



Transforming Construction and Demolition Waste into Soft-Soil Treatment for Paving Design

Eclesielter B. Moreira · Jair A. Baldovino ·
Ronaldo L. S. Izzo

Received: 8 April 2020 / Accepted: 12 May 2023 / Published online: 18 June 2023
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Abstract Construction and demolition wastes (CDW) are a concern in urban areas, in addition, it is well understood that soft soils are inappropriate for paving designs. Therefore, this paper presents an alternative solution combining CDW and a soft silty soil, aiming to overcome the soft soil drawbacks by repeated loadings. For this purpose, a laboratory study was developed, comprising both resilient modulus (M_R) and unconfined compressive strength (UCS) tests over soil and soil-CDW compacted blends, to evaluate the mechanical properties of the proposed stabilization. Also, three compaction efforts (standard, intermediate, and modified) and a curing time of up to 90 days were used. The UCS of blends was also measured with the identical specimens with which the resilience tests were carried out. The results indicated that incorporating CDW (size sand

and gravel materials) into the soil improves the q_u and M_R for all compaction energies, and the Resilient Modulus test affects the UCS of all blends, increasing its effect with the decrease in compaction effort. Repeated loads caused a decrease in the specimen's voids whereby the density increased and, therefore, q_u . Finally, the results conclude that the compacted mixtures in the intermediate effort and 40–60% CDW by weight are potentially applicable in pavements compared to the traditional soil–cement base/subbase.

Keywords Sedimentary soils · Construction and demolition wastes · Pavement · Reuse · Sustainability

1 Introduction

Urban growth and waste generation lead to severe problems in urban management (Rodríguez et al. 2007; Cardoso et al. 2016). Although construction is one of the essential activities for any country's development, it is also one of the most polluting due to its constructive methods, intense consumption of raw materials, wastage, and residual generation (Delongui et al. 2010; Gómez 2011). Thus, aiming to reduce the amount of raw material used and, therefore, to minimize the environmental impacts, such waste must be reused whenever possible.

Pavement damage (e.g., cracks and permanent deformation) depends on pavement responses, such as horizontal and vertical strains, due to repeated traffic

E. B. Moreira
Department of Civil Engineering, Graduate Program
in Civil Engineering, Universidade Federal do Rio Grande
do Sul, Porto Alegre 90035-190, Brazil
e-mail: eclesielter_ebm@hotmail.com

J. A. Baldovino (✉)
Civil Engineering Program, Universidad de Cartagena,
130015 Cartagena de Indias, Colombia
e-mail: jarrietab2@unicartagena.edu.co

R. L. S. Izzo
Department of Civil Construction, Federal University
of Technology- Paraná, Campus Curitiba, Street Deputado
Heitor Alencar Furtado, 5000, Curitiba 81280-340, Brazil
e-mail: izzo@utfpr.edu.br

loads, and these strains depend on the stiffness of pavement layers (Tarefder et al. 2016). Among construction actions, roadworks are one of the activities that most use raw materials since they are required during construction and maintenance. Brazil commonly uses granular materials for the layers below the asphalt concrete layer, such as soil, gravel, and pebble. When this natural material does not reach the required properties, techniques are devised to improve its mechanical behavior. Several materials are used to improve the soil's mechanical resistance. Several materials are used to improve the soil's mechanical resistance, comprising well-known traditional techniques, such as lime, ordinary Portland cement, natural rubber latex and fly ashes (Consoli et al. 2021; Ghorbani et al. 2022; Udomchai et al. 2022). Alternatively, even though the addition of alternative byproducts and residues such as coconut fiber, sisal, bamboo, wood, palm tree leaf, coconut leaf, metal, nylon, lime, CDW (ceramic, glass, concrete, and mixed), asphalt milling (containing conventional asphalt binder, modified by polymer and tire rubber), and agricultural residues (Prabakar et al. 2004; Leandro 2005; Consoli et al. 2007, 2009, 2016; Cardoso et al. 2016; Fedrigo et al. 2016; Kumar Yadav et al. 2017).

The use of CDW as an alternative material in construction is not a recent technique, and several studies were conducted to assess CDW's properties as a recycled aggregate. The highest percentage of CDW reuse in construction is through its use in pavement construction (Leite et al. 2011; Rahardjo et al. 2011; Lucena et al. 2014), being by far the most extensive application of recycled aggregates in geotechnical works around the world (Cardoso et al. 2016). Using alternative materials in any activity requires technical and environmental care. Thus, technological tests for mechanical properties evaluation of engineering material should seek to simulate field conditions since pavement fatigue over time occurs for many factors, such as transient loads of vehicles, climatic, morphological, geological, and pedagogic conditions of the region, and the format of cracks and fissures, as well as the wheel trail sinking.

In recent years, the use of recycled materials in pavement construction has gained significant attention due to its economic and environmental benefits. Studies have shown that alkali-activated recycled concrete and aluminum salt slag aggregates can be used as semi-rigid column inclusions in pavement

construction, providing adequate strength and stiffness (Lin et al. 2023). Geopolymer-stabilized washed recycled sands derived from demolition wastes have also been shown to have improved strength and stiffness, making them suitable for use in pavement subgrades (Xue et al. 2023). Furthermore, the use of waste foundry sand as a filling material for sub-bases, in combination with uniaxial geogrids, has been shown to improve the interaction properties of the pavement layers (Karnamprabhakara et al. 2022). Finally, incorporating bottom ash as fine aggregate in porous asphalt concrete has been found to improve permeability and drainage, while maintaining adequate mechanical performance for use in pavements (Suddeepong et al. 2023). These advancements in the use of recycled materials in pavement construction have the potential to not only reduce the environmental impact of pavement construction but also provide cost-effective solutions for the transportation infrastructure industry.

Unconfined compressive test determines the compressive strength of a material in the function of the straining and deformation this material suffers due to applied stress. Whereas the UCS test is considered a static test, alternatively, to simulate pavement conditions, a cyclic loading test also must be considered and, therefore, unable to determine materials' elastic properties such as Resilient Modulus (M_R). Since the M_R assay simulates the field conditions, the samples subjected to this assay also suffer damage to their structure and in the field, changing their structure and behavior (Nguyen and Mohajerani 2016).

There are constructions of industrial plants that contemplate roads of a low, medium, and high pavement classification number (PCN) and that from the moment of its construction until the beginning of its operation takes much more than 90 days. Moreover, highways in implantation usually take a relative time for their total operation. Within this perspective, this research aimed to obtain the unconfined compressive strength behavior of silty soil mixed with CDW after applying a dynamic load. For such, M_R and UCS tests were performed in samples with 90 days of curing, verifying whether, after 90 days of curing, there was some increase in resistance from reactions of the residues (e.g., cement, lime, tile, and glass) that make up the CDW. The option for a curing time of 90 days was because most chemical reactions between soil and

CDW have already occurred after this period (Jiménez 2013).

2 Materials and Experimental Details

The experimental program used in this research is explained below.

2.1 Materials

The present study used silty soil from the Guabirota sedimentary formation, sand material from CDW, gravel material from CDW, and distilled water.

The soil sample was collected in the south zone of Curitiba (Brazil), in the municipality of Fazenda Rio Grande, and belonged to the second layer of the Guabirota formation (this layer has thicknesses ranging from 0.5 to 5 m). The soil was extracted from an excavation at about 2.5 m. In its natural state, the soil presented hygroscopic moisture of 39%. The physical properties of soil, sand (CDW), and gravel (CDW) are synthesized in Table 1. Soil properties are similar to those reported by (Baldovino et al. 2018a), which

studied the soil improvement of the Guabirota formation with the addition of hydrated lime. For the determination of the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil, the American Standard D4318-e1 (ASTM 2010a) was used. Granulometric curves of the soil, blends, and CDW in the Sand and Gravel grain sizes are presented in Fig. 1. Note that the granulometric curves of the blends are more continuous. Thus, the finest particles filled the voids of coarser ones, stabilizing the soil. The highest percentage of soil grain size found corresponded to silt (53.6%); the specific gravity was 2.71 (ASTM 2010b). The predominant color of the soil was pink. In addition, from grain size distribution, the coefficients of uniformity (i.e., $C_u = D_{60}/D_{10}$) and curvature [i.e., $C_c = (D_{30})^2 / (D_{10} \times D_{60})$] presented values of $C_u = 21.74$ and $C_c = 0.48$, characterizing the soil as silt with sand according to Unified Soil Classification System criteria (ASTM 2011). Besides, the Transportation Research Board (TRB) classification system considers the soil as clayey (A-7-6).

The total quantitative chemical composition of the soil sample was investigated through energy-dispersive X-ray spectroscopy (EDX) using an

Table 1 Physical properties of the soil sample, sand, and gravel from CDW. *D* is the diameter of soil/CDW particles

Property	Value		
	Soil	Sand (CDW)	Gravel (CDW)
Liquid Limit (LL), %	53.1	–	–
Plastic Limit (PL), %	31.8	–	–
Plasticity Index (PI), %	21.3	–	–
Specific gravity (Gs)	2.71	2.65	2.69
Medium gravel (6 mm < <i>D</i> < 20 mm), %	–	–	55
Fine gravel (2 mm < <i>D</i> < 6 mm), %	–	15.3	44.4
Coarse sand (0.6 mm < <i>D</i> < 2 mm), %	5.2	49.5	0.6
Medium sand (0.2 mm < <i>D</i> < 0.6 mm), %	6.8	25.2	–
Fine sand (0.06 mm < <i>D</i> < 0.2 mm), %	24.6	10	–
Silt (0.002 mm < <i>D</i> < 0.06 mm), %	53.6	–	–
Clay (<i>D</i> < 0.002 mm), %	9.8	–	–
Mean particle diameter (<i>D</i> ₅₀), mm	0.025	0.8	6.8
Effective diameter (<i>D</i> ₁₀), mm	0.0023	0.2	3.4
C_u (i.e. $C_u = D_{60}/D_{10}$)	21.74	4.75	2.29
C_c [i.e. $C_c = (D_{30})^2 / (D_{60} \times D_{10})$]	0.48	1.53	1.14
Activity of clay, A [i.e. $A = PI / (D < 0.002 \text{ mm})$]	2.29	–	–
Classification USCS	MH	–	–
Classification TRB	A-7-6	–	–
Color	Pink	Gray	Multi-color
pH	3.8	–	–

Fig. 1 Grain size distribution of soil, CDW (sand and gravel), and blends

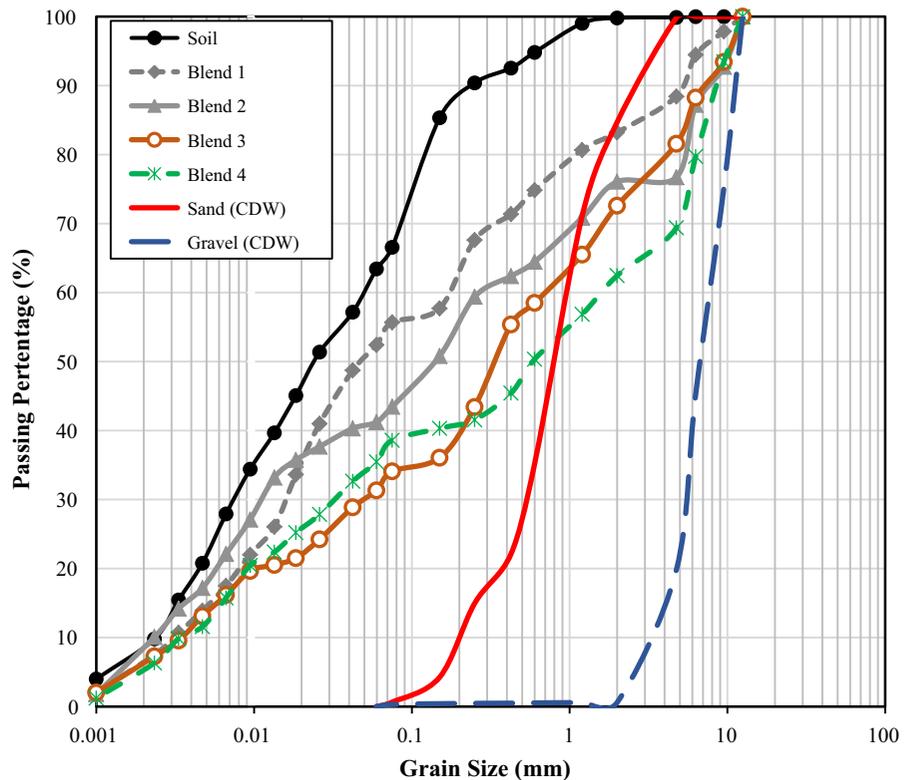


Table 2 Soil chemical composition (in wt. %)

Compost-symbol	Name	Concentration (%)
SiO ₂	Silicon dioxide	53.12
Al ₂ O ₃	Aluminum oxide	24.30
Fe ₂ O ₃	Ferric oxide	10.46
CaO	Calcium oxide	0.03
MgO	Magnesium oxide	0.28
K ₂ O	Potassium oxide	0.39
Na ₂ O	Sodium oxide	0.02
TiO ₂	Titanium dioxide	1.37
MnO	Manganese(II) oxide	0.17
P ₂ O ₅	Phosphorus pentoxide	0.22
LOI	Los of ignition	9.64

energy-dispersive X-ray fluorescence spectrometer. Table 2 shows the chemical composition of the soil sample, mainly SiO₂, Al₂O₃, and Fe₂O₃. In soil, these elements (i.e., SiO₂ and Al₂O₃) are generally unreacted. Silica tetrahedron and Alumina

octahedron are highly stable, and chemical stabilization by lime addition, for example, promotes a double layer reduction or cation exchange.

A recycling plant in the municipality of Almirante Tamandaré, in the Metropolitan Region of Curitiba (southern Brazil), produces construction and demolition waste. The crushing machine produces various sizes of aggregates for the crushing of the CDW. This study used CDW sand and gravel for granulometric soil stabilization. Table 1 and Fig. 1 show the results of the CDW sand and gravel tests. X-ray Diffraction Analysis (XRD) investigated the crystalline material structure of sand and gravel CDW. XRD tests detected quartz (SiO₂), calcite (CaCO₃), and dolomite [CaMg(CO₃)₂] for sand fraction, and quartz (SiO₂), calcite (CaCO₃), cordierite (Mg, Fe)₂Al₃(AlSi₅O₁₈), albite (NaAlSi₃O₈) and dolomite (CaMg(CO₃)₂) for gravel. The primary residues in the CDW were grout from concrete, roof tile, bricks, ceramic, aggregate from concrete, and mainly glass.

This research used distilled water for all tests, as it is free of impurities and prevents undesired reactions.

2.2 Methodology

The soil used in this research predominates fine particles, so we opted for mixing it to CDW in 5 distinctive proportions indicated in Table 3. The proportions of blends were chosen under previous studies (Baldovino et al. 2018b, 2022; Moreira et al. 2019). Each blend was named in concordance with Table 3. The B0 (without CDW addition) is also a denominated control blend since it is the soil without CDW. That way, it is possible to evaluate the strength increasing concerning it. The following tests were performed to characterize the distinct mixes: the granulometry test was performed according to the (ASTM 2011). The pH test was performed according to the (ASTM 2011). Finally, compaction tests were performed in the three energies established in Brazil (Standard Energy—SE, Intermediate Energy—IE, and Modified Energy—ME), as stated in the (ABNT 2016) standard. Brazilian modify effort is under standard ASTM D1557 (ASTM D1557 2012); SE corresponds to the effect of compaction with conventional field equipment [under standard ASTM D698 (ASTM D698-12 2012)], and IE is equivalent to $13 \text{ kN}\cdot\text{m}/\text{m}^3$, between SE and ME (Baldovino et al. 2020b). Compaction characteristics of soils are evaluated regarding two crucial parameters: Maximum Dry Density (MDD—in kN/m^3) and Optimum Moisture Content (OMC—in %). The Proctor tests, with 1 h aeration time, were conducted on reconstituted soils, including the natural soil and the soil–CDW.

Specimens with 150 mm in height and 75 mm in diameter were molded for the unconfined compression and resilient modulus tests (M_R). The soil was oven-dried at $100 \pm 5 \text{ }^\circ\text{C}$ and then placed in uniformly distributed portions to be mixed with the different CDW contents. Blends for the sample molding were statically compacted in two layers with a stainless-steel mold with aC.

Table 3 Percentage of CDW per blend in dry weight of soil

	Soil (%)	Sand (%)	Gravel (%)
Blend 0 (B0)	100	–	–
Blend 1 (B1)	60	30	10
Blend 2 (B2)	60	20	20
Blend 3 (B3)	50	30	20
Blend 4 (B4)	40	30	30

75-mm internal diameter, 150-mm high, and 10-mm thick, under optimum conditions [i.e., following the recommendations of the ASTM D2166 (ASTM 2003) standard for the maximum size of the particle concerning the mold diameter]. The samples were weighed on a scale with 0.01 g precision, and dimensions were measured with a 0.1 mm error pachymeter. Extracted samples were wrapped in transparent plastic to maintain the OMC. Finally, to prevent significant changes in moisture control until the day of the test, the samples were taken to a wet chamber for curing for 90 days at a mean temperature of $25 \text{ }^\circ\text{C}$. To be used in the UCS test and Resilient Modulus test, the samples had to meet the following maximum errors: $\pm 0.5 \text{ mm}$ for the diameter and $\pm 1 \text{ mm}$ for the height of the sample sizes, $\pm 1\%$ for the MDD and $\pm 0.5\%$ for the OMC.

Two hundred seventy (270) compacted samples were tested in the three compaction energies, being molded 90 samples in the optimum conditions of Standard Energy (SE), Intermediate Energy (IE), and Modified Energy (ME). For each energy, 45 samples were disposed of for an unconfined compressive test and 45 for the M_R . For a 90-day curing time, three samples were molded with 5 CDW levels, and both UCS and M_R results could not differ by 10% among themselves.

The samples used for the M_R test were subsequently subjected to an unconfined compressive test to evaluate the Resilient Modulus test effect on the UCS test. Samples were taken from the triaxial cells and mounted on the UCS testing machine. After the UCS test, the humidity of the samples was measured to measure the degree of saturation and resulted in $S > 92\%$, i.e., the influence of suction is not relevant. To perform the UCS test, a universal press (model DL_{30}) was used, with a calibrated load cell (TRD-29), a displacement rate of 1.00 mm per minute, and a maximum load capacity of 30 kN.

The procedures of the unconfined compressive strength (UCS) tests followed the ASTM D2166 (ASTM 2003) standard. The Resilient Modulus is calculated according to Eq. (1) below:

$$M_R = \frac{\sigma_d}{\epsilon} \quad (1)$$

where σ_d is deviatoric stresses, and ϵ is resilient axial deformation. All tests were performed using the Material Testing System machine with a closed-loop

hydraulic servo loading system. The load applied was measured using a load cell installed inside the triaxial cell. Axial displacement measurements were taken using two linearly variable differential transducers (LVDTs) installed inside the triaxial chamber to reduce the amount of extraneous axial deformation measured compared to external LVDTs. Air was used as a confining fluid for the samples. Resilient modulus tests were performed per (DNIT-EM 134 2010). In this test method, the samples are first conditioned by applying 200 load cycles to remove most irregularities on the top and bottom surfaces and suppress most of the initial permanent deformation. Following the test, after applying the confinement stress, 18 pairs of strength, according to Table 2.

The conditioning of the samples is followed by a series of steps, which consisted of applying 180 haversine-shaped load pulse cycles at different confining and deviatoric stress levels in a way that the resilient modulus is measured at varying, normal, and shear stresses. The load pulse used in this study had a 0.1-s load duration and a 0.9 s rest period. This procedure helps determine mechanical properties that can be used to predict the performance of materials and calculate the structural responses of pavement structures. The test applies to cylindrical specimens of unbound mixtures prepared by the laboratory compaction sample, with a maximum particle size less than or equal to 1/6 of the specimen diameter.

3 Results and Discussions

3.1 Results of pH Tests

Figure 2 shows the pH variation of the blends with the CDW content. It is observed that the CDW, being a primary alkaline material, reacts with soil, initially neutralizing it and later alkalizing it. Svehla (1979) states that pH values above 9 generate calcium carbonate (CaCO_3) precipitation over time. However, CaCO_3 appeared probably because two reasons. Firstly, because of secondary products from ordinary Portland cement, once some amount of Portlandite remains in suspension after C–S–H types gels have already developed. This Portlandite, in contact with

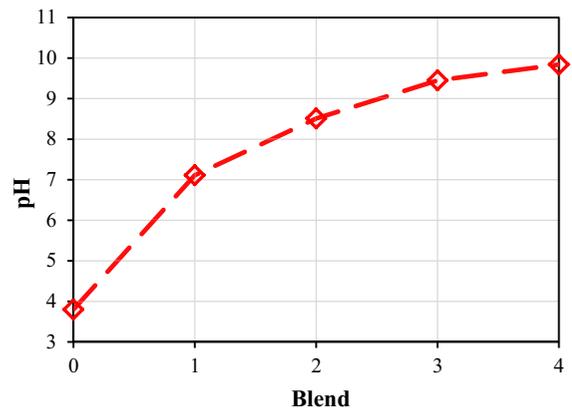


Fig. 2 Results of pH for the soil and blend (soil-CDW)

CO_2 , could precipitate CaCO_3 . The second option is owing to the presence of lime in CDW and follows a similar pattern of carbonation. A pH above nine demonstrates that hydroxyls remain released, enabling the CaCO_3 precipitation. However, to pozzolanic reactions occur, a minimum pH of 10.5 is required. Therefore, following this pattern, this pH is susceptible to CaCO_3 precipitation but not chemical stabilization, and it is well known that CaCO_3 did not work as a binder once that acquired a crystalline form. This fact might explain the presence of CaCO_3 in the studied CDW. These results indicate a potential reaction between soil and CDW, increasing the blend's resistance (Figs. 3, 4, 5).

3.2 Compaction Tests

An increase in MDD of ME compared to SE, of 16.5%, 14.7%, 18.5%, 14.1%, and 14.4% were observed for the B0, B1, B2, B3, and B4, respectively; additionally, a percentage reduction in the OMC reduction of 23.2%, 31.8%, 43.8%, 36.2%, and 33.5% to for the B0, B1, B2, B3, and B4 blends was also detected. This fact can be explained in terms of granular material increase and, consequently, fines reduction in fines percentage in the blends. Accordingly, there is a decrease in OMC with an increase in CDW (Figs. 3, 4, and 5). Figure 6 shows the MDD behavior in function of with the increased compaction

Fig. 3 Compaction curves of soil and soil–sand–gravel mixes under standard effort (SE)

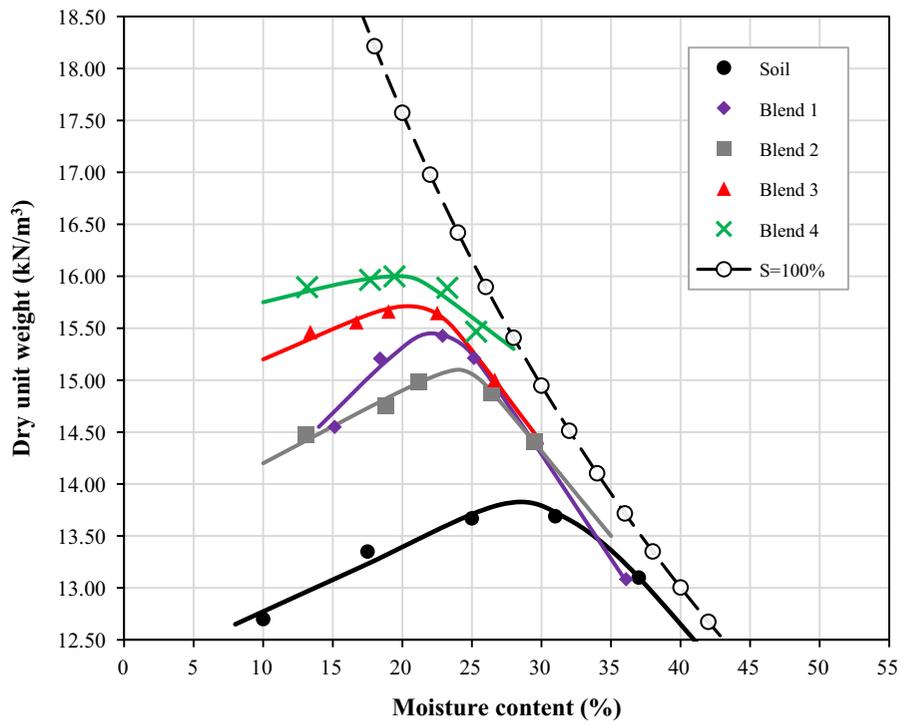


Fig. 4 Compaction curves of soil and soil–sand–gravel mixes under standard effort (IE)

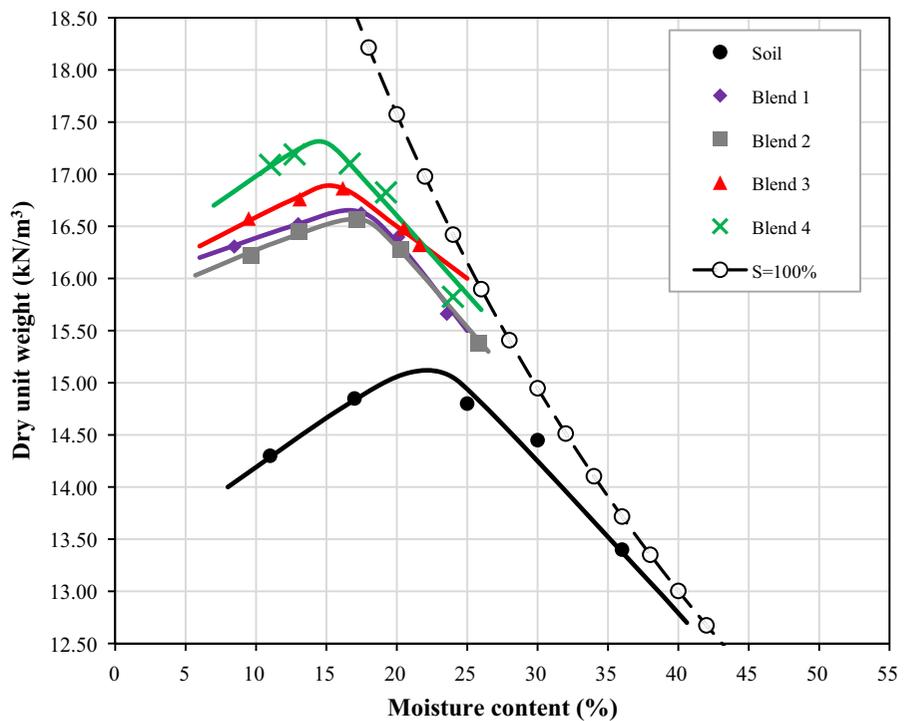


Fig. 5 Compaction curves of soil and soil–sand–gravel mixes under modified effort (ME)

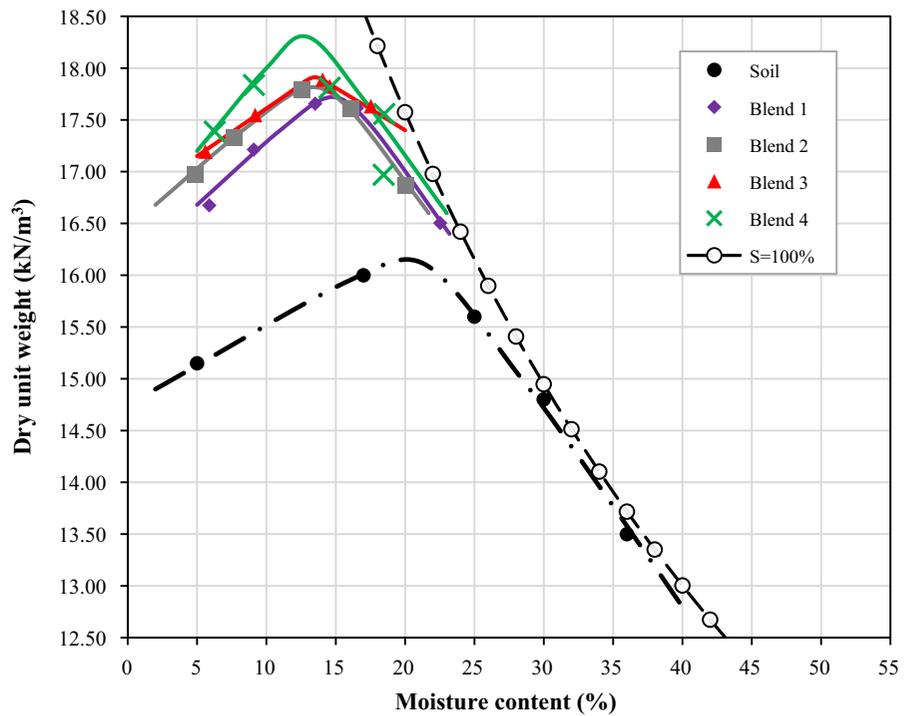
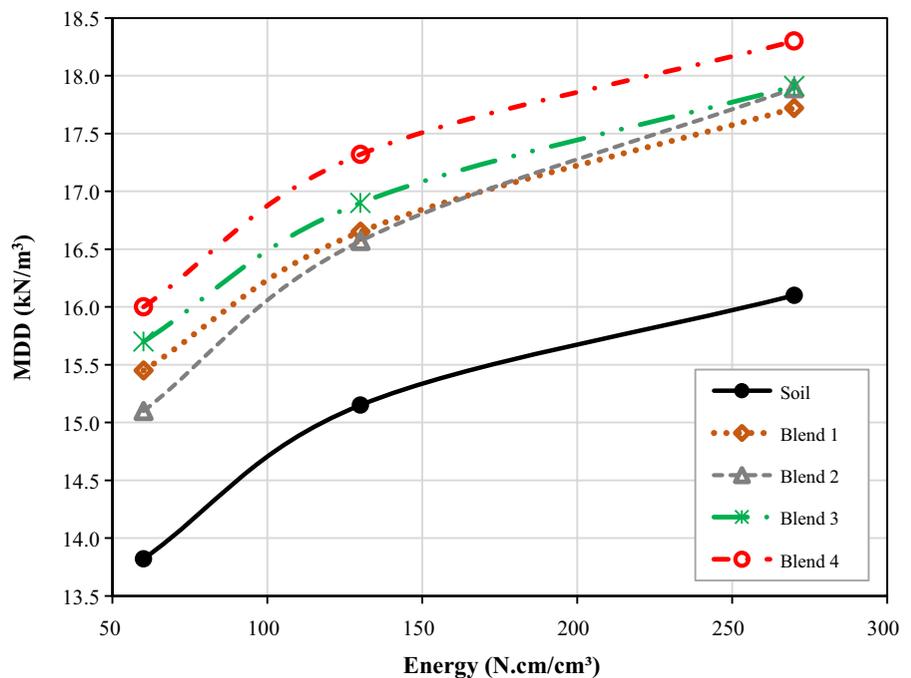


Fig. 6 Variation of maximum dry unit weight per compaction energy (in N.cm/cm³) employed



energy (i.e., 60, 130, and 270 N.cm/cm³, for the SE, IE, and ME, respectively).

There was a similar performance about the increase of the MDD with an increase of the

compaction energy. As the level of CDW added to soil increases, the curve shifts upward, thus increasing the MDD. It is assumed, then, that there is an MDD increase according to the added CDW.

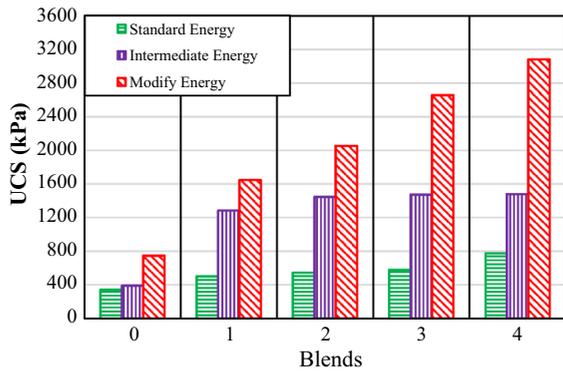


Fig. 7 Influence of the cure time on the UCS in the compaction energies

The MDD behavior in the function of compaction energy is similar for all blends, and the maximum MDD increase is observed in the B4 blend when compared to soil, with an increase of 15.8% in SE, 14.3% in the IE, and 13.7% of the increase in the ME.

3.3 Unconfined Compression Strength of Soil-CDW Mixes

Figure 7 presents the UCS values of soil and blends in compaction SE, IE, and ME at 90 days of curing. Notably, there has been a resistance increase according to the level of CDW in the soil and the function of the increased compaction energy.

The strength gains of the B0, B1, B2, B3, and B4 in the ME, compared to SE, were 118%, 227%, 277%, 359%, and 297%, respectively. A resistance increase was observed in all blends with the rise in compaction energy. However, all IE compaction energy blends reached a comparable resistance value, approximately 1,400 kPa. Compared to soil without a blend in the same compaction energy, strength gains of the B1, B2, B3, and B4 in SE were 46%, 59%, 69%, and 126%, respectively. Strength gains of the B1, B2, B3, and B4 in IE, compared to soil without a blend in the same compaction energy, were 56%, 94%, 113%, and 143%, respectively. Compared to soil without a blend in the same compaction energy, strength gains

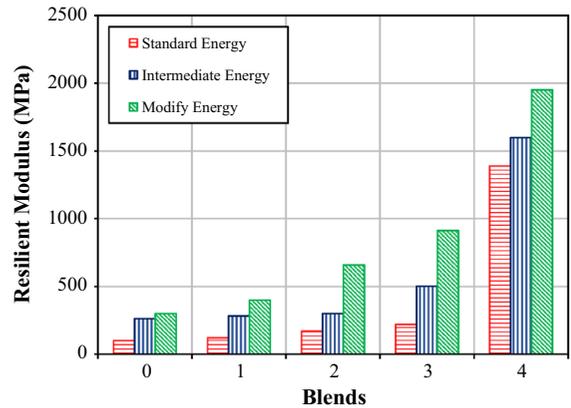


Fig. 8 Resilient modulus for CDW blends in the standard energy, intermediate energy, and modified energy

of the B1, B2, B3, and B4 in ME were 120%, 175%, 256%, and 312%, respectively. Besides, in Fig. 7, it is also possible to observe that the maximum strength received was 3081 kPa in the ME, 1679 kPa in the IE, and 776 kPa in the SE. These UCS improvement results after 90 days of curing are possible because be reactions from cement, lime, ceramic tile, ceramic brick, and ground glass. Some authors also improved soil with these mixed materials (e. g. Baldovino

Table 4 The 18 pairs of stress applied in the test specimens of the Resilient Modulus test

σ_3 (kPa)	σ_d (kPa)	σ_1/σ_3
20,7	20.7	2
	41.4	3
	62.1	4
34,5	34.5	2
	68.9	3
	102.9	4
50,4	50.4	2
	102.9	3
	155.2	4
68,9	68.9	2
	137.9	3
	206.8	4
102,9	102.9	2
	206.8	3
	309.0	4
137,9	137.9	2
	274.7	3
	412.0	4

et al. 2020a; Consoli et al. 2020; Moreira et al. 2019, 2020).

3.4 Resilience Modulus of Soil-CDW Mixes

The M_R of paving materials is currently Brazil's most widely used method for paving projects. In this article, the resilient modulus values for each sample are the last stress pairs of the dynamic triaxial test, which represents the highest stress level of the test: $\sigma_d=0.412$ MPa and $\sigma_3=0.137$ MPa. Figure 8 shows the blends' M_R in the last stress pairs (Table 4).

An increased M_R is observed as the compaction energy increases, reaching a maximum variation in the B3, i.e., a variation of 314% from the ME regarding SE. In the B0, B1, and B2, there was a mean variation of 200% and, in the B4, a variation of 43% between the obtained M_R values for ME and those obtained for SE. It also observed an M_R increase with the rise in CDW, reaching a maximum increase of

561% between the M_R values obtained for the soil and those for the B4. Also, Fig. 8 shows that all the blends in the three compaction energies presented a similar M_R behavior. The addition of CDW had a significant impact on M_R behavior. This can be explained due to CDW being granular and the solid skeleton of the mixtures, as Jiménez (2013) reported.

Table 6 presents some resilient modulus values for Brazilian soils taken from the current literature. The values presented by Lovato (2004) are very high in comparison to the others because this author used a laterite soil with a high percentage (5%) of lime (powder and paste form) in two compaction energies (intermediate and normal), which increased the results. Concerning the values obtained in this research, Table 5 is the average of the results presented in Fig. 8, which contains all compaction energies.

According to Costa and Motta (2006), the mean values of M_R in 290 MPa are indicated for the

Table 5 MDD and OMC of CDW per blend in the three compactions energies

Blends	Standard energy		Intermediate energy		Modify energy	
	MDD (kN/m ³)	OMC (%)	MDD (kN/m ³)	OMC (%)	MDD (kN/m ³)	OMC (%)
Soil	13.82	28.0	15.15	24.5	16.100	21.5
Blend 1	15.45	22.0	16.65	17.0	17.720	15.0
Blend 2	15.10	24.0	16.57	17.0	17.890	13.5
Blend 3	15.70	21.0	16.90	15.0	17.910	13.4
Blend 4	16.00	20.0	17.32	14.5	18.300	13.3

Table 6 Some studies on resilient modulus in granular layers of pavements in Brazilian soils and main results

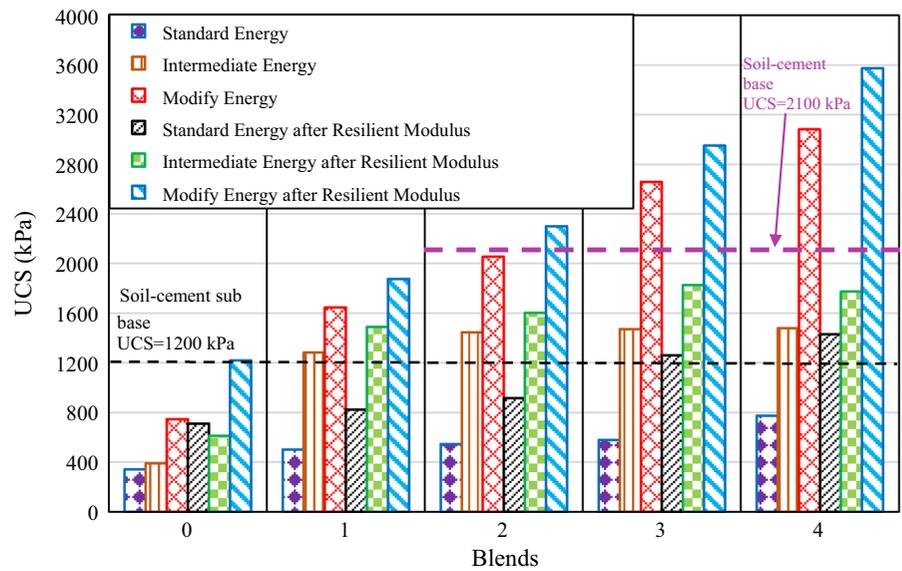
Type of soil	Origin	Resilient modulus (Mpa)	References
Clayey soil	Sergipe (Brazil)	290	Costa and Motta (2006)
Sandy soil	Rio de Janeiro (Brazil)	183	Thuler (2005)
Clayey soil	Ceará (Brazil)	265	Araújo (2009)
Clayey lateritic soil*	Cruz Alta (Brazil)	9,599	Lovato (2004)
Clayey lateritic soil**	Cruz Alta (Brazil)	2,677	Lovato (2004)
Sandy soil	Ceará (Brazil)	301	Bastos (2013)
CDW	Brasília (Brazil)	450	Gómez (2011), Jiménez (2013, 2016)
Soil–water sludge	Recife (Brazil)	815	Lucena et al. (2014)
Clayey soil-CDW blends***	Curitiba (Brazil)	614	This research

*Calcic lime

**Dolomitic lime

***Average results

Fig. 9 Influence of the Resilient Modulus test on the UCS in the standard energy, intermediate energy, and modified energy



pavement base layer for the stress pairs presented. As of this information, and after a qualitative analysis of the graphs, it was found that all stabilized blends in IE and ME presented higher values of resilient modulus than those reported by (Costa and Motta 2006) and that the M_R values of this research are consistent with the M_R results for Brazilian soils, presented in Table 6.

3.5 Unconfined Compression Test After Resilient Modulus Test for Mixes

After the M_R test, the samples were submitted to the UCS test. Figure 9 presents the UCS of soil and blends in the SE, IE, and ME compaction efforts after the Resilient Modulus test. It is observed that there was an increase in UCS in all energies after the M_R . During the M_R test, there is compaction of the samples due to the stress pairs that are applied. This process voids the reduction of the samples; due to this process, the UCS results performed after M_R test are greater. This increase in UCS after the Resilient test is more pronounced for samples molded at lower energies. This can be explained by the fact that the sample in standard energy (SE) has more air voids and, therefore, more space to densify concerning samples that have already been compacted in the energy modified (ME) for the M_R test (see Fig. 10). UCS increases of the B0, B1, B2, B3,



Fig. 10 Specimens before and after resilient modulus tests—Influence of the Resilient Modulus test on the UCS in the standard energy

Table 7 Increment of UCS after the M_R test

Blends	SE	IE	ME
B0	107%	57%	63%
B1	64%	16%	14%
B2	68%	11%	12%
B3	117%	24%	11%
B4	84%	20%	16%

and B4 mixes in the compaction SE, IE, and ME, can be observed in Table 7.

The highest UCS increase happened in SE. This is justifiable due to the compaction process during the resilient test, i.e., when applying cyclic loads, there was higher compaction in the SE samples; thus, the samples undergo a voids reduction during the resiliency test. It can be concluded that the smaller the compaction energy used to mold the samples, the smaller the resilient modulus will be since, according to Eq. (1), it is necessary to divide the deviation stress by the deformation to calculate the M_R . Thus, the M_R will be higher the more remarkable its density, which can be confirmed through Fig. 7 analysis, where all blends in the SE had a smaller M_R . Similarly, the smallest UCS increase, in general, was in ME since the highest M_R values were presented in this compaction energy.

UCS test results values of compacted blends were compared to traditional UCS values of traditional soil–cement base ($q_u = 2100$ kPa) and subbase ($q_u = 1200$ kPa) in Fig. 9. Both base and subbase thresholds were magnified in Fig. 9 to highlight mixtures proposed here that fit paving designs. Generally, blends containing sand and gravel from CDW are compacted in the intermediate energy suit subbase layers. Blends containing 40–60% CDW are suitable for base layers when compacted in modified energy.

4 Concluding Remarks

This research aimed to quantify the influence of the Resilient Modulus test (RM) on the Unconfined Compressive Strength test (UCS) and the influence of CDW addition in the geotechnical properties of sedimentary soil in different compaction energies. According to the type of soil and waste used, and tests conducted, the following final remarks can be made:

- The use of CDW in the soil results in an excellent technique to use in paving works as base layers, sub-base, and sub-grade reinforcement, according to the requirements of the Brazilian pavement project method. The B4 mix provided the most satisfactory result concerning UCS and M_R parameters since this blend had a significant increase in all these parameters, better than the other blends.
- The results showed an increase in UCS values after the Resilient Modulus test, with the tendency

remaining the same (i.e., there is an increase of strength by moving the tendency line upwards), which is justified by the sample's compaction during the Resilient Modulus test. The standard energy was observed that, in addition to the UCS increasing, there was a superior increase than in the other compaction energies. This can be justified due to the higher compaction of the samples in the standard energy during the Resilient Modulus test, and this is reflected in the M_R once the strength results are more minor in this energy.

- A mean increase of UCS resistance of 88% (SE), 26% (IE), and 23% (ME) occurred in the samples after the Resilient Modulus test when compared to the UCS samples that were not submitted to this test. The percentage of strength increasing diminishes as the compaction energy increases since there is a compaction process during the resilient test, which is greater the smaller the compaction energy used to mold the samples.

Acknowledgements The authors are thankful to the National Council for Scientific and Technological Development (CNPq, Brazil), Higher Education Personnel Improvement Coordination (CAPES, Brazil), and Fundação Araucária do Paraná in Brazil.

Funding Open Access funding provided by Colombia Consortium.

Data Availability Enquiries about data availability should be directed to the authors.

Declaration

Conflict of Interest The authors have not disclosed any competing interests.

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