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GEOTECHNICAL PROPERTIES OF SLUDGE BLENDED WITH CRUSHED CONCRETE AND INCINERATION ASH

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ABSTRACT: Generation of large amounts of waste material reduces the capacity of landfill disposal sites. To make effective use of drinking water sludge (DWS) and DWS blended with crushed concrete (CC) and incineration ash (IA) as geotechnical materials, the geotechnical properties of DWS for suitability of a road subgrade were examined. A series of laboratory tests measuring compaction, California bearing ratio (CBR), undrained triaxial compression, and consolidation was conducted by changing the mixing proportions of tested materials. The compaction test showed that maximum dry density and optimum water content have a unique linear relationship with the proportion of CC/IAs mixed with DWS. Measured CBR values of mixtures of CC/IA blended with DWS at both low energy (600 kJ/m^3) and high energy (1800 kJ/m^3) showed linear relationships, and an empirical equation was newly proposed in terms of mixing fraction and maximum dry density at low energy compaction. The result of the consolidated undrained triaxial compression test showed that the blend of CC/IA with DWS increased friction angles but did not contribute to an increase in the undrained shear strength. The results of consolidation tests showed that the blend of CC reduced the compressibility of DWS highly, especially samples that contained a proportion of CC and CC/IA greater than 50%. Overall, the blend of CC raised the compaction property of DWS accompanying an increase in bearing capacity, compressibility and can be effective to improve geotechnical properties of DWS for application as a road subgrade.

Keywords: Drinking Water Sludge, Crushed Concrete, Incineration Ash, Compaction, California Bearing Ratio (CBR), Compressibility

1. INTRODUCTION

The large amounts of waste material produced daily cause a disposal problem. It is difficult to dispose of all waste materials in landfill sites due to the scarcity of land and an increase in public resistance. With population increases in urban areas and the development of cities, waste management issues have gained much attention [1], and more use of construction and demolition waste and industrial byproducts, such as wastewater sludge and incineration ash, in geotechnical applications, is expected [2,3]. It is widely accepted that recycling and the subsequent use of construction and demolition waste will reduce the demand for virgin and raw materials [3,4]. Therefore, alternative uses of recycled materials along with the minimization of landfilling waste are essential in the development of sound solid waste management.

Much research has been conducted on the utilization of construction and demolition waste and industrial byproducts for engineering purposes: Crushed concrete and crushed bricks are used as road sub-base and base materials [2,4,6], and the mixing of stabilizers and additives such as lime, fly ash, cement, and loess improves sludge properties [6,7], while the mixing of coarser fractions (e.g. crushed bricks, recycled concrete) and recycled asphalt pavement) with clayey materials improves the geotechnical strength [8].

Drinking water sludge (DWS) is classified as industrial waste in Japan and is fully treated and recycled [9]. In developing countries, on the other hand, the use of DWS is very limited and most of DWS is dumped in waste landfill sites and vacant land without any treatment [10]. Several studies have been done on the utilization of DWS as a geotechnical material for road subgrades and backfilling [11,12]; however, the effects of mixing other recycled materials and industrial byproducts with DWS on the improvement of geotechnical properties have not been fully investigated. Therefore, the objective of this research was to characterize the geotechnical properties of DWS blended with crushed concrete (CC) and incineration ash (IA) for the potential use of mixed materials for road subgrade construction. CC and IA were blended with DWS at different proportions to analyze various geotechnical properties such as compaction, California bearing ratio (CBR), triaxial compression, and consolidation.

2. MATERIALS AND METHODS

DWS was collected from water treatment plants in Japan. CC and IA were collected from a recycling plant and final disposal site in Saitama Prefecture, Japan. These materials were sieved in the laboratory before use, and the particle size distributions were adjusted to less than 2 mm for DWS and IA and 2–9.5 mm for CC (Fig. 1).

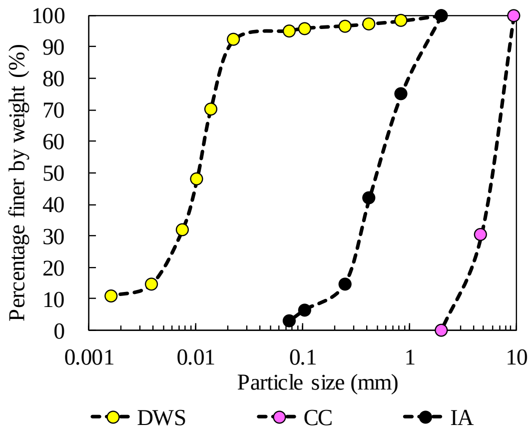


Fig. 1 Particle size distributions of tested materials.

2.1 Physical Properties

Index properties of tested materials were based on the American Standards for Testing of Materials (ASTM) and Japan Industrial Standards (JIS). Table 1 shows the basic physical properties of tested materials. DWS was a cohesive material, while CC and IA were cohesionless materials. Atterberg limits of DWS were similar to the previously reported values [7]. According to the unified soil classification system, DWS is categorized as a fat clay (CH), CC as well-graded gravel (GW), and IA as poorly graded sand (SP). According to the AASHTO soil classification, DWS is categorized as a clay soil (A-7-5), CC as a stone fragment gravel and sand (A-1), and IA as A-1-b.

Table 1 Physical properties of tested materials

Tests	DWS	CC	IA
Particle size (mm)	< 2.00	2 - 9.50	< 2.00
Liquid limit (%)	260	NM*	NM*
Plastic limit (%)	130	NP**	NP**
Specific gravity	2.39	2.59	2.69
pH	6.60	11.0	11.1
Loss on ignition (%)	38.2	9.5	1.6
Electrical Conductivity (mS/cm)	0.29	0.47	1.99

*NM: Not measurable, **NP: Non-plastic

2.2 Chemical Properties

Table 2 shows the element components of the tested samples based on the fundamental parameter method of energy dispersion X-ray spectrometry (FP-EDX). Major elements of DWS were Si, Al, and Fe. CC and IA were rich in Ca, and CaO exceeded 20%.

Water and acid extractable heavy metals were measured according to the testing methods in Japan to evaluate the environmental safety of tested materials [13,14]. Except for water-extractable Cr of IA and acid-extractable Pb of IA, all parameter values were lower than environmental standards [15], indicating that our tested IA is not suitable for an actual construction material as its original form but must have an insolubilization/immobilization treatment [16].

Table 2 Chemical analysis of tested materials

Components (%)	DWS	CC	IA
Na_2O	0.49	1.32	3.24
Al_2O_3	22.7	9.19	10.8
SiO_2	36.2	39.9	46.0
CaO	1.81	22.5	23.1
Fe_2O_3	5.53	7.52	4.42
SO_3	0.62	2.27	1.01
K_2O	0.96	2.68	1.36

Table 3 Water- and acid-extractable heavy metals of tested materials

Parameters	DWS	CC	IA	Environmental standards [15]
Water extractable ions				(mg/L)
As	ND*	ND*	ND*	0.01
Cd	ND*	ND*	ND*	0.01
Cr	ND*	0.005	0.15	0.05
Pb	ND*	ND*	ND*	0.01
Mg	ND*	ND*	ND*	0.0005
Se	0.001	0.001	0.002	0.01
F	ND*	ND*	0.2	0.8
B	ND*	ND*	0.4	1
Al	ND*	ND*	0.239	-
Acid-extractable ions				(mg/kg)
As	21	3	8	150
Cd	ND*	ND*	9	150
Cr	ND*	ND*	6	250
Pb	11	21	150	150
Mg	ND*	ND*	ND*	15
Se	ND*	ND*	ND*	150
F	200	82	230	4000
B	ND*	ND*	110	4000

*ND: Not detectable

2.3 Geotechnical Properties

A series of experiments to characterize the geotechnical properties was carried out according to the testing standards of ASTM. Standard Proctor compaction tests were conducted on an individual, 2 mixed and 3 mixed samples with various mixing proportions using a mold 10 cm in diameter and 12.75 cm in height [17]. The soaked California bearing ratio (CBR) tests were performed at two different energy levels. Low energy (600 kJ/m^3) is denoted as CBR-A, and high energy (1800 kJ/m^3) is denoted as CBR-D.

Consolidated undrained triaxial compression tests were performed to determine the cohesion and angle of internal friction at confining pressures of 50, 100 and 150 kPa. The tested samples were first packed in a split mold of 10 cm diameter and 20 cm height at the standard compaction effort [18]. Consolidation tests were conducted on the modified oedometer apparatus of 10 cm diameter and 10 cm height with particles size greater than 2 mm. After full saturation of the samples at 3.75 kPa to avoid swelling, loading was applied in 8 steps from 7.05 kPa to 905 kPa and prolonged for one day to achieve primary consolidation. The time square root method was used to determine 90% and 100% consolidation [19]. For both undrained triaxial compression and consolidation tests, the tested samples were compacted at more than 90% degree of compaction.

3. RESULTS AND DISCUSSION

3.1 Compaction Properties

Compaction plays a vital role in improving the packing of the particles of material by reducing the void spaces. Soil can reach its densest condition by optimal wetting and rearranging of the particles by mixing with water and compaction [20]. Compaction test results are shown in Fig. 2. DWS showed the maximum dry density (MDD) of 0.85 g/cm^3 at the optimum water content (OWC) of 68.20%, which were a lower MDD and higher OWC than previously reported values [11]. The difference could be due to the origin of suspended solids that form DWS under the water treatment process. For IA, measured dry densities did not show any peak and varied from 1.55 to 1.61 g/cm^3 with the initial water content of 6% to 14.7%. CC was slightly dependent on the initial moisture content and gave MDD with OWC of 8%. Compaction curves of the different mixtures of CC and IA were reduced over the absorption of the DWS and led to the improvement of the interlocking forces amongst the particles on the dry side of the compaction curve, which improved the strength of the mixed samples. This trend can be well observed in Figs. 2 (a)-(c).

Measured MDD (gcm^{-3}) and OWC (%) values were plotted against the mixing proportion, f (%), and are shown in Fig. 3. For DWS blended with CC and IA, both MDD and OWC showed a good linear relationship with f except for non-blended materials (DWS=100% and CC/IA=100%).

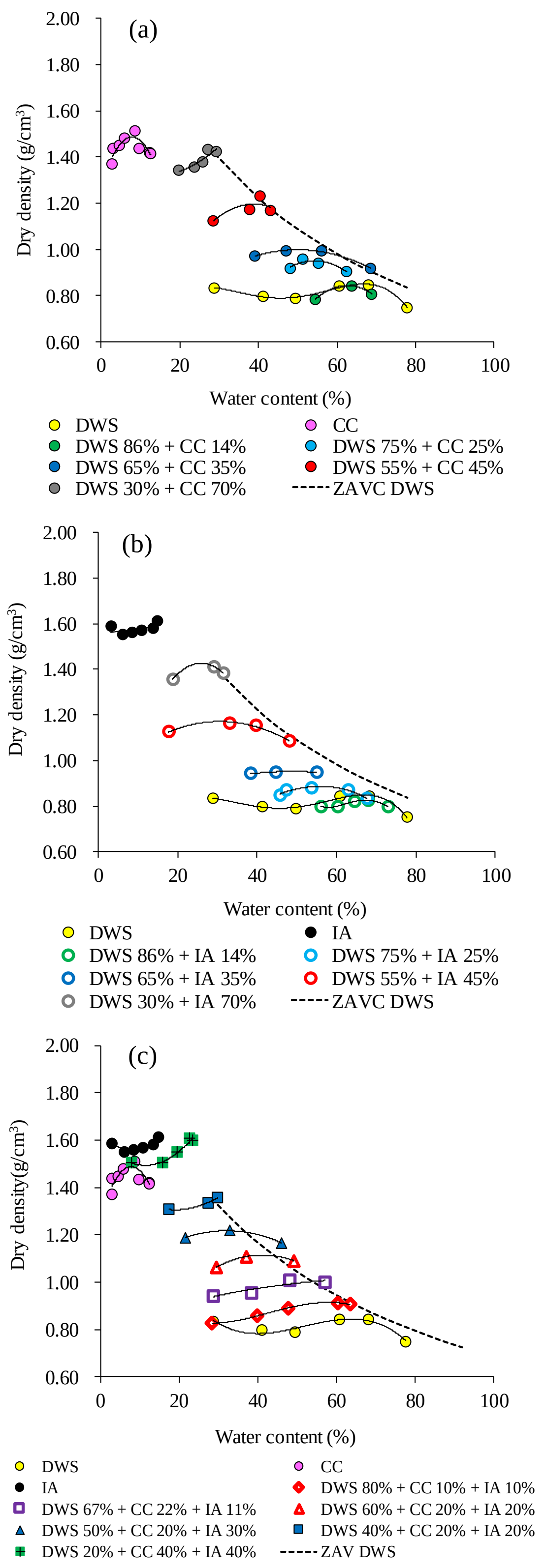
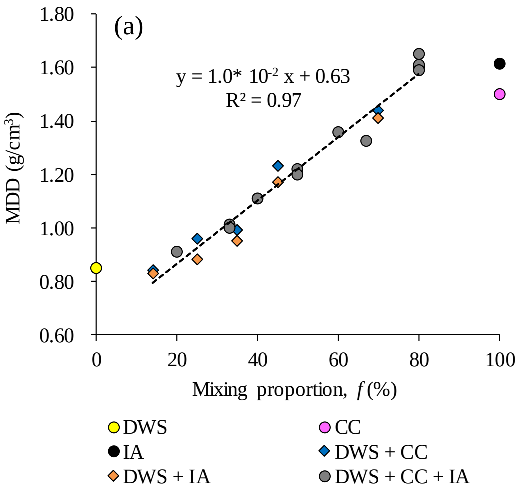


Fig. 2 Compaction curves for (a) DWS blended with CC, (b) DWS blended with IA, and (c) DWS blended with both CC and IA.

The linear regressions can be expressed as:

$$\text{MDD (gcm}^{-3}\text{)} = 1.0 * 10^{-2} f + 0.63 \quad (R^2 = 0.97) \quad (1)$$

$$\text{OWC (\%)} = -0.68 f + 73.3 \quad (R^2 = 0.94) \quad (2)$$



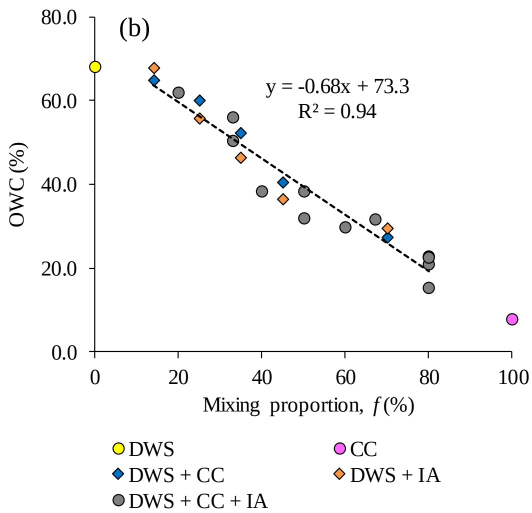


Fig. 3 Relationships between (a) the maximum dry density (MDD) and mixing proportion, f (%) and (b) optimum water content (OWC) and mixing proportion f (%) for CC and/or IA to DWS.

3.2 California Bearing Ratio (CBR)

A CBR value increases with the addition of course material due to the increase of frictional resistance and incompressibility of the additive material as well as leading to the enhanced bearing capacity of the mixed material [21]. Tested CBR results are shown in Table 4. The results from CBR-A revealed that the mixing of CC from 25% to 70% increased the CBR value from 1.21 to 2.39 times and became more effective than the mixing of IA. The results from CBR-D revealed that addition of CC with DWS from 25% to 70% enhanced CBR values from 1.44 to 2.97 times as compared to individual materials. This could be due to an increase of interlocking, well packing of fine and coarse proportions. On the other hand, IA blended with DWS did not show any improvement at higher compaction energy. The addition of both CC and IA to DWS increased CBR values, but the increase would be attributed to the inclusion of CC.

Several studies showed empirical relationships between measured CBR and index properties of soil such as particle size, compaction parameters, plasticity, and mixing fraction. Among of them, three empirical relationships, $\text{CBR} = -0.0029\text{x}^2 + 0.3985\text{x} + 5.014$ (x: fraction of sand to clay material) [22], $\text{CBR} = 28.09\,(\text{D}_{60})^{0.358}$ (D_{60}: diameter of particles at 60% finer by weight) [23], and $\text{CBR} = 21.28 - 16.29\log(w_o) + 0.07\,w_L$ (w_o= optimum water contents, w_L= liquid limit) [24] were tested against measured CBR-D values, and a scatterplot comparison of predicted and measured CBR values is shown in Fig. 4. Empirical relationships did not capture our tested data well and underestimated the measured CBR, indicating that CBR values vary depending upon the types of aggregates and fines that are mixed in, and it is difficult to develop a generalized predictive equation based on index properties.

Table 4 Measured CBR-A and CBR-D

Tested Samples	CBR-A (%)	CBR-D (%)
DWS	11.8	32.2
CC	22.1	30.4
IA	13.1	25.2
DWS 75% + CC 25%	14.3	46.0
DWS 30% + CC 70%	28.2	94.5
DWS 75% + IA 25%	15.8	31.3
DWS 30% + IA 70%	25.0	32.2
DWS 80% + CC 10% + IA 10%	16.6	37.9
DWS 67% + CC 11% + IA 22%	20.1	44.2
DWS 50% + CC 20% + IA 30%	24.1	57.8

Figure 5 shows the relationships between measured CBR values and MDD from compaction tests. For both CBR-A and CBR-D, there were relatively good linear relationships, and the linear regression can be expressed as:

$$\text{CBR-A} = 22.4\,\text{MDD} - 6.14 \quad (R^2 = 0.85) \quad (3)$$

$$\text{CBR-D} = 95.9\,\text{MDD} - 66.0 \quad (R^2 = 0.85) \quad (4)$$

Combining Eq. (3) with Eq. (1), we can derive an empirical equation:

$$\text{CBR-A} = 0.224 f + 9.09 \qquad (R^2 = 0.92) \qquad (5)$$

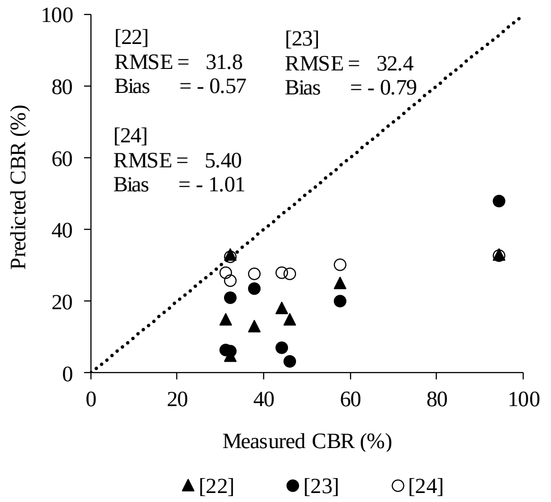


Fig. 4 Scatterplot comparison of measured and predicted CBR values by [22-24]. RMSE: Root mean square error

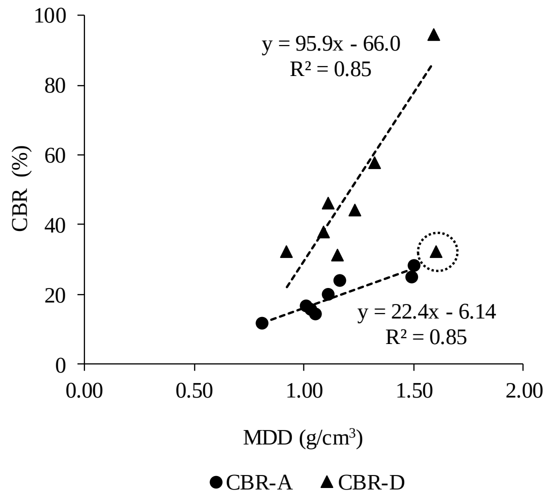


Fig. 5 Measured CBR values vs. maximum dry density (MDD) from compaction tests.
Note: The measured value in the broken circle for CBR-D was not used to determine the regression line

A scatterplot comparison of measured and CBR-A values predicted by Eq. (5) is shown in Fig. 6. The newly-derived empirical equation well fitted the measured CBR values with lower RMSE. Because of Eq. (5) can be applied easily using a single parameter of mixing proportion (such as crushed concrete, coarse aggregates), it would be a useful tool to estimate CBR values for compacted samples, especially in Standard Proctor condition.

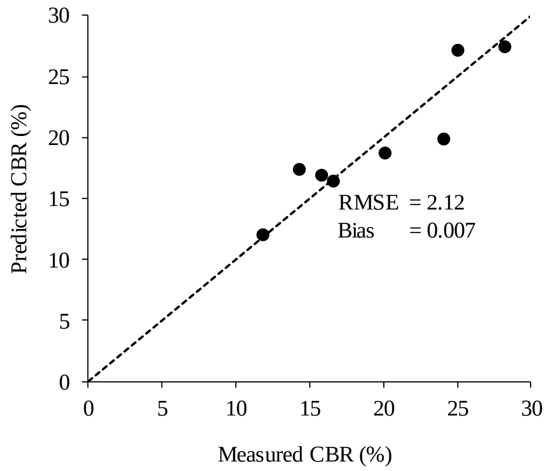


Fig. 6 Scatterplot comparison of measured and predicted CBR from the empirical equation, Eq. (5). RMSE: Root mean square error

3.3 Consolidated Undrained Triaxial Compression Test Properties

The measured stress-strain relationship determined by a consolidated undrained triaxial compression test is exemplified in Fig. 7 (DWS67%+CC11%+IA22%), and the corresponding Mohr circle is shown in Fig. 8. Measured values of effective cohesion (c') and frictional angle (Φ') for all tested samples were summarized in Table 5.

Table 5 Effective cohesion and frictional angle for all tested samples

Tested Samples	c' (kPa)	Φ' (degrees)
DWS	10	32.7
DWS75%+CC25%	3	36.0
DWS75%+IA25%	6	36.1
DWS80%+CC10%+IA10%	9	34.0
DWS67%+CC11%+IA22%	9	34.8

The tested results showed that DWS was a slightly cohesive material with c' = 10kPa. The c' values for CC and IA blended with DWS were lower than that of DWS and ranged from 3–9 kPa. The Φ' values for CC and IA blended with DWS became slightly higher than that of DWS and gave values ranging from 34.0° to 36.1°. The increase in friction angles with an increasing mixed fraction of coarser aggregates has been reported by a previous study [25].

Measured values of undrained shear strength (τ) were plotted against the consolidation pressure (σ_3) and are shown in Fig. 9. For all tested samples, the τ values increased linearly with increasing consolidation pressure. The mixing of CC and IA did not contribute to the increase of τ for DWS. Especially, the mixing of IA with DWS (DWS 75% + IA 25%) gave a slightly lower τ as compared to other tested samples.

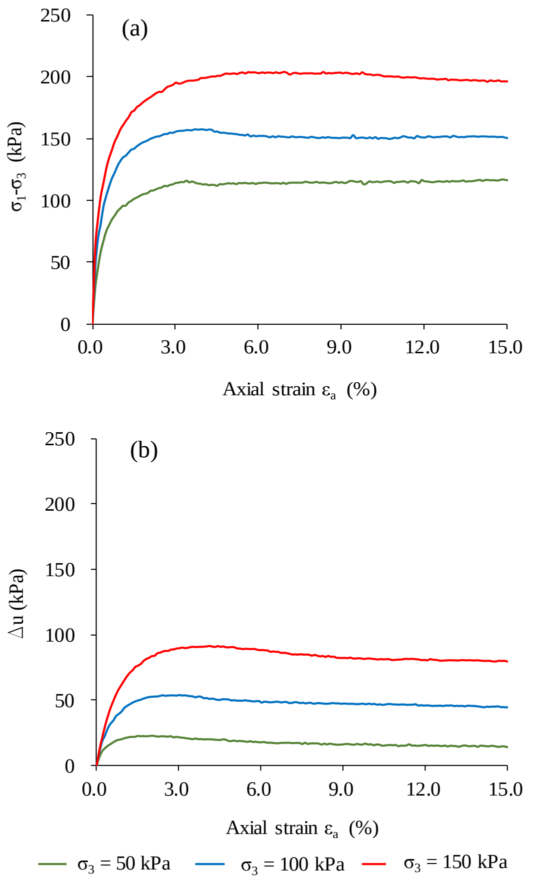


Fig. 7 Stress-strain relationship for the sample of DWS67%+CC11%+IA22%. (a) Deviatoric stress (σ_1- σ_3) and axial strain (ε_a), (b) excess pore pressure (Δu) and axial strain (ε_a).

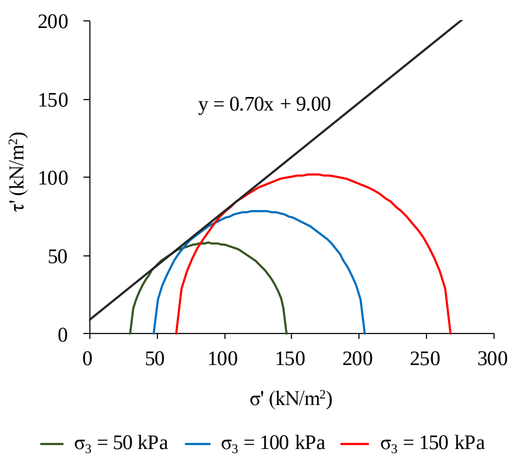


Fig. 8 Mohr circles for a sample of DWS67%+CC11%+IA22% to determine c' and Φ' in a consolidated undrained condition.

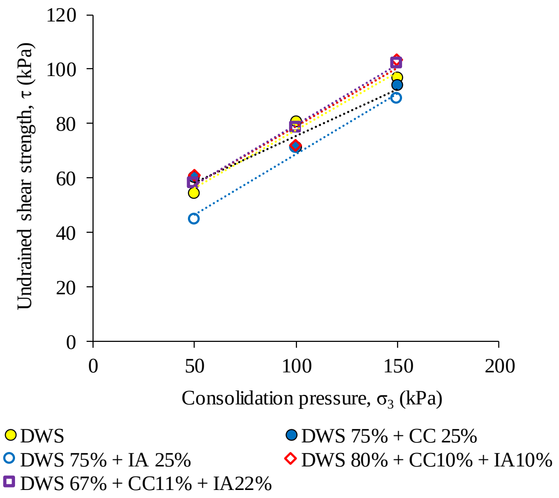


Fig. 9 Undrained shear strength (τ) of DWS blended with CC, IA, or with both CC and IA at 50, 100, and 150 kPa consolidated pressure (σ_3).

3.4 Consolidation Properties

The measured coefficient of consolidation (C_v) and compression index (C_c) was plotted against the mixing proportions are shown in Figs. 10 and 11. In Fig. 10, the measured C_v values at the consolidation pressure of 100 kPa were exemplified. No effect of consolidation pressure on the measured C_v was observed (data is not shown).

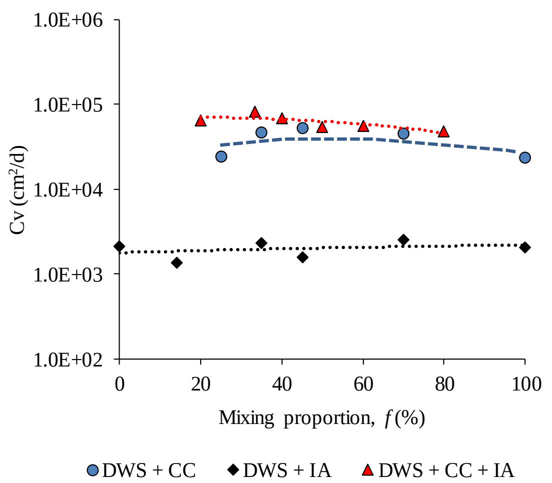


Fig. 10 Variation in C_v for DWS blended with CC and IA at 100 kPa consolidation pressure.

Tested results showed that the C_v of DWS blended with CC became about 10 times higher than that for DWS (f = 0%). As compared to CC, the mixing of IA did not contribute to the improvement of C_v, and the measured C_v values of DWS blended with IA became almost equal to those of DWS. It is interesting that the effect of the mixing proportion on C_v was not observed for tested DWS blended with both CC and IA.

The C_c values of DWS blended with IA reduced from 0.25 to 0.17, which was a 1.47 times reduction, while those of CC blended with DWS were reduced from 0.25 to 0.04 which was about 1/6 of C_c as compared to DWS (f = 0%). A similar reduction in C_c was observed for the three mixed samples (DWS+CC+IA).

It is evident from Fig. 11 that the measured C_c of tested samples with $f > 50\%$ (mixtures of CC or both of CC and IA with DWS) becomes almost stabilized. This implies that the proportion of CC would be the main factor for controlling the compressibility of DWS blended with CC/IA.

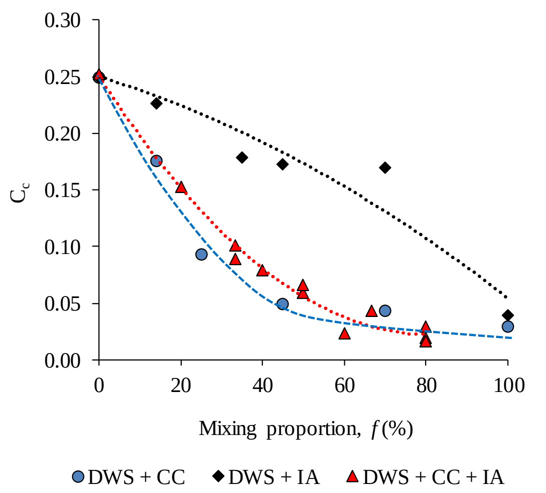


Fig. 11 Variation in C_c for DWS blended with CC and IA.

4. CONCLUSIONS

Based on the test results, the mix of CC/IA with DWS improved the compaction property of DWS, and measured CBR values increased in proportion to the mixed proportion of CC/IA. Especially in case of the mixing proportion of CC/IA >50%, the compressibility of DWS was reduced significantly. The inclusion of CC enhanced the consolidation. Therefore, the mix of CC can be effective to improve geotechnical properties of DWS for application to a road subgrade. In addition, an equation for predicting CBR was proposed, correlating with the mixing proportion (f) of CC/IA. The newly proposed equation well captured the measured CBR and would be effective to quickly assess CBR blended with CC/IA.

Further studies are needed to analyze the long-term sustainability of DWS blended with CC/IA, such as mechanical behaviors and segregation of fine and coarse aggregates under cyclic loading, leaching of fines (clogging effect of suspended solids) and chemicals underwater infiltration, considering the practical applications to a road subgrade.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] Shariatmadari N., Machado S.L., Noorzad A., and Karimpour-Fard M., Municipal Solid Waste Effective Stress Analysis. Waste Management, Vol. 29, Issue 12, 2009, pp. 2918-2930

[2] Arulrajah A., Piratheepan J., Disfani M.M., and Bo M.W., Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications. Journal of Materials in Civil Engineering, Vol. 25, No. 8, 2013, pp. 1077-1088.

[3] Zassa M.D., Zerlottin M., Refosco D., Santomaso A.C., and Canu P., Improved Compaction of Dried Tannery Wastewater Sludge. Waste Management, Vol. 46, 2015, pp. 472-479.

[4] Disfani M.M., Arulrajah A., Bo M.W., and Hankour R., Recycled Crushed Glass in Road Work Applications. Waste Management, Vol. 31, 2011, Issue 11, pp. 2341-2351.

[5] Arulrajah A., Piratheepan J., Aatheesan T., and Bo M. W., Geotechnical Properties of Recycled Crushed Brick in Pavement Applications. Journal of Materials in Civil Engineering, Vol.23, No.10, 2011, pp. 1444-1452.

[6] Lucena C.F.L.L., Juca J.F.T., Soares J.B., and Filho P.G.T.M., Use of Wastewater Sludge for Base and Subbase of Road Pavements. Transportation Research Part D, Vol. 33, 2014, pp. 210-219.

[7] Lim S., Jeon W., Lee J., Lee K., and Kim N., Engineering Properties of Water/Wastewater-Treatment Sludge Modified by Hydrated Lime, Fly Ash and Loess. Water Research, Vol. 36, 2002, pp. 4177-4184.

[8] Cabalar A.F., Abdulnafaa M.D., and Karabash Z., Influence of Various Construction and Demolition Materials on the Behaviour of Clay. Environmental Earth Sciences, Vol. 75, Issue 9, 2015, pp. 841-849.

[9] State of Discharge and Treatment of Environment, Editor 2013, Industrial Waste Information Center, Japan (In Japanese).

[10] Ahmad T., Ahmad K., and Alam M., Characterization of Water Treatment Plant's Sludge and its Safe Disposal Options. Conference Proceedings, in Int. Conf. on Solid Waste Management, 51conSWM, Vol. 35, 2016,

pp.950-955.
[11] Watanabe Y., Komine H., Yasuhara S., Murakami B., Jaehyoung B., and Toyoda K., Mixing Utilization of Drinking Water Sludge and Sandy Soil Based on Environmental and Economic Effects. Japan Soc. of Civil Engineers, Vol. 66, Issue 4, 2010, pp. 788-799 (In Japanese)
[12] Iso H., Watanabe Y., Komine H., Yasuhara S., Murakami B., Hiruta T., Tomatsuri S., and Toyoda K., Trial Construction Using Drinking Water Sludge as a Backfill Material of Water Pipe construction. Japan Soc. of Civil Engineers, Ser.C (Geosphere Engg.), Vol. 69, Issue 2, 2013. pp. 201-210. (In Japanese)
[13] Ministry of Environment Notification No. 18 on Test Method for Leachable Content from Soil, Ministry of Environment, Japan, 2003. (In Japanese)
[14] Ministry of Environment Notification No. 19 on Test Method for Soil Content, Ministry of Environment, Japan, 2003. (In Japanese)
[15] Ordinance of the Ministry of Environment (MOE) No. 29. Regulation on Soil Contamination Countermeasures Act, Ministry of Environment, Japan, 2002. (In Japanese)
[16] Mohammadinia A., Arulrajah A., Haghihi H., and Horpibulsuk S., Effect of Lime Stabilization on the Mechanical and Micro-scale Properties of Recycled Demolition Material. Sustainable Cities and Society, Vol. 30, 2017, pp.58-65.
[17] ASTM D698-12e2, Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lb/ft^3 (600 kN-m/m^3), 2007.
[18] ASTM D4767-11, Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soil. 2011.
[19] ASTM D2435/D2435M-11, Standard Test Method for One-dimensional Consolidation Properties of Soil Using Incremental Loading 1, 2011.
[20] Chen L., and Lin D.F., Stabilization Treatment of soft Subgrade Soil by Sewage Ash and Cement. Journal of Hazardous Materials, Vol. 162, Issue 1, 2009, pp. 321-327.
[21] Kesharwani R.S., Sahu A.K., and Khan N.U., CBR Value of Sandy Subgrade Blended with Coarse Aggregate. International Journal of GEOMATE, Vol. 10, No. 2, 2016, pp. 1743-1750.
[22] Liu, Z., Zhang, Y., and Di, J., Analysis of the Factors Affecting the CBR Value of Silt Roadbed. International Conference on Transportation Engineering, ASCE, Editor 2009.
[23] Ara I., National Cooperative Highway Research Program (NCHRP), Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, 2001: Illinois, pp. 1-204.
[24] Agarwal K.B., and Ghanekar K.D., Prediction of CBR from Plasticity Characteristics of Soil. In Proceeding of 2nd South East Asian Conference on Soil Engineering, Singapore, pp. 571-576.
[25] Vangla P., and Latha G.M., Influence of Particle Size on the Friction and Interfacial Shear Strength of Sands of Similar Morphology. International Journal of Geosynthetics and Ground Engineering, Vol. 1, Issue 1, 2015, pp. 1-12.