the percentage of surface runoff on Topsoil and Mixture

Note: S1-S4 = soil moisture sensor data during & after rainfall
DD = Drawdown, UF = Upward saturation

a) drying and wetting curves of Topsoil & Mixture

b) drying and wetting curves of mixture with experimental data from soil column test

(a) Finite element mesh & boundary conditions

(b) Initial pore-water pressure for numerical analysis

(a) Mixture of topsoil and concrete waste

(b) Topsoil

(a) In terms of rainfall intensity

(b) In terms of elapsed time after rainfall started