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EFFECT OF DEGREE OF SATURATION ON PARTICLE BREAKAGE OF RECYCLED CONCRETE AGGREGATE UNDER CYCLIC LOADING

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ABSTRACT: Construction of road infrastructure consumes a large volume of natural crushed rock, which is used in different layers of the road pavement structure. The use of construction and demolition waste (CDW) for manufacturing recycled concrete aggregates (RCA) that are suitable for engineering aspects of road construction contributes not only to decreasing the exhaustion of natural resources but also to the promotion of CDW recycling. The performance of recycled concrete aggregate (RCA) as a granular roadbed material depends on various field loading conditions (e.g., traffic load) and environmental factors (e.g., degree of saturation, S_r). Particle breakage is one of the important aspects that affect the performance of RCA, especially for evaluating the long-term pavement performance under field traffic conditions. However, the effect of variable saturation of RCA on particle breakage under cyclic loading is not fully understood. Therefore, this research performed both static and cyclic triaxial tests to study the strength and deformation behavior of RCA with variable S_r and examined the particle breakage of RCA based on Marsal's breakage ratio and mass reduction/accumulation of coarse aggregate using a coloring technique. The results showed that S_r affected the deformation of RCA and that the permanent axial strain increased with increasing *Sr*. On the other hand, S_r contributed to reducing the particle breakage of RCA under cyclic loading and the breakage of coarse fraction decreased with increasing S_r of RCA.

Keywords: Recycled Concrete Aggregate (RCA), Construction and Demolition Waste (CDW), Particle Breakage, Degree of Saturation, Cyclic Loading Triaxial Test

1. INTRODUCTION

Due to the demolition of existing infrastructures and occurrence of natural disasters recently, large amounts of construction and demolition waste (CDW) are being produced. In developing countries, the generated CDW is often dumped as waste without recycling for civil engineering purposes and causes a disposal problem. At present, it is difficult to discard a large quantity of CDW at designated landfill sites due to the shortage of land, especially in urban areas with rapid population growth. In order to solve the problem, the reuse and recycling of CDW as well as the effective use of industrial by-products such as wastewater sludge and incineration ash in the construction industry have gained much attention [1].

The history of the utilization of recycled materials in the construction industry goes back to the end of World War II when extensive demolition of the infrastructure occurred, and there was high demand to both get rid of the waste material and rebuild ruined countries. In the 1970s, the United States introduced the use of recycled concrete aggregate (RCA) for non-structural uses such as landfills, foundations, and base courses [2]. Since then, researchers have become interested in how to utilize RCA as an option to replace natural aggregate (NA) in construction activities to protect natural resources [3]. The increased demand and use of NA are depleting natural resources because much material is required for large construction projects. Therefore, use of RCA from CDW in geotechnical applications is increasing [4, 5].

Particle breakage is a critical aspect of the long-term durability of roadbed materials exposed to dynamic/cyclic loading under traffic conditions. To understand the impact of particle breakage on strength and deformation behaviors, several studies have been done using different laboratory tests, including cyclic triaxial systems and numerical methods [6]. Those studies found that particle breakage affected the shear strength of granular materials, including RCA, and induced more irrecoverable deformation [7]. Not only mechanical factors affecting the breakage behavior, but also physical characteristics of the granular materials and RCA were reported in the literature. For example, an increase in the coefficient of uniformity decreased the particle breakage at similar relative densities [8]. Moreover, a comprehensive laboratory assessment of physical and strength characteristics has been established for the utilization of recycled aggregates [9,10]. However, the effect of variations in the degree of saturation (S_r) on the breakage behavior of RCA has not been fully understood, even though roadbed layers with RCA are normally exposed to repeated wet and dry conditions in the field. Therefore, it is important to study the effects of S_r on the breakage of RCA to assess its long-term durability as a road pavement base material.

2. MATERIAL PROPERTIES

Recycled concrete aggregate (RCA) collected from a recycling plant in Japan was used in these experiments (Fig. 1). The specific gravity of RCA was 2.59. Absorption of particles >2.36 mm was 5.9% and particles <2.36 mm was 15.7%. The maximum dry density of RCA was 1.89 g/cm^3 with an optimum moisture concentration (OMC) of approximately 10%, corresponding to S_r = 67.2%. The tested RCA was sieved and graded from 19.0 to 0.075 mm in accordance with the RM-30 recommended by the Japan Road Association (2010) [11] as shown in Fig. 2.

3. EXPERIMENTAL SETUP AND TESTING CONDITIONS

3.1 Static and Cyclic Triaxial Testing System

The mechanical performance of RCA was determined by conducting a series of static and cyclic triaxial tests on compacted specimens at different S_r and selected stress conditions. A schematic of the cyclic triaxial system used in these experiments is shown in Fig. 3. A cylindrical RCA specimen 75 mm in diameter and 150 mm in height was used in the study. By pressurizing the air in the cell and spreading it through water, the confining pressure was applied and continuously monitored by a transducer connected to the cell.

Fig. 1 Recycled concrete aggregate (RCA) used in this study

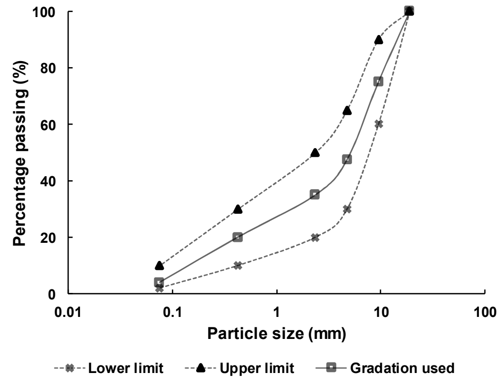

Fig. 2 Gradation curves of tested RCA in this study with upper and lower limit curves of RM-30 (Japan Road Association, 2010)

The cyclic load was applied using a double-action pressure cylinder mounted on top of the system. An electropneumatic (EP) transducer was used to convert a signal into pressure from a function generator. The vertical deformation of the specimen was calculated by measurements provided by a linear variable differential transformer (LVDT) attached to the vertical shaft on top of the triaxial cell. The volumetric deformation was measured through a low-capacity displacement transducer (LCDPT) by measuring the difference in water levels in a double cell. The cell pressure transducer and the load cell were connected to a data logging system that collected the responses of the transducers at specified time intervals. The test conditions used in cyclic triaxial tests are summarized in Table 1.

3.2 Sample Preparation and Placing

To evaluate the strength and deformation characteristics of RCA, tested samples were compacted with energy equivalent to modified proctor energy (2700 kJ/m^3). To assess the particle breakage of RCA under cyclic loading, coarse fractions of the tested material ranging from 19.0 to 4.75 mm were painted with fluorescent synthetic type resin paint. The colors used for these particle ranges are illustrated in Fig. 4. The fine fraction was kept in its original color due to difficulty in coloring. Next, the sample was mixed with distilled water to adjust the pre-determined value of S_r. The sample was then compacted in the mold in three layers with specified compaction energy of 2700 kJ/m^3. After compaction, the specimen was enclosed in a rubber membrane and placed on the pedestal of a triaxial cell. The specimen was sealed by O-rings at the top and bottom. Inner and outer cells were installed. After filling both cells with the water to the required level, cell pressure (σ_3) was applied and the sample was consolidated.

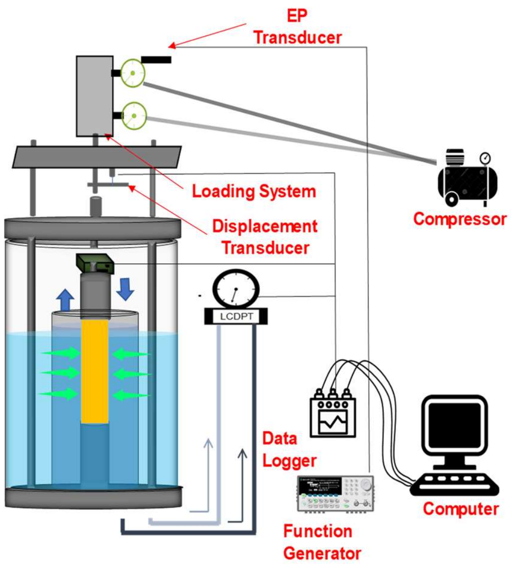

Fig. 3 A schematic diagram of cyclic loading triaxial test

3.3 Loading and Data Acquisition

For the static triaxial tests, strain controlled static triaxial tests were performed under a drained condition to get the strength and deformation characteristics of RCA samples. For the cyclic triaxial tests, on the other hand, stress controlled cyclic triaxial tests were performed under drained conditions to study the performance of RCA. The vertical axial load (σ_1) corresponding to the selected maximum and minimum deviatoric stresses (q) were applied as a waveform by generating a signal through a function generator and an EP transducer. A constant contact stress (10% of the maximum deviatoric stress) was applied to ensure constant contact between load assembly and specimen. Under the constant confining pressure, 2000 and 4000 repeated load cycles were applied. After completing the desired number of cycles, the tested sample was carefully retrieved, oven dried, and sieved to evaluate the particle breakage.

Table 1 Test conditions for sample compaction and cyclic loading triaxial test

Test conditions	
Compaction energy [kJ/m^3]	2700
Degree of saturation [%]	30, 40, 60, 80
Frequency [Hz]	0.2
Number of cycles [Nos.]	2000, 4000
Confining pressure [kPa]	70
Max. cyclic deviatoric stress [kPa]	590
Min. cyclic deviatoric stress [kPa]	59

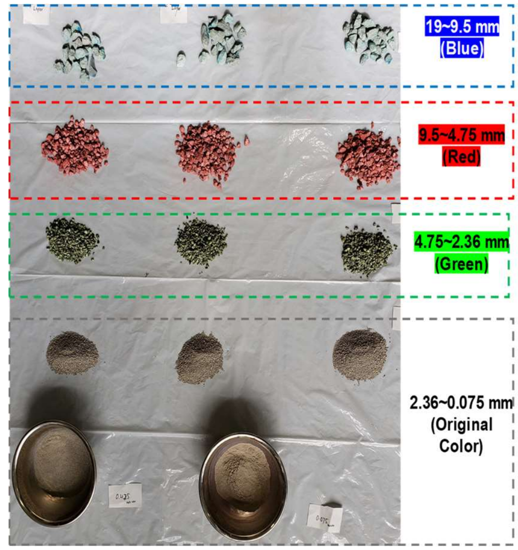

Fig. 4 A color scheme of each particle size fraction

4. RESULTS AND DISCUSSION

4.1 Static Triaxial Test

Prior to evaluating the performance of RCA during cyclic loading, static triaxial tests were performed. The test results are shown in Fig. 5. At σ_3= 70 kPa, the peak strength of the tested sample compacted at OMC was approximately 900 kPa. The sample failed after gaining slightly over 3% axial strain. The peak strength achieved from the static triaxial test was used to fix the maximum and minimum cyclic deviatoric stress values for assessing the long-term performance of RCA during the cyclic triaxial tests.

Similar to other reports in literature, the well-compacted RCA tested in this study exhibited greater strength rather than that of selected well-graded gravelly soil [12]. This is attributed to a distinctive feature of RCA, i.e., the mortar layer surrounding the thick core particles/aggregates, which might affect initial stiffness and volumetric strain. Past studies suggest that the negative effects of the mortar layer on the compressive strength of RCA could be eliminated by better compaction [13]. During triaxial compression loading, some mortar was crushed at inter-particle contact points, resulting in a low initial stiffness. Then, a better inter-particle contact condition between adjacent stiff cores of aggregate developed, resulting in an increase in tangent stiffness and ultimately in high compressive strength. The volumetric strain behavior showed a slight compression at the start and became more dilative towards the end of the test.

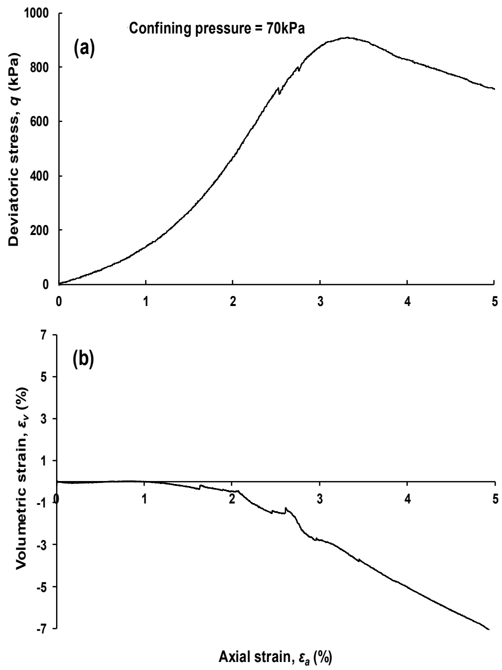

Fig. 5 (a) Strength and (b) Deformation behavior of RCA during static triaxial test

4.2 Cyclic Triaxial Test

Two series of cyclic triaxial tests were conducted to evaluate the long-term performance and particle breakage behavior of RCA with different S_r values. Figure 6 shows the maximum and minimum values of cyclic deviatoric stress applied in the cyclic triaxial test. The maximum deviatoric stress was taken as approximately 65% of the maximum stress achieved in the static triaxial test, and 10% of the maximum deviatoric stress was taken as the contact stress to ensure constant contact between loading rod, top cap, and sample [14]. Figure 7 explains the definition of permanent strain in this study. The accumulation of permanent axial and volumetric strains of the RCA specimens according to number of load cycles is shown in Fig. 8 at 2000 and 4000 cycles at a constant confining pressure (σ_3) of 70 kPa.

4.2.1 Permanent axial strain

As shown in Fig. 8 (a & c), higher permanent axial strains ($\mathcal{E}_{ap}$) were observed with higher S_r samples. The increment of permanent axial strain decreased as the number of load cycles increased at the constant maximum value of deviatoric stress (σ_d) and confining stress (σ_3).

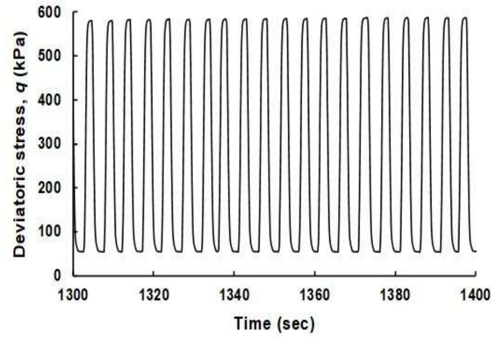

Fig. 6 Maximum and minimum cyclic deviatoric stress in the cyclic loading triaxial test

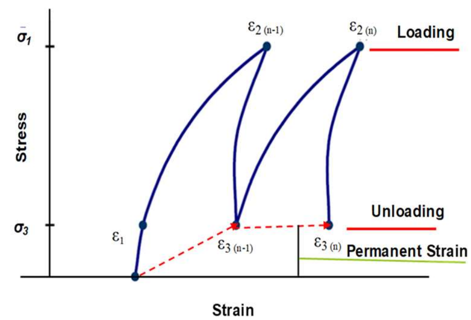

Fig. 7 A schematic to explain the permanent accumulated strain

The curves tended towards attaining a steady state of plastic response at the end of the test. In particular, the tested samples with lower S_r values (i.e., 30% and 40%) gave lower $\mathcal{E}_{ap}$ values in comparison to those with higher S_r samples. This behavior indicates the state of energy absorption by RCA on each stress-strain loop and its ability to resist after gaining minor permanent deformations. The decrease in $\mathcal{E}_{ap}$ over the number of loading cycles in an RCA sample indicates a state of plastic shakedown limit [15], and the accumulated $\mathcal{E}_{ap}$ of an RCA sample at lower S_r suggests the approach to plastic limit.

Moreover, the $\mathcal{E}_{ap}$ rose with increasing S_r, but RCA samples did not collapse under the cyclic loading, although the strain values were higher at saturation than the optimum value of RCA samples. A significant performance characteristic of RCA seems to be that it demonstrates resistance against plastic deformation at high water contents without collapse, which establishes its capacity for load bearing and its suitability as a high-quality granular pavement material. This is in accordance with the natural behavior of many conventional pavement materials that exhibit increases in plastic strain with increases in the water content [16].

4.2.2 Permanent volumetric Strain

As shown in Fig. 8 (b & d), the permanent volumetric strain ($\mathcal{E}_{vp}$) by number of load cycles was dependent on the Sr values of tested samples. The plastic volumetric strain showed a compressive behavior at higher S_r over the optimum value for both 2000 and 4000 cycles. When moved towards the dry state or lower S_r, the tested samples became more dilative. Based on this behavior, it is presumed that tested samples with higher S_r (wet) exhibited a compressive nature with increasing load cycles in comparison to lower S_r samples (dry) with more dilatancy. One possible reason may be inter-particle contacts in the soil matrix. When the sample contained more water (wet), it is supposed that the water escapes during drainage and settlement occurs. When the sample is dry, on the other hand, the particles are directly in contact with each other, and the particles slip over each other causing a dilatant behavior.

4.3 Particle Breakage

4.3.1 Marsal's breakage ratio

To quantify the extent of particle breakage, the most common method, Marsal's breakage ratio (B_g), was used [17]. B_g is a quantitative breakage index and is defined as the percentage by weight of the solid phase that has broken. It measures the percentage increase in mass of particles that pass through each sieve size as expressed in Eq. (1) and (2).

$$B_g = \Sigma\,(\Delta W_k > 0) \tag{1}$$

$$\Delta W_k = W_{ki} - W_{kf} \tag{2}$$

Where W_{ki} is the percentage of sample weight retained in each sieve size before the test, and W_{kf} is the percentage of sample weight retained in each sieve size after the test.

Calculated B_g values as a function of S_r are shown in Fig. 9. In the figure, a solid line represents the material subjected to 2000 loading cycles and a dotted line to 4000 loading cycles. The results showed that there was a minor shift in the curve upwards with the increase in the number of cycles from 2000 to 4000. A linear decrease of B_g values could be observed up to 60% of S_r, which is close to the measured optimum moisture content (OMC). Then, a slight increase was observed at S_r = 80% for both cases. Based on the overall trend, it is presumed that with the increase in S_r of RCA, the existing water provided a cushion effect and/or slippage surface around the particles, resulting in the less particle breakage of RCA.

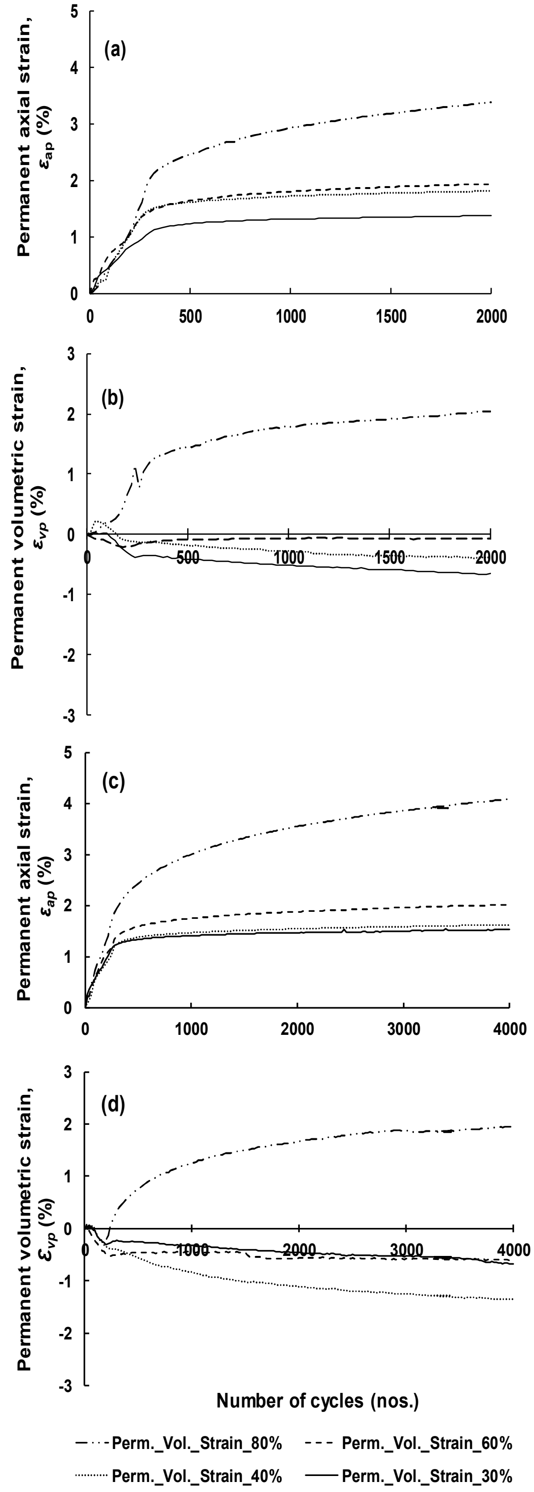

Fig. 8 (a) Permanent axial strain at 2000 cycles (b) Permanent volumetric strain at 2000 cycles (c) Permanent axial strain at 4000 cycles and (d) Permanent volumetric strain at 4000 cycles

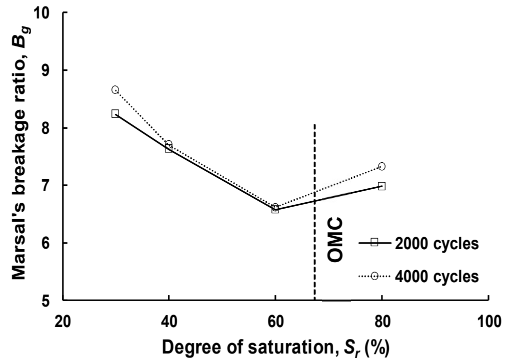

Fig. 9 Marsal's breakage ratio (B_g) as a function of degree of saturation (S_r)

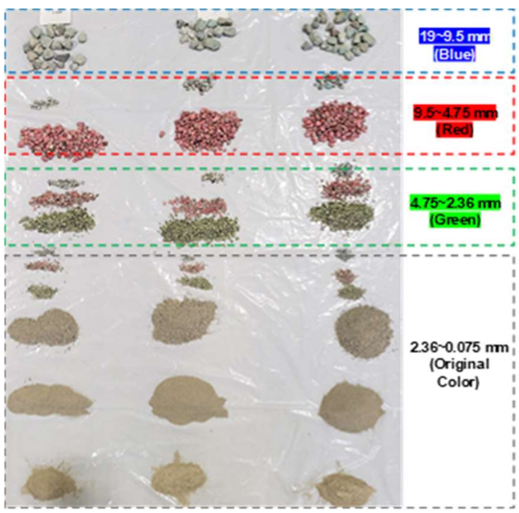

Fig. 10 Each particle size fraction after cyclic triaxial test

4.3.2 Mass reduction/accumulation coloring technique

To assess the particle breakage of each fraction, a coloring technique was introduced in this study. Tested materials after the cyclic loading triaxial test were sieved, and the colored-coarse fractions were segregated and weighed as shown in Fig. 10. Then, the mass reduction/accumulation of each fraction was calculated using the measured segregated weight:

$$\text{Mass reduction/accumulation (\%)} = [(\text{Initial mass} - \text{Final mass})/(\text{Initial mass})] \times 100 \quad (3)$$

Measured mass reductions/accumulations for tested RCA with different S_r are shown in Fig. 11. The coarser fractions such as 19.0–9.5, 9.5–4.75, and 4.75–2.36 mm were reduced under cyclic loading, and reductions ranged between 10–25%. In particular, the coarser fraction of 9.5–4.75 mm had a higher mass reduction compared to other fractions. The effects of S_r and cycle numbers on the particle breakage of coarse fractions were not very significant in the overall range of S_r. On the other hand, particle breakage of the finer fraction of 2.36–0.075 mm increased due to the accumulation and ranged between 9–17%. Further studies are needed to characterize particle breakage under cyclic loading of RCA, but the coloring technique is likely to be effective in quantitatively explaining breakage characteristics.

5. CONCLUSIONS

The performance characteristics of RCA with variable S_r were investigated by conducting a series of static and cyclic loading triaxial tests. The conclusions drawn are that axial strain was notably affected by S_r of RCA, and it increased with increasing S_r. The accumulation of permanent axial deformation of RCA moved towards a plastic state with the increased number of load cycles (especially for the RCA with low S_r), suggesting that S_r of RCA affects the performance of a road pavement system.

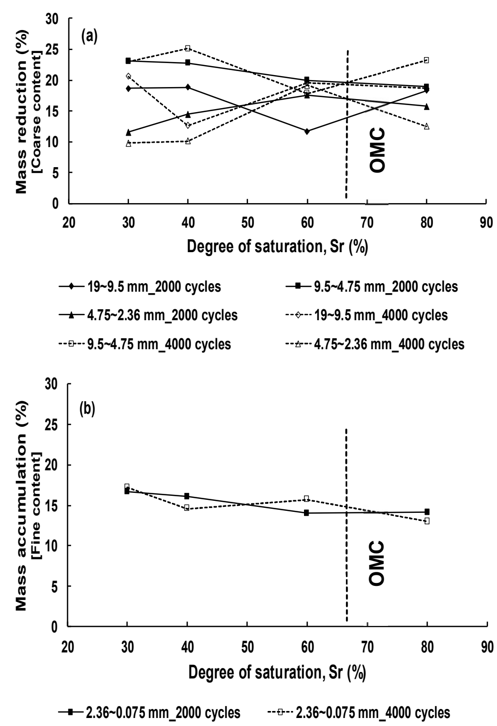

Fig. 11 (a) Mass reduction and (b) Mass accumulation in percentage

Results of both Marsal's breakage ratio and mass reduction/accumulation using a coloring technique showed that the particle breakage of RCA decreased with increasing Sr. In particular, the coloring technique introduced in this study was capable to giving a quantitative understanding of breakage characteristics (i.e., durability of RCA): the coarse fraction of 9.5–4.75 mm was more breakable than the other fractions, resulting in mass accumulations of finer fractions.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Iqbal M.R., Hashimoto K., Tachibana S., and Kawamoto K., Geotechnical Properties of Sludge Blended with Crushed Concrete and Incineration Ash. International Journal of GEOMATE, Vol. 16, Issue 57, 2019, pp. 116–123.

[2] Buck A. D., Recycled Concrete as a Source of Aggregate. ACI Journal. 74, 1977, pp. 212–219.

[3] McNeil K., Kang T.H.K., Recycled Concrete Aggregates: A Review. International Journal of Concrete Structures and Materials. Vol. 7, No. 1, 2013, pp. 61-69.

[4] Abukhettala M., Use of Recycled Materials in Road Construction. Proceedings of the 2nd International Conference on Civil, Structural and Transportation Engineering, ICCSTE'16, 2016, Paper No. 138.

[5] Sas W., Gluchowski A., and Szymanski A., The Geotechnical Properties of Recycled Concrete Aggregate with Addition of Rubber Chips during Cyclic Loading. International Journal of GEOMATE, Vol. 12, Issue 29, 2017, pp. 25-32.

[6] Coop M., Sorensen K., Freitas TB., and Georgoutsos G., Particle Breakage during Shearing of a Carbonate Sand. Geotechnique, 54(3), 2004, pp. 157-163.

[7] Yu F., Characteristics of Particle Breakage of Sand in Triaxial Shear. Powder Technology, 320, 2017a, pp. 656-667.

[8] Sun Y., Zheng C., Breakage and Shape Analysis of Ballast Aggregates with Different Size Distributions. Particuology, 35, 2017, pp. 84-92.

[9] Arulrajah A., Disfani M.M., Horpibulsuk S., Suksiripattanapong C., and Prongmanee N., Physical Properties and Shear Strength Responses of Recycled Construction and Demolition Materials in Unbound Pavement Base/Subbase Applications. Constr. Build. Mater, 58, 2014b, pp. 245-257.

[10] Nokkaew K. Characterization of Recycled Aggregate for Use as Base Course Material. International Journal of GEOMATE, Vol. 15, Issue 48, 2018, pp. 129-136.

[11] RM-30, Gradation Standard for Recycled Materials. Japan Road Association (JRA), 2010 (in Japanese).

[12] Aqil U., Tatsuoka F., Uchimura T., Lohani T.N., Tomita Y., and Matsushima K., Strength and Deformation Characteristics of Recycled Concrete Aggregate as a Backfill Material. Soils and Foundations, 45(4), 2005, pp. 53-72.

[13] Tatsuoka F., Tomita Y., Iguchi Y., and Harikawa D., Strength and Stiffness of Compacted Crushed Concrete Aggregate. Soils and Foundations, 53(6), 2013, pp. 835-852.

[14] Frost M.W., Fleming P.R., and Rogers C.D.F., Threshold Stress and Asymptotic Stiffness of UK Clays in the Repeated Load Triaxial Test. Proceedings of the 6th International Conference

[15] Cerni G., Cardone F., Virgili A., and Camilli S., Characterization of Permanent Deformation Behavior of Unbound Granular Materials under Repeated Triaxial Loading. Constr. Build. Mater., 28, 2012, pp. 79–87.

[16] Thom N.H., Brown S.F., Effect of Moisture on the Structural Performance of a Crushed-limestone Road Base. Transportation Research Record, 1 12 1, (1987).

[17] Marsal R.J., Large Scale Testing of Rockfill Materials. Journal of the Soil Mechanics and Foundation Division ASCE, 93(2), 1967, pp. 27-43.