https://doi.org/10.1051/e3sconf/202338212005

Water characteristic curve and permeability function of recycled concrete aggregate

Gulnur Pernebekova[1*], *Alfrendo* Satyanaga[1], *Rezat* Abishev[1], *Sung-Woo* Moon[1] and *Jong* Kim[1]

[1]Civil and Environmental Engineering Department, Nazarbayev University, Astana, Kazakhatan

Abstract. Construction and demolition waste are one of the major waste streams in the world. Aggregates must be used in significant quantities during road construction and maintenance as base and sub-base materials. Government and local businesses are promoting the use of recycled material in old pavement and construction material due to the high cost of virgin aggregates. Concrete, road subgrade, and railroad ballast materials can all be made from recycled concrete aggregate (RCA), a type of recycled material. The engineers must properly comprehend the material's qualities, including its unsaturated properties, in order to use RCA in these projects. The goal of this project is to investigate the unsaturated permeability and the water characteristic curve of RCA. These unsaturated qualities were discovered through sophisticated laboratory experimentation. The study's findings showed that the RCA has the same qualities as gravel or natural aggregate.

1 Introduction

Urban regions are in greater demand as a result of the population's exponential growth, which also contributes to the abundance of construction projects and related activities. Accordingly, it causes the problem of an increase in the volume of solid waste generated by constructions that in turn fosters an ecological issue due to a lack of land disposal sites [1]. In order to ensure sustainable development, it is crucial to handle such wastes [2]. The primary source of solid wastes in the construction industry is well known to be construction and demolition waste.

For instance, it is estimated that 40% of all energy and half of all-natural resources are used in construction activities. Therefore, a careless attitude to waste disposal results in the discharge of a huge amount of energy and natural resources [1]. However, the fact that around 80% of the composites in building and demolition wastes may be recycled makes them economically advantageous [3]. The amount of water that is present in a material's pores is known as "water content." The suction of the soil affects the volume of water in an unsaturated soil.

The relationship between water content and suction can be demonstrated using the soil-water characteristic curve (SWCC), which shows the variation of water storage capacity inside the soil's micro and macro pores with respect to soil suction. There have been several studies done on the characteristics of recycled materials in saturated environments [4]. The permeability of recycled materials and the water characteristic curve in unsaturated conditions, on the other hand, have not received much research attention. Thus, a principal objective of this paper is to examine the unsaturated permeability and soil-water characteristic curve of recycled concrete aggregate (RCA).

2 Recycled concrete aggregate

Numerous studies have been conducted on the possible application of RCA, and they have found that it can be successfully used for highway road base, subbase and concrete [5]. The characteristics would be impacted considerably differently depending on the type of RCA source. The mechanical strength and shrinkage characteristics of concrete made using RCA salvaged from old railway pre-stressed concrete sleepers were evaluated by [6]. According to the test results, RCA concrete had values for its elastic modulus and drying shrinkage parameters that were comparable to those of natural aggregate (NA).

The reported RCA water absorption ratings are higher than the specified 3%. For all of the examples that have been documented, fine RCA absorbs more water than coarse RCA. In comparison to NA, RCA has a lower specific gravity. The study by [7] demonstrates that the specific gravity of RCA might also be lower than the recommended values. Although NA has greater qualities in terms of the aggregates' abrasion resistance and crushing values, the values for RCA are likewise within the confines of the required criteria. The three main reasons identified from the literature as the primary sources of these inferior attributes in

---

[*] Corresponding author: gulnur.pernebekova@gmail.com

RCA are internal cracks, heterogeneity, and the presence of residual mortar.

For usage as pavement basis and subbase materials, RCA has superior geomechanical and geoenvironmental qualities over crushed bricks, reclaimed asphalt aggregates, and recycled glass, according to a different study by [8]. When hydraulically bound materials created with RCA were compared to NA, there was no noticeable change in their sensitivity to moisture. Additionally, a strength ratio increases of up to 20% in comparison to the control mix was noted. According to [9], the robust modulus of RCA was found to be double that of NA in their testing. In comparison to routinely utilized subbase natural materials, the results of a series of repeated load triaxial tests on RCA from building demolition showed that the permanent strain was relatively reduced, and the resilient modulus was higher [10].

3 Laboratory testing

To ascertain the minimum and maximum dry densities of the recycled materials, relative density measurements were performed in accordance with ASTM D4253-00 (2006). The processed recycled materials were compacted to a relative density of 90%, based on the minimum and maximum dry densities, and the corresponding dry densities. In accordance with ASTM D6913-04 (2009) and ASTM D2487- 10 (2010), the grain size analyses, and categorization of the recycled materials were established. The ASTM D6836-02 methods were followed while testing the water characteristic curve (WCC) of the recycled materials using the Tempe cell apparatus (2008).

The specifics of the WCC tests for recycled materials throughout the drying process are identical to those described by [11]. Once establishing the WCC drying curve, the WCC test was conducted during the wetting phase. When the WCC drying process was complete, the air pressure was lower than it had been. Following that, water began to enter the recycled material. The drying WCC tests followed identical techniques, with the exception that after the mass of the recycled material specimen had attained equilibrium, the air pressure was reduced rather than increased. When the matric suction was zero, the air pressure was reduced in accordance with the predetermined steps. A determination of the recycled material's water content was made following the wetting WCC test. The Satyanaga equation (Eq. 1) with a correction factor of 1 was used to fit the experimental data of WCC.

The saturated permeability tests of the RCA and RAP were carried out Utilizing a triaxial cell with two back pressure systems [12]. The following are some benefits of testing recycled material saturation permeability in a triaxial cell:

1) In order to remove obstacles of water flow caused by air bubbles within pores of RCA and RAP, the recycled materials can be wet before conducting permeability tests.
2) Effective stress and pore pressures that are comparable to field environments can be used in the permeability test.
3) Using digital pressure volume change, the rapid transition in water volume during the permeability test may be precisely recorded (DPVC).
4) Various hydraulic gradient numbers may be used during the permeability test.

The specimens used in the permeability test were 1 mm thick, specially made rubber membranes that were 100 mm thick and 200 mm in height. The greatest particle size in a triaxial test specimen shall not be larger than one-sixth of the specimen diameter in accordance with accepted geotechnical testing procedures [13]. Therefore, the largest particle size of the recycled materials used in this investigation was about 16 mm. The rubber membrane was connected to the pedestal with O-rings before the recycled material was put inside the triaxial cell, and a three-part specimen split mold was put over the rubber membrane. On top of a porous stone, the needed quantity of dry recycled material was then added, and it was hand-compacted to the requisite dry density. In order to compact the specimen into 10 layers of similar thickness, the same number of blows were used to manage the compaction energy. Following ASTM D7181-11, the operations for saturation and consolidation were then initiated (2009). If the specimen's water volume change approached equilibrium, the consolidation process was complete. De-aired distilled water was applied from the bottom of the specimen following the consolidation process at a constant pressure that was 10 kPa greater than the pore-water pressure inside the specimen. De-aired distilled water, on the other hand, was applied from the top of the specimen at a constant pressure that was 10 kPa lower than the pore-water pressure inside the specimen. As a result, when a steady pressure differential of 20 kPa was applied inside the specimen to test for permeability, water began to flow upward. The permeability test was terminated once the flow rate remained steady for a predetermined amount of time [14]. The specimen was then reinforced to a greater effective confining pressure, and the same processes were carried out once more to gauge the permeability of the recycled material at higher effective confining pressures.

4 Results and discussion

Table 1 and 2 depicts index qualities of fine and coarse RCA.

RCA SWCC was produced as a result of the laboratory experiments that were done. Figure 1 and Figure 2 illustrate this link between matric suction and volumetric water content. The experimental data from SWCC were best fit by Equation (1). Each parameter needs to have a suitable initial value before Equation (1) can be used to model SWCC [15]. The Microsoft Excel software provides an iterative non-linear regression approach that may be used to alter all the parameters for the best fit to the laboratory data of the SWCC [16].

Table 1. Index properties of fine RCA.

	Fine RCA
USCS Classification	SP (Poorly graded sand)
Specific gravity, G_s	2.57
Porosity, n	0.31
Dry density (Mg/ m^3), ρd	1.67
Water content (%)	6.74

Table 2. Index properties of coarse RCA.

	Coarse RCA
USCS Classification	GP (Poorly graded gravel)
Specific gravity, Gs	2.66
Porosity, n	0.35
Dry density (Mg/ m3), ρd	1.57
Water content (%)	6.98

SWCC data are eventually used in later seepage analyses. Following the steps outlined by the statistical technique was used to determine the permeability function of coarse and fine RCA from SWCC and saturated permeability (Figure 3 & Figure 4). Together with the SWCC data that were best fitted, the permeability function was also included in the numerical analysis. Grain size distribution chart of coarse and fine RCA is illustrated in Figure 3.

$$\theta_w = \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right] \times [\theta_r + \left\{(\theta_s - \theta_r)(1 - (\beta)erfc\left(\frac{\ln\left(\frac{\psi_a-\psi}{\psi_a-\psi_m}\right)}{s}\right)\right. \quad (1)$$

where:

$\beta = 0$ when $\psi \leq \psi_a$; $\beta = 1$ when $\psi > \psi_a$
θ_w= calculated volumetric water content
θ_s = saturated volumetric water content
ψ = matric suction under consideration (kPa)
ψ_a = parameter representing the air-entry value of the soil (kPa)
ψ_m = parameter representing the matric suction at the inflection point of the SWCC (kPa)
s = parameter representing the geometric standard deviation of the SWCC
θ_r = parameter representing the residual water content

ψ_r= parameter representing the matric suction corresponding to the residual volumetric water content (kPa)

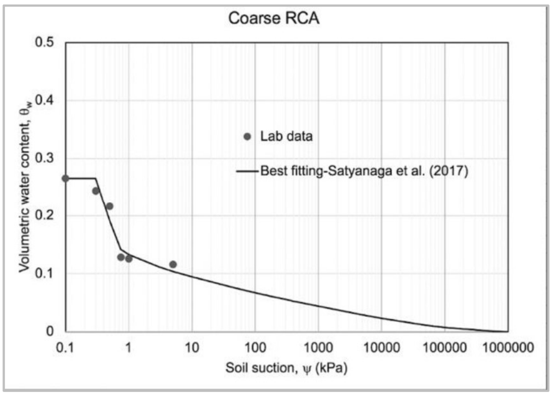

Fig. 1. SWCC of coarse RCA.

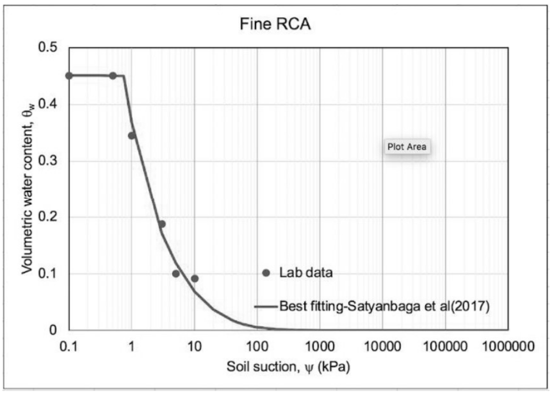

Fig. 2. SWCC of fine RCA.

Table 3. Best fitting parameters of coarse RCA

θ_s	0.202
θ_r	0
ψ_m	1.000
σ	8.000
ψ_{aev}	0.495
ψ_r	5000
r2	0.9992

Table 4. Best fitting parameters of fine RCA

θ_s	0.280
θ_r	0
ψ_m	2.000
σ	2.000
ψ_{aev}	0.800
ψ_r	100
r2	0.8809

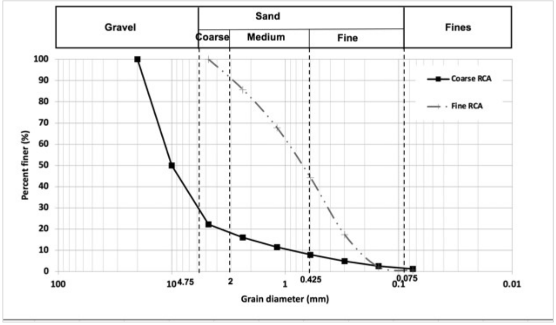

Fig. 3. Grain size distribution chart

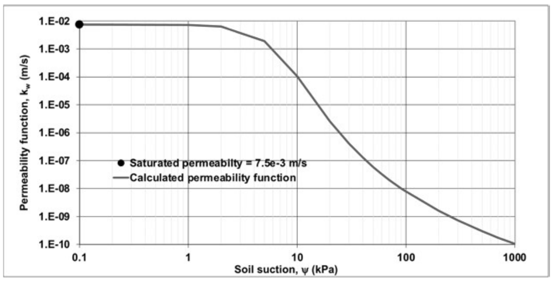

Fig. 4. Unsaturated permeability of fine RCA

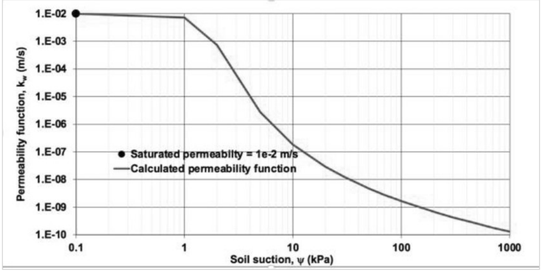

Fig. 5. Unsaturated permeability of coarse RCA

5 Conclusion

The study's findings showed that characteristics of recycled concrete aggregate are comparable to those of natural aggregate. The air-entry value of coarse and fine RCA is 4.95 and 8 kPa which is corresponding to its saturated permeability 1e-2 m/s and 7.5e-3 m/s, respectively.

Acknowledgement

This research was supported by the Nazarbayev University Research Fund under Grants 11022021CRP1512 and 20122022FD4133. The authors are grateful for this support. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Nazarbayev University.

References

1. B. Hadavand, R. Imaninasab, Innovative Infrastructure Solutions, **4** (2019)
2. A. E. B. Cabral, Eco-Efficient Concrete, 340–367 (2013)
3. O. A. Ahmad, Int. J. GEOMATE, **19,** 18 (2020)
4. H. Rahardjo, N. Gofar, A. Satyanaga, Environ. Earth Sci., **77** (2018)
5. A. Arulrajah, J. Piratheepan, M.M. Disfani, J. Mater. Civ. Eng., **26**, 349-357 (2014)
6. S. Yang, Y. Lim, Constr. Build. Mater., **185**, 499-507 (2018)
7. H. Qasrawi, I. Asi, Constr. Build. Mater., **121**, 18-24 (2016)
8. A. Arulrajah, J. Piratheepan, M.M. Disfani, M.W. Bo, J. Mater. Civ. Eng., **25**, 1077-1088 (2013)
9. I. Haider, B. Cetin, Z. Kaya, M. Hatipoglu, A. Cetin, H.A. Ahmet, Soc. Civil Eng. (2014)
10. J. Wang, Z. Fang, Y. Cai, J. Chai, P. Wang, X. Geng, Geotext. Geomembr., **46**, 575-585 (2018)
11. H. Rahardjo, K. Vilayvong, E.C. Leong, Geotech. Test. J., ASTM, **34** (2010)
12. K.H. Head, Manual of Soil Laboratory Testing, Pentech Press, London, UK. (1986)

13. A.F. Sevi, L. Ge, W.A. Take, Geotech. Test. J. **32** (2009)
14. S.S. Agus, E.C. Leong, H. Rahardjo, Can. Geotech. J., **40**, 559−574 (2003)
15. A. Satyanaga, H. Rahardjo, Q. Zhai, Soils Found., **5**7, 789–801 (2017)