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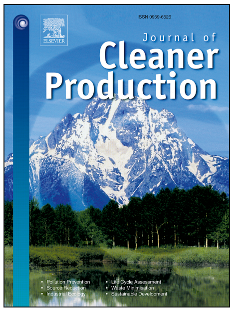


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# Use of Building-Related Construction and Demolition Wastes in Highway Embankment: Laboratory and Field Evaluations

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## Abstract

This paper aimed at assessing the feasibility of using the recycled building-related construction and demolition (C&D) wastes in highway embankment. First, the recycling of C&D wastes was elaborated, which involved both the manual and mechanical sorting processes. The recycled C&D wastes were classified as an excellent embankment material according to their gradation and Atterberg limits. The physical and chemical composition of recycled C&D wastes were also investigated, which all met the requirements of DB 41/T 1193 in Chinese Standard. Subsequently, the laboratory triaxial tests were conducted to measure the resilient modulus and permanent deformation of recycled C&D wastes. For comparison, one type of embankment clay soil was also evaluated in this study. The triaxial test results indicated that the recycled C&D wastes exhibited stress-dependent and moisture-sensitive characteristics. The existing resilient modulus and permanent deformation models were found to be capable of accurately predicting these characteristics for recycled material. Compared to the embankment clay soil, the recycled C&D wastes had much higher resilient moduli and lower accumulated permanent deformation. This demonstrated that the substitution of recycled wastes for clay soil would improve the structural capacity and reduce rutting damage. Moreover, compared to the clay soil, the recycled material had less moisture sensitivity to resilient modulus and permanent deformation. This characteristic would be beneficial for use of recycled C&D waste in a hot and humid area. Finally, a field project was constructed on G95 Beijing Capital Area Loop Expressway, which utilized 100% recycled C&D wastes to fill embankment. The embankment application were found to utilize much more recycled materials than other potential applications such as asphalt mixture, cement concrete, and base and subbase. The practices of construction of embankment containing recycled C&D wastes were also elaborated in this study. The lightweight deflectometer was used to measure the in-situ resilient moduli of embankment. The measured results indicated that the recycled C&D wastes had significantly higher structural capacity than the clay soil.

**Keywords:** Construction and demolition wastes, Embankment, Resilient modulus, Permanent deformation, Field construction, Lightweight deflectometer

## Introduction

The building-related construction and demolition (C&D) wastes refer to the debris generated from the construction, renovation, and demolition of buildings, which consist of concrete, brick, wood, metal, gypsum, glass, and plastic, etc. The United States Environmental Protection Agency (EPA) estimated that 548 million tons of C&D debris were generated in the United States in 2015, and over 70% of these wastes were recovered and recycled (EPA 2018). In European Union, there are around 530 million tons of C&D wastes generated every year, and 46% of these wastes are recycled (Vieira and Pereira 2015). In China, there are approximately 2 billion tons of building-related C&D wastes produced annually, accounting for 30-40% of municipal wastes. This is substantially higher than those generated by the developed countries. However, there are only less than 5% of C&D wastes presently recycled in China. The primary reason is that there are limited domestic engineering projects utilizing the recycled C&D wastes. The majority of these wastes are directly disposed of in landfills in suburban or rural areas, which results in high costs of transportation and land use (Kartam et al. 2004, Huang et al. 2018). Meanwhile, many environmental issues are associated with the disposal of C&D waste streams, including but not limited to the pollution of ground water and soil, and the increase of dust particles in the air (Huang et al. 2002). Therefore, there is an urgent need to solve the problem of C&D wastes management in China. In other words, the engineering applications of C&D wastes should be explored, so that the recycling rate of these wastes can be improved.

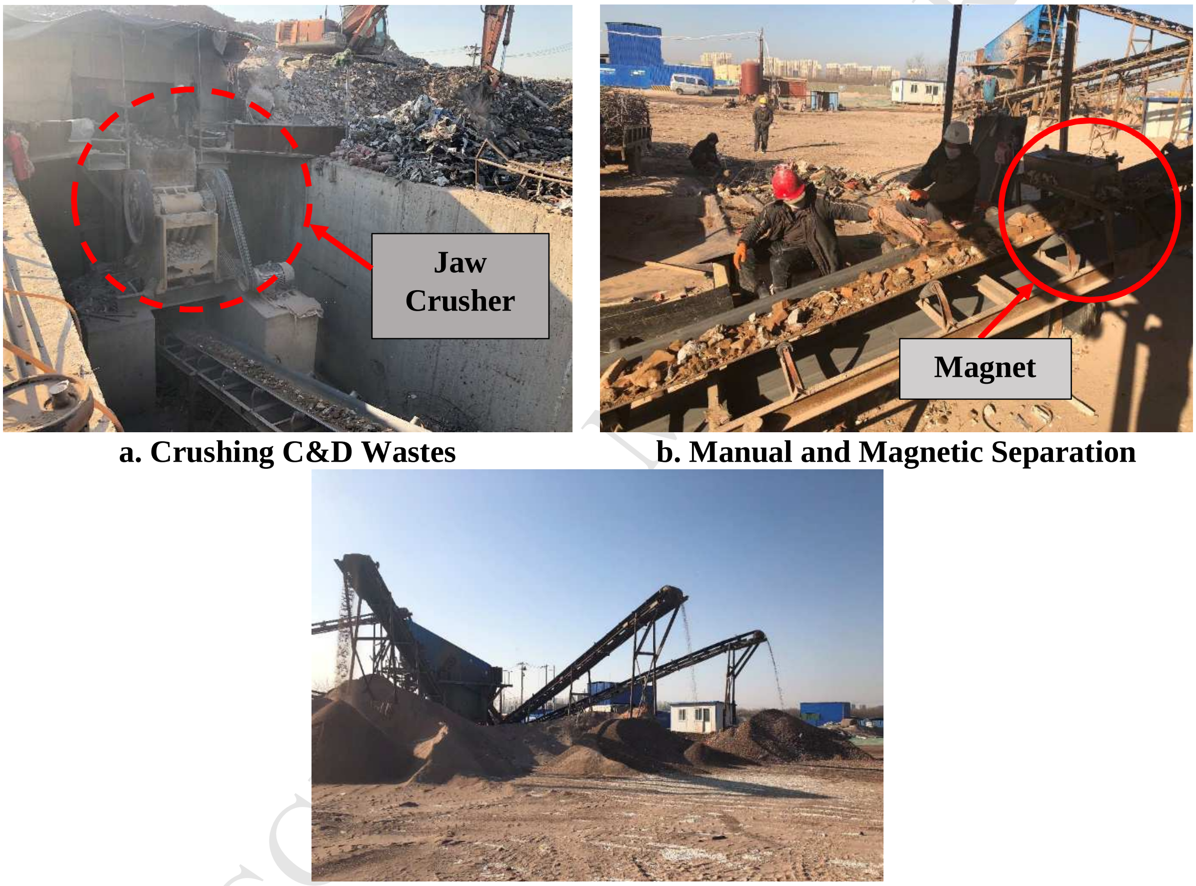
In pavement engineering, the C&D wastes are considered the alternative aggregates, which are typically used in asphalt and cement concrete, granular base and subbase (Herrador et al. 2012, Silva et al. 2014, Rahman et al. 2015, Cardoso et al. 2016, Shi et al. 2018 & 2019, Gu et al. 2019). Ossa et al. (2016) evaluated the engineering performance of hot asphalt mixture containing the recycled C&D waste aggregates. They found that the hot asphalt mixture with 10-20% of recycled aggregates showed comparable rutting and moisture damage resistances to the asphalt mixture in wearing course. Zhu et al. (2012) used the C&D wastes from earthquake damaged buildings in asphalt mixtures. They reported that the recycled aggregates had high absorption, low specific gravity, and low strength, which were suggested to be pretreated by liquid silicone resin to improve their physical properties. Gomez-Meijide et al. (2016) evaluated the feasibility of using the recycled C&D waste in cold asphalt mixture. They evaluated the stiffness of cold asphalt mixtures at different curing times, and found that the use of C&D waste yielded stiffer asphalt mixture, and had no detrimental effect on the curing process. Rao et al. (2007) presented an overview of using recycled aggregates from C&D wastes in concrete. They demonstrated that the recycled aggregates can be used in low-end applications of concrete, and in normal structural concrete with the addition of other additives (e.g., fly ash and condensed silica fume). They considered the use of recycled aggregates in concrete as a promising solution to the problem of C&D waste management. Park (2003) applied the recycled C&D waste aggregates in rigid pavement base. He evaluated the engineering properties of the recycled aggregates using the laboratory gyratory compaction test and field falling weight deflectometer test. He concluded that the recycled aggregates showed similar compactibility and stability to the natural mineral aggregates, which can be used as an alternative base material. Arulrajah and his coworkers comprehensively evaluated the geotechnical and geoenvironmental properties of several recycled C&D wastes (e.g., recycled concrete aggregate, crushed brick, waste rock, reclaimed asphalt pavement, and fine recycled glass) in pavement subbase applications (Arulrajah et al. 2011, 2013a, 2013b, and 2014). They concluded that the recycled concrete aggregate and waste rock showed equivalent or superior geotechnical properties to those of quarry subbase materials, while the crushed bricks, reclaimed asphalt pavement, and fine recycled glass were recommended to be blended with high-quality aggregates or additives for use in pavement subbases. Jimenez et al. (2012) reported that the recycled aggregates from C&D wastes also showed satisfactory structural capacity and performance in the unpaved rural roadways. In sum, these existing studies pointed out that the recycled C&D wastes are considered as the low-quality aggregates, which can partially or fully replace the natural aggregates in asphalt and cement concrete, granular base and subbase. However, from the perspective of application rate, these identified applications might not be promising to solve the current serious issue of C&D waste management in China. For instance, substituting 10-20% of natural aggregates with recycled C&D aggregates might be beneficial for reducing the production cost of asphalt mixture, but not quite helpful to consume the tremendous amount of C&D wastes generated every year. Thus, the key issue of C&D waste management becomes seeking other engineering applications that can significantly consume these recycled wastes.

In the plain area of China, the highway construction usually starts from the fill of embankment, which typically requires filling the soil with a depth of 3 meters. For instance, the average fill depth of Shanghai-Nanjing expressway is 3.7 meters, and the highest fill depth is even up to 12 meters. Given that the width of embankment is 42 meters and the length of Shanghai-Nanjing expressway is 275 kilometers, the total fill volume of soil is approximately 43 million cubic meters. This estimation indicates that the construction of highway embankment requires the massive amount of soils. Accordingly, if the recycled C&D wastes are qualified as fill material, the significant amount of C&D wastes will be utilized in this application. However, there are few studies focused on the engineering performance of recycled C&D wastes for use in highway embankment. Moreover, there is no field experience to instruct such application.

To address the aforementioned problems, this study aimed at comprehensively evaluating the feasibility of using recycled building-related C&D wastes in highway embankment. The laboratory tests were conducted to evaluate the engineering and environmental properties of C&D wastes. A field project was constructed to investigate the structural performance of the embankment containing recycled C&D wastes. For comparison, the laboratory and field tests were also performed on a typical embankment material (i.e., clay soil) to evaluate its engineering performance as the control baseline. In addition, the recycling process of C&D wastes and the corresponding field construction procedures were documented in this study.

## Recycling of C&D Wastes

Among the C&D wastes, the concrete, brick and waste rock can be recycled as alternative aggregates, but the metal, glass, and plastic should be removed via the sorting process. This is because the addition of glass and plastic reduces the strength of the recycled aggregates, while the metal is usually recycled for other applications. In this study, the facility was designed to process 200 tons of material per hour. The raw C&D wastes were obtained from the abandoned buildings within the distance of 100 km. At the beginning, the raw C&D wastes were sorted manually and water was sprayed to suppress dust. Next, the wastes were delivered for the mechanical sorting process by conveyor. Figure 1 illustrates the mechanical sorting process, which includes crushing C&D wastes into small particles, manual and magnetic separation of metals and plastics, and screening and stockpiling material (Fatta et al. 2003, Dahlbo et al. 2015). As shown in Figure 1, the jaw crusher was employed to crush the recycled C&D wastes, because of its simplicity and high efficiency. Finally, the recycled C&D wastes were separated into three stockpiles with various particle sizes.




**a. Crushing C&D Wastes** **b. Manual and Magnetic Separation**

**c. Screening and Stockpiling**

**Figure 1. Mechanical Sorting Process of C&D Wastes**

According to China national testing standards, JTG E40/T0115 (corresponding to ASTM D6913), the sieve analysis was conducted on the blended recycled C&D wastes. Figure 2 shows the particle size distribution of the blended recycled aggregates. As presented, all of the recycled wastes are smaller than 40 mm, and the passing percentage of particles to sieve size 0.075 mm is 4.9%. The Hazen uniformity coefficient $C_u$ indicates the general shape of the particle size distribution, which is calculated by Equation 1.

$$C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

where $D_{60}$ is the diameter for which 60% of the particles are finer, and $D_{10}$ is the diameter for which 10% of the particles are finer. The coefficient of curvature $C_c$ is another index of distribution shape, which is given by Equation 2.

$$C_c = \frac{D_{30}^2}{D_{10} D_{30}} \quad (2)$$

where $D_{30}$ is the diameter for which 30% of the particles are finer. In this study, the Hazen uniformity coefficient $C_u$ of the recycled C&D wastes is 95, and the coefficient of curvature $C_c$ is 8.9.

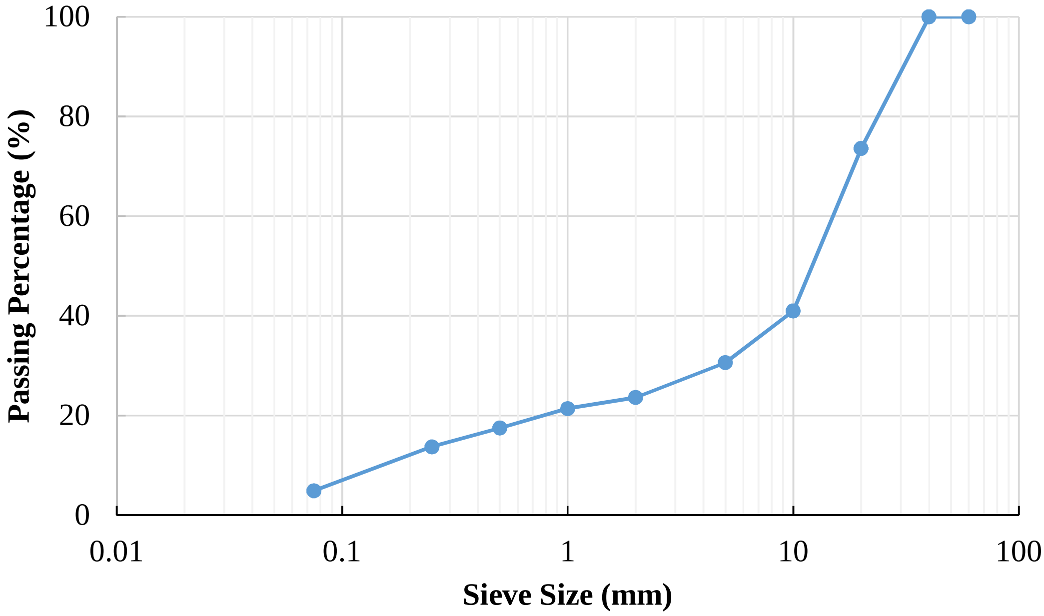



**Figure 2. Particle Size Distribution of Blended Recycled C&D Wastes**

In the meanwhile, the Atterberg limits of the recycled aggregates were measured based on JTG E40/T0118 (corresponding to ASTM D4318). The liquid limit and plastic limit of the recycled aggregates were 28 and 22, respectively. Accordingly, the plasticity index of the material was 6. Based on the Unified Soil Classification System (USCS), the recycled material was classified as GP (gap-graded gravels). According to the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System, the recycled C&D wastes were classified as A-1-a (stone fragments). Both of the system ratings indicate that the recycled C&D wastes were an excellent embankment material. In addition, the modified proctor test was used to determine the compaction characteristics of the recycled C&D wastes, which followed JTG E40/T0131 (corresponding to ASTM D1557). In this study, the optimum moisture content (OMC) of recycled material was 14.8%, and the corresponding maximum dry density was 1.843 $g/cm^3$.

This study also investigated the contents of organic matter, soluble salt, and remaining debris in the recycled wastes. Causarano (1993) showed that a large organic matter content weaken the strength of dry soils. Vegas et al. (2011) found that the C&D wastes with a soluble salt less than 3.7% do not yield any stability problems. Jimenez et al. (2012) stated that the recycled C&D wastes usually have higher contents of organic matter and soluble salt than the natural aggregates, which are sometimes beyond the limits of technical specifications. Table 1 compares the measured contents of organic matter, soluble salt, and remaining debris to those specified in Chinese Standard DB 41/T 1193. As presented, the recycled C&D wastes met all of the requirements in DB 41/T 1193.

**Table 1. Physical and Chemical Composition of Recycled C&D Wastes**

| Composition Indicator | Recycled C&D Wastes | DB 41/T 1193 Requirement |
|---|---|---|
| Organic Matter Content (%) | 1.9 | Less than 5 |
| Soluble Salt Content (%) | 0.38 | Less than 0.5 |
| Remaining Debris Content (%) | 0.9 | Less than 1 |

## Laboratory Performance Evaluation of Recycled C&D Wastes

In this section, the resilient modulus and permanent deformation tests were performed to evaluate the mechanical performance of the recycled C&D wastes and one embankment clay soil. For embankment clay soil, the OMC was 23.5%, the maximum dry density was 1.562 $g/cm^3$, the liquid limit was 57, and plastic limit was 29. The specimens of recycled aggregates and clay soils were both prepared using a vibratory compaction method based on the recommendation of AASHTO T307. The recycled C&D waste specimens were compacted at the three moisture levels, which were 13.3% (0.9 OMC), 14.8% (OMC), and 16.3% (1.1 OMC). Likewise, the clay soil specimens were compacted at 21.1% (0.9 OMC), 23.5% (OMC), and 25.9% (1.1 OMC). In this study, the dimensions of the recycled aggregate specimens were 150 mm diameter with 300 mm height, and the dimensions of the clay soil specimens were 100 mm diameter with 200 mm height. The repeated load triaxial tests were conducted on these cylindrical specimens using the testing system shown in Figure 3.

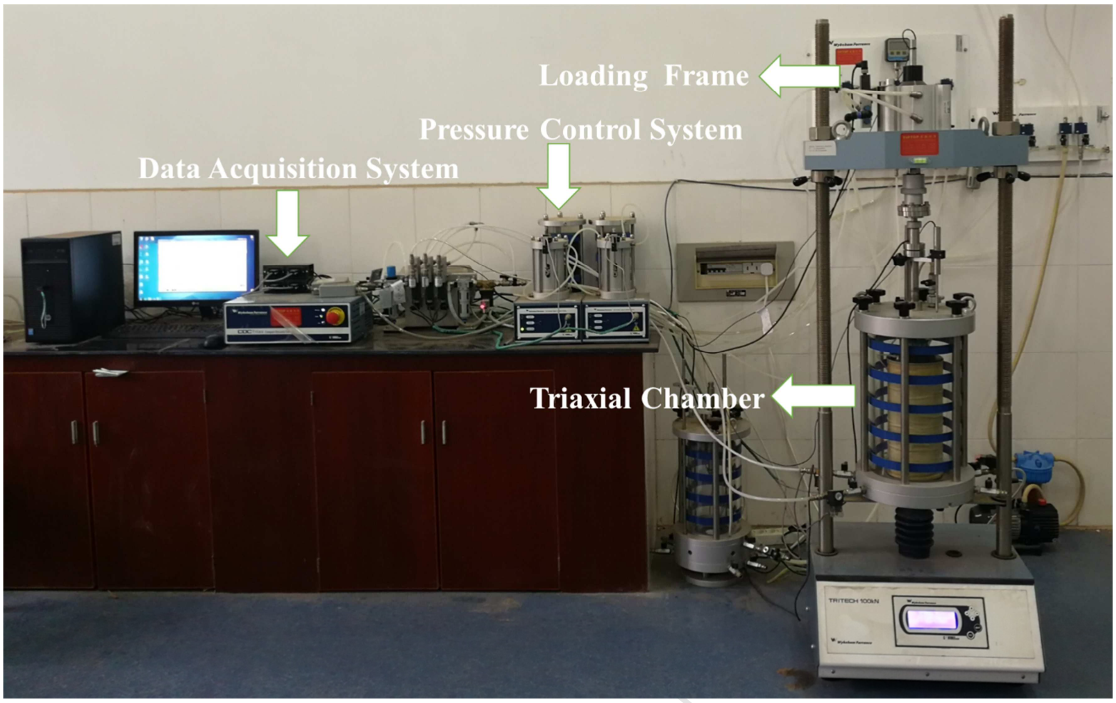



**Figure 3. Configuration of Repeated Load Triaxial Test**

The resilient modulus test followed the AASHTO T307 test procedures, which included 15 loading sequences with 100 load applications each. The permanent deformation test protocol is shown in Table 2, which contains 5 stress levels with 10,000 load applications. As illustrated, stress states 1, 2, and 3 employed the same confining pressure with various deviatoric stresses, whereas stress states 2, 4, and 5 applied the same deviatoric stress with different confining pressures. This testing protocol was designed to investigate the influences of confining pressure and deviatoric stress on the permanent deformation behavior of the recycled C&D wastes. Prior to loading, 500 cycles of 41.4 kPa confining pressure and 27.6 kPa deviatoric stress were applied to precondition the specimen. In the permanent deformation test, different stress levels were applied to the duplicate specimens. For each loading sequence, the specimens were tested at a constant confining pressure and under a specific axial cyclic stress using a haversine shape with a 0.2-s load duration and a 1.0-s cycle duration (Zhang et al. 2019). The axial load was applied to the specimen through the loading frame, and the confining stress was directly applied to the specimen through the air pressure. The linear variable differential transformers (LVDTs) were used to measure the vertical deformations of the specimen. The test data were used to determine the recoverable and unrecoverable behaviors of the tested materials. The relevant discussion of testing results are presented as follows.

**Table 2. Permanent Deformation Test Protocol**

| Stress State | Confining Stress (kPa) | Deviatoric Stress (kPa) | No. of Load Applications |
|---|---|---|---|
| 1 | 28 | 28 | 10,000 |
| 2 | 28 | 48 | 10,000 |
| 3 | 28 | 69 | 10,000 |
| 4 | 12 | 48 | 10,000 |
| 5 | 42 | 48 | 10,000 |

***Resilient Modulus Characteristic***

Figure 4 shows the resilient moduli of the recycled C&D wastes compacted at the optimal moisture content (OMC) and at different stress levels. As presented, the recycled material exhibited the stress-dependent resilient characteristic. The increasing of confining pressure and deviatoric stress both enhanced the resilient moduli, which resulted in a stiffer material. This was consistent with the stress-hardening resilient characteristic of unbound aggregates (Gu et al. 2015, 2016, Saha et al. 2018). Figure 5 presents the resilient moduli of embankment clay soil at the OMC. As illustrated, the resilient modulus of embankment soil was lower than the recycled C&D wastes at every stress level. This demonstrates that the recycled C&D wastes may provide a stronger structural support than the traditional clay to the upper layers. It is also shown that the increase of confining pressure yielded higher resilient moduli of embankment soil and the recycled C&D wastes, while the increase of deviatoric stress diminished the soil's resilient moduli but promoted the recycled C&D wastes' resilient moduli. This indicates that the increase of confining pressure stiffened the embankment soil and the recycled C&D wastes, while the increase of deviatoric stress softened the soil but strengthen the recycled C&D wastes. This might be because increasing deviatoric stress could improve the interlocking effect for the coarse-grained C&D wastes, but weaken the interlocking effect for fine-grained clay soil. At the deviatoric stress of 13.8 kPa, the resilient moduli of the recycled C&D wastes were greater than the embankment soil by 20-50%. However, at the deviatoric stress of 68.9 kPa, the difference of resilient moduli increased by 130-165%. This infers that the recycled C&D wastes can provide a much higher structural bearing capacity than the traditional embankment clay soil at the location with high shear stresses.

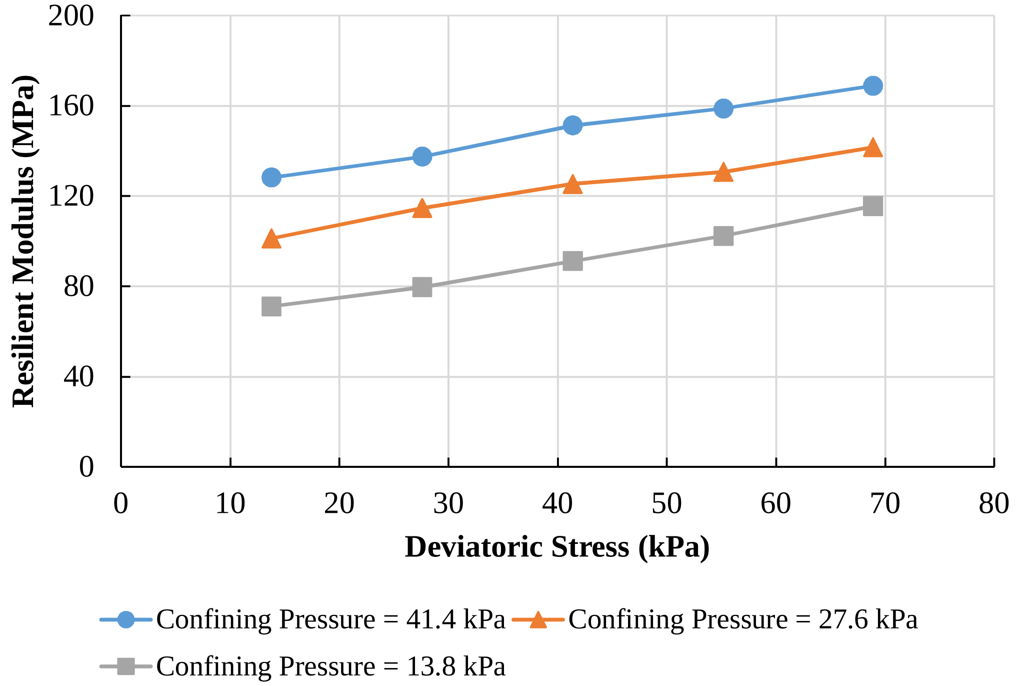



**Figure 4. Resilient Moduli of Recycled C&D Wastes at Optimal Moisture Content (OMC)**

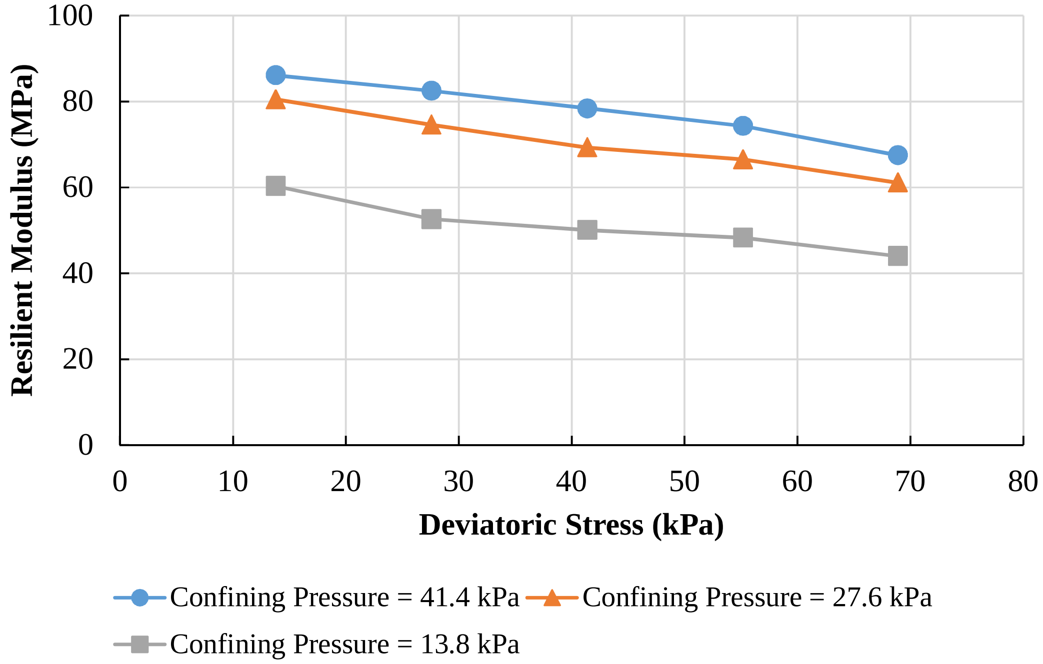



**Figure 5. Resilient Moduli of Clay Soil at OMC**

In the National Cooperative Highway Research Program (NCHRP) project 1-28A, the generalized model was developed to predict the resilient moduli of granular material at any given stress level, which is presented in Equation 3 (Witczak 2003).

$$M_R = k_1 P_a \left(\frac{I_1}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3} \tag{3}$$

where $M_R$ is the resilient modulus, $I_1$ is the first invariant of stress tensor, $\tau_{oct}$ is the octahedral shear stress, $P_a$ is the atmospheric pressure, and $k_1$, $k_2$, and $k_3$ are the regression coefficients. By fitting the test results shown in Figure 4, the k-values of recycled C&D wastes at OMC were determined as: $k_1$ = 1061.5, $k_2$ = 0.69, and $k_3$ = -0.28. Similarly, the k-values of clay soil at OMC were calculated as: $k_1$ = 887.3, $k_2$ = 0.53, and $k_3$ = -2.29. For embankment material, Witczak (2003) suggested to report the resilient modulus at 14 kPa confining pressure and 41 kPa deviatoric stress, which is hereafter referred as to representative resilient modulus. Figure 6 shows the representative resilient moduli of the recycled C&D wastes at different moisture contents, and compares them to the embankment soil. As presented, the resilient moduli of recycled C&D wastes also had the moisture-sensitive characteristic. Increasing moisture content reduced the matric suction of unbound material, which thereby decreased its resilient moduli (Gu et al. 2015). The change percentage of resilient moduli at different moisture contents are also presented in Figure 6. Compared to the embankment soil, the resilient moduli of recycled C&D wastes showed much less sensitivity to moisture variation. This characteristic is extremely beneficial for use in a hot and humid area of China, where the in-situ moisture content of embankment sometimes can double the OMC.

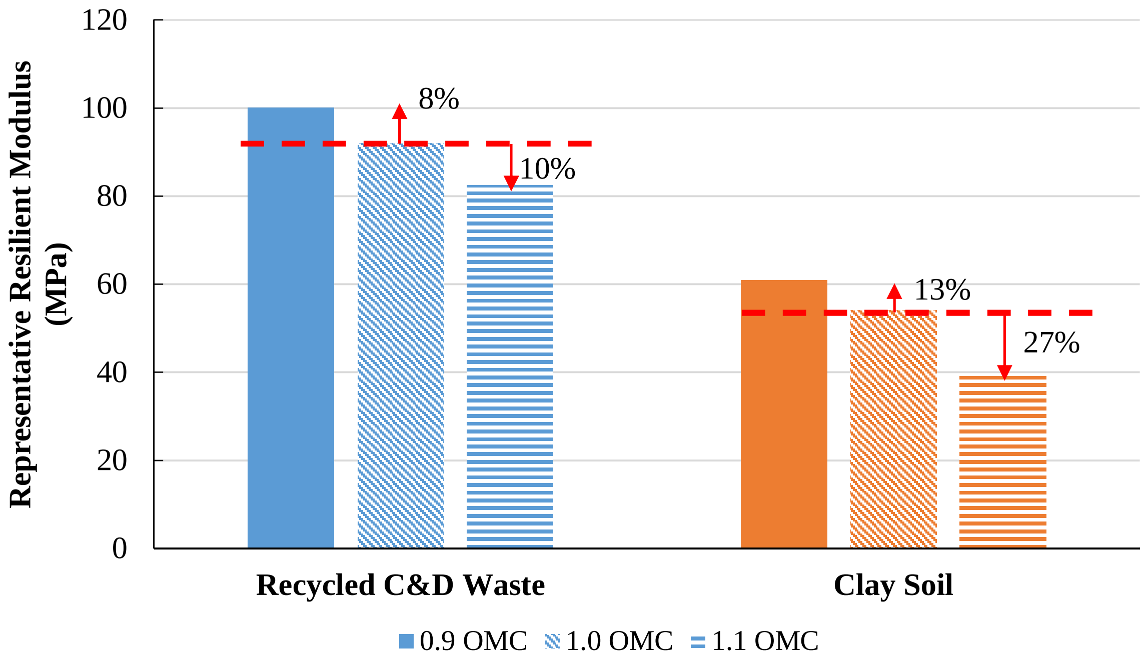



**Figure 6. Representative of Resilient Moduli of Recycled Wastes and Clay Soil at Various Moisture Content**

***Permanent Deformation Characteristic***

Figure 7 shows the permanent strain curves of the recycled C&D wastes at the different deviatoric stresses and confining pressures. As presented, increasing deviatoric stress and decreasing confining pressure both increased the accumulated permanent strain of the recycled C&D wastes.

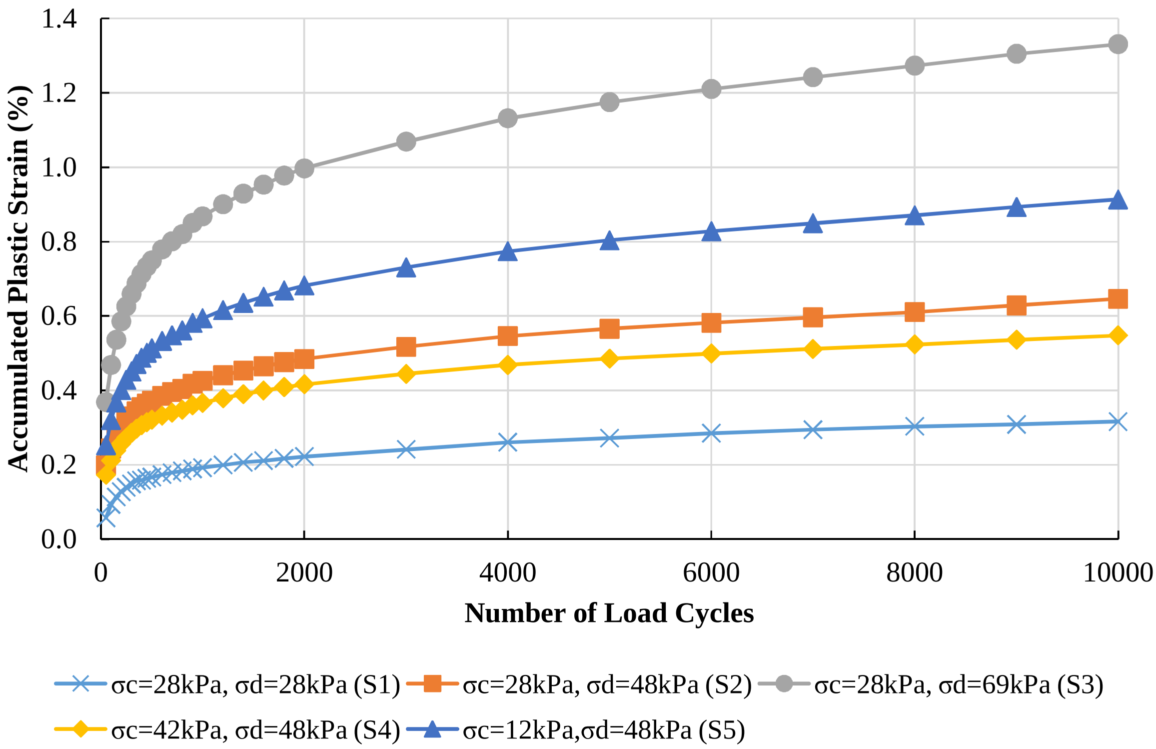



**Figure 7. Permanent Strain Curves of Recycled C&D Wastes at Different Stress Levels**

Gu et al. (2016) developed a mechanistic-empirical model to characterize the stress-dependent permanent deformation behavior of unbound material, which is given in Equations 4-6.

$$\varepsilon_p = \varepsilon_0 e^{-\left(\frac{\rho}{N}\right)^{\beta}} \left(\sqrt{J_2}\right)^m \left(\alpha I_1 + K\right)^n \tag{4}$$

$$\alpha = \frac{2\sin\phi}{\sqrt{3}\left(3-\sin\phi\right)} \tag{5}$$

$$K = \frac{c\cdot 6\cos\phi}{\sqrt{3}\left(3-\sin\phi\right)} \tag{6}$$

where $\varepsilon^p$ is the permanent strain of granular material, $J_2$ is the second invariant of the deviatoric stress tensor, $I_1$ is the first invariant of the stress tensor, $\varepsilon_0$, $\rho$, $\beta$, $m$ and $n$ are model coefficients, $c$ and $\phi$ are cohesion and friction angle, respectively. In this study, this mechanistic-empirical model was used to fit the laboratory-measured permanent strain curves. For the recycled C&D wastes, the cohesion $c$ was 30.1 kPa, and the friction angle $\phi$ was 51.2°, which were both determined by the compressive strength test. As illustrated in Figure 8, the root mean square error (RMSE) between laboratory-measured and model-predicted permanent strains only varied from 0.013% to 0.037%. This demonstrates that the developed model could accurately predicted the stress-dependent permanent deformation behavior of the recycled C&D wastes. The determined model coefficients shown in Figure 8 were used to predict the permanent deformation of the recycled C&D wastes at any given stress levels.

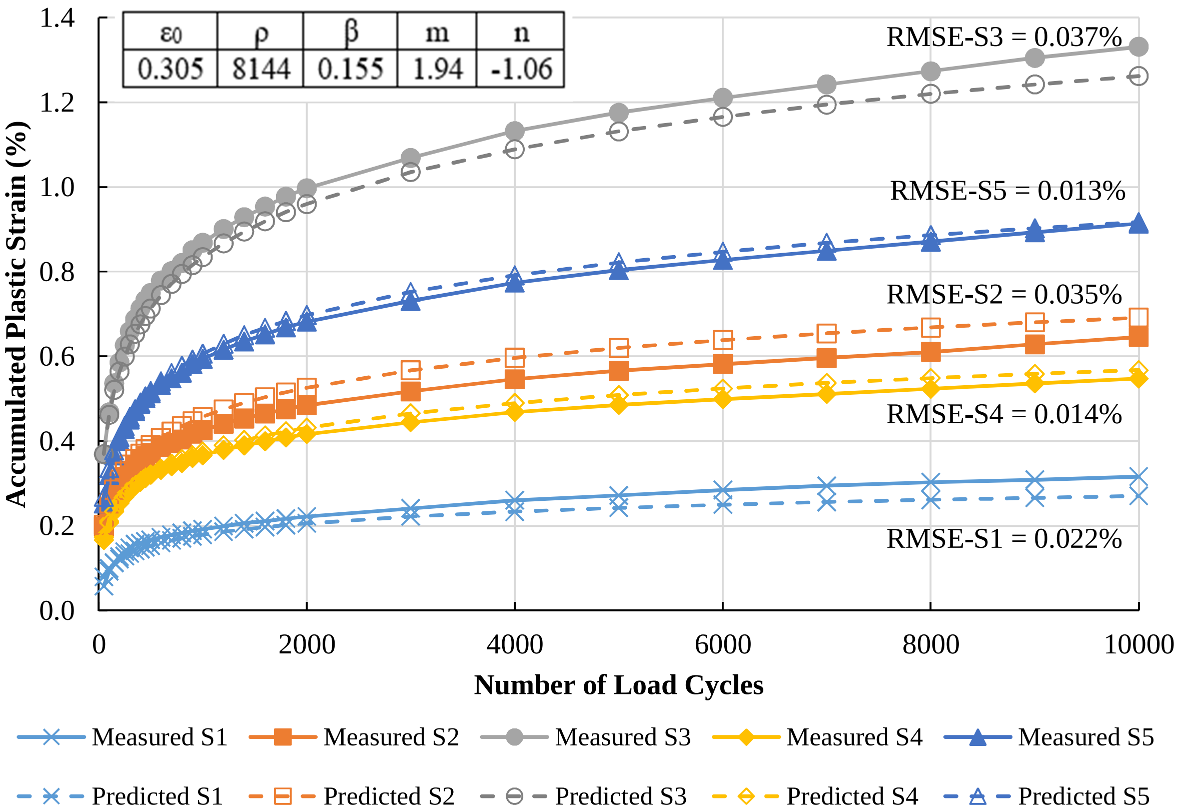



**Figure 8. Prediction of Permanent Strain Curves of Recycled C&D Wastes**

This study also investigated the effect of moisture variation on permanent deformation characteristic. A typical stress combination of 28 kPa confining pressure and 48 kPa deviatoric stress was selected for the permanent deformation test. The specimens were prepared at three different moisture contents, namely, 0.9 OMC, 1.0 OMC, and 1.1 OMC. Figure 9 shows the final accumulated permanent strains of the recycled C&D wastes, and compares them to those of the embankment soil. It is shown that the increase of moisture content significantly increased the accumulated permanent strain of both recycled C&D waste and clay soil. In comparison with the clay soil, the permanent deformation of the recycled C&D waste still showed less sensitivity to moisture variation. In addition, at any given moisture content, the recycled C&D wastes always had less accumulated permanent strains than the embankment soil. Thus, this infers that the substitution of recycled C&D wastes for embankment soil should yield a higher resistance to rutting damage.

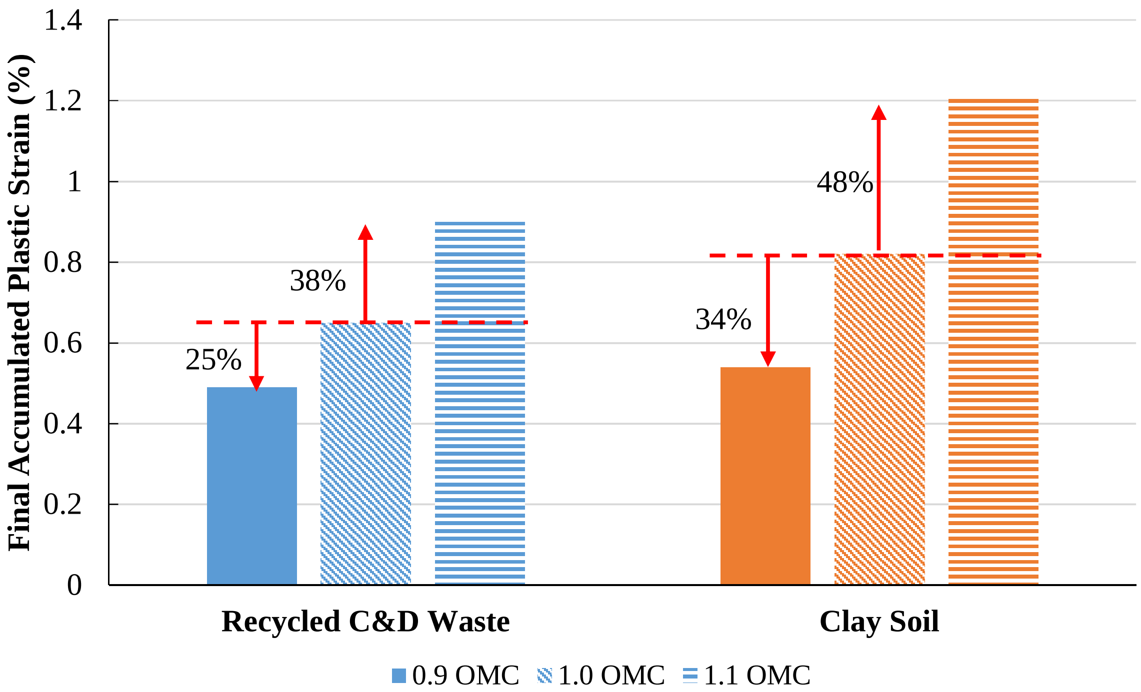



**Figure 9. Influence of Moisture Variation on Permanent Deformation Characteristic**

## Field Evaluation of Recycled C&D Wastes

In 2018, a field section with 100-meter long was constructed on G95 Beijing Capital Area Loop Expressway, which utilized 100% recycled C&D wastes to fill embankment. For the purpose of comparison, a control section was also constructed using the clay soil. Note that the performance of clay soil had been evaluated in the previous section. Figure 10 shows the cross-section of designed embankment. The designed fill depth was 4-meter, and the side slope was 1:1.5. According to the degree of compaction, the embankment was divided into three zones:

- Zone 1: 96 degree of compaction with a depth of 0.8-meter;
- Zone 2: 94 degree of compaction with a depth of 0.7-meter;
- Zone 3: 93 degree of compaction with a depth of 2.5-meter.

The width of the top embankment was 34.5-meter. Given that the maximum dry density was 1.843 g/cm$^3$, the required amount of recycled material was approximately 280 ton per 1 meter long. Thus, the entire field section utilized around $2.8\times10^4$ ton of recycled C&D wastes in total.

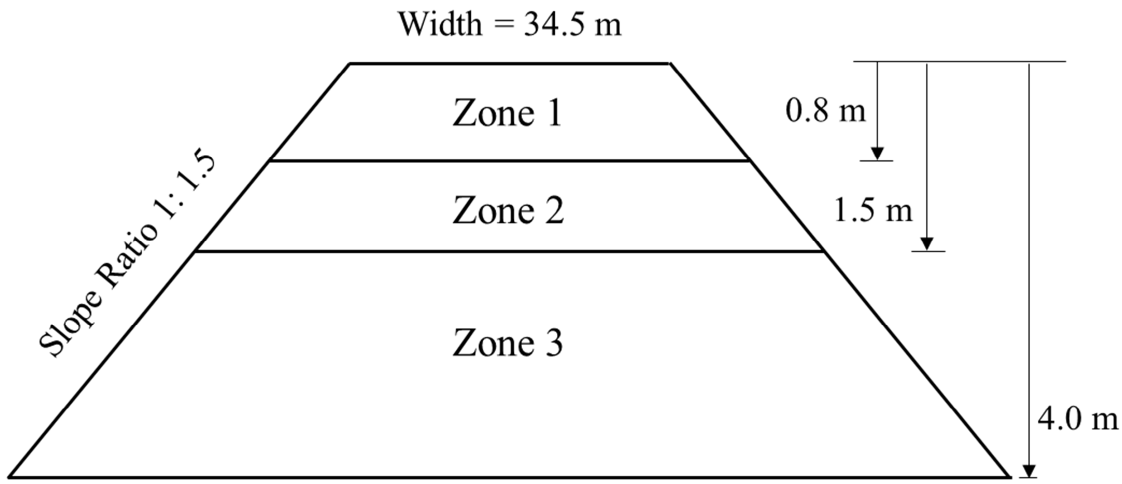



**Figure 10. Cross-Section of Designed Embankment**

Table 3 lists the estimated consumption of recycled C&D wastes if it is used for different pavement applications. In comparison, the embankment application utilizes much more recycled materials than other applications. If the use of recycled C&D wastes in embankment is a successful application, the pressure of C&D wastes recycling and reuse will be substantially relieved.

**Table 3. Estimated Consumption of Recycled C&D Wastes in Different Applications**

| Application | Layer Thickness (mm) | Usage Rate (%) | Amount of Consumed C&D Wastes (ton/m$^2$) | Reference |
|---|---|---|---|---|
| Asphalt Mixture | 200 | 10-20 | 0.04-0.07 | Ossa et al. 2016 |
| Cement Concrete | 300 | 20 | 0.1 | Rao et al. 2007 |
| Base Course | 300 | 30-50 | 0.2-0.3 | Not available |
| Subbase | 300 | 100 | 0.6 | Arulrajah et al. 2013 |
| Embankment | 4000 | 100 | 7.4 | This study |

As shown in Figures 11a-11d, the embankment construction involves four critical steps: 1) dumping material using bulldozers; 2) flattening material using motor graders; 3) spraying water to slightly adjust the in-situ moisture content; and 4) compacting each sublayer. Note that the compaction of each sublayer requires 1 cycle of weak vibratory compaction with 35-38 Hz frequency and 0.86-1.1 mm amplitude, and 3-7 cycles of strong vibratory compaction with 28-31

Hz and 1.6-2 mm amplitude. After compaction, the final surface of embankment is shown in Figure 11e.

**a. Dump material using bulldozer**

**b. Flattening material using motor grader**

**c. Spray water**

**d. Vibratory compaction**

**e. Embankment surface after compaction**

**Figure 11. Construction of Embankment Using Recycled C&D Wastes**

During construction, two thicknesses of uncompacted layer and the number of cycles (i.e., 250 mm and 300 mm), and three levels of strong vibratory compaction (i.e., 3, 5, and 7 cycles) were adopted. Their influences on the degree of compaction are shown in Figure 12. At the same number of compaction cycles, increasing the thickness of uncompacted layer always resulted in a lower degree of compaction. When laying down 300-mm thick loose recycled wastes, it required 3 cycles of strong vibratory compaction to achieve 93 degree of compaction. To reach 94 degree of compaction, it took at least 3 cycles of strong vibratory compaction for 250-mm thick loose material, and 7 cycles for 300-mm thick material. For 96 degree of compaction, the thickness of uncompacted layer had to be 250 mm and the number of strong vibratory compaction cycles had to be 7 cycles.

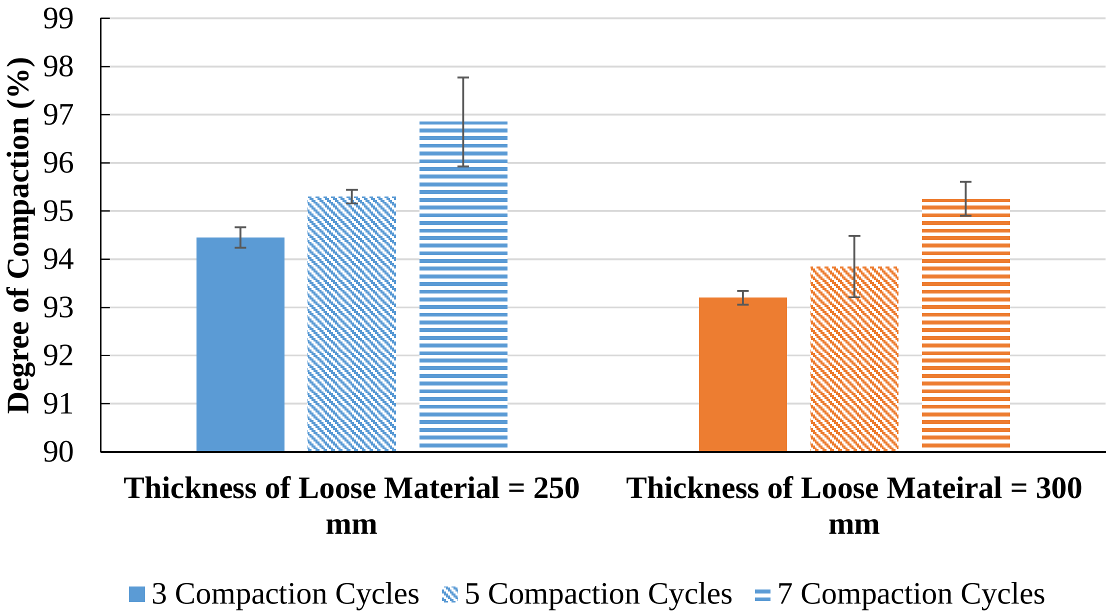



**Figure 12. Degree of Compaction of Recycled Wastes at Different Conditions**

To evaluate the secondary breakage effect, this study compared the gradation of recycled C&D wastes before and after compaction, which is shown in Figure 13. Herein, the recycled materials were taken from Zone 1 (Figure 10), which received the greatest compactive effort. As shown in Figure 13, the recycled wastes had a noticeable shift to a finer gradation after compaction. According to Equations 1 and 2, the Hazen uniformity coefficient $C_u$ was slightly reduced from 95 to 91, and the coefficient of curvature $C_c$ was significantly decreased from 8.9 to 1.2. According to Craig (2007), the coefficient of curvature $C_c$ between 1 and 3 represents the granular material is well-graded. Therefore, it is indicated that the field compaction yielded a secondary breakage of recycled C&D wastes, which thereby formed a finer and denser gradation.

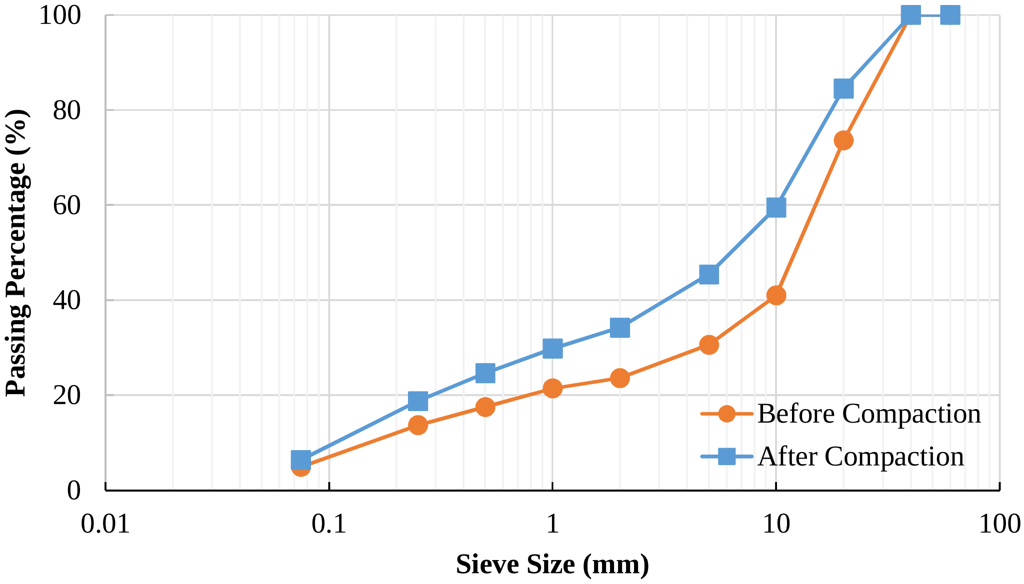



**Figure 13. Effect of Secondary Breakage on Gradation of Recycled C&D Wastes**

In this study, a portable device, lightweight deflectometer (LWD), was used to measure the in-situ resilient modulus of embankment surface. The LWD has seven essential components, which are loading plate, load housing, geophone, force transducer, urethane load damper, guide rod, and a drop mass. The loading plate was circular with a diameter of 300 mm. A 2Hz geophone was mounted to the load plate. The drop mass with 10 kg in weight drops from 0.85-meter high onto the loading plate. The geophone sensor measured the corresponding deflection caused by the mass impact on the loading plate. The measured deflection at the center of loading plate was used to estimate the in-situ resilient modulus using Boussinesq's solution, which is presented in Equation 7 (Mooney and Miller, 2009).

$$E_{LWD} = \frac{2F_p\left(1-\nu^2\right)}{Ar_0 w_p} \quad (7)$$

where $E_{LWD}$ is the in-situ resilient modulus, $F_p$ is the peak applied force, $\nu$ is the Poisson's ratio (assuming as 0.5), $A$ is a stress distribution factor (A=4 for an inverse parabolic distribution; A=$\pi$ for a uniform distribution, and A=$\frac{3\pi}{4}$ for a parabolic distribution), $r_0$ is the radius of loading plate, and $w_p$ is the peak vertical displacement of loading plate. Schwartz et al. (2017) suggested that the stress distribution of granular material followed a parabolic distribution. Therefore, this study assumed that A equals to $\frac{3\pi}{4}$ for the embankment containing recycled wastes. Figure 14 presents the calculated in-situ resilient moduli of the two embankment sections (i.e., recycled C&D wastes and clay soil). As illustrated, the recycled wastes always exhibited significantly higher resilient moduli than the clay soil at different compaction levels. The increase of degree of compaction appeared to increase the in-situ resilient modulus of both materials. An analysis of variance (ANOVA) with Tukey honestly significant difference (HSD) test was conducted to statistically rank these results, which is also shown in Figure 14. Note that the results of recycled wastes and clay soil were analyzed separately. The confidence level is assigned as 95% ($\alpha$=0.05). Labels A and A' represented the groups of recycled wastes and clay soil had the highest in-situ resilient moduli, respectively. It is clearly demonstrated that the recycled C&D wastes had statistically different in-situ resilient moduli at different compaction levels. While the clay soil showed statistically different when the degree of compaction increased to 96. Since the LWD is capable of differentiating the compaction level of recycled C&D wastes, it might be an efficient tool for quality control of embankment compaction when utilizing the recycled wastes.

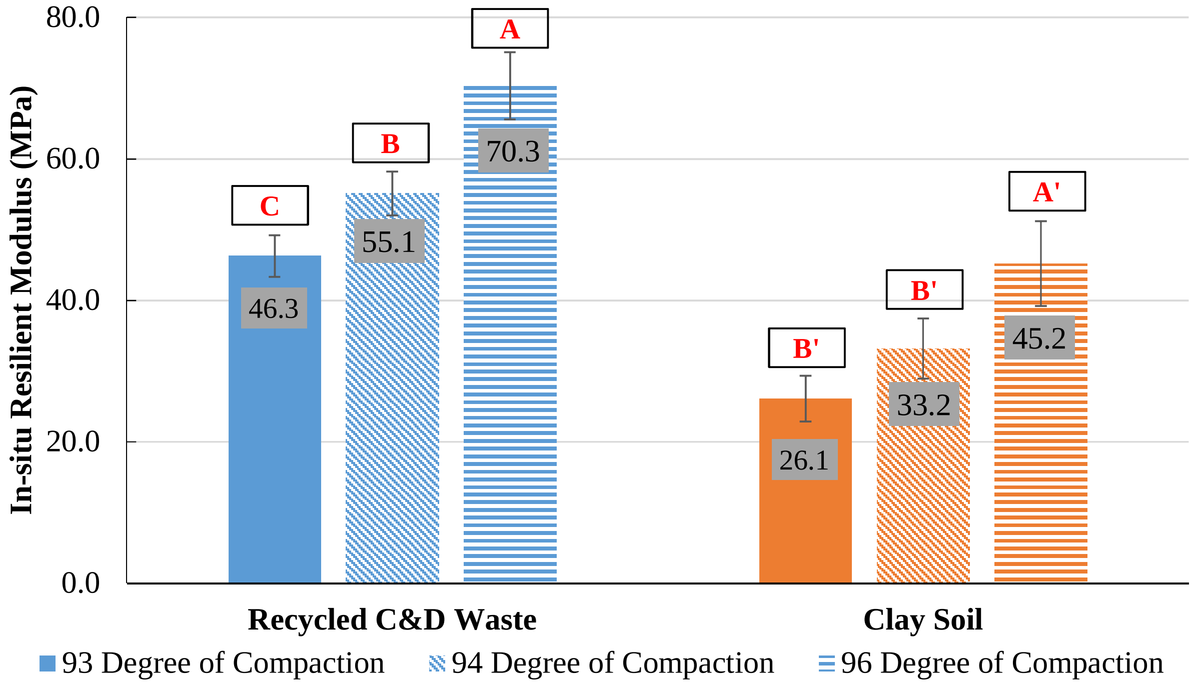



**Figure 14. Comparison of In-Situ Resilient Moduli between Recycled C&D Wastes and Clay Soil**

## Conclusions

This study explored the feasibility of using the recycled building-related construction and demolition (C&D) wastes in highway embankment. Both the laboratory and field tests were performed to comprehensively evaluate the engineering properties of the C&D wastes. The major contributions of this paper were summarized as follows:

- The recycled C&D wastes via the manual and mechanical sorting met the engineering requirements of Chinese Standard DB 41/T 1193. Both the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System rated the recycled C&D wastes as an excellent embankment material.
- The recycled C&D wastes exhibited stress-dependent characteristic in both resilient modulus and permanent deformation tests. The existing resilient modulus and permanent deformation models were capable of accurately predicting the stress-dependency of the recycled material. Compared to the embankment clay soil, the recycled C&D wastes had much higher resilient moduli and lower accumulated permanent deformation. This demonstrated that the substitution of recycled wastes for clay soil would improve the structural capacity and reduce rutting damage.
- The recycled C&D wastes also showed moisture-sensitive characteristic in the laboratory triaxial tests. Compared to the traditional clay soil, the recycled material had less moisture sensitivity to resilient modulus and permanent deformation. This characteristic would be substantially beneficial when using the recycled C&D waste in a hot and humid area.
- A field project was constructed on G95 Beijing Capital Area Loop Expressway, which utilized 100% recycled C&D wastes to fill embankment. The embankment application was found to consume much more recycled waste materials than other applications. The lightweight deflectometer (LWD) results indicated that the recycled C&D wastes exhibited significantly higher in-situ resilient moduli than the clay soil. The statistical analysis indicated that the LWD could statistically differentiate the compaction level of recycled C&D wastes. The LWD might be an efficient tool for quality control of embankment compaction when utilizing the recycled C&D wastes.

It is worth mentioning that this study only investigated one source of C&D wastes with one blended gradation. The future studies should focus on the influences of material source and blended gradation on the engineering properties of C&D wastes. In addition, the cost-effectiveness and environmental impact should be evaluated for use of the recycled C&D wastes in highway embankment.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- Use of recycled wastes in highway embankment would improve the structural capacity.
- Recycled wastes had less moisture sensitivity to resilient modulus and plastic deformation.
- A field project was constructed by utilizing 100% recycled wastes to fill embankment.
- Lightweight deflectometer was efficient for quality control of recycled wastes compaction.