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Analysis of the feasibility of manufacturing concrete paving blocks with recycled aggregates from construction and demolition waste

Análise da viabilidade da fabricação de blocos intertravados de concreto para pavimentos com o uso de agregados reciclados da construção civil

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ABSTRACT

This paper aims to analyze the feasibility of using interlocking concrete blocks with recycled aggregates from construction and demolition waste for paving. First, dry concrete was produced, known to have zero slump, requiring a vibro-press machine for compaction and immediate stripping. Then, four dry concrete mixtures, CDW-0.63, REF-0.73, 50CDW-0.63, and 50CDW-0.73 (the first two and the last two without and with recycled aggregates, respectively), were applied with two water/cement ratios (0.63 and 0.73). In the next step, empirical and mechanistic-empirical design methods were used for interlocking block pavement, simulating the construction of this structure with cost evaluation. The results showed that the reference mixture REF-0.73, with more water, presented the highest characteristic compressive strength at 28 days (25.34 MPa). Furthermore, the interlocking pavement simulation from the mechanistic-empirical design, with recycled aggregates in the blocks (mixture 50CDW-0.63), generated savings of around US$76,000.00 compared to the pavement of reference blocks (mixture REF-0.73). Finally, dry concrete can present better mechanical behavior with the addition of water, and the interlocking pavement technology is more financially attractive applying the mechanistic-empirical design method.

RESUMO

O objetivo deste artigo é analisar a viabilidade de utilização de blocos intertravados de concreto, com agregados reciclados de resíduos de construção e demolição, para pavimentação. Primeiro, foi produzido concreto seco, o qual é conhecido por apresentar *slump*-zero, sendo necessária máquina de vibro-prensa para compactação e desforma imediata. Assim, quatro misturas de concreto seco, REF-0.63, REF-0.73, 50CDW-0.63 e 50CDW-0.73 (os dois primeiros e os dois últimos sem e com agregados reciclados, respectivamente) foram aplicadas com duas relações água/cimento (0.63 e 0.73). Na próxima etapa, foram utilizados métodos de dimensionamento empírico e mecanístico-empírico para pavimento de blocos intertravados, sendo simulada a construção dessa estrutura com avaliação de custos. Os resultados indicaram que a mistura de referência REF-0.73, com mais água, apresentou a maior resistência característica à compressão aos 28 dias (25.34 MPa). Além disso, o pavimento intertravado resultante do dimensionamento mecanístico-empírico, com agregados reciclados nos blocos (mistura 50CDW-0.63), gerou economia da ordem de US$76.000,00 em comparação ao pavimento de blocos de referência (mistura REF-0.73). Por fim, o concreto seco pode apresentar melhor comportamento mecânico com a adição de água e a tecnologia de pavimento intertravado é mais atrativa financeiramente, aplicando método de dimensionamento mecanístico-empírico.

1. INTRODUCTION

The interlocking pavement (IP) consists of a flexible, rigid, or semi-rigid structure, depending on the composition of the base and sub-base layers. These two layers can be roller-compacted concrete for rigid pavement, graded crushed stone treated with cement or soil-cement for semi-rigid pavement, and simple crushed stone for flexible pavement. In Figure 1, the IP layers above the foundation (a subgrade layer, top of the foundation, is optional) are the sub-base, the base, and the surface (concrete blocks, bedding sand, and joint material).

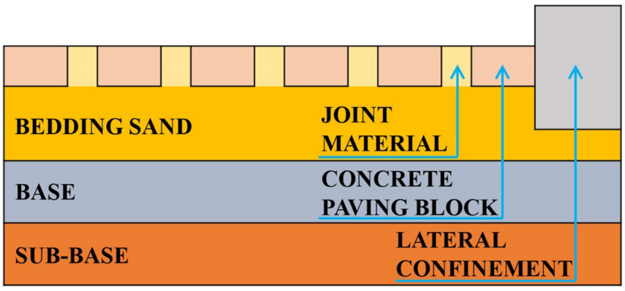


Figure 1. Interlocking pavement layers

Most of the design methods for IP come from adaptations of the calculation methodology for asphalt pavements, according to Cruz (2003). These adaptations may result in overestimated expenses in IP construction. Then, applying rational design methods specially developed for IP can make the construction more favorable from an economic point of view. Shackel (1988) commented that, regarding the advantages of IP application, with adequate dosage, concrete paving blocks (CPB) could be more durable in an industrial environment than asphalt pavements.

Over the years, in Fortaleza, Brazil, the requalification of Beira Mar and Desembargador Moreira avenues was done using CPB. According to Silva (2020), approximately 66,705 m^2 and 6,500 m^2 of CPB were used, respectively. Internationally, this technology application grows roughly 100% in the USA every five years. Similar growth rates have been recorded in Belgium, Germany, Australia, New Zealand, and South Africa (Silva, 2020).

By-product reuse is a strategy to manufacture CPB. Then it is essential to highlight that construction and demolition waste (CDW) is widely generated in urban centers due to civil construction activities. According to Crispim (2018), in Fortaleza, Brazil, the amount of CDW destined for the 61 ecopoints of the city was 276,000 tons per year. Therefore, evaluating ways to reuse this waste is essential to encourage recycling by public or private companies. Then, the company Recycling Plant of Fortaleza (USIFORT) generates recycled aggregates from CDW for reuse in Fortaleza, Brazil. Nationally, the studies by Francisco, Souza and Teixeira (2019) and

Ono, Balbo and Cargnin (2017) evaluated the application of CDW recycled aggregate in IP layers, such as CPB and the base. Internationally, research by Luo et al. (2022), Chu et al. (2021), Özalp et al. (2016), and Poon and Chan (2007) showed the beneficial use of recycled aggregate for concrete blocks in IP.

Therefore, the reuse of by-products, such as recycled materials from CDW, in CPB has the potential to be explored, contributing to sustainability in IP construction. Thus, this paper aims to analyze the properties of CPB through CDW recycled aggregates to verify the technical feasibility of manufacturing blocks for paving. Furthermore, a simulation of IP construction in a parking area is done to evaluate the economic feasibility of manufacturing CPB.

2. EXPERIMENTAL PROGRAM

Natural and alternative aggregates were used. Natural materials were phonolitic 19 mm and 12.5 mm gravels as nominal maximum size (NMS) and crushed sand with a finess modulus (FM) of 1.55. Alternative materials were two CDW recycled coarse aggregates (19 mm and 12.5 mm as NMS) and a CDW recycled sand (FM=2.27) from USIFORT. High-early-strength Portland Cement (ABNT CP V-ARI) and water from the public distribution system were also used. Finally, a high-quality additive, free of chlorides, with a chemical action providing a cement dispersion, produced a lubricating effect during production.

The aggregates were characterized according to tests from the Brazilian Technical Standards Association (ABNT), such as granulometric distribution by the sieves (mm): 19; 12.5; 9.5; 6.3; 4.75; 2.36; 1.18; 0.6; 0.3 and 0.15 (ABNT, 2022); dry density of fine and coarse aggregates, and cement by Equations 1, 2 and 3, respectively (ABNT, 2017; 2021a; 2021b); unit weight by Equation 4 (ABNT, 2021c) and water absorption by Equation 5 (ABNT, 2021a; 2021b). The leaching and solubilized extraction environmental tests were also done on CDW sand and cement. The chemical compounds' concentration limits are from the standard ABNT NBR 10004 (ABNT, 2004).

$$\rho_{sm}=m_A/(V-V_a) \quad (1)$$

$$\rho_{sg}=m_A/(m_B-m_C) \quad (2)$$

$$\rho_c=m_D/V_b \quad (3)$$

$$\rho_{ap}=(m_E-m_F)/V_c \quad (4)$$

$$Abs=(m_B-m_A)/m_A\times 100 \quad (5)$$

where ρ_{sm}, ρ_{sg} and ρ_c: dry density of fine and coarse aggregates and cement, respectively (g/cm^3); ρ_{ap}: unit weight (kg/m^3); Abs: water absorption (%); m_A, m_B, m_C and m_D: aggregate mass in oven-dried at (105±5)°C, saturated dry surface, submerged in water, and cement mass, respectively (g); m_E and m_F: mass of container with aggregate and empty container, respectively (kg); V, V_a and V_b: calibrated flask volume, water added to the flask, and volume displaced by the cement mass, respectively (cm^3); and V_c: container volume (m^3).

The granulometric distribution, along with special zones for fine (usable zone) and coarse aggregate (zones 9.5/25 mm and 4.75/12.5 mm), are in Figure 2 (ABNT, 2022). Furthermore, the average between two samples shows the characterization and environmental test results in Tables 1 and 2, respectively.

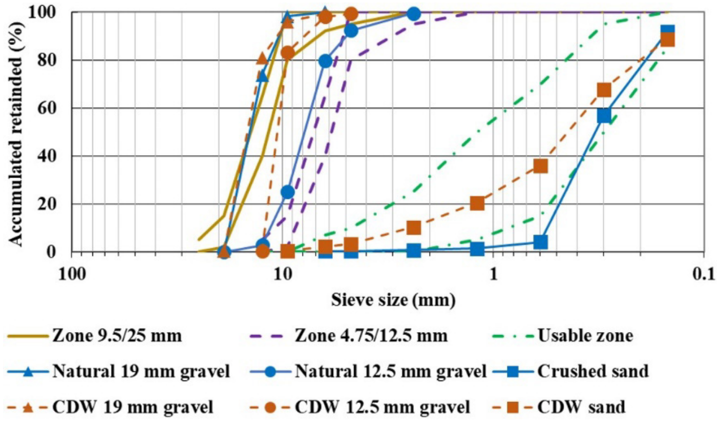


Figure 2. Aggregates granulometric distribution

Table 1: Aggregates and cement characteristics

Materials	Density (g/cm³)	Unit weight (kg/m³)	Water absorption (%)	NMS (mm)	FM
Natural 19 mm gravel	2.49	1,330.37	0.8	19.0	6.99
Natural 12.5 mm gravel	2.51	1,370.54	1.3	12.5	6.17
Crushed sand	2.62	1,460.57	0.5	0.6	1.55
CDW 19 mm gravel	2.55	1,326.29	3.1	19.0	6.95
CDW 12.5 mm gravel	2.56	1,290.04	4.4	12.5	6.81
CDW sand	2.54	1,575.27	4.4	4.75	2.27
Cement	3.13	–	–	–	–

Table 2: Results of leaching and solubilized extractions for recycled sand and cement

Tests	Materials	Fluoride F^- (mg/L)	Chloride Cl^- (mg/L)	Bromide Br^- (mg/L)	Nitrate NO_3^- (mg/L)	Nitrite NO_2^- (mg/L)	Phosphate PO_4^{3-} (mg/L)	Sulfate SO_4^{2-} (mg/L)
Leaching extraction	CDW sand	278.99	5.96	–	–	–	–	50.99
	Cement	427.80	0.25	0.25	0.25	0.25	0.50	414.29
	Limit	150.00	–	–	–	–	–	–
Solubilized extraction	CDW sand	0.67	6.97	–	–	0.51	–	131.11
	Cement	0.05	16.14	0.25	0.25	0.25	0.50	995.59
	Limit	1.50	250.00	–	10.00	–	–	250.00

The granulometric distribution curves of the natural 19 mm gravel and the CDW 19 mm were located close. However, the same does not happen with the pairs of materials: natural 12.5 mm gravel and CDW 12.5 mm gravel, crushed sand and CDW sand. Furthermore, except for the CDW sand, the material curves were partially outside the special zones. However, by mixtures between the natural and recycled aggregates (see Figure 3), the granulometric distribution can reduce the voids in the concrete, favoring the CPB mechanical performance. Also, the special zones in Figure 2 are valid, according to the standard ABNT NBR 7211 (ABNT, 2022), for the mixture of aggregates to provide compactness to the concrete. As dry concrete tends to present a higher air content than the plastic mix (expected value of 5%), according to Silva (2020), it makes sense that the mixture does not provide significant compactness (see Table 3). Therefore, it may be recommended that the curves of the materials for dry concrete do not fully fit the zones in Figure 2.

Concerning the leaching extraction, the concrete constituents are class I (hazardous) due to the fluoride concentration above the limit (278.99 mg/L and 427.80 mg/L>150.00 mg/L). The fluoride may come from fluorite, also called calcium fluoride (CaF_2). The calcium salt of hydrofluoric acid is a mineral that occurs mainly in granite and other volcanic rocks, such as phonolite. Regarding the solubilized extraction, the cement showed sulfate concentration above the limit (995.59 mg/L>250.00 mg/L), reinforcing the need for care regarding its use. However, the solubility of contaminants can decrease with the mixing of materials. Furthermore, according to Baird and Cann (2011), the compaction of CPB by the vibro-press machine may encapsulate the waste in the concrete.

2.1. Concrete mixes and tests on fresh and hardened concrete paving blocks

Mixtures of materials for dry concrete were designed by adjustments in the commercial mix adopted by a company specialized in CPB manufacturing in the Metropolitan Region of Fortaleza, Brazil. Four mixtures were produced, two reference (REF-0.63 and REF-0.73) and two alternative mixtures with mixed CDW recycled aggregate (50CDW-0.63 and 50CDW-0.73). It is essential to highlight that 0.04% of the additive was used in proportion to the total mass of the mixture. For the evaluation of the concrete with recycled materials, aggregates were replaced based on the granulometric distribution.

Two water/cement ratios were applied in the mixtures: 0.63 and 0.73. It is essential to highlight that, to keep the materials' proportions in the reference mixes (REF-0.63 and REF-0.73), the mortar (70.05%) and moisture (7.80%) contents of the concrete were kept constant. Then, on the mixtures with CDW recycled aggregate, the following 50% replacement by mass of the materials were applied: natural 19 mm and 12.5 mm gravels, and crushed sand by CDW 19 mm and 12.5 mm gravels, and CDW sand, respectively (50CDW-0.63 and 50CDW-0.73). The granulometric distribution curves of the mixtures between the aggregates are present in Figure 3. Equations 6 and 7 by Helene and Terzian (1992) were used to determine concrete components' consumption (kg/m³).

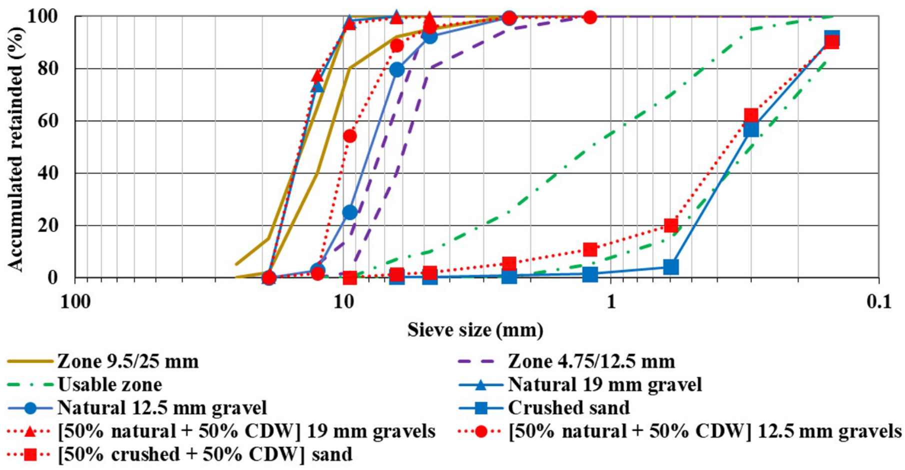


Figure 3. Granulometric distribution of the mixtures between natural and recycled aggregates

$$C=(1000-10\times air)/(1/\gamma_c+a/\gamma_a+p/\gamma_p+w/c) \quad (6)$$

$$C_{mat}=C\times P_{mat} \quad (7)$$

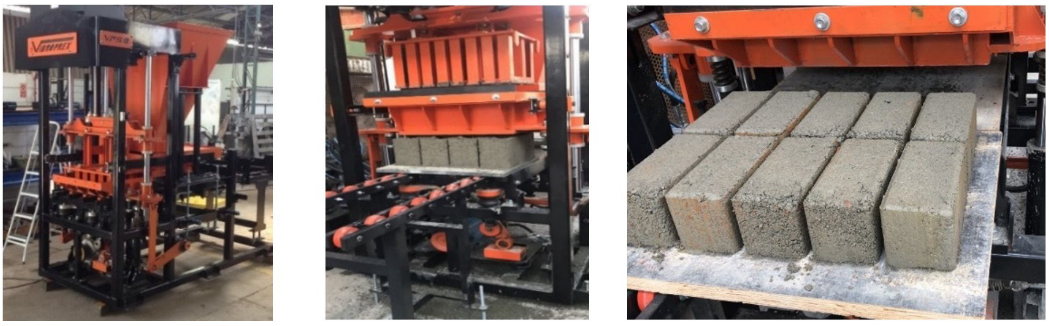
where C: cement consumption per cubic meter of concrete densified (kg/m³); C_{mat}: consumption of the concrete component materials (kg/m³); *air*: content of incorporated and/or trapped air of the concrete (%); γ_c, γ_a and γ_p: density of cement, fine and coarse aggregate, respectively (kg/dm³); a and p: ratio of fine and coarse aggregate, as a function of cement, in the mixture, respectively; w/c: water/cement ratio; and P_{mat}: ratio of the concrete components, as a function of the cement, in the mixture.

The air content of concrete in the fresh state (parameter "*air*" in Equation 6) was determined according to standard ABNT NBR 9833 (ABNT, 2008a). However, instead of using a cylindrical container, which should be filled with fresh concrete, it was chosen to analyze three fresh blocks produced by the vibro-press machine (see Figure 4) for each of the four mixtures. Then, the CPB mass and volume were determined to obtain the fresh concrete average unit weight (property necessary to calculate the air content). This procedure was adopted due to the inability to simulate the energy provided by the vibro-press machine through manual or vibratory compaction. Furthermore, the consistency test by the VeBe method for one value per mix was done on fresh concrete, according to ACI 211.3R-02 (ACI, 2009). The mixtures are shown in Table 3.

Table 3: Concrete components' consumption and fresh concrete properties

Mixtures	Unit weight (kg/m³)	Air content (%)	Consumption (kg/m³)								
			Cement	Crushed sand	Natural 12.5 mm gravel	Natural 19 mm gravel	CDW sand	CDW 12.5 mm gravel	CDW 19 mm gravel	Water	Additive
REF-0.63	2,117.52	10.2	243.1	1,132.9	478.9	109.4	–	–	–	153.2	0.85
REF-0.73	2,199.85	6.5	218.0	1,212.1	497.1	113.4	–	–	–	159.1	0.88
50CDW-0.63	2,101.29	10.5	241.2	562.1	237.6	54.3	562.1	237.6	54.3	152.0	0.84
50CDW-0.73	2,176.18	7.1	215.7	599.6	245.9	56.1	599.6	245.9	56.1	157.4	0.87

The dry concrete blocks were produced by a vibro-press machine (model VP50 from Tprex), with a compression force of 4 tons and a 7.35 kW motor responsible for the vibration. Rectangular blocks of 20 cm × 10 cm × 8 cm (length × width × thickness) were made, as shown in Figure 4. The following tests from ABNT were performed using the average value for three CPB tested per mixture: void index (ABNT, 2005), elasticity modulus (ABNT, 2008b), and water absorption (ABNT, 2013). For the compressive strength test (ABNT, 2013), six CPB per mixture were used to obtain the characteristic result. These tests were done at 7 and 28 days, except for the elasticity modulus test, only at 28 days, which was done by an ultrasonic wave propagation device.



(a) Vibro-press machine (b) Machine operation (c) Block manufacturing

Figure 4. Vibro-press machine model VP50 from Tprex brand

2.2. Interlocking pavement construction simulation

The construction simulation of an IP was done in a parking area in Fortaleza, Brazil. The engineers involved in this construction aimed to use CDW recycled aggregate from the Convention Center demolition in Fortaleza. Then, the by-products from CDW were present in the concrete composition for CPB. This parking area is shown in Figure 5 and has a total area of approximately 22,720 m^2.

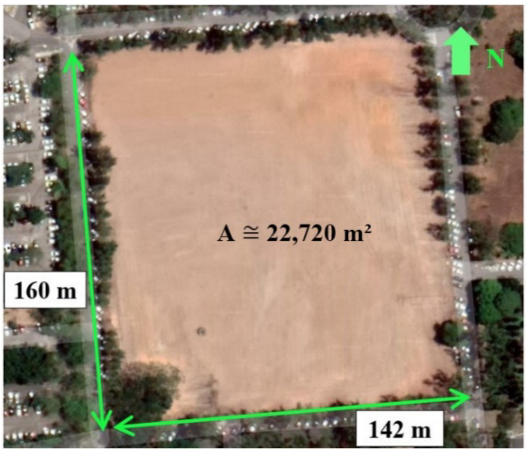


Figure 5. Top view of the land to be built for the interlocking pavement in Fortaleza, Brazil

For the IP design, empirical and mechanistic-empirical design method was used. Then, the IP structures were compared to analyze which design method provides a more rational pavement construction. Furthermore, in Table 4, the road, traffic, and material parameters are shown, according to the road function, the number N (the number of applications of the standard single axle, which transmits a total load of approximately 8.2 tf or 80 kN), the California Bearing Ratio (CBR) and the layers' thickness.

Table 4: Road, traffic, and material parameters for the parking area

Road parameter	Traffic parameters		Material parameters			
Predominant functions	Predicted vehicle traffic	Number N	Foundation CBR	Layer thickness		
				CPB	Bedding sand	Joint material
Collecting and local roads	Medium	6×10^5	10%	8 cm	5 cm or 4 cm	5 mm

Note 1: the road and traffic parameters were taken from PMSP Project Instruction 06 (São Paulo, 2004).
Note 2: the bedding sand's thickness is 5 cm when using the empirical design method or 4 cm when applying the mechanistic-empirical design method.
Note 3: the joint material's thickness of 5 mm is a requirement of the standard ABNT NBR 15953 (ABNT, 2011).

The traffic in the parking area generally consists of vehicles, such as cars and motorcycles. Thus, it was decided that the vehicle traffic in the region was medium (Table 4), with the number N of 6×10^5, associated with a collecting and local road. Regarding the foundation with a CBR of 10%, this soil is more present in the Metropolitan Region of Fortaleza, Brazil (Vasconcelos, 2016). All the data in Table 4 were applied to the IP structures from the empirical and mechanistic-empirical design methods. The quantities (in mass) of each material used in the pavement layers were also determined.

Regarding the materials in the bedding sand and sub-base layers, the results by Vasconcelos et al. (2019) were used in which coal fly ash was studied in the pavement's granular layers. This by-product was approved in the environmental tests of leaching and solubilized extraction. The compositions by mass of the chosen mixtures are shown in Table 5. The material properties, such as CBR, expansion, optimal moisture, maximum dry density (MDD), simple compressive strength (SCS), and resilient modulus (RM), presented in Table 6, were also measured by Vasconcelos et al. (2019).

Table 5: Compositions by mass of the mixes chosen for the interlocking pavement

Layers	Mixtures	Soil (%)	Coal fly ash (%)	Lime (%)
Bedding sand and joint material	M1	100.0	–	–
Sub-base	M7	48.5	48.5	3,0

Note 1: the soil was from a deposit in the Metropolitan Region of Fortaleza, Brazil. This material was A-2-4, according to the standard AASHTO M 145 (AASHTO, 1995), being a silty sand with 17% passing through the sieve 0.075 mm.
Note 2: the coal fly ash was from the Thermoelectric Power Plants Pecem I and Pecem II, Brazil. This material was A-4, according to the standard AASHTO M 145 (AASHTO, 1995), being a silty material, with 69% of the particles passing through the sieve 0.075 mm.
Note 3: the lime was a commercially hydrated calcite type from a company in Ceara, Brazil.
Source: Vasconcelos et al. (2019).

Table 6: Properties of mixes for granular interlocking pavement layers

Mixtures	CBR (%)	Expansion (%)	Optimal moisture (%)	MDD (g/cm³)	SCS (MPa)	RM parameters RM = $k1 \times \sigma_3^{k2} \times \sigma_d^{k3}$				Average RM (MPa)
						k1	k2	k3	R^2	
M1	20.0	0	15.10	1.97	0	139.3	-0.269	-0.538	0.78	161.0
M7	205.0	0	20.70	1.56	2.37	2,649.0	0.282	-0.199	0.50	735.0

Note 1: CBR, expansion, optimum moisture, and MESM were determined by the standard DNIT-ME 172 (DNIT, 2016). SCS and RM were found by the standards DNER-ME 180 (DNER, 1994) and DNIT-ME 134 (DNIT, 2018), respectively.
Note 2: the mixture M7 was tested at 28 days because of the use of lime.
Note 3: in the composite model for RM (definition close to the elasticity modulus), the term σ_3 means confining stress, and the term σ_d refers to the deviation stress.
Note 4: despite the low correlation value observed for some mixes, the composite model was still the one that best represented the mixtures M1 and M7.
Source: Vasconcelos et al. (2019).

The model by Carvalho (1998) was used for the empirical design method for IP, an adaptation of research by Lilley and Walker (1986). Then, this model recommends IP for commercial vehicle traffic, and the number N ranges between 2.7×10^4 and 3.3×10^7. The data required are the CBR values of the foundation and sub-base and the number N. Therefore, the IP sections were similar for the four concrete mixtures.

The program DesignPave from CMAA (2018) was used for the mechanistic-empirical method for IP. On the premises, the multilayer system in CPB is converted into an equivalent homogeneous layer with a single material property. This procedure is known as the Method of Equivalent Thickness (MEF) by Odemark (1949), shown in Equation 8.

$$h_{eq} = n h_i (E_i/E_m)^{1/3} \times [(1-v_m^2)/(1-v_i^2)]^{1/3} \quad (8)$$

where h_{eq} and h_i: thicknesses of the top layer after and before the MEF application, respectively (cm); $n = 0.9$; E_i and E_m: vertical elasticity modulus of the top layer and half-space, respectively (MPa); and v_i and v_m: Poisson ratios of the top layer and half-space, respectively.

For the program DesignPave from CMAA (2018), the input data were the materials' Poisson ratio, the elasticity modulus in the IP layers, and the number N and CBR of the foundation. The values of elasticity modulus and Poisson ratio are shown in Table 7.

Table 7: Elasticity modulus and Poisson ratios for interlocking pavement

Poisson ratios		Elasticity modulus	
Pavement layers	**Values adopted**	**Mixtures**	**Average results (GPa)**
CPB	0.20	REF-0.63	40.1
Bedding sand	0.35	REF-0.73	37.5
Sub-base	0.35	50CDW-0.63	36.4
Foundation	0.40	50CDW-0.73	37.3

As the four mixtures' elasticity modulus exceeded the maximum of 7.5 GPa allowed by the program DesignPave, this limit was considered in the design. Then, all IP structures were equal for the four mixtures used in the CPB manufacturing.

Finally, a reference and alternative concrete mixtures with the best SCS results at 28 days were adopted for the IP construction simulation. Table 027 (without tax) from the Secretary of Infrastructure of Ceara (SEINFRA-CE, 2022) was used for the cost analysis (see Table 10). In the simulation, the CDW purchase cost was zero. Then, the construction costs for IP in the parking area were compared using CPB with and without CDW recycled aggregates.

3. RESULTS AND DISCUSSION

3.1. Tests on fresh and hardened concrete

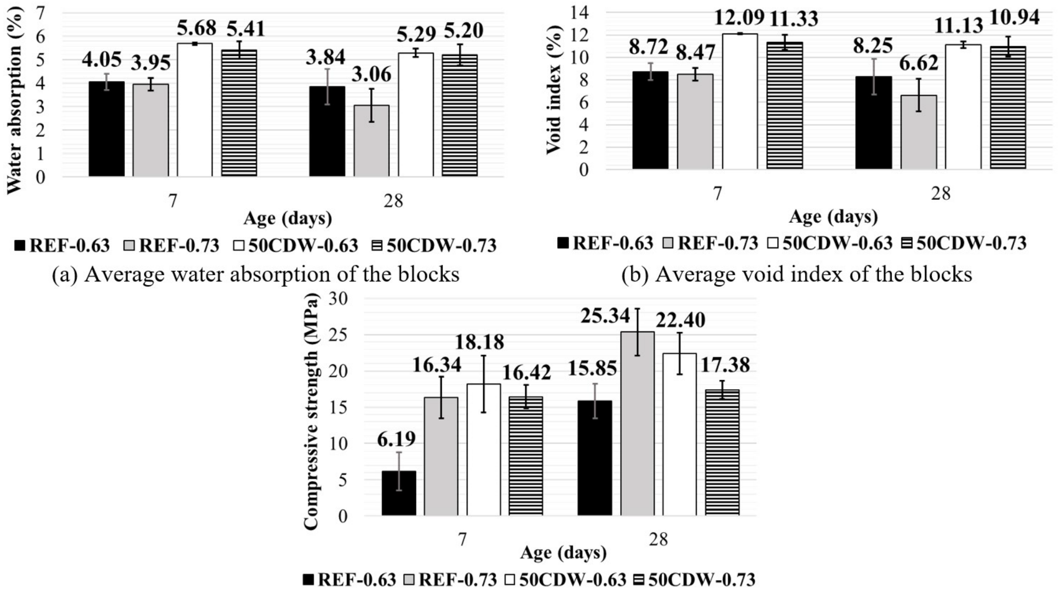
The consistency of fresh concrete's results are shown in Table 8.

Table 8: VeBe results for concrete mixtures

Standard ACI 211.3R-02 (ACI, 2009)		Mixtures	VeBe time (s)	Concrete classes
Consistency descriptions	**VeBe time (s)**			
Extremely dry	>18≤32	REF-0.63	19.9	Extremely dry
Very stiff	>10≤18	REF-0.73	18.2	
Stiff	>5≤10	50CDW-0.63	15.1	Very stiff
Stiff plastic	>3≤5	50CDW-0.73	17.3	

The mixtures were classified as extremely dry and very stiff. Therefore, strong vibration and compression methods are recommended for concretes with these characteristics. The alternative mixtures, 50CDW-0.63 and 50CDW-0.73, showed a VeBe time decrease in VeBe of 24.1% and 4.9% compared to the respective reference mixes, REF-0.63 and REF-0.73. However, the alternative mixtures presented the highest air content results compared to the reference mixes (see Table 3). These results can be due to a higher FM by recycled aggregates (CDW 12.5 mm gravel and CDW sand) than natural materials (natural 12.5 mm gravel and crushed sand) (see Table 1). Then, with more voids, the mixtures 50CDW-0.63 and 50CDW-0.73 should not show a VeBe time decrease, which can be caused by the recycled aggregates' shape properties, such as texture. In their mass composition, these materials presented 84.7% of rock, 1.1% of ceramic, and 14.2% of old bitumen. Therefore, the old bitumen, which can be rougher than phonolite (original rock of the natural 19 mm and 12.5 mm gravels and crushed sand), provided a more significant interaction between the cement paste and the recycled materials' surface. With this contact, the transition zone may have been smaller, causing workability associated with the alternative concrete, which caused a VeBe time decrease.

The average water absorption and void index for CPB are shown in Figures 6a and 6b, respectively. Furthermore, the characteristic SCS is presented in Figure 6c. Standard deviation bars were put in for better data distribution understanding. Also, concerning the SCS test, it is essential to know the specifications from other CPB standards in Table 9.



(a) Average water absorption of the blocks (b) Average void index of the blocks

(c) Characteristic compressive strength of the blocks

Figure 6. Physical and mechanical properties of the blocks

Table 9: Compressive strength test specifications for paving blocks

Standards (Countries)	Traffic descriptions	Value descriptions	SCS at 28 days (MPa)
ABNT NBR 9781 (ABNT, 2013) (Brazil)	Special vehicles or loads that produce abrasion effects	Characteristic value	≥ 50
	Commercial vehicles		≥ 35
ASTM C936 (ASTM, 2021) (USA)	Any traffic	Average value	≥ 55
		Individual value	≥ 50
SA AS/NZS 4456.4 (SA, 2003) (Australia)	Special vehicles or loads that produce abrasion effects	Characteristic value	≥ 60
	Light vehicles		≥ 25
	Bike paths and parking lots		≥ 15

The American standard ASTM C936 (ASTM, 2021) has a higher minimum SCS for CPB than other standards. The reason is that in the USA, the freezing temperatures in winter favor ice on the roads. Then, ice crystals into the concrete pores with the consequent melting on the surface or inside the CPB can damage the mixture microstructure. Therefore, low-temperature regions with ice and melting problems usually specify higher minimum SCS for CPB.

The average water absorption values in Figure 6a were below 6.0%, a specification of the standard ABNT NBR 9781 (ABNT, 2013). Then, the CPB of all mixtures were approved on this test. However, the alternative mixtures, 50CDW-0.63 and 50CDW-0.73, showed CPB with increases of 40.2% and 37.0% (7 days), 37.8% and 69.9% (28 days) in water absorption compared to the respective reference mixtures, REF-0.63 and REF-0.73. The two mixes with CDW recycled materials also had, in Figure 6b, the highest average void index values (12.09% and 11.33% at 7 days; 11.13% and 10.94% at 28 days). These results were expected, as the alternative fresh concrete showed higher air contents (see Table 3) than the respective reference mixes (10.5% by 50CDW-0.63 > 10.2% by REF- 0.63; 7.1% by 50CDW-0.73 > 6.5% by REF-0.73). Therefore, a more significant air incorporated into the concrete pores decreased the hydration reactions during the curing process, which favored the void formation in the alternative mixtures. Furthermore, the CDW recycled aggregates were more porous than natural materials because of higher water absorption (see Table 1). Then, with liquid retention and consequent growth in the alternative CPB's water absorption, the effect did not benefit these mixtures' mechanical behavior.

The mixture REF-0.73 presented higher SCS than the mix REF-0.63 at 7 days (16.34 MPa > 6.19 MPa) and 28 days (25.34 MPa > 15.85 MPa) in Figure 6c. As dry concrete had reduced water content, the water/cement ratio is not the main factor for the CPB strength. Then, adding more water can improve the mixtures' workability, favoring the SCS increase. However, the mixture 50CDW-0.73's SCS was not superior to the mix 50CDW-0.63 at 7 days (16.42 MPa < 18.18 MPa) and 28 days (17.38 MPa < 22.40 MPa). Therefore, the material packing by the vibro-press machine in mixing natural and recycled aggregates with more water did not provide the necessary compactness of the concrete.

Finally, the SCS results were below the specifications in Table 9. However, according to the Australian standard SA AS/NZS 4456.4 (SA, 2003), the minimum value for the characteristic SCS of CPB is 15 MPa for bicycle paths and parking lots. Then, a revision in the Brazilian standard ABNT NBR 9781 (ABNT, 2013)'s criteria can be made with the creation of a new traffic category for bike paths or parking lots with lower specifications.

3.2. Interlocking pavement construction simulation

The concrete mixtures REF-0.73 and 50CDW-0.63 were chosen to simulate the IP construction in a parking area. These mixes presented the best SCS results at 28 days, as shown in Figure 6c (25.34 MPa by REF-0.73 and 22.40 MPa by 50CDW-0.63). The sections from empirical and mechanistic-empirical design applications for IP are in Figure 7 (without scale). Furthermore, Figure 8 presents the materials' mass needed to construct the IP for each concrete mix and design method using the parking area (see Figure 5).

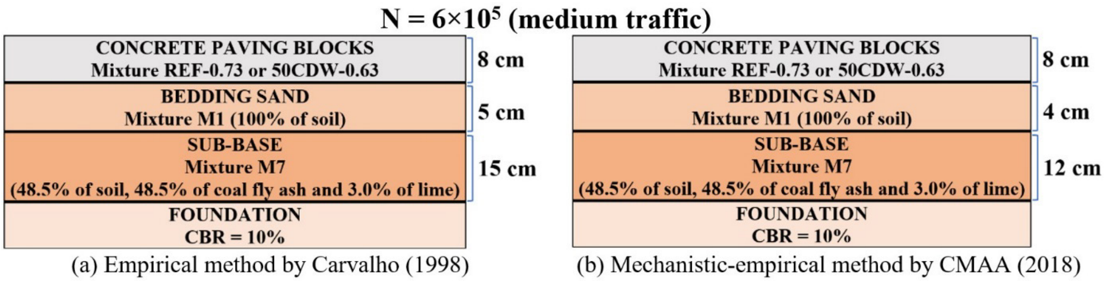


Figure 7. Interlocking pavement sections with the mixtures in the layers

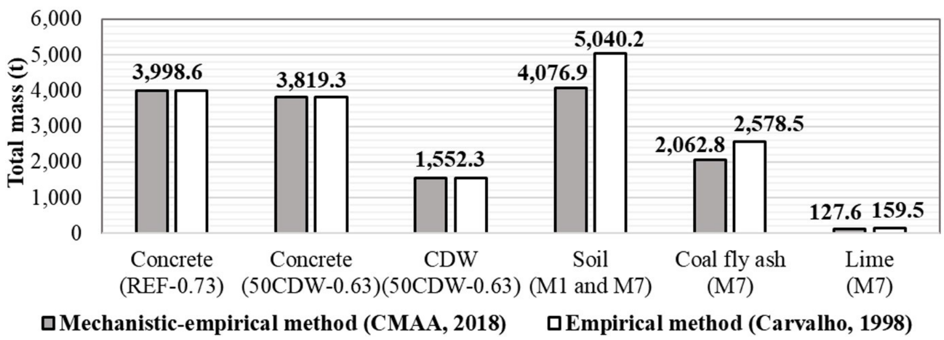


Figure 8. Total mass for the materials present in the interlocking pavement layers

In Figure 8, the significant difference between the soil quantities from the two design methods (5,040.2 t and 4,076.9 t) is a main factor in the IP construction cost because of the efforts to purchase materials. Then, the program DesignPave by CMAA (2018) proved more economically advantageous. Furthermore, the significant by-products' consumption (CDW recycled aggregates and coal fly ash) above 1,000 t is environmentally beneficial because these materials were given a useful purpose. The general costs per service were put in Table 10 to simulate the IP construction in the parking area, with the total costs shown in Figure 9 depending on the concrete mixture and design method.

Table 10: Service costs for the interlocking pavement construction

Design methods	Services	Concrete mixtures	General values of services (US$) {1}	Quantities {2}	Total costs of services (US$) {1×2}
Mechanistic-empirical method	1) Mechanized land cleaning		0.04/m^2	22,720.0 m^2	908.80
	2) Foundation regularization		0.43/m^2	22,720.0 m^2	9,769,60
	3) Loading, transport, and unloading of materials		8.56/m^3	5,452.8 m^3	46,675.97
	4) Mechanical compaction of the sub-base layer with moisture control		5.58/m^3	2,726.4 m^3	15,213.31
	5) Drainage with a manhole for the rainwater gallery	–	1,132.27/unit	1.0 unit	1,132.27
CMAA (2018)					
	6) Reinforcement of compaction and moisture control in the sub-base layer		13.07/m^3	2,726.4 m^3	35,634.05
	7) Grain size stabilization of the soil present in the settlement layer		4.28/m^3	908.8 m^3	3,889.66
	8) Paving in interlocking blocks with grouting material	REF-0.73	11.86/m^2	22,720.0 m^2	269,459.20
		50CDW-0.63	8.49/m^2	22,720.0 m^2	192,892.80
Empirical method	1) Mechanized land cleaning		0.04/m^2	22,720.0 m^2	908.80
	2) Foundation regularization		0.43/m^2	22,720.0 m^2	9,769,60
	3) Loading, transport, and unloading of materials		8.56/m^3	6,361.6 m^3	54,455.30
	4) Mechanical compaction of the sub-base layer with moisture control		5.58/m^3	3,408.0 m^3	19,016.64
	5) Drainage with a manhole for the rainwater gallery	–	1,132.27/unit	1.0 unit	1,132.27
Carvalho (1998)					
	6) Reinforcement of compaction and moisture control in the sub-base layer		13.07/m^3	3,408.0 m^3	44,542.56
	7) Grain size stabilization of the soil present in the settlement layer		4.28/m^3	1,136.0 m^3	4,862.08
	8) Paving in interlocking blocks with grouting material	REF-0.73	11.86/m^2	22,720.0 m^2	269,459.20
		50CDW-0.63	8.49/m^2	22,720.0 m^2	192,892.80

Note: the commercial dollar was quoted on February 20th, 2023, equivalent to R$ 5.16 (Brazilian currency).

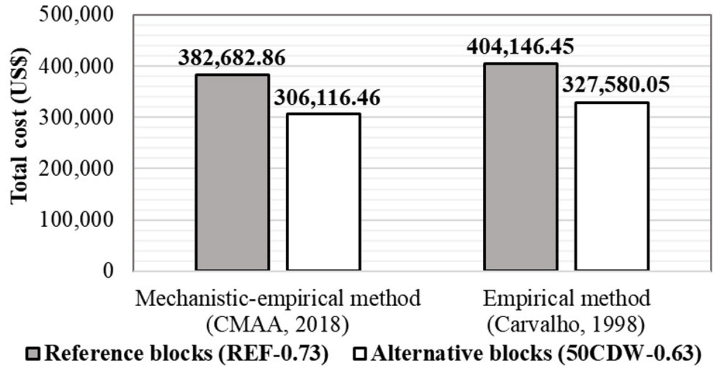


Figure 9. Total costs for the interlocking pavement construction

The majority cost for IP construction came from the execution of CPB with grouting material in Table 10 (8th service). This service was considered with the blocks being prefabricated. Then, the main cost can be reduced with CPB manufacturing on-site, where only the purchase of the concrete components would be necessary. Furthermore, in Figure 9, the mechanistic-empirical method by the program DesignPave by CMAA (2018) provided a more economical construction solution than the empirical method by Carvalho (1998). Therefore, considering the same mix for CPB, the savings were approximately US$ 20,000.00. Assuming the same IP design method, the economy generated was about US$ 76,000.00. Due to the zero acquisition cost of the CDW recycled aggregates, the IP construction with alternative CPB by a mechanistic-empirical method is a reasonable measure. For example, when comparing the construction cost with the IP of reference blocks and empirically designed, the savings were approximately US$ 98,000.00. These savings are advantageous for the company responsible for the construction, showing alternatives for managing the capital in services to IP.

4. CONCLUSIONS

This paper presented research with the primary objective of analyzing the CPB properties with CDW recycled aggregates to verify the technical and economic feasibility of manufacturing blocks for paving. With the main results, the leading direct inferences can be as follows:

- Concerning the leaching extraction test, due to the fluoride concentration above the limit, this chemical compound may come from CaF_2. The reason is CaF_2 is found in phonolite (the original rock of the aggregates in this research);
- Although the mixture 50CDW-0.73 was not better than 50CDW-0.63, regarding the SCS at 7 and 28 days, the alternative CPB could be used in bike paths and parking lots, according to the Australian standard SA AS/NZS 4456.4 (SA, 2003). However, the decrease in SCS by the mix 50CDW-0.73 with a higher water/cement ratio showed that the material packing by the vibro-press machine did not provide the required compactness for dry concrete;
- By mechanistic-empirical design, the alternative mixture, 50CDW-0.63, made the IP construction less expensive, generating savings of up to US$ 98,000.00. In addition to the zero CDW acquisition cost, the DesignPave program by CMAA (2018) approached the MEF, which allowed for a more rational IP design.

Finally, it can be said that the study mechanically supports the use of CPB in areas with light traffic but implies the adaptation of the specifications for IP. Also, this research endorses using mechanistic-empirical design for IP to decrease construction costs.

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