STUDY OF INTERLOCKING CONCRETE BLOCK PAVEMENT AND ASPHALT PAVEMENT

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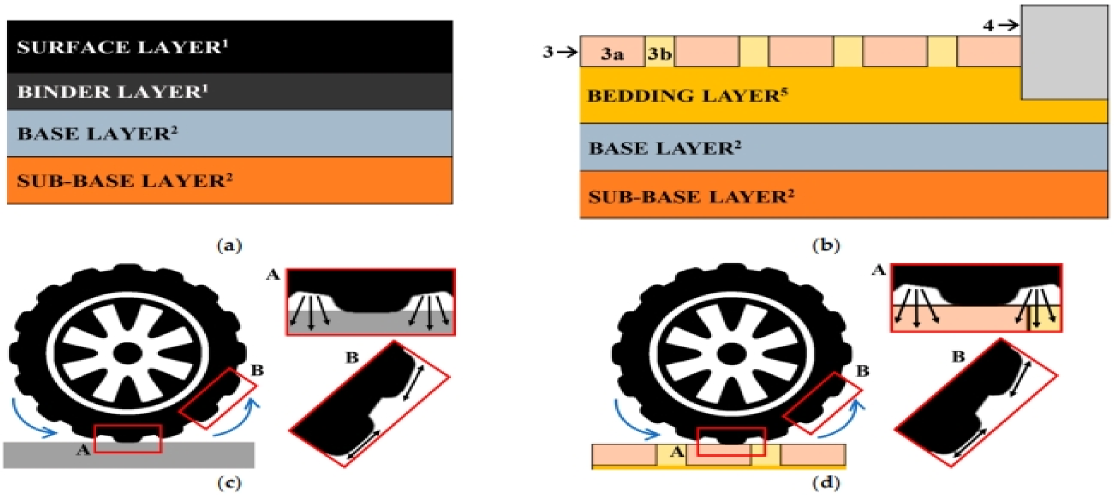
***Abstract*—This paper does an appraisal of the performance evaluation of an interlocking concrete block pavement incorporating waste materials such as coconut fibers and construction and demolition waste and examines their suitability against asphalt pavement for light traffic urban road use. There is an emphasis on mechanical behavior (mixture proportions and their constituents) pavement structure and thermal sustainability (heat island phenomenon) control asphalt paver blocks of contaminant loading to infiltrates in relation to infiltrate permeability and Life Cycle Assessment. After a comprehensive pavement performance analysis, concrete block pavement was the most promising option because it was about thirty-three to forty-four percent low in maintenance cost, cooler by a temperature of between 2.2 and 15 degrees Celsius and more porous by 0.4 cm/s to 0.6 cm/s than asphalt pavement thus lowering expenditure enhancing drainage and thermal comfort to people. On the other hand, asphalt pavement was about 35% cheaper during the construction stage (primarily resulting from energy expenditures), and it had a 32% lower nitrogen oxide concentration. The paper revealed both drawbacks and advantages of the two types of pavements. The further stage of the research should be concentrated on integrating such factors into wider area decision making process for making selections between the options.**

***Index Terms*—interlocking concrete block pavement; asphalt pavement; by-products; performance analysis; Life Cycle Assessment, porous, coconut fibres, sub-base layer, workability, stiffness, binding layer, bedding layer, asphalt, concrete, packing dense spacing, thermoplastic, coolant layer, permeability.**

I. INTRODUCTION

The interlocking concrete block pavement (ICBP) has concrete paving blocks (CPBs) in many shapes and combinations [1,2]. Figure 1a, b shows ICBP and regular asphalt pavement (AP) layers: sub-base, base, and surface layer (asphalt concrete for AP or paving blocks + joint materials for ICBP). Also, the AP surface layer has uniform mixes with high stiffness (Figure 1c) [3]. In contrast, ICBP has CPBs with higher stiffness and joint materials with low stiffness (Figure 1d) [4]



(a) (b) (c) (d)

Figure 1: Interlocking Concrete Block Pavement (ICBP) and Asphalt Pavement (AP) in terms of layers and contact with the traffic load from taken from [3]). 1 Asphalt concrete (AC); 2 Aggregates with continuous gradation; 3 Top layer; 3a Concrete paving blocks (CPBs); 3b Material for joints; 4 Side restraint at the shoulder's edge or at the sidewalk controlled and sand material. (a) AP layers, (b) ICBP layers, (c) AP surface layer. (d) ICBP surface layer.

II. PROCEDURE/METHODOLOGY

The Dutch created a revolution in paving blocks all over the world with CPBs during the 1950s [6]. Throughout the years, in Rio de Janeiro, Brazil, the urbanization programs, such as "Rio Cidade" and "Favela Bairro", produced 1,000,000 m2 of CPBs [7]. In Fortaleza, Brazil, the CPBs were used to requalify the "Beira Mar" and "Desembargador Moreira" avenues; the amount of CPBs used was about 66,705 m2 and 6500 m2, respectively [8]. In the USA, it is reported that this application grows by about 100% every five years, similar growth rates have been recorded in Belgium, Germany, Australia, New Zealand, and South Africa [9].

1. Mechanical Behavior for the ICBP

On the mechanical behavior of ICBP, the joint material "networks" reduce the total stiffness of the surface layer and are able to distribute horizontally along with vertical load transmission due to shear stresses. Apart from this, the traffic load during post-construction compacts the bedding layer, and hence, causes some deformation on the surface [4]. In addition, in respect to mechanical and physical requirements, CPBs ought to have compressive strength fc and water absorption as set by different standards among others: This paper aims to review the performance analysis of ICBP with by-products, like coconut fibers and recycled materials from CDW, and to compare the skills with AP, especially for light-traffic urban roads applications. To achieve this aim, the authors analyzed the studies published on the Scopus search engine (www.scopus.com, accessed on 6 May 2023) related to ICBP. This tool was used by searching in the article's title, abstract, and keywords with the following query string: ("concrete" AND "paving" AND "blocks") OR ("interlocking" AND "pavements"). The search gave 1125 documents from 1972 to 2022, categorized into six groups. The most direct inferences were the following.

Finally, this review paper focuses on pavements' mechanical behavior and design. Besides, it gives the sustainability seen as contributing to the HIE, the management of contaminant concentrations within infiltration related to permeability, and LCA. Figure 4 presents the general framework of this review paper.

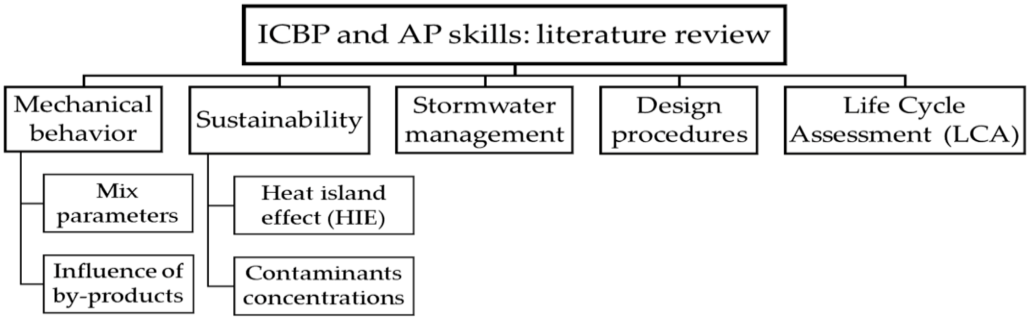


Figure 2. Review framework.

2. Mechanical and Durability Properties of Asphalt Concrete and Concrete Paving Block

2.1. Mix parameters and their influence on pavement performance.

The results from current studies show that the structural and functional performances of AP and ICBP can be influenced by many factors. The following aspects can be mentioned: surface type and geometrical configurations, for example, cross-sectional design, aggregate characteristics, and environmental conditions, for example, rainfall and HIE [3,40–43]. Then, this section emphasized some parameters, e.g., aggregate packing and mixing temperature, on the AC and CPB properties for AP and ICBP, respectively.

With regard to mixing temperature, Navaro et al. [48] discussed experiments with RAP and mixes produced at various temperatures. The microscopic observations revealed that agglomeration of materials appeared on the surface of the biggest aggregate in case of the blend of RAP components. Such agglomeration is known as a cluster. This cluster consists of small particles of RAP's aggregate and binder, resulting in mixes having worse mechanical and durability properties. In addition, Bressi et al. [49] found that mixing temperature had a direct relationship with clustering, RAP quantity in the mixtures, and particle size. It is also worth noting the distinction between warm and hot AC. The constituents of warm AC are usually mixed at temperatures between 100 ◦C and 140 ◦C, while hot AC is made at between 140 ◦C and 160 ◦C [50]. This temperature reduction is possible through additives such as organic waxes and chemical surfactants [51]. Finally, the effects on the mechanical performances of warm and hot AC through incorporation of RCAs are presented in Table, which exhibit satisfactory results for marshal stability [52]. In contrast, using RCAs in AC led to a weak resistance to water result.

The packing density was found to be the critical factor that influences the properties of the CPB regardless of its aggregate type, allowing a better understanding of the characteristics of the components of the concrete. Chu et al. [42]. The aggregates were graded into six classes, A, B, C, D, E, and F with size ranges: A is 5–10 mm, B is 2.36–5 mm, C is 1.18–2.36 mm, D is 0.6–1.18 mm, E is 0.3–0.6 mm, and F is 0–0.3 mm. Materials entered the mix sequentially, starting with the coarsest and finishing with the finest. A detailed procedure is presented in Figure 5.

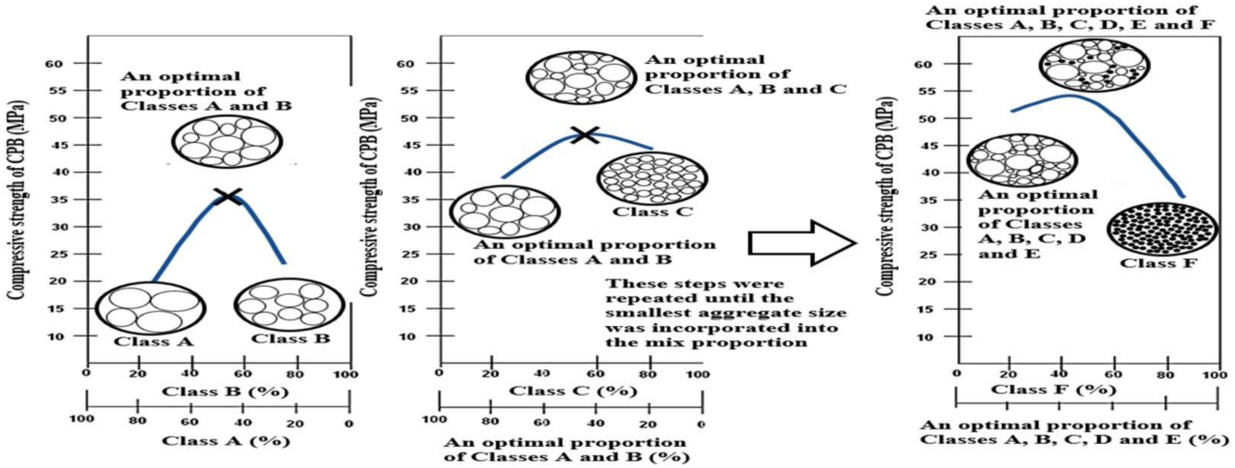


Figure 3. Steps for advanced packing optimization (adapted from [42])

Such decrease may be attributed to increased volatility loss of the components of the AC with elevated mixing temperature. Moreover, heterogeneities in the spatial properties of viscosity can explain the anisotropic nature of the aggregate distributions. Finally, increased temperatures can lead to better homogeneity and isotropy of spatial aggregate distribution, which explains improved mechanical and durability characteristics of the AC.

2.2. Impact of Fibers and Materials from Civil Construction Industry on Pavements' Performances

Rising development in the urban sectors has had increased consumption of natural resources coupled with massive production of quantities of CDW. With approximate statistics amounting to 1.3 billion tonnes of solid by-product per year from world cities, this is expected to reach 2.2 billion tonnes by 2025 [55]. When CDW is reused as aggregates in new construction, it may be called RCAs from the demolition of concrete structures, or RAP from the pavement repair process. Table 3 displays the compositions and percentages of waste recycling for some countries.

Studies on the knowledge and utilization of CDW are still under way, particularly in AC, CPB, and the base course of the pavement [15,16,60–63]. In addition, waste plastics such as PET and LDPE can be used as substitutes for aggregates. Due to workability and air permeability, a relevant suggestion would be to include this by-product in permeable pavements.

Pervious AP or ICBP has a surface layer that allows easy air and water passage from the top of the pavement and through an interconnected network of void structures to the layers underneath.

3. Sustainability Considerations of Asphalt and Interlocking Concrete Block Pavements

3.1. The Heat Island Effect from Pavement Surfaces

A built environmental issue associated with pavements is the HIE. Heat islands are typically regarded as both surface and atmospheric impacts, which influence air quality and human thermal comfort [73]. In addition, in many regions in the US, more than 90% of pavements are black AC or dark seal-coated pavements [38]. Then, there are high AP surface temperatures over summer, during the hot periods. An analysis of the HIE in Osaka, Japan, showed that the albedo of the CPB was approximately five times higher than AC [74].

Finally, the HIE is not always negative because of the climatic conditions of the countries. e.g., the temperature ranges of each season. Then, while HIE produces negative impacts during hot climates, it can also benefit people near the pavement surfaces, reducing building heating energy with less human thermal discomfort in the cold regions. Thus, the insulation from the aggregate in the concrete composition delays the formation of a frost layer in a pervious pavement [81]. Additionally, the use of RCAs and RAPs in geothermal pavement construction with a heat exchanger system to obtain the renewable thermal energy of water for domestic and industrial usage is another [82].

3.2. Contaminant Concentrations from Pavement Infiltration

Increased traffic density causes a higher concentration of contaminants on the pavement's surface. In terms of the pollutants, there are suspended solids (TSS) and heavy metals such as cadmium (Cd), iron (Fe), manganese (Mn), copper (Cu), lead (Pb), and zinc (Zn). In addition, the pollutants are chemical oxygen demand (COD), and nutrients, which are total nitrogen (TN), total phosphorus (TP), and ammonia (NH_3), causing water pollution [85]. Because concrete for CPBs has pores in its structure, pollutants can be retained inside the pervious ICBP system effectively due to filtration, sedimentation, and microbial removal [39]. In addition, the pervious AP is composed of porous AC on the surface layer, and this pavement contributes to the retention of contaminants such as ICBP.

The studies conducted by Zhang et al. [96] have demonstrated that the average difference of metal removal between ICBP and AP is not more than 5%. However, the section permapave of ICBP performed the best on heavy metal removal due to the fact that the permapave average outflow concentrations of heavy metals were 71% and 56% that of the hydrapave and porous ACs, respectively. Moreover, the AP section had the lowest average removal for Cu (66.5%), Zn (55.5%), and Mn (18.5%) because the basalt material from the AP base layer was much coarser than the stones and gravel in the ICBP sections, hydrapave, and permapave, respectively.

4. Stormwater management in permeable pavements

Typically, urban areas roads, parking, and sidewalk land for transport applications are usually covered with conventional AP [36]. As most of the conventional APs are impermeable, the infiltration is instead sent to the storm drains, not towards the foundation [37]. A remedy to this issue is porous pavement, regarded as an affordable best management practice for stormwater which absorbs runoff in cities [98]. Thus, among the most common permeable pavements are porous AC, concrete, and CPB [38]. These constructions are typically used in car parks but they are generally not suitable for high-velocity traffic..

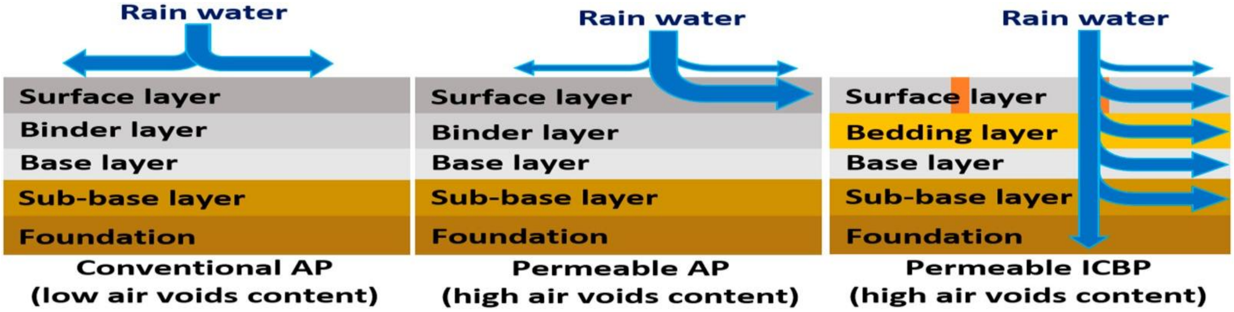


Figure 4. Mechanism of run-off infiltration in permeable pavement layers (adapted from [3,78]).

Figure 12 from the research of Huang et al. [103] has presented regression analysis with regard to the operation time of AP and ICBP depending on surface porosity. The type of regression was chosen depending on R2 values.

According to the study of Cheng et al. [83], regression analysis were carried out on the relationship between the runoff reduction rate by the ICBP pedestrian walkway and the rainfall parameters, including the total volume per specific period, intensity, and time variation. The runoff reduction rate versus the total amount of rainfall per hour had the highest correlation (R2 = 0.9109), and Figure 13 depicts this relation. The runoff reduction averaged 35% to 41% based on the simulations from the stormwater management model (SWMM). However, when the hourly rainfall exceeded 100 mm, the reduction rate decreased to about 10%. Then, low-impact development practices, which were mainly designed for 1-year to 2-year return period storms, could only control smaller storm events. For storms, a combination of green infrastructure was needed.

Figure 5. Surface porosity degradation before and after pressure washing (adapted from [103]).

(**a**) Surface porosity of AP, (**b**) Surface porosity of ICBP.

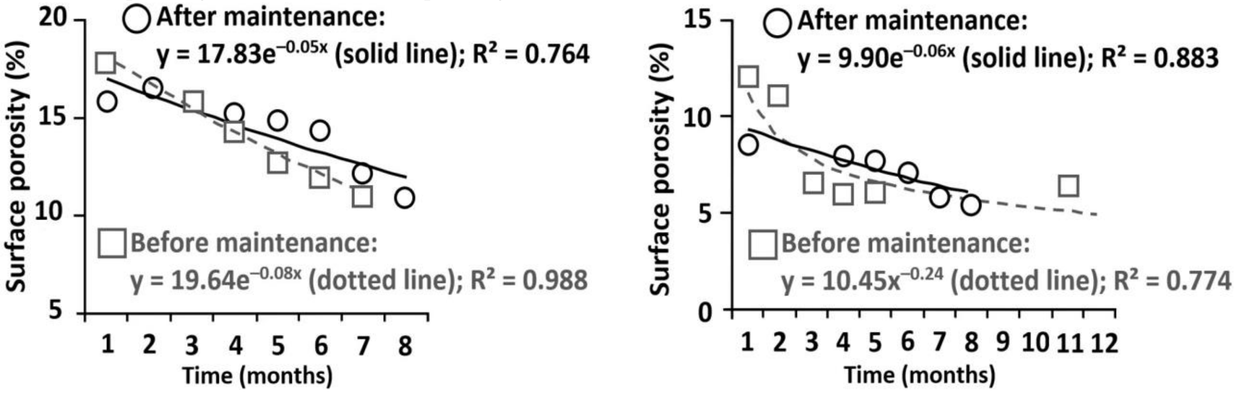
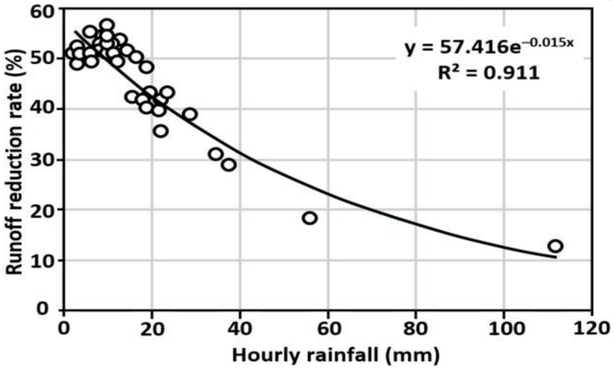


Figure 6. Relation between runoff reduction rate and hourly rainfall (adapted from [83]).



5. Structural Design of Asphalt and Interlocking Concrete Block Pavements

Pavements are designed to carry different types of traffic, such as pedestrians, bicycles, cars, and trucks. The design process must be carried out with post-work evaluation over the years. Then, evaluating key indicators for AP, such as the structural behavior, is necessary, as derived from FWD campaigns, the International Roughness Index (IRI), and transversal roughness results [104].

For low-speed traffic, such as pedestrian walkways and parking lots, a few critical issues exist with regard to the structural performances of conventional impermeable or permeable pavements [38]. In addition, the structural design of permeable pavements should be carried out to prevent surface runoff during rainfall [105]. In addition, particular focus was laid on geotextiles, materials that consist of woven or non-woven permeable fabrics which may act as filters and drainages of the pavement system [106]. Geotextiles are usually installed between the bedding layer and the sub-base, or at the lower level separating the sub-base from the foundation. Figure 14 presents those structures for AP and ICBP with light traffic, such as pedestrian walkways.

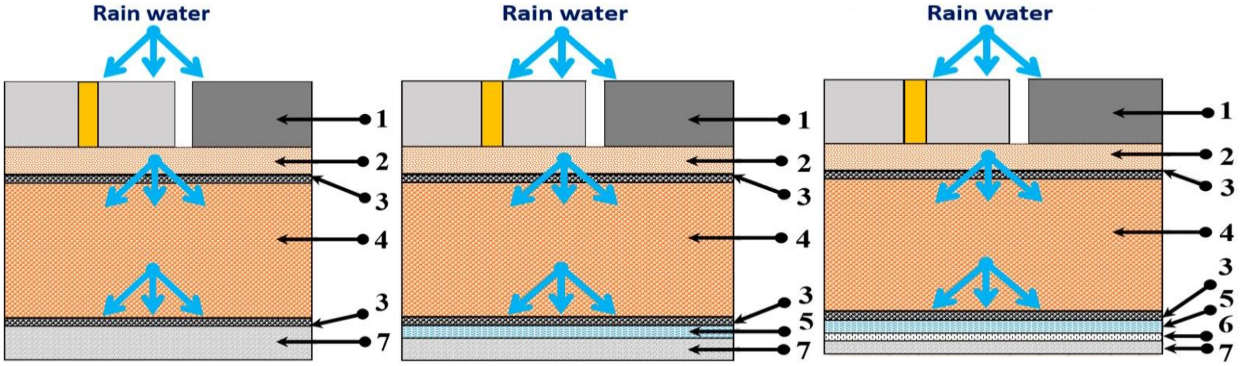


Figure 7. Structures of pavements with geotextiles (adapted from [107]). [1] Surface materials, such as CPB or AC; [2] Laying course; [3] Geotextiles (optional); [4] Coarse aggregates; [5] Drainage pipe; [6] Impermeable membrane; [7] Foundation. (a) Full infiltration pavement, (b) Partial infiltration pavement, (c) No-infiltration pavement.

6. Pavement Construction, Maintenance, and Rehabilitation Based on Life Cycle Assessment

The economic advantages and disadvantages of pavements are based on the LCA outputs. It is a challenging task to apply LCA to all pavement design problems [121]. However, LCA is a decision-making tool based on various variables. However, within so much risk in a transportation infrastructure project, sensitivity analysis is also performed on the Life Cycle Cost (LCC) model to be used as the decision support tool [122]. LCC could also be optimized for a better transportation infrastructure investment within the developing countries [123]. Costs may be reduced by an alternative in using by-products through pavement construction such as the RAP and RCAs. Warm AC with RAP and RCAs was 5% to 8% cheaper in a field application when compared to a conventional hot AC [124].

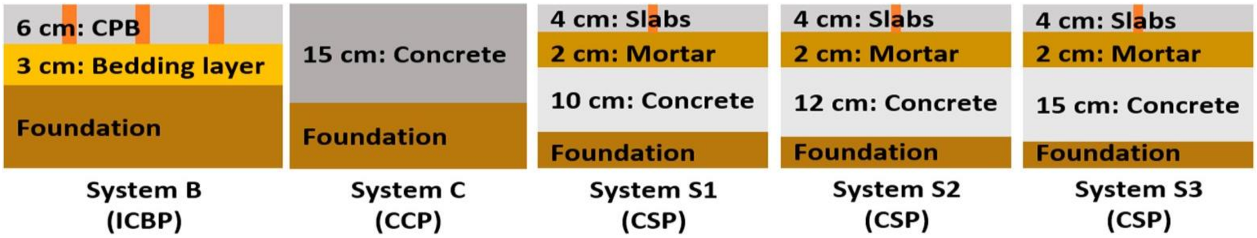


Figure 8. Pavement systems B, C, and S1–3 (adapted from [127]).

Table 1. LCA results for each pavement (adapted from [127]).

LCA Results		Systems (Type of Pavement)			
	System B (ICBP)	System C (CCP)	System S1 (CSP)	System S2 (CSP)	System S3 (CSP)
ADP (kg Sb [1] eq.)	2.65×10^{-1}	7.39×10^{-1}	7.74×10^{-1}	8.69×10^{-1}	1.01
APO (kg SO_2 [2] eq.)	8.62×10^{-2}	2.28×10^{-1}	2.43×10^{-1}	2.66×10^{-1}	3.00×10^{-1}
EP (kg PO_4^{3-} [3] eq.)	1.60×10^{-2}	4.16×10^{-2}	4.43×10^{-2}	4.85×10^{-2}	5.47×10^{-2}
GWP (kg CO_2 [4] eq.)	1.97×10	5.33×10	5.79×10	6.45×10	7.43×10
HTP (kg 1.4–DB [5] eq.)	1.32	3.33	3.63	4.04	4.65
ODP (kg CFC–11 [6] eq.)	1.40×10^{-6}	3.32×10^{-6}	3.55×10^{-6}	3.93×10^{-6}	4.49×10^{-6}
POCP (kg C_2H_4 [7] eq.)	8.78×10^{-3}	2.14×10^{-2}	2.27×10^{-2}	2.49×10^{-2}	2.81×10^{-2}

ICBP (system B) showed the lowest environmental impacts by far, with the effects being reduced by approximately 70% in all impact categories compared to the highest impact type (CSP: system S3). Then, CPB was the best choice in urban environments, but these blocks may have functional and maintenance problems, depending on the use conditions. In light of this finding, redesigning sidewalks using environmental criteria brought significant benefits.

The technical analysis showed that the scenarios considerably reduced the runoff by minimizing the waterproof cover and introducing natural filtration and storage systems. Moreover, the financial feasibilities of IT, BC, and ICBP with the net present costs of $11.6, $14.5, and $17.0 million, respectively, were concluded. Combining ICBP with IT and BC reduced the net present cost by about 48% and 32%, respectively. Further, it was revealed that the hybrid scenarios with IT + ICBP and BC + ICBP lowered the runoff significantly in comparison with conventional system AP by 78.2% and 63.5%, respectively. ICBP with IT and BC decreased environmental impacts by 84% and 79%, respectively. Finally, all the scenarios had reduced environmental impacts and were cheaper compared to traditional stormwater; thus, they had more propensity towards implementation.

III. RESULT

This review discussed the performance evaluation from ICBP to AP with by-products such as coconut fibers and recycled materials from civil construction, in relation to mechanical, sustainability, permeability, design, and LCA features. The authors have performed considerably in AP with by-products [21,51,52,62,64–66,104,124], and currently are seeking to involve ICBP with by-products [8] in practical solutions for urban light-traffic pavements. These years of working in road paving technologies have induced the need to provide more sustainable solutions, and have justified the present review. This review enables the following direct inferences:

•Mix parameters (Section 2): fc was increased by 156% for CPB with appropriate packing optimization. Gyratory compaction was enough for an adequate air void range (3–5%) for AC, according to studies found in the literature. Moreover, a higher mixing temperature resulted in a lower clustering of RAP in an AC, which contributed to a more isotropic spatial distribution of the aggregates, and then better AC mechanical and durability properties;

•Impact of by-products (Section 3): For AC with RCAs, alternative mixes gave the test results of Marshall stability to be 13–45% higher than those of the control mix based on studies in the literature. Moreover, the inclusion of fibers resulted in the enhancement of fc by 10.52% and abrasion resistance by 45% for CPB as based on studies in the literature;

•Stormwater management (Section 4): The runoff reduction by permeable pavements averaged 35% to 41% in SWMM simulations, but the rate declined as the rainfall intensity increased, according to studies published in the literature. In addition, permeable ICBP had permeability or infiltration rate results that were higher than porous AP by 0.4–0.6 cm/s but declined over the months and thus required more frequent routine maintenance;

•Structural design (Section 5): Information from software developed for each pavement, such as fatigue cracking, stress–strength ratios, and the quantity of materials for the structures, were derived from FlexPAVE and MeDiNa for AP, PICP tool, and DesignPave for ICBP. The design, using mechanistic–empirical programs, helped to improve the long-term sustainability of the pavement compared with the empirical design methods;

•CA (Section 6): ICBP was about 33–44% less expensive than AP in the maintenance stage. But AP was around 35% less expensive in the construction stage mainly because of energy consumption. Besides, in ICBP construction, cement production and CPB manufacturing occupied about 50% and 48% of the total embodied energy, respectively, based on studies available in the literature. Besides, the by-products are alternatives for saving costs in pavement construction. In a field application, RAP and RCAs-warmed AC was 5–8% less expensive (direct and environmental) compared to a traditional hot AC.

IV. FUTURE DIRECTIONS

Table 2 outlines future directions or recommendations for further research in each review section, which can be applied to pavement planning, design, and maintenance decision-making to continue.

Section 2			Section 3	Section 4	Section 5	Section 6
Mix Parameters	Influence of By-Products	HIE Effect	Contaminants Concentrations	Stormwater Management	Structural Design	LCA
Proposed granulometric zones for concrete used in porous CPB to ensure adequate packing density.	Testing RCAs and RAP together in AC to verify the increase or not of Marshall stability and indirect tensile strength.	Comparison of applying cool AP and ICBP for one year to check the albedo and temperature of each pavement over the seasons.	Explaining the higher effect of nitrification in ICBP than in AP. Then, the on-road emissions in different applications should be evaluated, e.g., highways, ports, and airports.	Software can be developed for AP or ICBP that combine the hydraulic design with the mechanical performance of the structure.	Developing progressive models regarding ICBP failures as a function of block shape, joint width, traffic loading, and pavement application.	Applying different methods for CPB production and installation, which may have effects on the environmental management and carbon footprint of ICBP.

V. CONCLUSION

This review discussed the performance evaluation from ICBP to AP with by-products such as coconut fibers and recycled materials from civil construction, in relation to mechanical, sustainability, permeability, design, and LCA features. The authors have performed considerably in AP with by-products [21,51,52,62,64–66,104,124], and currently are seeking to involve ICBP with by-products [8] in practical solutions for urban light-traffic pavements. These years of working in road paving technologies have induced the need to provide more sustainable solutions, and have justified the present review.

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