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COMPACTION CHARACTERISTICS AND CBR OF SLUDGE BLENDED WITH RECYCLED CLAY BRICKS FOR ROAD SUBGRADE APPLICATION

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ABSTRACT: Reuse and recycling of non-hazardous construction and demolition waste and industrial byproducts in the construction industry is vital to promote environmentally sound waste management. In particular, the effective utilization of sludge and waste clay bricks is greatly required in developing countries. This paper studied compaction characteristics and the California bearing ratio (CBR) of water treatment sludge (WTS) blended with clay brick aggregates for the road subgrade application. Raw and waste clay bricks from Vietnam were used for preparing clay brick (CB) and recycled clay brick (RCB) aggregates of three different particle sizes, Coarse 10–30 mm, Graded 2–30 mm, and Fine 2–10 mm. In addition, fine residues of clay bricks with a size of < 2 mm were tested. WTS sieved under 2.0 mm blended with CB/RCB aggregates with different mixing proportions (f) were used for compaction and CBR tests in the laboratory. Results showed that the measured maximum dry densities (MDD) were dependent solely on mixing proportion f and increased linearly with f irrespective of blended fractions of CB/RCB aggregates. Unlike MDD, the measured CBR was dependent on both f and blended fractions. Especially, the WTS blended with coarse and graded fractions with a range of $60 \leq f \leq 80\%$ showed a significant improvement in CBR (>100%). Due to its limited particle breakage and high CBR, the WTS blended with graded CB/RCB aggregates was preferable for the road subgrade application.

Keywords: Construction and Demolition Waste (CDW), Water Treatment Sludge, Recycled Clay Bricks, Compaction, California Bearing Ratio (CBR), Particle Breakage

1. INTRODUCTION

With new construction activities and renovation of existing infrastructures, a huge amount of construction and demolition waste (CDW) is generated, especially in urban areas in developed countries. In the developing countries, there is minimal CDW recycling, and most CDW is dumped on-site without treatment and/or is brought to landfills off-site. The disposal of CDW at landfills is not an appropriate or sustainable solution for CDW management and causes a shortage of land, an illegal dumping in vacant areas, and environmental problems [1,2]. On the other hand, a massive quantity of sludge, including water treatment sludge (WTS), is generated. Along with CDW, the sludge is not adequately treated and reused in the developing countries, and most of the collected sludge is dumped in an unsafe manner [1]. In order to promote the reuse and recycling of CDW and sludge, various kinds of engineering utilization and applications of recycled materials have been proposed and adopted. One of the prevalent geotechnical utilizations of CDW is to use the recycled aggregates from CDW in road construction works. The requirements for developing road base/subbase and subgrade utilizing recycled aggregates from CDW are summarized in Table 1. Although the use of recycled aggregates in road construction works has been established technically, it has not been sufficiently disseminated.

Among the types of CDW, clay brick is a significant part of the total generated CDW, typically ranging from 10-30 % [3]. As shown in Table 2, clay brick from CDW is generally crushed and sieved to produce recycled aggregates and used as a road base/subbase and subgrade. Currently, the engineering utilization and application of WTS have also been examined: WTS is not only used for making new bricks and pavement materials but also is used for various geotechnical and environmental applications after improving the sludge quality.

From the viewpoints of availability and cost-effectiveness in developing countries, further recycling of waste clay brick can be expected. Many studies have been done on utilizing waste clay brick in construction purposes, especially for road construction. Among them, recycled clay brick (RCB) aggregates were mixed with superior quality materials such as recycled concrete aggregates and crushed waste rocks. Aatheesan [4] and Arulrajah [5] suggested that mixing 25–30% of RCB aggregates with a crushed rock could satisfy the technical requirements for road subbase construction. Cabalar [6] reported that blending 20% of RCB aggregates with clay was suitable to improve road subgrade. Compared to the use of recycled aggregates, the use of sludge, including WTS, is limited. This is mainly due to technical and economic constraints such as the difficulties in quality control and environmental safety of generated sludge [2,7], and the need for improving soil/sludge quality with additives [8].

Especially, the application of soil stabilization/solidification technique using additives for improving sludge quality is not feasible in developing countries from the viewpoint of cost-effectiveness.

According to the increasing demand for the recycling of CDW and sustainable waste management, further engineering utilization of recycled clay brick and sludge has been expected in developing countries. This study, therefore, aimed to examine the use of WTS and recycled aggregates from clay brick for road subgrade applications. The specific objectives were (i) to measure the geotechnical properties such as compaction and California bearing ratio (CBR) of WTS blended with recycled aggregates of clay brick, (ii) to assess the gradation effect of clay brick aggregates on the geotechnical properties and breakage of aggregates, and (iii) to propose an appropriate mixing proportion of clay brick aggregates based on the bearing capacity of the road subgrade.

Table 1 Requirements for developing road base/subbase and subgrade utilizing recycled aggregates from CDW

No	Items	Key points	Description	References
1	Available	Easy availability of CDW material	A massive quantity of CDW is available, some of it used in landfill or stockpiled	[9,10]
2	Cost-effective	Less investment as compared to virgin material	Use of available CDW is cost-effective and saves disposal charges	[11,12]
3	Environmentally friendly	No harmful contaminants	Most CDW is safe and poses no significant environmental and leaching hazard into the soil, surface, and groundwater	[11,13]
4	Sustainable management	Promoting reuse and recycling	Avoiding the utilization of natural resources and landfill sties	[14,15]
5	Engineered	High strength and proven engineering applications	Strength equivalent to virgin material	[1,6]

Table 2 Summary of engineering utilization of recycled clay brick (RCB) and water treatment sludge (WTS)

No	Area of use	Description	References
Recycled clay brick (RCB)			
1	Building and construction materials	Replacement constituents in the mortar, concrete making, paving blocks making	[16,17]
2	Geotechnical utilization	Road asphaltic wearing course, road base/subbase, and subgrade	[5,18,19]
3	Environmental utilization	Removal of heavy metals in wastewater as a filter bed	[20,21]
4	Others	Decorative qualities purposes of ancient architectural bricks, and as a filler in rubber	[22,23]
Water treatment sludge (WTS)			
1	Building and construction materials	Brick making, cement, pavement materials	[24,25]
2	Geotechnical utilization	Soil improvement and buffer soil qualities	[7]
3	Environmental utilization	Coagulant, substrate, absorbent, soil conditioner	[26,27]
4	Others	Animal feed, sewage sludge neutralization, gardening application	[7,28]

2. MATERIALS AND METHODS

2.1 Tested Materials

Water treatment sludge (WTS) generated at a drinking water treatment plant in Saitama Prefecture, Japan, was used in this study. The sample WTS was sieved into a < 2 mm particle size. Based on the sieve analysis, approximately 80% of WTS was < 0.075 mm (Fig.1). WTS is categorized as high plasticity silt (MH) according to the Unified Soil Classification System (USCS) and a member of the A-5 group, according to the American Association of State Highway and Transportation Officials (AASHTO).

Two different types of clay bricks, raw and waste clay bricks, were used for preparing clay brick (CB) and recycled clay brick (RCB) aggregates. Both clay bricks were taken from Vietnam: The raw clay bricks were purchased at a building material store, while the waste clay bricks were collected from Thanh Tri

CDW landfill site in Hanoi [29]. Both clay bricks were crushed by a mechanical crusher and sieved/graded in the laboratory, and CB and RCB aggregates with three different particle sizes (fractions), Coarse 10–30 mm, Graded 2–30 mm, and Fine 2–10 mm were prepared. In addition, fine residues (< 2 mm) of clay bricks were prepared. The particle size distribution of sieved/graded CB/RCB aggregates and fine residues < 2 mm is shown in Fig. 1.

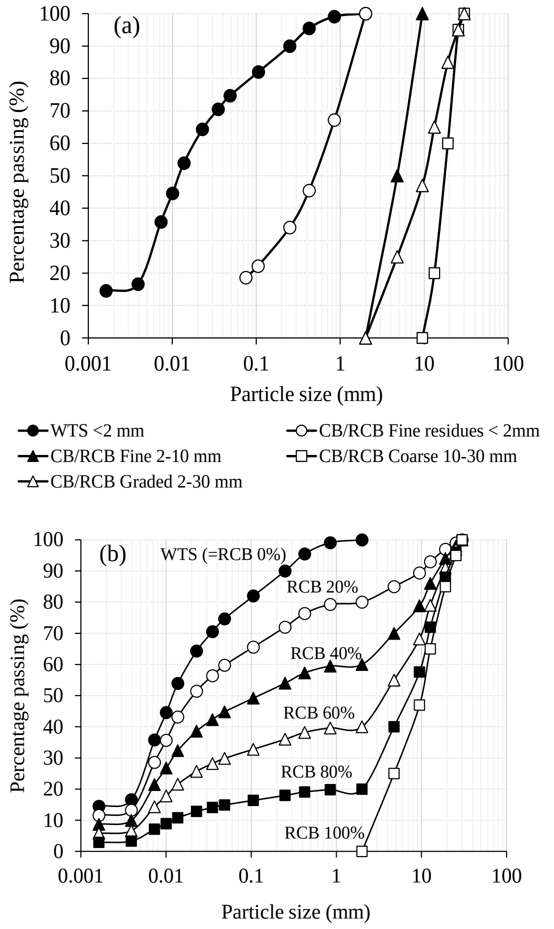


Fig. 1 Particle size distributions of tested materials: (a) individual materials and (b) WTS blended with CB/RCB aggregates

2.2 Physical Properties

The physical and chemical properties of the tested materials were determined following the American Standards for Testing of Materials (ASTM) and are summarized in Table 3. WTS was slightly cohesive and the measured plastic limit (PL) was 62%. The water absorption of RCB aggregates (12.2%) was slightly higher than that of CB aggregates (11.9%), probably due to the deterioration over time.

Table 3 Physical and chemical properties of tested materials

Tests	WTS	CB	RCB
G_s	2.36	2.67	2.58
Liquid Limit (%)	70	–	–
Plastic Limit (%)	62	–	–
W_{abs} [(a)] (%)	–	11.9	12.2
pH	6.3	8.4	10
EC [(b)] (mS/cm)	1.3	0.47	0.28
LOI [(c)] (%)	31	2.7	2.0
LA [(d)] (%)	–	44	44
Chemical components			
Na_2O	0.49	0.23	0.45
Al_2O_3	22.7	17.8	16.5
SiO_2	36.2	70.7	68.1
CaO	1.81	0.48	2.6
Fe_2O_3	5.53	6.10	6.4
SO_3	0.62	0.13	0.13
K_2O	0.96	2.40	2.90

[(a)] W_{abs}: Water absorption, [(b)]EC= Electrical conductivity, [(c)]LOI: Loss on ignition, [(d)]LA: Los Angeles abrasion test for CB/RCB aggregates (Coarse 10-30 mm)

The mineralogy of tested samples was determined by FP-EDX analysis. The oxides, such as SiO_2, Al_2O_3, and Fe_2O_3, which form through a pozzolanic reaction, were abundant in CB and RCB aggregates [16]. It is noted that the measured CaO (quicklime) in CB aggregates was lower compared to that in RCB. This could result in the lower pH of CB aggregates than that of RCB. In addition, water and acid extractable leaching tests [30,31] were conducted to determine the environmental safety of the tested materials (data not shown). The test results showed that all measured values from water and acid leaching tests were below the permissible levels of Japanese standards except for arsenic (As) in CB aggregates. The water-extractable concentration of As was 0.026 mg/L, which exceeded the permissible level of 0.01 mg/L. This might be attributed to the high As concentration in groundwater and geological deposits in the Red River basin, Hanoi [32].

2.3 Preparation of Blended Materials

The prepared CB/RCB aggregates of three fractions (Coarse 10–30 mm, Graded 2–30 mm, and Fine 2–10 mm) and fine residues of clay bricks (< 2 mm) were blended with WTS (< 2 mm) on a dry mass basis, ranging from 0 to 100% in the mixing proportion (*f*) with 20% increments. The particle size distributions for CB/RCB aggregates blended with WTS at different *f* values are shown in Fig. 1b. For the subsequent experimental studies such as compaction and CBR tests, initial water contents of blended samples were adjusted. First, distilled water was added to the blended sample to make the initial target water in a bag and the sample was mixed gently in the bag to make the moisture condition uniform. Then, the bag was sealed tightly and kept at least 48h to gain the moisture equilibrium under controlled temperature and relative humidity (20ºC and 60%) until the use for the experimental works.

2.4 Compaction and CBR tests

In order to characterize the geotechnical properties of blended samples, compaction and CBR tests were carried out in the laboratory. The compaction tests were performed at different water contents using the modified Proctor method [33] with a mold having an internal diameter of 12.75 cm and a height of 10 cm. The sample was compacted in the mold with a rammer weighing 4.5 kg and a drop height of 45 cm to achieve the compaction energy of 2700 kN-m/m^3 (five layers with 27 blows per layer). Based on the measured compaction curves, the maximum dry density (MDD) and optimum moisture content (OMC) were determined.

After the compaction test, wet sieving was performed using the compacted sample to evaluate the particle breakage of CB/RCB aggregates (size > 2.0 mm). The measured particle size distribution after compaction was compared to the original particle size distribution of CB/RCB aggregates, and for characterizing the particle breakage, particle breakage factor (B_g) was derived from Marsal's method [34], which was the change in particle size distribution and difference of percentage retained at each sieve is calculated as:

$$\Delta W_k = \Delta W_{ki} - \Delta W_{kf} \quad (1)$$

Where ΔW_{ki} and ΔW_{kf} represent the percentage retained at the same sieve size k before and after the tests, respectively. This difference could be either positive or negative, and B_g (%) is the sum of the difference (ΔW_k) having the same sign:

$$B_g = \sum \Delta W_k \quad (2)$$

California bearing ratio (CBR) tests were conducted to evaluate the potential bearing capacity of the blended samples following [35]. First, the moisture of the tested sample was adjusted to OMC (determined by the results of compaction tests), and the moisture-adjusted sample was compacted in a mold having an internal diameter of 14.98 cm and a height of 12.50 cm at modified compaction effort (close to MDD). Then, the compacted sample was soaked for 96h in water, and the expansion/contraction of the soaked sample was monitored with a dial gauge attached over the surcharge load. After the soaking, excess water was removed and then the standard plunger of 50 mm diameter was penetrated the sample at the rate of 1.00 mm/min up to 12.5 mm depths. Finally, CBR values at 2.5 mm and 5.0 mm depths were calculated. CBR test was performed in triplicate for each test sample to evaluate the variability of measured values.

3. RESULTS AND DISCUSSION

3.1 Compaction Characteristics

Measured compaction curves for tested samples, WTS blended with RCB aggregates with three fractions, (a) Fine 2–10 mm, (b) Coarse 10–30 mm, and (c) Graded 2–30 mm, are shown in Fig. 2. As shown in Fig. 2, a clear peak can be observed in the measured compaction curve of WTS 100%, and MDD became 0.95 g/cm^3 at OMC. On the other hand, all fractions of both 100% of CB/RCB aggregates did not show any clear peaks in the compaction curves, indicating that the compacted dry densities were independent of the initial water contents of tested samples in this study. Such absent and/or unclear peaks in the compaction curves have been reported for cohesionless recycled materials like concrete and RCB aggregates [19] and recycled crushed glass blends [36]. However, several researchers in the literature have reported the peaks (i.e., MDD) in the compaction curves for RCB aggregates at OMC = 9–12 % [5]. This difference might be attributed to the difference of particle size distribution/grading of tested CB/RCB aggregates and the quantity of fine particles (typically < 0.075 mm) because the compaction properties are sensitive to the fine contents and the moisture adsorption with such fine particles [37].

Similar to the tested samples of CB/RCB aggregates 100%, the WTS blended with CB/RCB aggregates did not show clear peaks in the measured compaction curves and gave flatter curves. The measured MDD in this study were plotted against f along with reported values for WTS 100%, WTS blended with concrete aggregates, and various recycled aggregates made from concrete, CB/RCB, asphalt, and glass are shown in Fig. 3.

The measured MDD of WTS 100% and CB/RCB aggregates 100% in this study ranged well within the reported values, and the MDD of WTS blended with CB/RCB aggregates increased linearly with increasing f [MDD = $5.4\times10^{-3} f + 0.98$ ($R^2 = 0.93$), MDD in g/cm^3 and f in %]. As shown in Fig. 3, the fraction size, gradation of mixed aggregates and the difference between raw and recycled aggregates did not affect the measured MDD from compaction tests, resulting in the mixing proportion of aggregates solely controlling the MDD of WTS blended with CB/RCB aggregates. This indicates, conversely, that the MDD can be easily estimated/controlled if the mixing proportion *f* (%) of CB/RCB aggregates is known. Similar characteristics of compaction have been reported in different tested recycled materials such as crushed glass blended with the waste rock for a footpath [1] and crushed concrete and incineration ash blended with WTS for road subgrade [38].

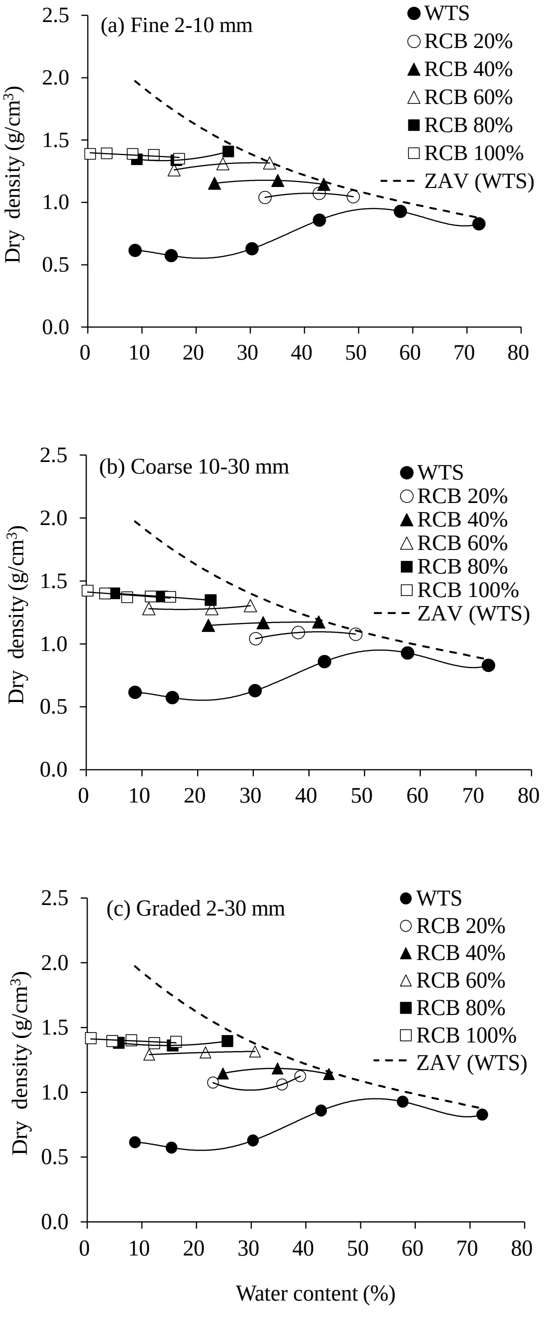


Fig.2 Compaction curves of WTS blended with RCB aggregates: (a) Fine 2–10 mm, (b) Coarse 10–30, and (c) Graded 2–30 mm

3.2 Particle Breakage of Clay Brick Aggregates After Compaction

Figure 4 exemplifies the measured particle size distributions before and after compaction of tested samples of WTS 20%–RCB 80% with three fractions of aggregates [(a) Fine 2–10 mm, (b) Coarse 10–30 mm, and (c) Graded 2–30 mm]. Based on the results from all tested samples, an index for characterizing particle breakage, the particle breakage factor (B_g) [Eq. (2)][34] was calculated.

The calculated B_g values were plotted against the mixed proportion of CB/RCB aggregates (*f*) and are shown in Fig. 5. The B_g increased monotonically with the increment of *f* for all tested samples (Fig. 5). The particle breakage was not significant up to 40% of CB/RCB aggregates, and the B_g values became approximately < 10%. This could be because a high amount of WTS in the sample prevented the breakage of aggregates under the compaction process (i.e., cushion effect). In the range of *f* ≥60%, on the other hand, the B_g values exceeded 10%, and the WTS blended with coarse CB/RCB aggregates (Coarse 10–30 mm) gave especially high B_g values ranging from 20–50%. Compared to the samples blended with Coarse 10–30 mm, B_g values for the samples blended with Graded 2–30 mm became lower at the high *f* range, and the values became less than 25% even for the samples of 100% CB/RCB aggregates.

This suggests that the graded particles of CB/RCB aggregates were dispersed well by the compaction impact and were effective in preventing the particle breakage under the compaction process. In addition, the reported B_g values for 100% concrete and rock aggregates [42-43] were plotted in Fig. 5. Compared to those reported values, the B_g values of 100% CB/RCB aggregates in this study (Graded 2–30 mm and Fine 2–10 mm) ranged within the variation of 100% concrete aggregates except for the samples of Coarse 10–30 mm.

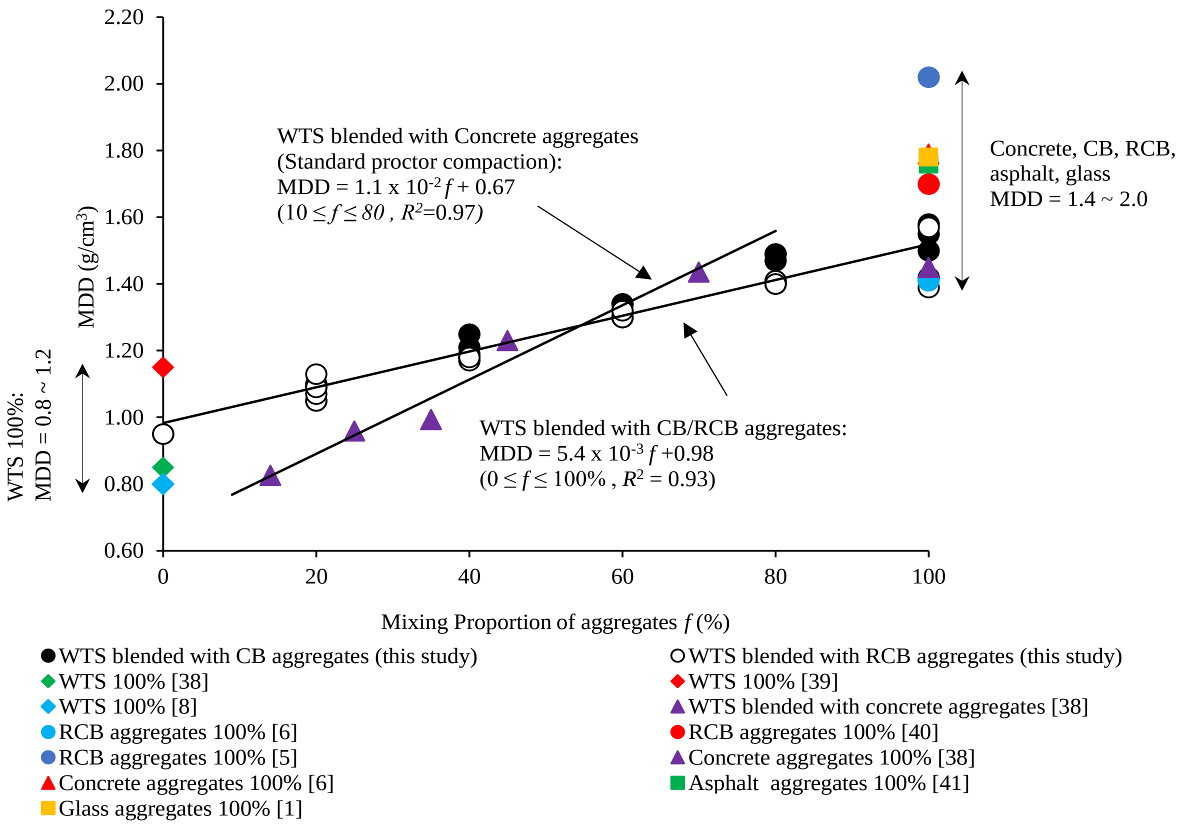
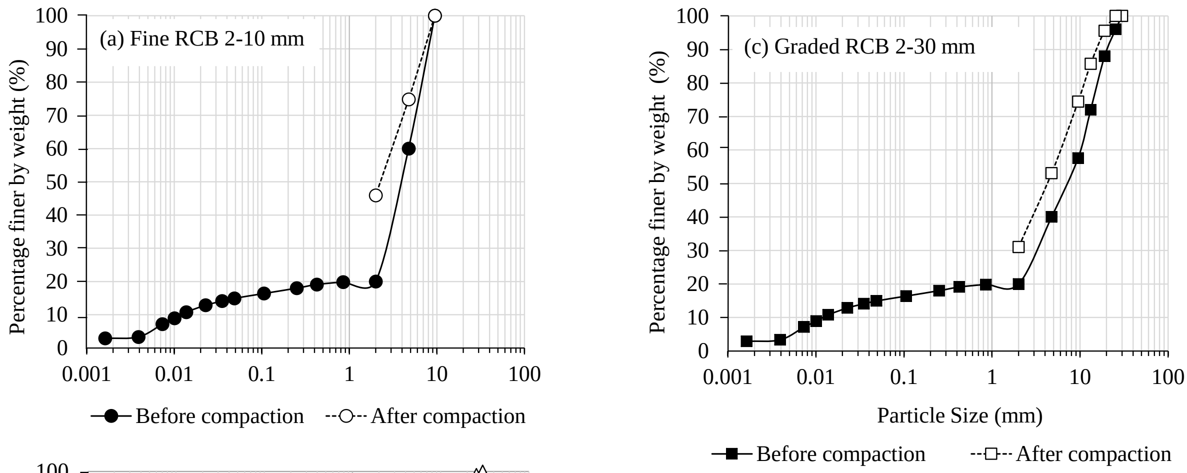


Fig. 3 MDD vs. mixing proportion of aggregates f



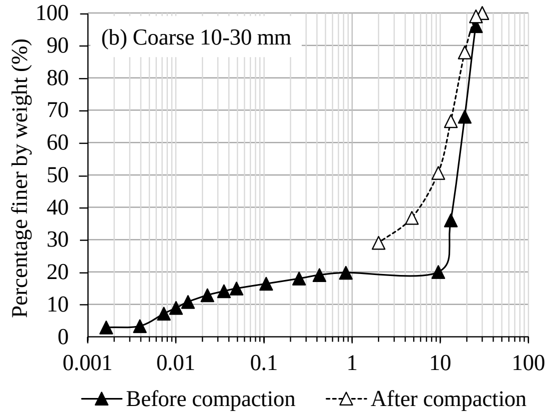


Fig.4 Particle size distributions of tested samples (WTS 20% – RCB 80%) before and after compaction: RCB aggregates (a) Fine 2–10 mm, (b) Coarse 10–30, and (c) Graded 2–30 mm

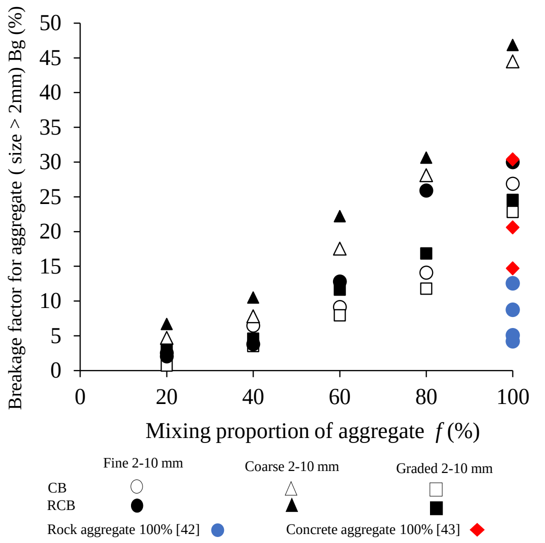


Fig.5 Particle breakage factor B_g of aggregates (size > 2 mm) by Marsal's method vs. mixing proportion of aggregates *f*

3.3 California Bearing Ratio (CBR)

The measured CBR values of WTS blended with CB/RCB aggregates and fine residues (< 2 mm) as a function of *f* are shown in Fig. 6a (Coarse 10–30 mm and Graded 2–30 mm) and Fig. 6b (Fine 2–10 mm and fine residues < 2 mm). The average values of triplicate measurements and coefficient of variations (CV) are given in Table 4.

Because there was no significant difference in the measured CBR for tested samples blended with CB and RCB aggregates, the average value and standard variations were calculated by combining the data of CB and RCB aggregates and are shown in Fig. 6. For all tested samples blended with CB and RCB aggregates with different *f* values, the measured CBR values became relatively uniform and the CV values mostly ranged 4–20% except for some tested samples (Table 4).

With the blending of CB/RCB aggregates and fine residues, the CBR values increased linearly till *f* = 80% and then decreased at *f* = 100%. In particular, the blending of Coarse 10–30 mm and Graded 2–30 mm much improved the CBR, and the measured values exceeded 100% with the range of 60≤ *f* ≤80% (Fig. 6a). The WTS blended with Fine 2–10 mm and fine residues (< 2 mm) also improved the CBR values with increasing *f*; on the other hand, most of the measured CBR values did not exceed 100%. It is worth mentioning that the measured MDD values for compacted samples were dependent solely on the mixing proportions of clay brick aggregates and gave approximately the same MDD at the same *f* irrespective of different blended fractions of whether they were clay brick aggregates or fine residues (Table 4 and Fig. 3). In contrast to the MDD, the CBR values became highly dependent on the blended fractions of clay brick aggregates.

The CBR values for different types of recycled aggregates (*f* = 100%) reported in the literature are also given in Fig. 6. Compared to the reported values for RCB and concrete aggregates (Fig. 6a), our tested data ranged well within the reported values. Notably, the CBR values for Coarse 10–30 mm (*f* = 100%) was similar to the reported values of RCB aggregates [5] and became higher than some recycled concrete aggregates [6,18]. The CBR values for Graded 2–30 mm (*f* = 100%) became slightly lower than those of Coarse 10–30 mm; however, they became higher than the reported values of RCB and concrete aggregates [6,18]. Besides, the measured CBR for Fine 2–10 mm in this study (Fig. 6b) became higher than those for recycled aggregates from asphalt and glass particles [6,44].

As shown in the particle breakage factor in Fig. 5, the WTS blended with coarse clay brick aggregates gave the highest particle breakage during the compaction process. For the WTS blended with graded clay brick aggregates, in contrast, the compaction impact was significantly reduced due to the cushioning effect of particle gradation. In addition, the mixing of WTS (< 2 mm) and graded aggregates (2–30 mm) can be expected to prevent particle separation under water percolation, leaching of fine particles, and subsequent clogging by continuous particle accumulation in the road subgrade (i.e., reduction in hydraulic conductivity) due to the similarity of particle size range [45,46]. Considering the significant enhancement of CBR values shown in Fig. 6a, therefore, the blending of graded clay brick aggregates (Graded 2–30 mm) with the range of 60% ≤ *f* ≤ 80% was the most suitable to improve the mechanical properties of WTS and preferable among tested conditions in this study. Further investigation and analysis of the application of WTS blended with recycled clay brick aggregates to the road subgrade should be performed in terms of its feasibility and sustainability. For example, not only investigating the mechanical properties under field conditions but also its ability to control hydraulic properties should be investigated by its long-term performance of water percolation.

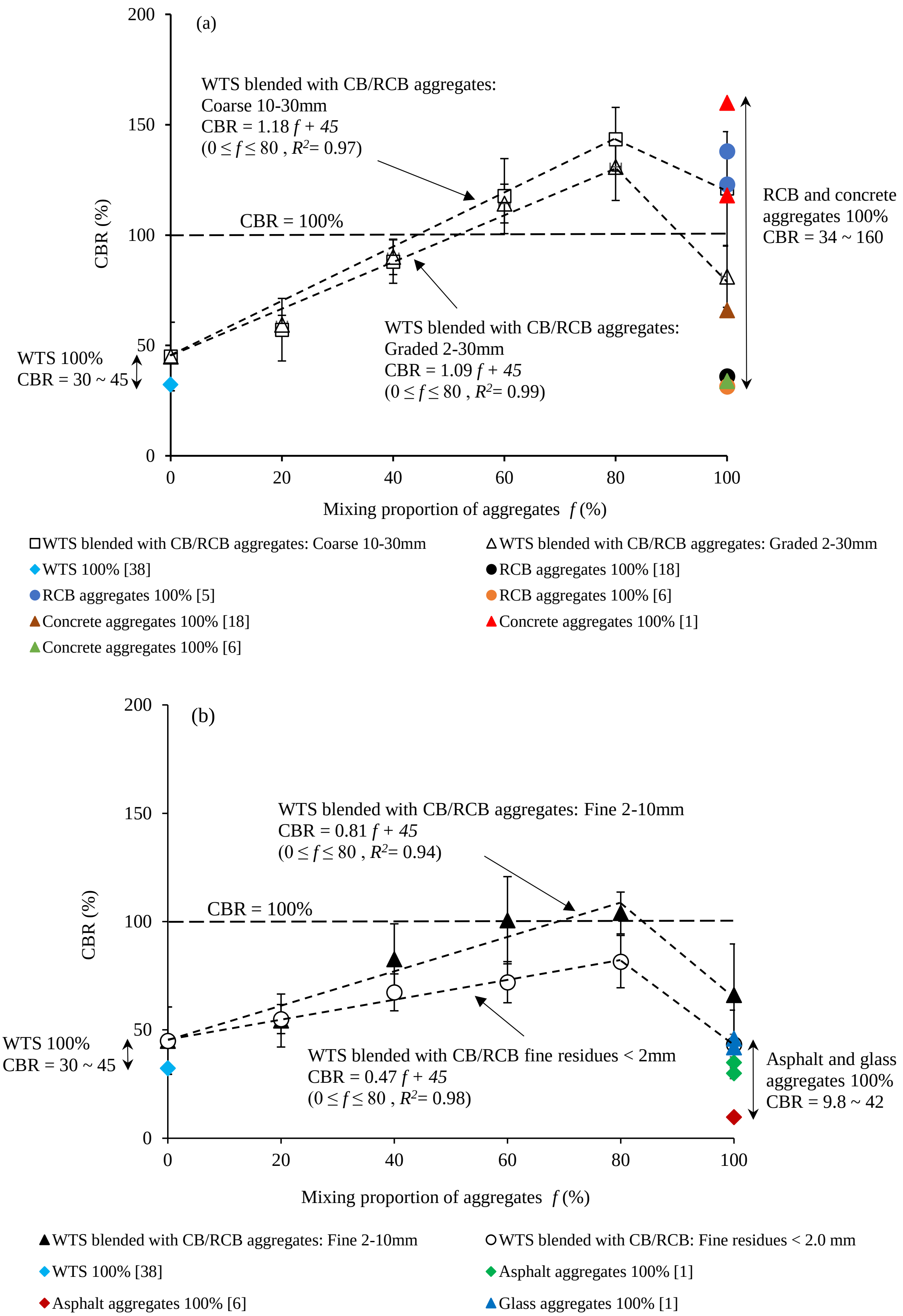


Fig. 6 CBR vs. mixing proportion of aggregates *f*. WTS blended with CB/RCB aggregates (a) Coarse 10–30 mm and Graded 2–30 mm, (b) Fine 2–10 mm and Fine residues < 2 mm. The plots show average values and error bars show a coefficient of variation.

Table 4 MDD, particle breakage factor B_g, and CBR of CB/RCB aggregates blended with WTS at different proportions

Mixing proportion *f*		CB aggregates				RCB aggregates			
WTS	CB/RCB	<2.0 mm	Fine 2-10 mm	Coarse 10-30 mm	Graded 2-30 mm	<2.0 mm	Fine 2-10 mm	Coarse 10-30 mm	Graded 2-30 mm
MDD (g/cm^3)									
100%	0%	0.95				0.95			
80%	20%	1.05	1.10	1.09	1.10	1.05	1.07	1.09	1.13
60%	40%	1.18	1.21	1.25	1.19	1.18	1.18	1.17	1.18
40%	60%	1.30	1.34	1.34	1.34	1.30	1.32	1.30	1.32
20%	80%	1.41	1.49	1.49	1.47	1.40	1.41	1.40	1.40
0%	100%	1.58	1.50	1.55	1.53	1.57	1.39	1.42	1.40
B_g (%)		CB aggregates				RCB aggregates			
100%	0%	-				-			
80%	20%	-	3.5	4.7	0.7	-	2.1	6.7	3.0
60%	40%	-	6.5	7.8	3.5	-	3.8	10.5	4.6
40%	60%	-	9.1	17.6	8.0	-	12.8	22.2	11.6
20%	80%	-	14.1	28.1	11.8	-	25.9	30.6	16.9
0%	100%	-	26.9	44.5	22.8	-	30.0	46.9	24.5
CBR (%)*		CB aggregates				RCB aggregates			
100%	0%	45 (16)				45 (16)			
80%	20%	52 (4)	52 (14)	57 (22)	57 (4)	58 (4)	56 (12)	58 (5)	62 (17)
60%	40%	67 (10)	84 (24)	82 (8)	90 (8)	67 (9)	82 (9)	94 (8)	90 (9)
40%	60%	73 (13)	95 (28)	109 (4)	122 (8)	71 (7)	116 (11)	126 (22)	107 (16)
20%	80%	84 (14)	95 (7)	134 (6)	151 (13)	79 (12)	108 (6)	153 (18)	111 (5)
0%	100%	41 (16)	76 (15)	145 (16)	89 (13)	46 (16)	57 (26)	98 (17)	73 (3)

*Average values of triplicate measurements are given. The values in parenthesis are coefficients of variation (%).

4. CONCLUSIONS

In order to examine the effective utilization of sludge and waste clay bricks for the road subgrade application, compaction characteristics and CBR of WTS blended with clay brick aggregates were quantified using laboratory tests. The results of the compaction tests showed that the blended fractions of clay brick aggregates did not affect the measured MDD values, and the values increased linearly with the mixing proportion of aggregates.

However, the degree of particle breakage varied depending on the blended fractions of clay brick aggregates, and the particle breakage was enhanced in the tested samples blended with coarse clay brick aggregates. From the results of the CBR test, the measured CBR values were dependent on both mixing proportion and blended fractions of clay brick aggregates. In particular, the blending of coarse and graded fractions showed a significant improvement in CBR. WTS blended with coarse and graded fractions with a range of $60 \leq f \leq 80\%$ showed a significant improvement in CBR (>100%). Overall, WTS blended with graded clay brick aggregates was preferable for road subgrade applications due to its small particle breakage and high improvement of CBR values.

5. ACKNOWLEDGEMENT

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