

## Article

# Influence of Crumb Rubber and Coconut Coir on Strength and Durability Characteristics of Interlocking Paving Blocks

Sajani Gamage<sup>1</sup>, Sandini Palitha<sup>1</sup> , D. P. P. Meddage<sup>1</sup>, Shayani Mendis<sup>2,\*</sup>, Hazi Md. Azamathulla<sup>3</sup>   
and Upaka Rathnayake<sup>1</sup> 

<sup>1</sup> Department of Civil Engineering, Faculty of Engineering, Sri Lanka Institute of Information Technology, Malabe 10115, Sri Lanka; sajani.g@sliit.lk (S.G.); sandini.p@sliit.lk (S.P.); pasindu.m@sliit.lk (D.P.P.M.); upaka.r@sliit.lk (U.R.)

<sup>2</sup> Department of Civil Engineering, Faculty of Engineering, General Sir John Kotelawala Defense University, Rathmalana 10390, Sri Lanka

<sup>3</sup> Department of Civil and Environmental Engineering, The Faculty of Engineering, The University of West Indies, St. Augustine 32080, Trinidad and Tobago; hazi.azamathulla@sta.uwi.edu

\* Correspondence: mendisasm@kdu.ac.lk or shaeni.12@gmail.com

**Abstract:** Interlocking Paving Blocks (IPB) are, nowadays, a widely used construction material. As a result of the surge in demand for IPBs, alternative materials have been investigated to be used for IPBs. This study investigated the strength and durability characteristics (compressive strength, split tensile strength, density, water absorption, skid resistance, and abrasion resistance) of IPBs in the presence of (waste materials) crumb rubber (CR) and coconut coir fibers (CCF). Both compressive and split tensile strength increased in the presence of CCF to a certain extent. CR-based IPBs showcased an increase in skid resistance that satisfied both SLS 1425 and BS EN 1338 specifications. Abrasion depths of CR-based and CCF-based samples show a comparable increase in values when the respective fraction (CR or CCF) increases. Therefore, this research fills the knowledge gap, highlighting the importance of incorporating waste materials (CR and CCF) for the IPB industry rather than open dumping.

**Keywords:** coconut coir fiber; crumb rubber; durability characteristics; interlocking paving block; strength characteristics



**Citation:** Gamage, S.; Palitha, S.; Meddage, D.P.P.; Mendis, S.; Azamathulla, H.M.; Rathnayake, U. Influence of Crumb Rubber and Coconut Coir on Strength and Durability Characteristics of Interlocking Paving Blocks. *Buildings* **2022**, *12*, 1001. <https://doi.org/10.3390/buildings12071001>

Academic Editor: Pengfei Liu

Received: 24 June 2022

Accepted: 10 July 2022

Published: 13 July 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Interlocking paving blocks (IPBs) are widely used for pathways as a result of their strength, durability, and architectural appearance [1,2]. IPB is a small, non-reinforced, pre-cast block composed of cement, sand, water, and coarse aggregate [3,4]. They are laid on thin compacted bedding material paved over a profiled sub-base and suitable for areas of vehicles traveling with a speed less than 60 km/h [5]. Applications of paving blocks can be divided into light-duty (pavements, and footpaths), medium-duty (housing streets, and car parks), and heavy-duty (ports, and factory yards) categories [6].

IPBs' popularity has increased due to various reasons. IPBs are identified as more reliable compared to concrete, due to their interlocking nature and formation (Interlocking Concrete Pavement Institute, 2012). They also have high impact resistance as well as the ability to withstand freeze-thaw, high temperatures, moisture, and concentrated loads [7]. Regular maintenance is considered easier when compared to bitumen or concrete roads, and defective paving units can be replaced, recycled, and reused easily [7,8]. Subsequently, producing IPBs on a large scale has become a necessity with the increasing demand [9].

As a result, several studies have used various materials as substitutes and additions to increase desired characteristics such as the compressive strength, abrasion and skid resistance, impact energy, and durability of IPBs [9]. Estolano et al. [10] investigated the production of concrete paving blocks by adding metakaolin. Their results displayed an increase in the compressive strength and a decrease in abrasive resistance in the presence

of metakaolin. The block with 10% of metakaolin was identified as the most suitable for construction purposes. Sadek et al. [11] used cement kiln dust (CKD) to produce paving blocks. Partially substituting CKD instead of cement reduced the block's quality. CKD additions of 20% and 40% were recommended for use in areas with heavy traffic, and 60% CKD for areas such as city streets with medium traffic density. The use of 40% and 60% CKD was not advised in areas with a high concentration of hydrochloric acid, whereas 20% CKD was good to be used after 11 months of exposure to 1% hydrochloric acid [11]. For the production of IPBs, crushed glass (CG) of size 5.0–25.0 mm was used by Wang et al. [12] by replacing coarse aggregate at 10%, 20%, 30%, and 40%. Compared to the control block, the compressive strength has increased, and the water absorption decreased due to the increase in CG content. The highest splitting tensile strength was obtained for the 40% CG mix. Similarly, the highest abrasive resistance was obtained for the 30% CG [12]. Bhandari et al. [13] substituted Ordinary Portland Cement (OPC) with Geopolymer. The Geopolymer concrete (GPC) IPB samples showed satisfactory results, except for the poor workability. Geopolymer requires less energy for production and generates less carbon dioxide. Similarly, Santos et al. [14] produced concrete IPBs using spent foundry sand (SFS) and exhausted dust (ED). Overexploiting natural resources can be reduced by using waste foundry sand. Santos confirmed the blocks use in pedestrian circulation areas owing to the acceptable results obtained for the physical and mechanical properties. Olofinnade et al. [15] reported that using crushed waste furnace steel slag for IPB units will conserve the non-renewable resource consumption. These studies were conducted by utilizing inexpensive and abundantly available local waste materials, reducing the environmental footprint [9,16].

The waste tire is a global and local waste material that pollutes the environment (refer to Figure 1a). Grammelis et al. [17] stated that around 3 billion waste tires are discarded annually worldwide. In the Sri Lankan context, it is estimated that 2.1 million tires are produced and imported yearly [18], eventually ending up as waste in landfill sites. Several problems arise due to waste tire collection. Waste tire is not biodegradable; it remains for prolonged periods in the environment allowing water accumulation, which contributes to the breeding of insects. In addition, the buildup of tires leads to fire hazards producing harmful gases and oils [18,19]. It is required to implement possible alternative approaches to reduce waste tires [20].



(a)



(b)

**Figure 1.** Open dumping of: (a) Waste tire; (b) Coconut coir fibers; (source: World Wide Web).

Several studies have utilized waste tires for IPB production due to their environmentally harmful nature [21–25]. It has been used in the form of shredded, crumb, and ground rubber. Shredded rubber particle sizes vary from 13 mm to 76 mm and can be

used as gravel replacement; crumb rubber varies from 0.42 mm to 4.75 mm and usually replaces sand, and ground rubber from 0.075 mm to 0.475 mm and can be used as a cement replacement [26]. The use of CR in concrete has improved the elastic behavior, ductility, and energy-absorbing ability compared to plain concrete [27]. Murugan et al. [23] and Silva et al. [25] investigated CR-based concrete IPBs by substituting sand. Results showed an overall decrease in the compressive and flexural strength with the increase in rubber content. Murugan et al. [23] showed an increment in the modulus of elasticity and impact resistance with the increase in rubber. The failure mode of the paving block also changed from brittle to ductile, allowing it to absorb more vibrations. Silva et al. [25] showed that the density and porosity did not have any significant changes and that the water absorption was within the standard requirement. The abrasion resistance improved, and the impact resistance displayed an overall decrease after reaching a maximum impact resistance for the mix with 20% of sand replacement. All mixes achieved a reasonable consistency in terms of workability. Murugan and Natarajan [24] partially replaced sand with rubber by volume and casted the blocks following a wet casting method where a high water: cement ratio was used, and the blocks were kept under continuous vibration. They observed an increase in the compressive strength, flexural strength, and split tensile strength till the 10% replacement of sand but decreased with the further increase in CR. The density, however, decreased gradually with the addition of CR. Nor et al. [28] concluded that the sound absorption and toughness of the block improved with the increase in rubber particles. A considerable capability in absorbing dynamic loading and resisting crack propagation was also observed. Ling and Nor [22] reported that when rubber particles of a wider gradation were used, the compressive strength increased. Reusing waste tires will be a solution to the environmental problems caused due to open dumping and will serve as an alternative to the exploitation of natural resources such as sand [29].

Amongst agricultural waste, coconut coir fibers were focused on for the present study (refer to Figure 1b). It has been found that coconut coir fibers (CCF) act as a reinforcing material in concrete [30]. However, limited related work is found on the use of coconut coir in IPBs. Ali et al. [31] proved that the CCFs' ability to act as a reinforcing material will give the IPB extended durability compared to the conventional block by achieving high tensile strength values. Kochova et al. [32] stated that due to the presence of low cellulose and high lignin contents, CCFs are strong and flexible, and the fibers have low density and high thermal conductivity of 0.126 W/M·K. Syed et al. [30] recommended incorporating CCF to produce blocks at a lower cost compared to other substitutes. Navya and Roa [33] cast blocks by changing the additions in the top layer and the bottom layer and subsequently tested for compressive strength, flexural strength, and water absorption. The study showcased that utilizing waste materials has resulted in cost reduction, and an increase in both strength and durability [34].

A lack of experimental studies on both the strength and durability characteristics of IPBs with CR was noted. Furthermore, very few studies focused on the strength and durability characteristics of CCF-based IPBs. Therefore, it is imperative to fulfill the knowledge gap in this research area. In this workflow, IPBs were manufactured by using CR and CCF, and were tested for abrasion and skid resistance, water absorption, compressive strength, and split tensile strength. The objective of this study is to investigate the compressive strength, splitting tensile strength, water absorption, skid resistance, abrasion resistance, and density of CR and CCF-based IPBs. The authors believe that this study is important as it emphasizes the possibility of combining waste materials: disposed tires, and coconut coir fibers, into the production of IPBs.

## 2. Materials and Methods

### 2.1. Materials

Ordinary Portland Cement conforming to SLS 107:2008 [35], river sand passing through a 4.75 mm sieve (refer to Figure 2 for the passing percentage vs particle size) with a specific gravity of 2.65 as fine aggregate (refer to Figure 3a), and crushed gravel

(10 mm & 12 mm) with a specific gravity 2.80 as coarse aggregate (refer to Figure 3b) were used in this study. The grading curve displayed the particle distribution of sand, rubber particles of sizes 2 mm and 0.595 mm (shown in Figure 3c), and a CR mixture (both sizes mixed at 50% proportions) to obtain a distribution similar to that of sand. CCFs were obtained from fresh husk after five days from post removal (6 mm in length, and 0.01 mm in diameter as shown in Figure 3d).

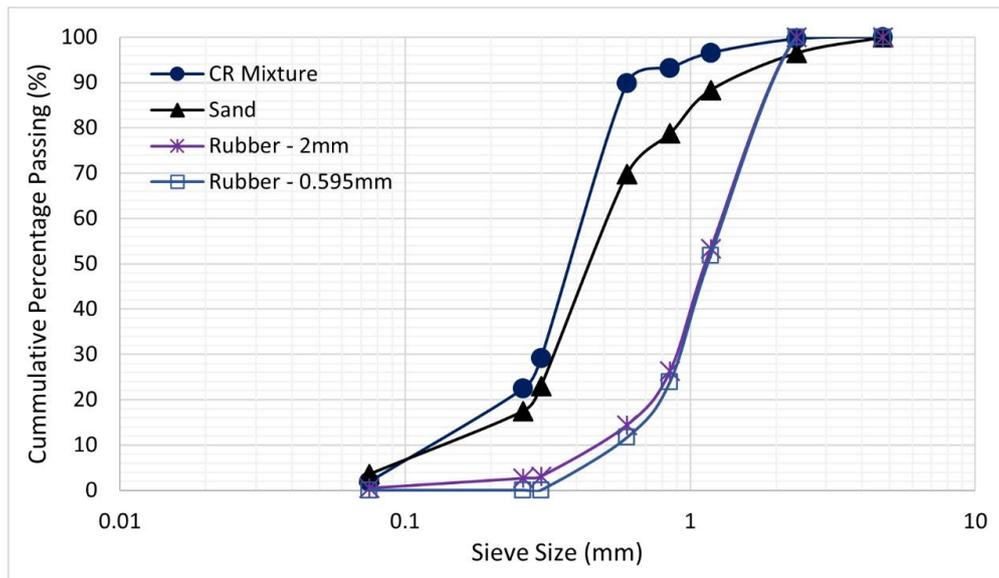


Figure 2. Particle Size Distribution Curve for Sand, Rubber, and Rubber Mix.



(a)



(b)

Figure 3. Cont.



**Figure 3.** Materials used (a) River sand; (b) 10/12 mm sized chips; (c) CR; (d) CCF.

## 2.2. Sample Preparation

The 1 (cement): 2 (sand): 3 (crushed aggregate) ratio was maintained by volume and the water to cement ratio ( $w/c$ ) of 0.5 was used in preparation of the IPBs [23]. First, cement and sand were mixed, and CR and CCF were added subsequently for respective batches. CR substituted sand at percentages of 0%, 5%, 10%, 20% and 30% [21,23] by weight, and CCF was added at percentages of 0.2%, 0.3%, and 0.4% by weight of concrete (weight of concrete was pre-determined by the control sample as 1940 kg for  $1\text{ m}^3$ ). A total of 30 blocks were cast for the CR and CCF-based IPBs, with a minimum of 3 blocks being tested per test. Table 1 displays the mix proportions for each batch (Batch with CR of 0%, 5%, 10% and 20% were denoted by PBR0, PBR5, PBR10, PBR20 and PBR30, respectively, and batch with CCF of 0.2%, 0.3%, and 0.4% by PBC0.2, PBC0.3, and PBC0.4, respectively). Coarse aggregate was then added with water, maintaining a  $w/c$  of around 0.5 (exact water-cement ratios are given in Table 1). Molds (Standard size of  $200 \times 100 \times 60\text{ mm}^3$ : SLS 1425 PART 1:2011) were prepared by applying mold oil on their inner surfaces. The mixing process ensured proper compaction, where manual compaction was used for batch 1 and mechanical vibration was used for batch 2. Next, molds were kept aside in a covered and dry location for 24 h. Finally, the samples were demolded and kept in water for curing. Table 2 provides IPB specifications provided in codes of practice.

**Table 1.** Material Requirement for  $1\text{ m}^3$  mix of IPB of CR and CCF Batches.

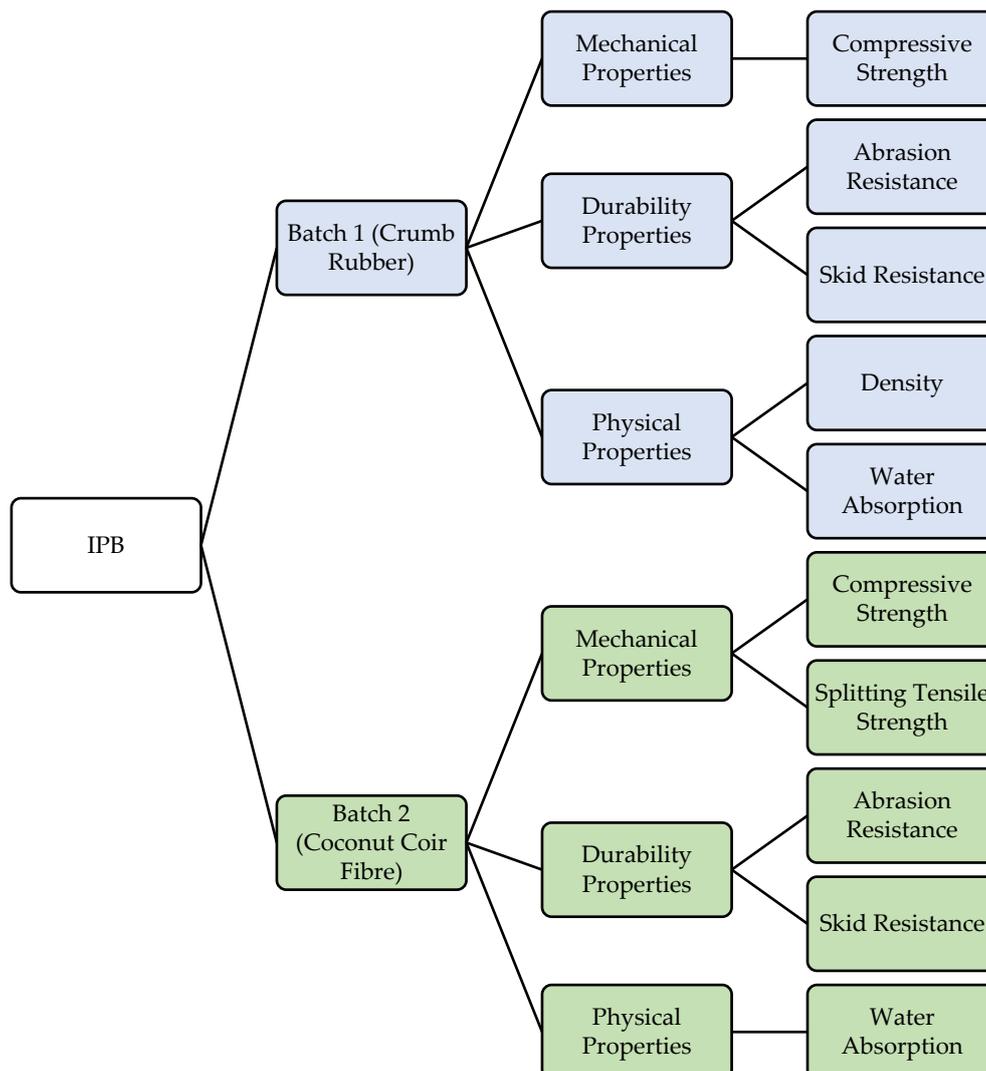
Material	CR (Batch 01)					CCF (Batch 02)			
	PBR0	PBR5	PBR10	PBR20	PBR30	PBC0	PBC0.2	PBC0.3	PBC0.4
Cement (kg)	525.00	525.00	525.00	525.00	525.00	525.00	525.00	525.00	525.00
Sand (kg)	883.30	839.10	795.00	706.60	618.30	883.30	883.30	883.30	883.30
Coarse Aggregate (kg)	1400.00	1400.00	1400.00	1400.00	1400.00	1400.00	1400.00	1400.00	1400.00
Crumb Rubber (kg)	-	44.10	88.30	176.60	265.00	-	-	-	-
Coconut Coir (kg)	-	-	-	-	-	-	3.88	5.82	7.76
W/C ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.44	0.48	0.55

**Table 2.** Standards specified in code of practice for IPBs.

	<i>SLS 1425</i> [36]	<i>BS EN 1338</i> [37]	<i>IS 15658</i>	<i>ASTM C936</i> [38]
Compressive Strength (N/mm <sup>2</sup> )	≥50 MPa (Class 1) ≥40 MPa (Class 2) ≥30 MPa (Class 3) ≥15 MPa (Class 4)	-	30–55 MPa	≥55.2 MPa
Abrasion Resistance	≤20 mm	≤20 mm	-	≤15 cm <sup>3</sup> /50 cm <sup>2</sup> (volume loss)
Spitting Tensile strength (N/mm <sup>2</sup> )	-	≥3.6	-	-
Skid Resistance (USRV)	≥55 USRV	40–75 USRV (Low skid potential) ≥75 USRV (Extremely low potential to slip)	-	-
Water Absorption (%)	≤6%	≤6%	≤6%	≤5%

### 2.3. Interlocking (Paver) Block Testing

In the present study, the experiments carried out on IPBs are illustrated in Figure 4.

**Figure 4.** Experimental Procedures for the IPBs.

### 2.3.1. Compressive Strength

The compressive strength of the IPBs for both batches was tested at 7, 28, and 56-days according to SLS 1425 [39] guidelines. The block was subjected to compressive loading until failure occurred.

### 2.3.2. Abrasion Resistance

The abrasion resistance of the IPBs was tested by a standard wide-wheel abrasion test according to the BS EN 1338: 2003 standard. Blocks were tested 28 days after casting. The area on the block to be abraded was marked and then placed on the tester. Three liters of Silica sand were then abraded against the surface of the block at the specified rate in the standard. The average abrasion value was noted by measuring the highest groove made using a digital vernier caliper.

### 2.3.3. Splitting Tensile Strength

In order to evaluate the splitting tensile strength of the interlocking paving blocks, a standard splitting tensile test was conducted as per SLS 1425 [39]. The interlocking block was placed in between the circular halves of the semi-circular metal of the universal testing machine, and the load was applied. Tests were conducted after 28 days of casting. Tests were repeated three times per each type of block.

### 2.3.4. Skid Resistance

Skid resistance of the interlocking paving blocks was determined according to SLS 1425:2011 standards [40]. This method uses the Portable Skid Resistance Tester to measure the Unpolished Slip Resistance Value (USRV). The block was placed ensuring that the two points where the slider touches the block were 5 inches apart. The average value of readings was taken along both edges of the top surface of a block.

### 2.3.5. Water Absorption

The water absorption of the IPBs was estimated by initially immersing the blocks in the water allowing full saturation, and ensuring the water was at a temperature of 20 °C as per BS EN 1338 [37]. The blocks were then taken out of the water, wiped with a cloth and the mass was recorded (M1). Then the blocks were dried in a ventilated oven at 107 °C. Later, the dry mass of the sample was recorded (M2). Accordingly, the water absorption percentage was calculated as given in Equation (1).

$$\text{Water absorption percentage} = \frac{M1 - M2}{M2} \times 100, \quad (1)$$

where M1 refers to the saturated mass of the interlocking block, and M2 refers to the dry mass of the block. The water absorption test was conducted 28 days after casting.

### 2.3.6. Cost of an Interlocking Paving Block

The cost of manufacturing a rubber-based, interlocking paving block and coconut coir-based, interlocking paving block were also calculated by considering the current market prices of cement, sand, crushed aggregate, and rubber. This was undertaken to compare the cost of manufacturing a block with the rubber and coconut coir vs. the control sample.

## 3. Results and Discussion

### 3.1. Compressive Strength

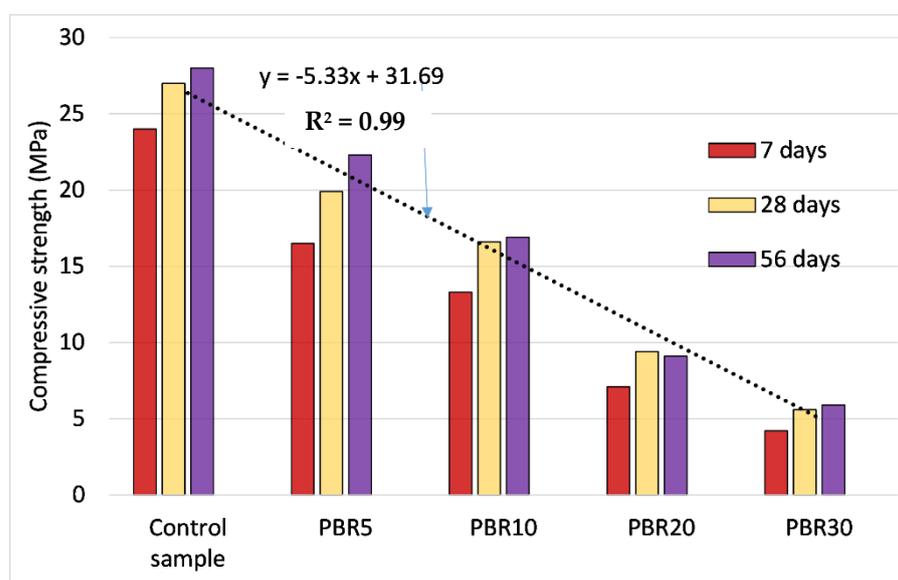
Compressive strength results were obtained in different ranges as shown in Table 3. Control samples from batch 1 achieved compressive strength values within (20–30) MPa whereas control samples from batch 2 achieved between (30–45) MPa. The main reason is the compaction method. Batch 1 was compacted manually, and batch 2 samples were compacted using mechanical vibration. Therefore, batch 2 samples are more likely to have a less void ratio compared to batch 1. For less void ratio, compressive strength becomes

higher, which is reflected in overall samples in batch 2. These arguments were witnessed by using the water absorption values. For example, with fewer voids, batch 2 samples have absorbed less water content in contrast to batch 1 samples.

**Table 3.** Summary of the test results.

Batch ID	% Replaced/Added	Compressive Strength (MPa)			Abrasion Resistance (mm)	Splitting Tensile (MPa)	Skid Resistance (USRV)	Water Absorption (%)	Density (kg/m <sup>3</sup> )
		7 Days	28 Days	56 Days					
Control sample	0	24.0	27.0	28.0	19.0	-	9.0	9.7	2350.0
PBR5	5	16.5	19.9	22.3	17.7	-	85.0	10.9	2293.0
PBR10	10	13.3	16.6	16.9	17.7	-	85.0	11.8	2258.0
PBR20	20	7.1	9.4	9.1	18.7	-	85.0	13.9	2143.0
PBR30	30	4.2	5.6	5.9	19.3	-	75.0	16.2	2027.0
Control sample	0	33.0	44.0	43.0	17.8	2.1	65.0	3.0	-
PBC0.2	0.2	38.3	45.3	48.9	18.2	2.5	60.0	4.5	-
PBC0.3	0.3	28.5	42.4	46.2	18.4	2.6	70.0	5.5	-
PBC0.4	0.4	26.1	34.0	35.7	18.7	2.4	55.0	6.1	-

Figure 5 shows the variation in compressive strength with age for batch 1. The overall variation shows a decrease in compressive strength with the increase in CR content. For example, compressive strength of 22.31 MPa was obtained for the PBR5 mix during the 56-day testing. However, PBR10 reached 16.58 MPa at the 28-days test, which satisfies the Class 4 requirement for IPBs as per the SLS 1425. PBR20 and PBR30 mixes both obtained low strengths below the requirement owing to the high presence of CR. 56 days compressive strength was low when compared to 28 days strength in PB20, since one of the tested blocks slightly deviated from the pattern which resulted in a moderately low average value. The average compressive strength gradually decreased with the increase in CR. The CR weakens the compressive capacity in the IPB. The rubber particles in the IPB have poor adhesion with the cement paste and aggregates in the block resulting in a weak rubber to cement matrix thus, once a large load is applied to the IPB, it tends to fail [21,41]. Silva et al. [25] mentions an optimum rubber percent (10%) used, which results in an acceptable compressive strength due to the CR particles being evenly distributed in the block, which, in turn, evenly distributes the applied load such that the compressive strength remains satisfactory. It was implied that the further increase in the rubber particles will not result in an even distribution of it in the block [25].



**Figure 5.** Compressive strength of CR IPB at 7, 28 & 56 days (Trendline for 28 days).

However, paver blocks with CCF behaved differently from the samples with CR. For example, a CCF content of 0.2% increased the compressive strength with respect to the control sample. As shown in Figure 6, the increase was 16% for 7 days sample, 3% for 28 days sample, and 14% for 56 days sample. Further increase in CCF results in a decrease in compressive strength. It was believed that fibers fill up the pores in the mix, therefore, a better bond between cement and fibers could be anticipated. The same observation has been made by Syed et al. [30]. Moreover, coconut coir has high lignin content and low cellulose content, which makes it strong and durable [32]. In contrast, Kochova et al. [32] reported that a constant increase in fiber fraction lowers the compressive strength. Regardless of the CCF fraction, the increase in w/c ratio has some influence on the compressive strength of PBC 0.3 and PBC 0.4 [42].

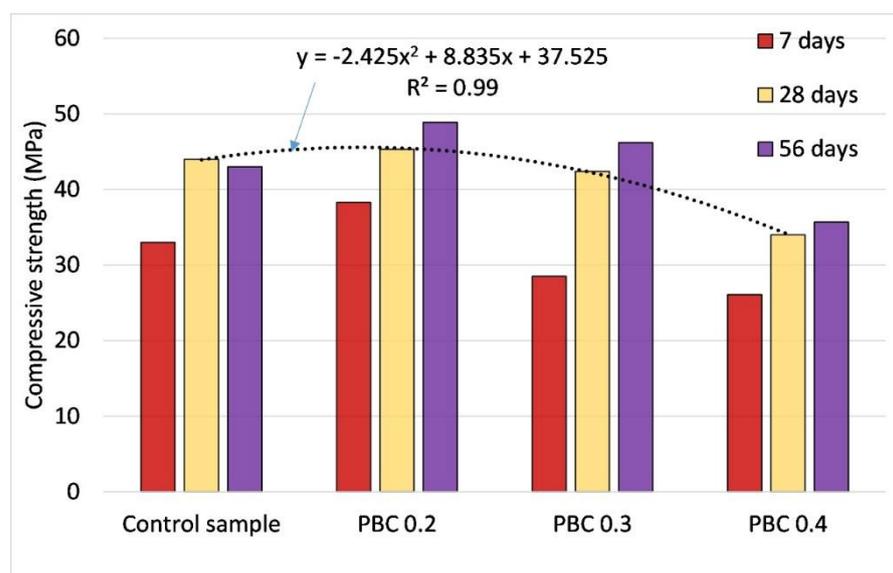


Figure 6. Compressive strength of CCF IPB at 7, 28 & 56 days (Trendline for 28 days).

SLS 1425 defines four classes based on compressive strength, whereas no such specification is provided in BS EN 1338. Based on 28 days of strength, paving blocks with CR content of 5% and 10% satisfy class 4 requirements, and blocks with CCF of 0.2% and 0.3% satisfy class 2 requirements, according to SLS 1425. IS 15658 specifies compressive strength values to be within 30–55 MPa. ASTM recommends a relatively higher value (55.2 MPa) for the required compressive strength.

The failed samples (after the 28-day compressive strength test) of the CR and CCF-based mixes are shown in Figure 7a,b, respectively. Cracks have occurred around and on the edges of the blocks (Figure 7). A similar pattern was observed for the blocks tested at 7 and 56-days. This pattern is caused by the tensile stresses that are experienced at the edges and compression stresses experienced at the center of the blocks due to the IPBs Poisson Ratio. A conical pattern can be observed when viewed from the side of the IPB, which is caused by the deformation of the block due to the friction between the apparatus and the top surface of the block [43].

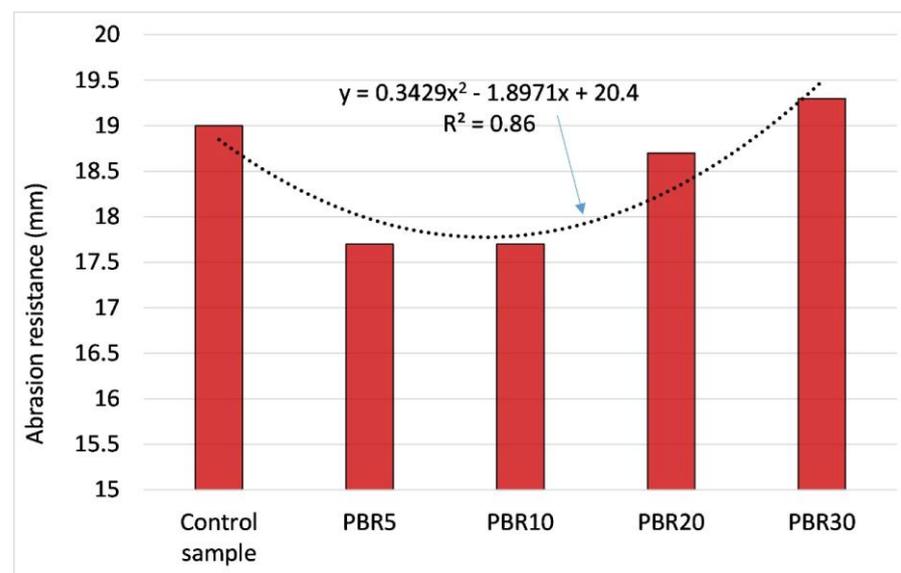
### 3.2. Abrasion Resistance

An abrasion depth of 19 mm was achieved for the control sample of the CR batch. When the CR percentage was increased up to 5%, a drop in the abrasion value was observed (17.7 mm). The same value was obtained for the sample with 10% CR. However, abrasion depth had increased for mixes of PBR20 and PBR30 to values of 18.70 mm and 19.30 mm, respectively, which is a result of the increase in air voids of the IPBs due to the increase in CR content [44].



**Figure 7.** Failure Patterns of the IPB from Batch 1 and 2: (a) CR-based block; (b) CCF-based block.

This variation shows an overall increase in abrasion according to the CR percentage which is described by the trendline drawn in Figure 8. A similar trend of decreasing resistance was observed previously, too [45]. As stated by Singh [44], the porosity and contact area of concrete are two factors affecting the abrasion resistance of concrete. The presence of rubber in IPBs increases the formation of air voids, reducing the contact area of concrete. Thus, the top surface of the IPB wears out due to increasing stresses applied to it [44].



**Figure 8.** Abrasion resistance of CR IPB at 28 days.

An increase in abrasion resistance was observed with the addition of coconut coir (Figure 9). The top surface (top 2 mm) condition of the paving block critically affects the results as a result of silica sand poured on this surface [46]. However, with the addition of coconut coir, abrasion depth increased from 17.8 mm to 18.7 mm. This can be due to the high moisture condition of the fibers [47]. Also, due to a decrease in connectivity with the addition of coconut coir between the cement mix [32], the top surface can have a higher abrasion loss [46].

As per SLS 1425: Part 2 [40] and BS EN 1338 [37] standards, the maximum allowable abrasion depth is 20 mm for IPB blocks. The obtained abrasion values for both batches satisfy these conditions. However, the IS 15658 specification does not provide a limiting value for abrasion depth.

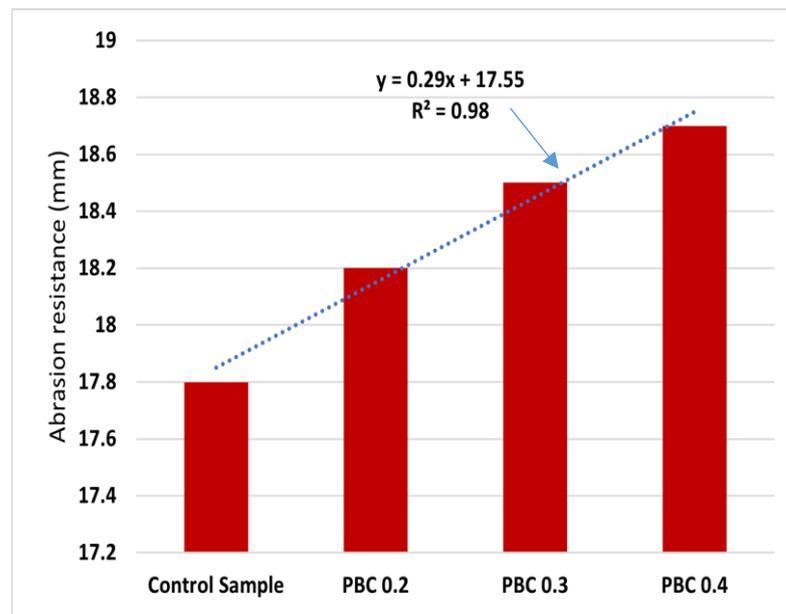


Figure 9. Abrasion resistance of CCF IPB at 28 days.

### 3.3. Splitting Tensile Strength

The split tensile test was conducted only for the samples with CCF (refer to Figure 10). The overall variation depicts that the split tensile strength increases with the CCF content. The maximum split tensile value was observed for the PBC0.3. It shows a 24.4% increase with respect to the value corresponding to the control sample. However, beyond 0.3% addition, split tensile strength tends to decrease. The PBC 0.3 sample can be identified as the optimum coir percentage for Splitting tensile strength, 2.55 MPa, according to Figure 10. Similar argument for the Compressive strength increment is applied for the Splitting tensile strength increment, since the addition of CCF fills up the pores in the mix building a better bond, and the high lignin content and low cellulose content of CCF makes the fibers strong and durable [30,32]. However, the obtained values (including the control sample) did not satisfy the BS EN 1338 specification on the split tensile strength (>3.6 MPa). The remaining codes of practice have failed to provide a recommendation on the split tensile strength of IPBs.

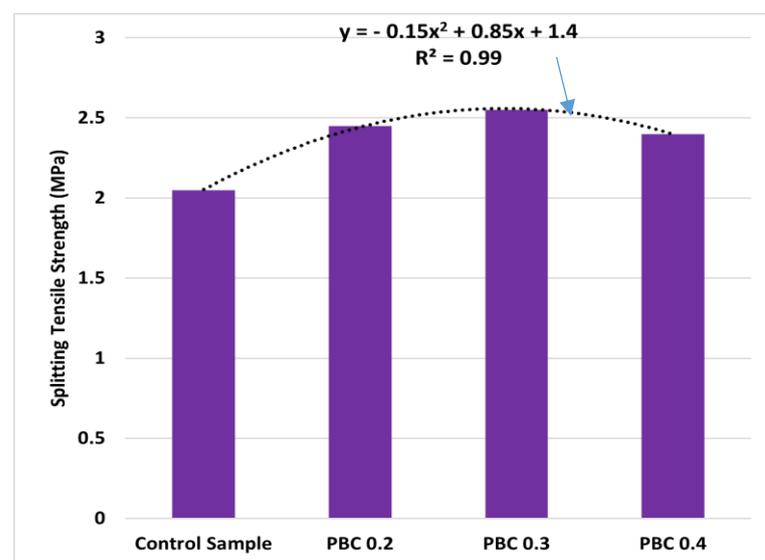


Figure 10. Split Tensile strength of CCF IPB at 28 days.

### 3.4. Skidding Resistance

Figure 11 depicts the skid resistance values obtained for batch 1. The PBR0 mix obtained the highest resistance of 90 USRV, which then decreased to a constant 85 USRV for the PBR5, PBR10, and PBR20 batches. Therefore, it shows a trivial effect of the increase in rubber content. The lowest value of 75 USRV was obtained for the PBR30 mix. One out of three samples from both, PBR5 and PBR20, showcased a moderately lower skid-resistance value, which resulted in a comparatively abrupt variation in the average value.

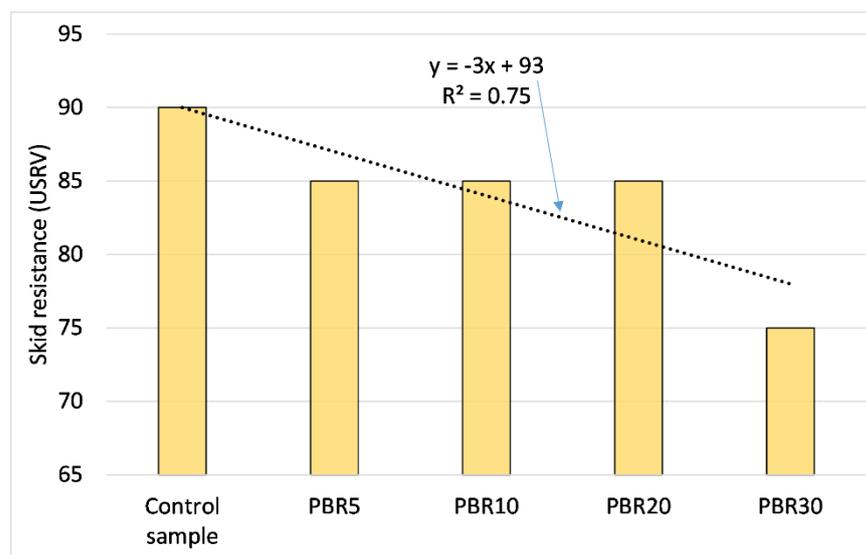
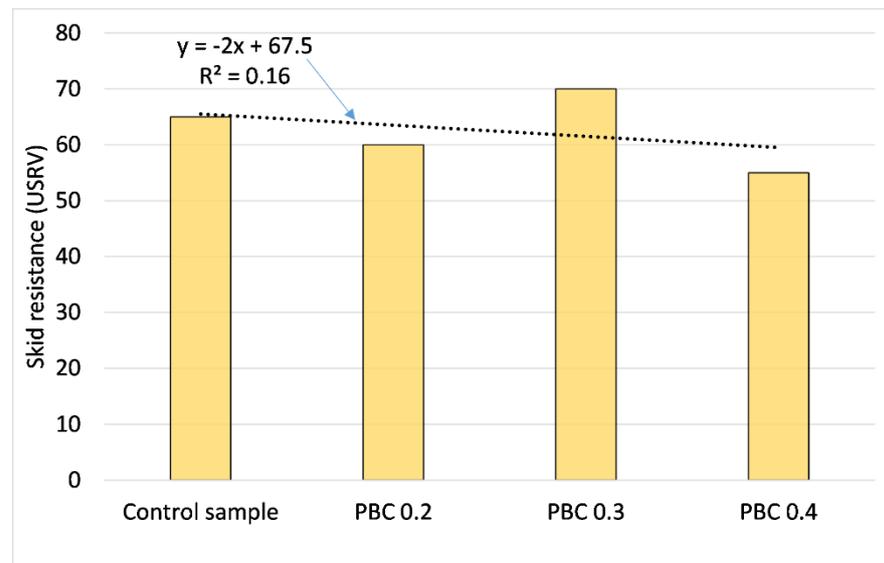


Figure 11. Skid resistance of CR IPB at 28 days.

The overall trendline shows a decrease in skid-resistance values when the rubber content increases. As mentioned by Ling et al. [28], the overall decreasing trend could be due to the presence of rubber particles on the surface of the block which reduces the contact area between the slider of the pendulum arm and the surface of the block. Nor and Ling [22] obtained somewhat similar results, wherein the skid resistance was seen to reduce from the 10% CR mix to the 30% CR mix. The resistance obtained for the control was, however, lower than the 10% CR mix. Given the predictions, their results showcased a variation similar to Figure 11. The smooth surface of CR also increased the tendency of slipping [28].

Skid resistance obtained for batch 2 is illustrated in Figure 12. The PBC0.3 block contained more CCF on the surface, which increased the USRV value to 70 as the surface of the block became rougher. The other samples showed decreasing USRV values from 65 to 55. The decrease in USRV values can be due to less amount of fibers being present on the surface of the block with PBC0.2 and PBC0.4 [47]. Additionally, due to mechanical vibration was used in preparation of CCF IPBs, surface texture may have reduced resulting a smooth top surface [32]. The overall trend shows a reduction in skid resistance values (refer to Figure 12) with a weak relationship of  $R^2 = 0.16$ .

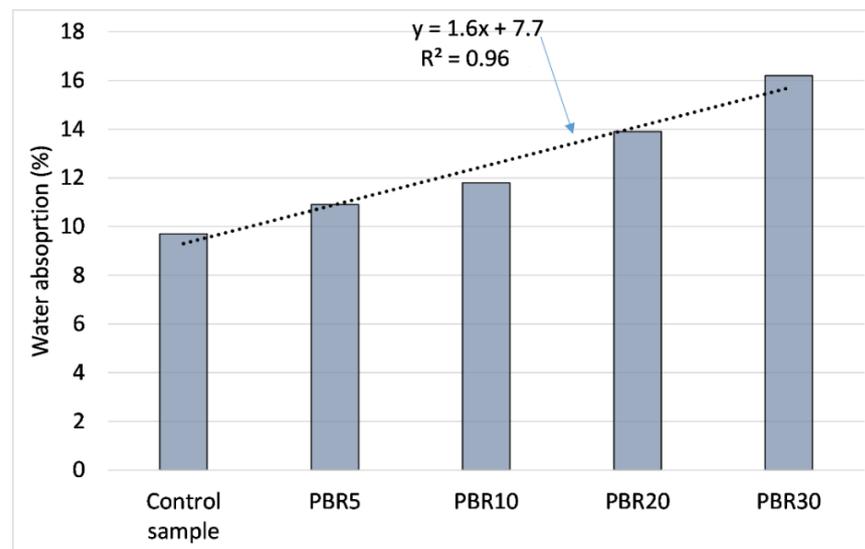


**Figure 12.** Skid resistance of CCF IPB at 28 days.

Samples with CR agree with the recommended values in both SLS 1425:2011 (>55 USRV) and BS EN 1338 (>75 USRV: extremely low potential to slip), whereas the sample with CCF only satisfies SLS 1425:2011 specifications. ASTM C936 and IS 15658 standards did not provide their recommendation on skid resistance.

### 3.5. Water Absorption

Water absorption increased gradually for batch 1 blocks from 9.65% for PBR0 to 16.18% for PBR30 (refer to Figure 13). The presence of rubber particles causes volume expansion of the blocks after demolding. During mixing and casting, CR particles contracted due to the pressure applied. This deformation was recovered after demolding the blocks, causing the volume of the block to expand, which, in turn, increased its water absorption and decreased its compressive strength [12].



**Figure 13.** Water absorption for CR IPB at 28 days.

A similar trend was observed for the IPBs with CCF, as shown in Figure 14. The water absorption increases with the increase in CCF content. Navya and Roa [33] reported that the water absorption increased as a result of the hydrophilic nature of the fibers. Interestingly,

the sample of batch 2 showcased less water absorption compared to batch 1. The reason was previously mentioned with compressive strength results due to the effect of the compaction method used. Batch 2 blocks satisfactorily achieved water absorption of less than 6% for the CCF0, CCF0.2, and CCF0.3. However, the CCF0.4 block achieves 6.1%, which is slightly above the specification. BS EN 1338, SLS 1425, and IS 15658 suggested a value of 6%, whereas ASTM C936 proposed a value of 5%. Accordingly, the batch 1 sample did not follow to the specified values in codes of practice.

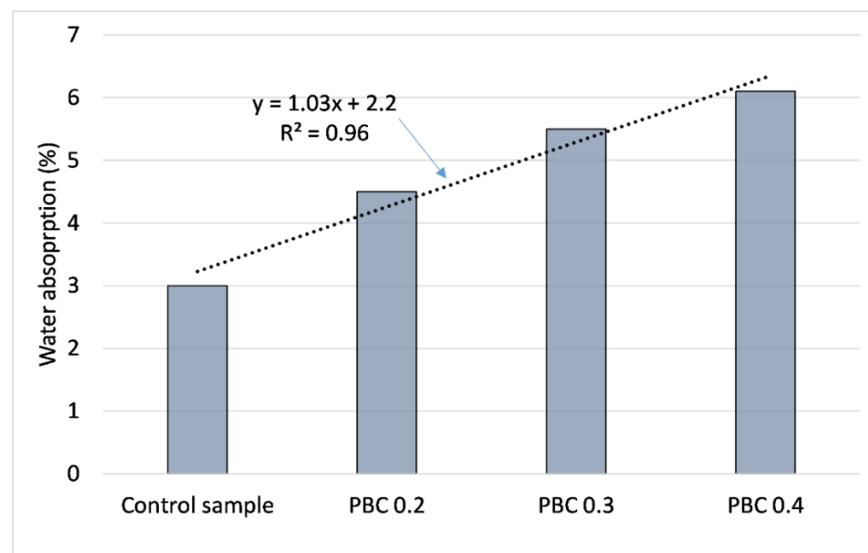


Figure 14. Water absorption for CR IPB at 28 days.

### 3.6. Density Analysis

The density reduced with the further increase in CR (Figure 15). For example, the sample with 30% CR has reduced its density by 14% in contrast to the control sample. The presence of rubber increases the number of air voids, which decreases the density [41,48]. Moreover, the specific density of rubber is lower than that of sand, which also contributes to the decrease in density [41,48]. Similar trends have been observed before where the density has decreased due to the increase in rubber fraction [25,48].

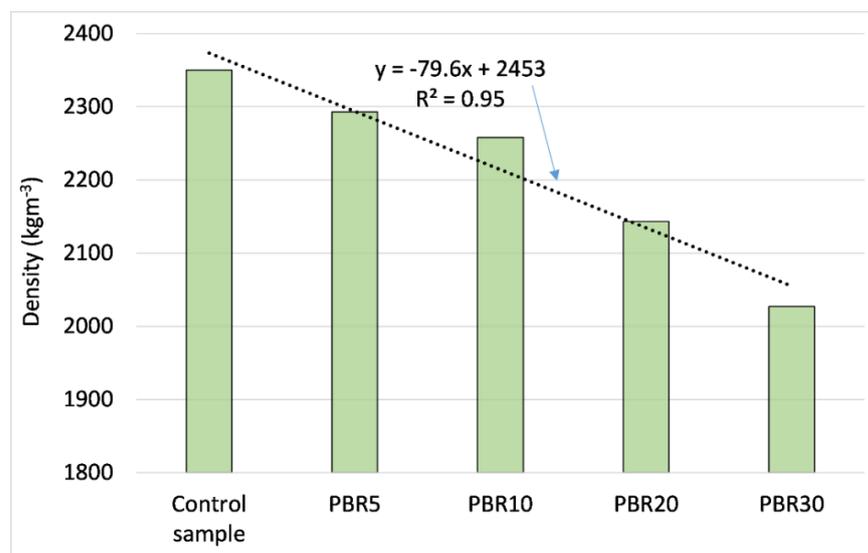


Figure 15. Density of CR IPB at 28 days.

### 3.7. Cost Analysis of Interlocking Paving Blocks

#### 3.7.1. Crumb Rubber (Batch 1)

The material quantity required to produce one block from each batch (PBR0, PBR5, PBR10, PBR20, and PBR30) and its cost are presented in Table 4. In the local context, the price of 1 kg of crumb rubber is 0.132 USD; as a result, the further replacement of sand with rubber, increases the cost of the IPB to 0.053 USD for PBR5, 0.061 USD for PBR10, 0.074 USD for PBR20, and 0.087 USD for PBR30. (1 USD = 340 LKR).

**Table 4.** Cost analysis per CR-based IPB (200 × 100 × 60 mm).

Material	Unit	Unit Price (USD)	PBR0		PBR5		PBR10		PBR20		PBR30	
			Quantity (Unit)	Price (USD)								
Cement	50 Kg Bag	2.9410	0.6300 (kg)	0.0370								
Sand	1 Cube	44.7060	0.0004 (m <sup>3</sup> )	0.0060	0.0004 (m <sup>3</sup> )	0.0060	0.0004 (m <sup>3</sup> )	0.0050	0.0004 (m <sup>3</sup> )	0.0050	0.0003 (m <sup>3</sup> )	0.0040
Crushed Aggregate	1.25 Cube	25.2940	0.0006 (m <sup>3</sup> )	0.0040								
Crumb Rubber	1 Kg	0.1320	-	-	0.0500 (kg)	0.0060	0.1100 (kg)	0.0150	0.2100 (kg)	0.0280	0.3200 (kg)	0.0420
Total Price per Block (USD)				0.0470	0.0530	0.0610	0.0740	0.0870				

#### 3.7.2. Coconut Coir Fibers (Batch 2)

Table 5 shows the quantity calculation of the materials used in the preparation of the Coconut-coir-based IPBs (Mix proportion for Cement: Sand: Chips is 1:2:3). Table 6 provides the cost calculation of the materials. According to Table 6, the increase in cost is negligible (<0.0002 USD) for IPBs with CCF (<0.5%). Therefore, CCF used as waste material is an effective use of IPBs, rather than open dumping.

**Table 5.** Material Quantity Calculation.

Material	Compacted Weight (per 1 Block)	Bulk Weight (per 1 Block)	Bulk Weight + 5% Wastage (per 1 Block)
Cement	441.93 g	530.32 g	556.83 g
Fine Aggregate-River Sand	743.57 g	892.28 g	936.89 g
Coarse Aggregate-Chips	1178.49 g	1414.19 g	1484.90 g
0.2% Coconut Coir by weight	-	-	5.96 g
0.3% Coconut Coir by weight	-	-	8.94 g
0.4% Coconut Coir by weight	-	-	11.92 g

**Table 6.** Cost Analysis per CCF-based IPB (200 × 100 × 60 mm).

Material	Unit	Unit Price (USD)	Quantity Required per Block (g)	Price of material per Block (USD)
Cement	50 Kg Bag	2.941	556.830	0.032
Fine Aggregate-River Sand	1 Cube (2.83 m <sup>3</sup> )	44.706	936.890	0.006
Coarse Aggregate-Chips	1 Cube (2.83 m <sup>3</sup> )	25.294	1484.900	0.004
0.2% Coconut Coir by weight	1 Kg	0.015	5.960	<0.0002
0.3% Coconut Coir by weight	1 Kg	0.015	8.940	<0.0002
0.4% Coconut Coir by weight	1 Kg	0.015	11.920	<0.0002

### 3.8. Comparison of Results with Related Work

#### 3.8.1. Comparison of CR-Based IPB Results with Previous Work

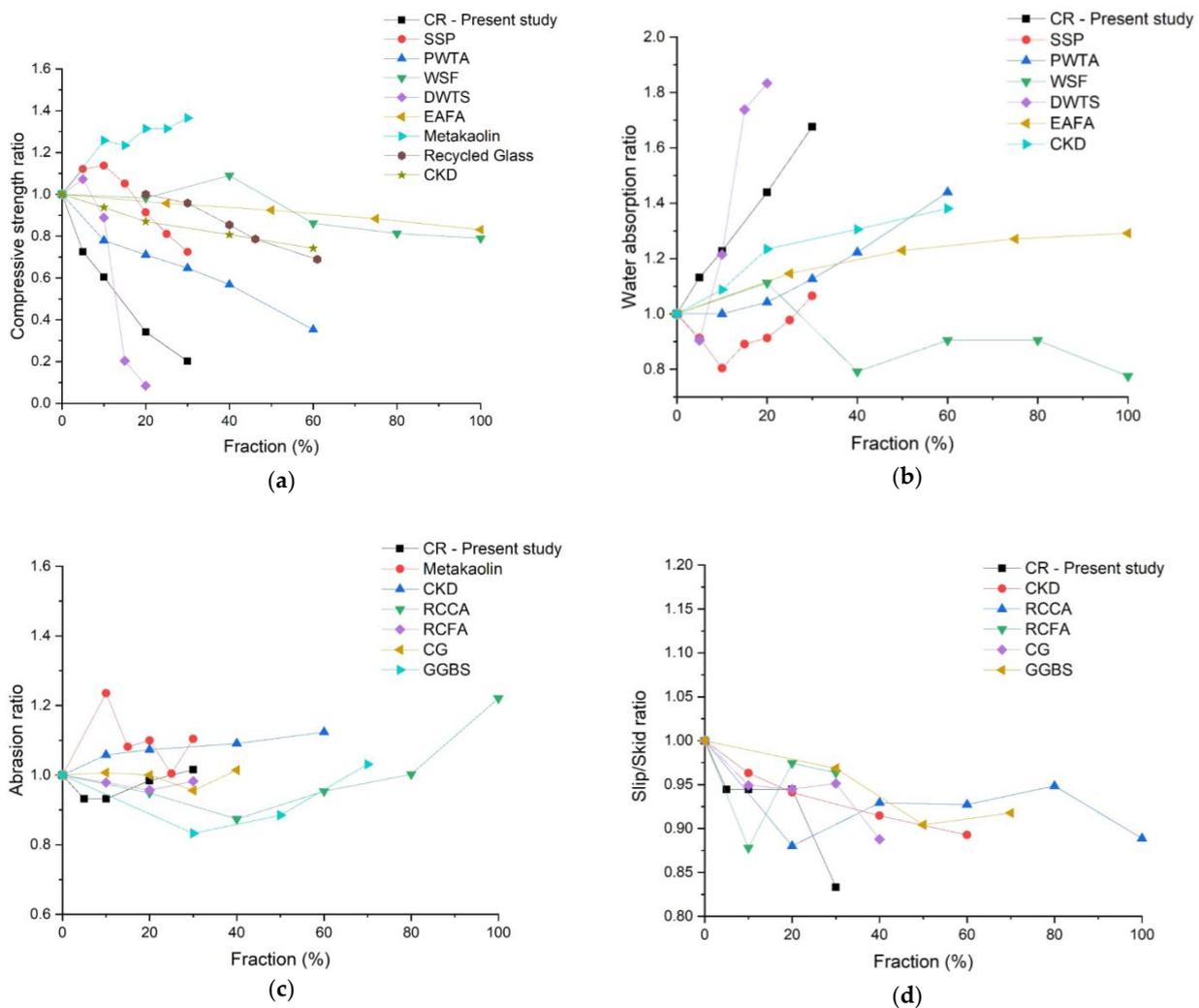
Past research studies carried out on interlocking paving blocks were considered for comparison. Table 7 shows each study considered, the type of alternative material used,

whether it was used as a replacement or an addition, the material it is replacing, and the tested properties. The compressive strength (CS), water absorption (WA), abrasion resistance (AR), and skid resistance (SR) properties were compared among studies conducted on IPBs using various alternative materials to observe their behavior. For the comparison, each property variation was normalized using its corresponding initial value. The graphs of the variation in the normalized ratio of the CS, WA, AR, and SR are displayed in Figure 16.

**Table 7.** Studies considered for the property comparison.

Alternative Material Used	Replacement (R)/Addition (A)	Replaced Material	Properties Considered	References
Crumb Rubber (CR)	R	Sand	CS WA AR SR	This study
Steel Slag Powder (SSP)	R	Cement	CS WA	Hussain et al. [49]
Processed Waste Tea Ash (PWTA)	R	Cement	CS WA	Djamaluddin et al. [50]
Crushed Waste Slag Furnace (WSF)	R	Sand	CS WA	Olofinnade et al. [15]
Drinking-Water Treatment Sludge (DWTS)	R	Sand	CS WA	Liu et al. [51]
Electric Arc Furnace Aggregate (EAFA)	R	Natural Coarse Aggregate	CS WA	Evangelista et al. [52]
Metakaolin	A	-	CS AR	Estolano et al. [10]
Recycled Glass	R	Mineral aggregate	CS	Torres de Rosso and Victor Staub de Melo [53]
Cement Kiln Dust (CKD)	R	Cement	CS WA AR SR	Sadek et al. [11]
Recycled Concrete Coarse Aggregate (RCCA)	R	Coarse aggregate	AR and SR	Wang et al. [12]
Recycled Concrete Fine Aggregate (RCFA)		Fine aggregate		
Crushed Glass (CG)		Coarse aggregate		
Ground Granulated Blast Furnace Slag (GGBS)		Cement		

Figure 16a shows the variation in the compressive strength ratio due to the presence of various additives and substitutes. Both WSF and EAFA have been replaced with up to 100% of the weight of sand. Overall, most of the materials contributed to a decrease in the compressive strength with respect to the amount of alternative material added or replaced. Within the 10% fraction, the crumb rubber (present study) and PWTA content influenced a considerable reduction in the compressive strength up to 0.6 and 0.8, respectively. However, within the same range DWTS, SSP, and Metakaolin showcased an increase in the compressive-strength values, which continue to increase for the added Metakaolin content. The addition of metakaolin increases the compaction, allowing the blocks to withstand compression tests [10]. Recycled glass and CKD content resulted in a gradual decrease in strength. From the current study, it is observed that the crumb-rubber content significantly brings down the compressive strength. For the 30% CR fraction, the reduction is almost 80%.



**Figure 16.** Effects of various materials on the properties of IPB, (a) compressive strength; (b) water absorption; (c) Abrasion, and; (d) Skid resistance.

Figure 16b shows all materials (excluding WSF) increase the water absorption ability with the increase in the fraction percent. DWTS achieves the highest ratio of 1.82 at a 20% fraction compared to the initial value. The decrease in water absorption due to WSF addition is caused by the low tendency of the particles to absorb water as the cement in the paver matrix covers WSF particles [15]. PWTA, EAFA, CKD, and CR exhibited a continuous increase in the water absorption ratio. Considering the 30% fraction, PWTA, EAFA, CKD, and CR have increased the water absorption by 12%, 18%, 27%, and 68%, respectively. The water absorption of blocks depends on their pore system. Although aggregates contain pores, they are enveloped by the cement in the block's matrix, so that it does not contribute to the water absorption of the IPB. Thus, the pores caused due to the addition of the alternative materials may result in the water absorption variation [11,50].

Figure 16c displays the influence on the abrasion ratio due to the alternative materials used in the production of IPBs. Each study tested the wear depth in mm of the IPB, which was subsequently used to normalize the trends. All materials exhibited an increase in the abrasion ratio with the increase in their content. RCCA and GGBS both achieved a ratio of 0.95 at the 60% fraction from which then RCCA increases at a slower rate compared to the GGBS replacement. The CR, metakaolin, and RCFA have been incorporated up to the 30% fraction. Metakaolin and CR achieve a 1.24 increase and a 0.94 decrease at the 10% fraction, respectively. The CG content affected the abrasion depth less. Similarly, RCFA replacement

shows a marginal increase with the increase in the content. CKD replacement displayed a continuous increase in abrasion depth to the 60% fraction.

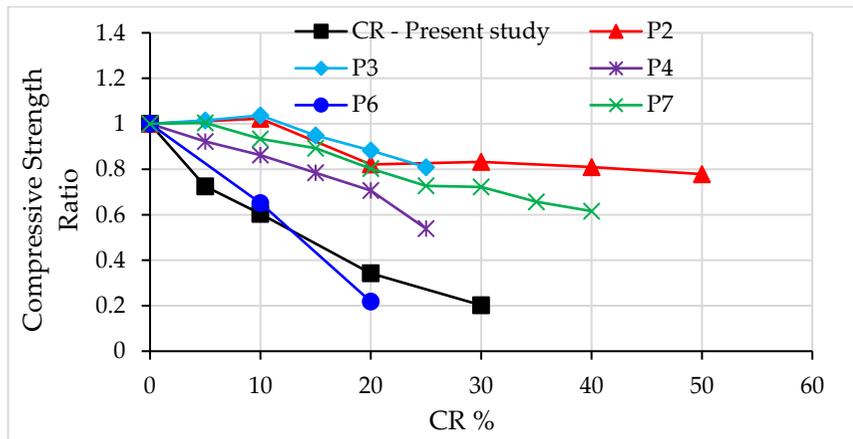
Figure 16d illustrates that the skid resistance ratio varies based on the fraction percent. All trends displayed a general decrease in the skid resistance of the IPB. CKD involvement resulted in a steady decrease up to 60% fraction, achieving a reduction of 10% from its initial value.

Several previous studies have focused on IPBs produced using crumb rubber as a partial replacement. Table 8 displays the tested IPBs with crumb rubber. Figure 17a–d show the graphs of variation for each property considered. For comparison purposes, each variation was normalized by using the initial value (control sample).

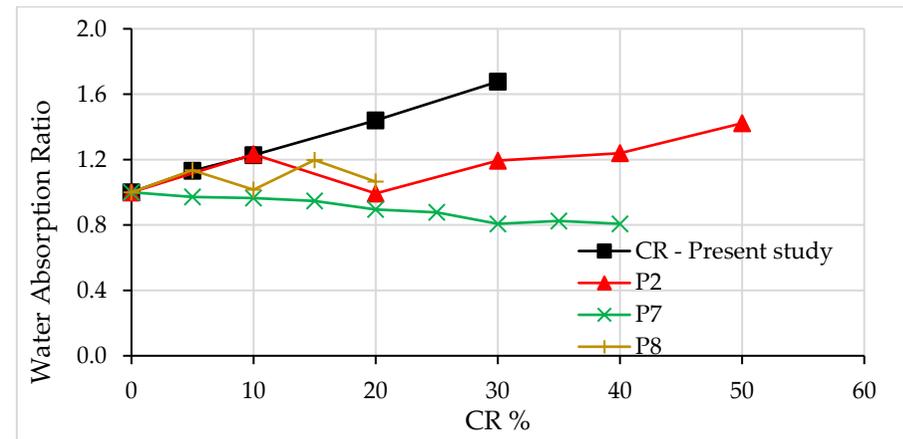
**Table 8.** Each Study Considered for the Property Comparison.

Paper No.	References	Rubber Type	Rubber Size	Replaced Material	Properties Considered
P1	<b>This study</b>	CR	Mesh 30 and 2 mm–(50% each)	Sand	CS WA AR SR
P2	Silva et al. [25]	CR	1.18 mm–2.36 mm	Sand	CS WA AR
P3	Murugan and Natarajan [24]	CR	4.75 mm–0.15 mm	Sand	CS
P4	Murugan et al. [23]	CR	4.75 mm–0.075 mm	Sand	CS
P5	Nor et al. [28]	CR	Passing BS sieve No. 4 (4.75 mm)	Sand	SR
P6	Sukontasukkul and Chaikaew [45]	CR	No.6 (Passing Sieve No.6); No.20 (Passing Sieve No.20)–50% each	Fine and Coarse Aggregate (50% each)	CS AR SR
P7	Soni and Mathur [54]	CR	4.75 mm–0.075 mm	Sand	CS WA AR
P8	Aboelkheir et al. [55]	Ground Tire Rubber (GTR)	120 mesh	Fine aggregate	WA

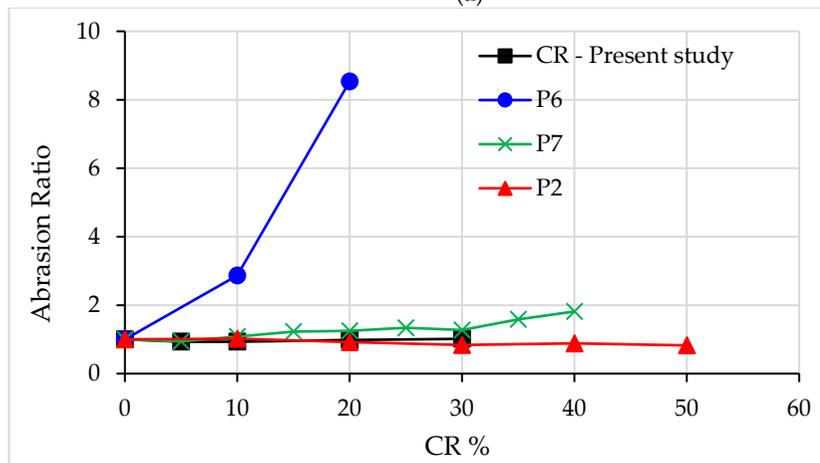
Figure 17a displays the compressive strength-ratio graph against the increase in CR percent. It shows a decrease in compressive strength with rubber for all the studies. The decrease is due to the weak bonding between the rubber and cement paste [21]. Figure 17b illustrates the graph of the water-absorption ratio with the increase in CR content. The present study and study P2 both display a gradual increase in the absorption with the increase in rubber, which is due to the increase in the number of pores in the block [25]. However, research study P7 has shown a 20% decrease in water absorption with the increase in rubber. Soni and Mathur [54] argued that this decrease occurs as a result of proper vibration carried out during manufacturing. Considering Figure 17c, the abrasion depth increased slightly for P7 and the present study and increased drastically for study P6. The porosity and contact area are two factors that affect the abrasion resistance of concrete. The presence of rubber in paving blocks increases the number of air voids formed, reducing the contact area of concrete. Thus, when high specific loads are applied to it, the top surface of the IPB tends to wear out [44]. Figure 17d displays the variation in skid-resistance ratios with the change in CR content. It shows the ratio of the present study and P5 slightly decreases. The skid resistance of study P6 increased with the substitution of CR. Study P6 has carried out the test on a dry block. This study has also carried out a field test that showed the skid resistance decreased slightly, which occurs as a result of moisture in the environment [45].



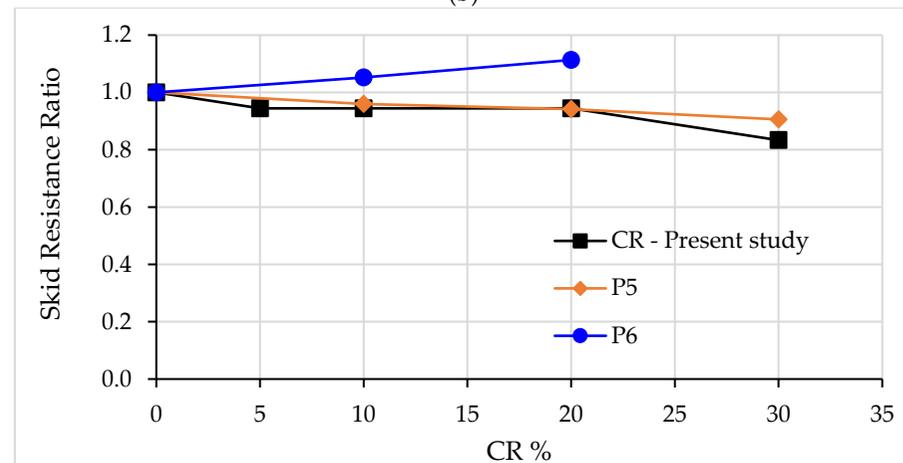
(a)



(b)



(c)



(d)

**Figure 17.** Effect CR on the properties of IPBs: (a) Compressive strength results with CR; (b) Water absorption results with CR; (c) Abrasion results with CR; (d) Skid resistance results with CR.

### 3.8.2. Comparison of CCF-Based IPB Results with Previous Work

The CCF content of our study varies within a small range (0% to 0.4%) which is inferior compared to the fractions used in previous studies. Therefore, the authors provided a tabular comparison.

Table 9 gives Compressive-strength results from the detailed study of various additives and substitutes. A 100% replacement was undertaken for coarse aggregate and sand using an electric arc furnace and waste furnace slag, respectively. A decrease in compressive strength was observed in most cases when materials were substituted. However, an increase was observed in compressive strength when coconut coir and cement kiln dust were added by 0.2% and 20% weight of cement. It was noticed that compressive strength had increased when steel slag powder was substituted until 15% by mass of cement and then decreased when substituted further. Furthermore, it was observed that the waste slag furnace, initial strength had decreased with 20% substitution and then increased the strength until 40% substitution. Moreover, the highest decrease in compressive strength was observed with processed waste tea ash (65%) compared with the initial sample.

**Table 9.** Comparison of compressive strength of IPBs with other materials.

References	The Material Used in the Study	Substituted (S)/Added (A) Amount	28-Days Compressive Strength (N/mm <sup>2</sup> )	Ratio to Control Sample
This study	Coconut Coir	0%	42.95	1.00
		0.2% (A)	45.30	1.05
		0.3% (A)	42.35	0.99
		0.4% (A)	34.04	0.79
Djamaluddin et al. [51]	Processed waste tea ash substituted for Cement	0%	19.81	1.00
		10% (S)	15.46	0.78
		20% (S)	14.12	0.71
		30% (S)	12.10	0.61
		40% (S)	10.24	0.52
Hussain et al. [50]	Steel slag powder substituted for Cement	0%	60.30	1.00
		5% (S)	67.60	1.12
		10% (S)	68.60	1.14
		15% (S)	63.40	1.05
		20% (S)	55.10	0.91
		25% (S)	48.90	0.81
		30% (S)	43.70	0.72
Olofinnade et al. [15]	Waste Furnace slag substituted for sand	0%	22.80	1.00
		20% (S)	22.50	0.99
		40% (S)	25.30	1.11
		60% (S)	19.90	0.87
		80% (S)	18.90	0.83
Sadek et al. [11]	Cement kiln dust substituted for cement	0%	62.30	1.00
		10% (S)	58.40	0.94
		20% (S)	54.20	0.87
		40% (S)	50.30	0.81
		60% (S)	46.20	0.74
		20% (A)	65.90	1.06
Evangelista et al. [53]	Electric arc furnace aggregate substituted for coarse aggregate	0%	49.10	1.00
		25% (S)	47.00	0.96
		50% (S)	45.40	0.92
		75% (S)	43.40	0.88
		100% (S)	40.80	0.83

Table 10 gives abrasion resistance results for various additives and substitutes. An increase in abrasion resistance was observed with coconut coir addition and cement kiln dust substitution. However, a decrease was observed up to 40% recycled concrete coarse aggregate, 20% recycled concrete fine aggregate, 30% crushed glass, and 30% granulated blast furnace slag. Furthermore, the maximum increase in abrasion resistance was observed with recycled concrete coarse aggregate, which had increased by 21% when it was completely substituted for coarse aggregate. Moreover, the highest decrease in abrasion resistance was observed with granulated blast furnace slag, which is a 17% reduction.

**Table 10.** Comparison of abrasion resistance of IPBs with other materials.

References	Material Used in the Study	Substituted (S)/Added (A) Amount	28-Days Abrasion Resistance (mm)	Ratio to Control Sample
This study	Coconut Coir	0%	17.80	1.00
		0.2% (A)	18.20	1.02
		0.3% (A)	18.40	1.03
		0.4% (A)	18.70	1.05
Sadek et al. [11]	Cement kiln dust substituted for cement	0%	19.74	1.00
		10% (S)	20.88	1.06
		20% (S)	21.19	1.07
		40% (S)	21.53	1.09
		60% (S)	22.18	1.12
		20% (A)	19.50	0.99
Wang et al. [12]	Recycled concrete coarse aggregate substituted for coarse aggregate	0%	29.25	1.00
		20% (S)	27.59	0.94
		40% (S)	25.42	0.87
		60% (S)	27.91	0.95
		80% (S)	29.22	0.99
		100% (S)	35.49	1.21
	Recycled concrete fine aggregates substituted for Sand	0%	29.25	1.00
		10% (S)	28.73	0.98
		20% (S)	27.99	0.96
		30% (S)	28.73	0.98
	Crushed Glass substituted for Coarse aggregate	0%	29.25	1.00
		10% (S)	29.40	1.00
		20% (S)	29.25	1.00
		30% (S)	28.06	0.96
40% (S)		29.70	1.02	
Crumb Rubber substituted for Sand	0%	29.18	1.00	
	1% (S)	30.79	1.06	
	2% (S)	28.76	0.99	
	3% (S)	28.22	0.97	
Granulated blast furnace slag substituted for cement	0%	29.28	1.00	
	30% (S)	24.35	0.83	
	50% (S)	25.94	0.89	
	70% (S)	30.07	1.03	

Table 11 gives splitting tensile strength results of IPB obtained from the various studies. A decrease in splitting tensile strength was observed when substituted with cement kiln dust, recycled concrete fine aggregate, and crumb rubber. The highest decrease (52%) in splitting tensile strength occurs when sand is substituted for sand. The highest increase of 24% was observed in the present study at 0.3% CCF.

**Table 11.** Comparison of splitting tensile strength of IPBs with other materials.

References	Material Used in the Study	Substituted (S)/Added (A) Amount	28-Days Splitting Tensile Strength (N/mm <sup>2</sup> )	Ratio to Control Sample
This study	Coconut Coir	0%	2.05	1.00
		0.2% (A)	2.45	1.20
		0.3% (A)	2.55	1.24
		0.4% (A)	2.40	1.17
Olofinnade et al. [15]	Waste Furnace slag substituted for sand	0%	2.53	1.00
		20% (S)	2.73	1.08
		40% (S)	2.30	0.91
		60% (S)	2.19	0.87
		80% (S)	2.11	0.83
		100% (S)	1.73	0.68
Sadek et al. [11]	Cement kiln dust substituted for cement	0%	4.71	1.00
		10% (S)	4.63	0.98
		20% (S)	4.16	0.88
		40% (S)	3.87	0.82
		60% (S)	3.63	0.77
		20% (A)	5.11	1.08
Wang et al. [12]	Recycled concrete coarse aggregate substituted for coarse aggregate	0%	11.18	1.00
		20% (S)	11.61	1.04
		40% (S)	10.19	0.911
		60% (S)	9.03	0.81
		80% (S)	8.60	0.77
	Recycled concrete fine aggregates substituted for Sand	100% (S)	6.26	0.56
		0%	11.30	1.00
		10% (S)	10.67	0.94
	Crushed Glass substituted for Coarse aggregate	20% (S)	10.33	0.91
		30% (S)	7.40	0.65
		0%	11.31	1.00
		10% (S)	12.35	1.09
		20% (S)	12.50	1.11
	Crumb Rubber substituted for Sand	30% (S)	12.42	1.10
40% (S)		12.79	1.13	
0%		11.30	1.00	
1% (S)		9.54	0.84	
Granulated blast furnace slag substituted for cement	2% (S)	8.04	0.71	
	3% (S)	5.46	0.48	
	0%	11.18	1.00	
	30% (S)	12.62	1.13	
	50% (S)	12.88	1.15	
		70% (S)	9.32	0.83

Table 12 summarizes the skid-resistance results obtained from related work. A decrease in skid resistance was observed with cement kiln dust substitution. However, most of the skid-resistance results followed a zig-zag pattern that increases and decreases with the substitution of additive materials. Furthermore, the maximum increase was observed with coconut coir addition of 0.3%. Moreover, the highest decrease in skid resistance was also observed for samples with 0.4% CCF.

**Table 12.** Comparison of Skid resistance of IPB with various materials.

References	Material Used in the Study	Substituted (S)/Added (A) Amount	28-Days Skid Resistance	Ratio to Control Sample
This study	Coconut Coir	0%	65.00 (USRV)	1.00
		0.2% (A)	60.00 (USRV)	0.92
		0.3% (A)	70.00 (USRV)	1.08
		0.4% (A)	55.00 (USRV)	0.85
Sadek et al. [11]	Cement kiln dust substituted for cement	0%	68.00 (USRV)	1.00
		10% (S)	65.50 (USRV)	0.96
		20% (S)	64.00 (USRV)	0.94
		40% (S)	62.20 (USRV)	0.91
		60% (S)	60.70 (USRV)	0.89
		20% (A)	69.30 (USRV)	1.02
Wang et al. [12]	Recycled concrete coarse aggregate substituted for coarse aggregate	0%	90.46 (BPN)	1.00
		20% (S)	79.42 (BPN)	0.88
		40% (S)	83.77 (BPN)	0.93
		60% (S)	83.72 (BPN)	0.93
		80% (S)	85.71 (BPN)	0.95
		100% (S)	79.95 (BPN)	0.88
	Recycled concrete fine aggregates substituted for Sand	0%	90.55 (BPN)	1.00
		10% (S)	79.32 (BPN)	0.88
		20% (S)	88.19 (BPN)	0.97
		30% (S)	87.00 (BPN)	0.96
	Crushed Glass substituted for Coarse aggregate	0%	90.47 (BPN)	1.00
		10% (S)	85.75 (BPN)	0.95
		20% (S)	85.28 (BPN)	0.94
		30% (S)	85.98 (BPN)	0.95
		40% (S)	79.95 (BPN)	0.88
	Crumb Rubber substituted for Sand	0%	90.23 (BPN)	1.00
		1% (S)	88.76 (BPN)	0.98
		2% (S)	85.28 (BPN)	0.95
3% (S)		87.25 (BPN)	0.97	
Granulated blast furnace slag substituted for cement	0%	90.29 (BPN)	1.00	
	30% (S)	87.43 (BPN)	0.97	
	50% (S)	81.71 (BPN)	0.90	
	70% (S)	82.57 (BPN)	0.91	
Ling [56]	Crumb Rubber substituted for sand	0%	78.00 (BPN)	1.00
		10% (S)	74.00 (BPN)	0.95
		20% (S)	69.00 (BPN)	0.88
		30% (S)	64.00 (BPN)	0.82

Table 13 gives water-absorption results obtained from related studies. The results showcase an increase in water absorption in the presence of additive materials. However, a moderate decrease in water absorption can be observed for IPBs with steel slag powder and waste furnace slag.

**Table 13.** Comparison of Water Absorption of IPB'S with various materials.

References	Material Used in the Study	Substituted (S)/Added (A) Amount	28-Days Water Absorption (%)	Normalized Value
This study	Coconut Coir	0%	3.00	1.00
		0.2% (A)	4.51	1.50
		0.3% (A)	5.48	1.83
		0.4% (A)	6.05	2.01
Djamaluddin et al. [51]	Processed waste tea ash substituted for Cement	0%	7.71	1.00
		10% (S)	7.76	1.00
		20% (S)	8.04	1.04
		30% (S)	8.81	1.14
		40% (S)	9.63	1.25
		60% (S)	11.23	1.46
Hussain et al. [50]	Steel slag powder substituted for Cement	0%	5.15	1.00
		5% (S)	4.70	0.91
		10% (S)	4.14	0.80
		15% (S)	4.59	0.89
		20% (S)	4.70	0.91
		25% (S)	5.04	0.98
Olofinnade et al. [15]	Waste Furnace slag substituted for sand	0%	5.40	1.00
		20% (S)	6.00	1.11
		40% (S)	4.30	0.80
		60% (S)	4.90	0.91
		80% (S)	4.90	0.91
		100% (S)	4.20	0.77
Sadek et al. [11]	Cement kiln dust substituted for cement	0%	2.39	1.00
		10% (S)	2.60	1.09
		20% (S)	2.95	1.23
		40% (S)	3.12	1.31
		60% (S)	3.30	1.38
Evangelista et al. [53]	Electric arc furnace aggregate substituted for coarse aggregate	20% (A)	2.29	0.96
		0%	4.80	1.00
		25% (S)	5.50	1.15
		50% (S)	5.90	1.23
		75% (S)	6.10	1.27
100% (S)	6.20	1.29		

### 3.9. Limitations

Crumb rubber and coconut coir (waste materials) were used for the manufacturing process of IPB. Crumb rubber was substituted instead of fine aggregates, whereas coconut coir was used as additional material. The limitations of this research are as follows:

- The study did not investigate the effect of CR on the split tensile strength and the effect of CCF on the density of IPBs. It was assumed that the addition of CCF (<0.5%) would not have a significant impact on the density. However, further studies are recommended in this regard.
- The blocks were examined using naked-eye observations. Therefore, the effect of CR and CCF on the microstructure of IPB was not discovered in this study. Such visualization will be imperative to interpret the results observed for various properties (Water absorption, compressive strength, etc.).
- The study limited its CR fraction to 30% and CCF fraction to 0.4%. However, the CCF fraction showcased some variations where different results could have been observed if the CCF content had increased. However, the results obtained from the present study do not rule out the findings to be elaborated in a future study, as interesting observations were noted. Therefore, it is recommended to add CCF within a relatively

more extensive range to explore the relationships between the strength and durability characteristics.

- Experiments were limited to properties of durability and strength. However, further studies are encouraged on properties such as shrinkage, impact energy, etc.
- Further testing of each property, including a greater number of samples, will provide a clearer understanding of the trend of the results obtained.
- This study used manual compaction and mechanical vibrations for batch 1 and batch 2 blocks, respectively. However, we have highlighted the variation in compaction method. Therefore, for future studies, the authors recommend using a different sample preparation method.

#### 4. Conclusions

This research study focused on the manufacture of CR and CCF-based IPBs. The effect on the compressive strength, splitting tensile strength, water absorption, density, abrasion resistance, and skid resistance were evaluated. The obtained results warrant the following remarks:

- The compressive strength of IPB decreases with adding CR. Blocks with 5% and 10% CR satisfied the class 4 specification as per SLS1425. However, at 0.2% of CCF, the compressive strength of IPB has increased. Further increase in CCF content resulted in a reduction in compressive strength.
- Splitting tensile strength is significantly improved when the percentage of coconut coir fibers' addition by weight increases from 0% to 0.3% in 28 days splitting tensile strength test and decreases to 0.4% CCF level. It is believed that the lignin content and low cellulose content make IPB stronger and more durable up to a limited extent.
- The presence of CR increases the air content present, increasing the water absorption of the IPB mixes. The increase in air void content decreases the density of the block, which is observed in the density results obtained in the study (density of the blocks decreased from 2350 kg/m<sup>3</sup> to 2027 kg/m<sup>3</sup> for mixes with 0% to 30% CR, respectively). As a result of manual compaction, the water absorption values were relatively larger compared to the obtained results for batch 2 (with CCF) samples. For batch 2, water absorption increased from 3.00% to 6.1% when the CCF fraction increases from 0% to 0.4%. This occurs due to the hydrophilic nature of the coconut coir fibers.
- The specific density of rubber is low thus, the higher the amount of CR partially substituted in the IPB, the lower the density of the IPB.
- PBR5 and PBR10 IPBs displayed the highest abrasion resistance. Abrasion depth has an overall increase in the presence of CR and CCF. However, a reduction is observed for PBR20 and PBR30, regardless of the overall trend. Furthermore, the obtained values comply with the values specified in SLS 1425 and BS EN 1338 (<20 mm).
- The skid resistance of the CR-based IPB satisfied SLS 1425 (>55 USRV) and BS EN 1338 (>75 USRV) recommendations. However, IPBs with CCF only satisfied the specification given in the SLS1425 standard (>55 USRV).
- The cost-effectiveness of these coconut coir-based interlocking paving blocks is significant. As a waste material, CCF improves the strength and durability characteristics of IPB without affecting its cost. As coconut coir is dumped as a waste and can be collected for a free or very low price in the local context. For batch 1, the IPB from the PBR10 mix was recommended as the optimum fraction of CR, because increasing the CR percentage beyond 10% decreased the block's compressive strength.

**Author Contributions:** Conceptualization, S.M.; methodology, S.G., S.P. and S.M.; validation, S.G., S.P., S.M. and D.P.P.M.; formal analysis, S.G., S.P., S.M. and D.P.P.M.; resources, S.G., S.P. and S.M.; data curation, S.G. and S.P.; writing—original draft preparation, S.G. and S.P.; writing—review and editing, D.P.P.M., S.M., H.M.A. and U.R.; visualization, S.G., S.P., H.M.A., U.R. and D.P.P.M.; supervision, S.M. and D.P.P.M.; project administration, D.P.P.M., S.M. and U.R.; funding acquisition, H.M.A. and U.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data can be made available upon a reasonable request from the authors.

**Acknowledgments:** The authors would like to convey their sincerest gratitude to the Sri Lanka Institute of Information Technology, Sri Lanka, for providing the required materials and equipment. Moreover, the authors are grateful to the National Building Research Organization (NBRO) and the Road Development Authority (RDA) for aiding us with the necessary equipment to conduct this research successfully.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Interlocking Concrete Pavement Institute. *How Do Interlocking Pavers Work. PaveShare: A Segmental Paving Resource for Landscape Architects*. Available online: <http://www.paveshare.org/1/post/2012/01/how-do-interlocking-pavers-work.html> (accessed on 10 November 2021).
2. Limbachiya, V.; Ganjian, E.; Claisse, P. Strength, durability and leaching properties of concrete paving blocks incorporating GGBS and SF. *Constr. Build. Mater.* **2016**, *113*, 273–279. [[CrossRef](#)]
3. Concrete Paving Blocks: An Overview. Final Technical Report. Available online: <https://www.wsdot.wa.gov/research/reports/fullreports/319.1.pdf> (accessed on 1 December 2021).
4. Edayadiyil, J.B.; Mathew, S.; Joy, M. A methodology for the effective use of materials in concrete paving block. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1114*, 012011. [[CrossRef](#)]
5. Interlocking Concrete Paver Blocks. Available online: <https://www.nbcmw.com/product-technology/construction-chemicals-waterproofing/concrete-admixtures/interlocking-concrete-paver-blocks.html> (accessed on 10 November 2021).
6. Elnouhy, H.; Zeedan, S. Performance evaluation of interlocking paving units in aggressive environments. *HBRC J.* **2012**, *8*, 81–90. [[CrossRef](#)]
7. Palanikumar, P.U.K.E. Structural Design of Interlocking Concrete Paving Block. *Int. J. Eng. Res.* **2016**, *5*, 230–232. [[CrossRef](#)]
8. Unilock. Design Considerations for Interlocking Concrete Pavements. Available online: <https://3vdf1d71bfa9odb2zenhe14-wpengine.netdna-ssl.com/wp-content/uploads/sites/10/mp/files/assets/files/design-considerations-interlocking-pavements17.pdf> (accessed on 10 December 2021).
9. Sojobi, A.; Aladegboye, O.; Awolusi, T. Green interlocking paving units. *Constr. Build. Mater.* **2018**, *173*, 600–614. [[CrossRef](#)]
10. Estolano, A.M.; de Lima, N.B.; Junior, R.V.; Belarmino, M.K.; Silva, A.I.; Nascimento, C.; Oliveira, N.T.; Lima, V.; Ioras, R.U.; Oliveira, R.A.; et al. Concrete paving blocks: Structural, thermodynamic, fluorescence, optical and mechanical properties. *J. Mol. Struct.* **2019**, *1184*, 443–451. [[CrossRef](#)]
11. Sadek, D.M.; El-Attar, M.M.; Ali, A.M. Physico-mechanical and durability characteristics of concrete paving blocks incorporating cement kiln dust. *Constr. Build. Mater.* **2017**, *157*, 300–312. [[CrossRef](#)]
12. Wang, X.; Chin, C.S.; Xia, J. Material Characterization for Sustainable Concrete Paving Blocks. *Appl. Sci.* **2019**, *9*, 1197. [[CrossRef](#)]
13. Bhandari, P. Experimental Investigation on Corrugated Interlocking Paving Blocks (CIPB) for strength and durability study. *Int. J. Mod. Trends Eng. Res.* **2016**, *3*, 86–90.
14. Santos, C.; Valentina, L.O.V.D.; Cuzinsky, F.; Witsmieszyn, L. Interlocking Concrete Paving Blocks Produced with Foundry Sand Waste. *Mater. Sci. Forum* **2018**, *912*, 191–195. [[CrossRef](#)]
15. Olofinnade, O.; Morawo, A.; Okedairo, O.; Kim, B. Solid waste management in developing countries: Reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production. *Case Stud. Constr. Mater.* **2021**, *14*, e00532. [[CrossRef](#)]
16. Abdullah, A.; Lee, C. Effect of Treatments on Properties of Cement-fiber Bricks Utilizing Rice Husk, Corncob and Coconut Coir. *Procedia Eng.* **2017**, *180*, 1266–1273. [[CrossRef](#)]
17. Grammelis, P.; Margaritis, N.; Dallas, P.; Rakopoulos, D.; Mavrias, G. A Review on Management of End of Life Tires (ELTs) and Alternative Uses of Textile Fibers. *Energies* **2021**, *14*, 571. [[CrossRef](#)]
18. Technical Guidelines on Solid Waste Management in Sri Lanka. Available online: <https://www.cea.lk/web/en/publication> (accessed on 4 April 2021).
19. Kordoghli, S.; Paraschiv, M.; Kuncser, R.; Tazerout, M.; Prisecaru, M.; Zagrouba, F.; Georgescu, I. Managing the environmental hazards of waste tires. *J. Eng. Stud. Res.* **2016**, *1–20*, 50–60. [[CrossRef](#)]
20. Tsang, H.H. Uses of Scrap Rubber Tires. In *Rubber: Types, Properties and Uses*; Tsang, H.H., Ed.; Nova Science Publishers: New York, NY, USA, 2013; pp. 477–491.
21. Ling, T.C.; Nor, H.M.; Hainin, M.R.; Lim, S.K. Long-term strength of rubberised concrete paving blocks. *Proc. Inst. Civ. Eng. Constr. Mater.* **2010**, *163*, 19–26. [[CrossRef](#)]
22. Ling, T.C.; Nor, H. Granulated waste tyres in concrete paving block. In Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference, Kuala Lumpur, Malaysia, 5–6 September 2006.
23. Murugan, R.B.; Natarajan, C.; Chen, S.-E. Material development for a sustainable precast concrete block pavement. *J. Traffic Transp. Eng.* **2016**, *3*, 483–491. [[CrossRef](#)]

24. Murugan, R.B.; Natarajan, C. Investigation on the use of waste tyre crumb rubber in concrete paving blocks. *Comput. Concr.* **2017**, *20*, 311–318. [[CrossRef](#)]
25. da Silva, F.M.; Barbosa, L.A.G.; Lintz, R.C.C.; Jacintho, A.E.P. Investigation on the properties of concrete tactile paving blocks made with recycled tire rubber. *Constr. Build. Mater.* **2015**, *91*, 71–79. [[CrossRef](#)]
26. Ganjian, E.; Khorami, M.; Maghsoudi, A.A. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr. Build. Mater.* **2009**, *23*, 1828–1836. [[CrossRef](#)]
27. Siddika, A.; Al Mamun, M.A.; Alyousef, R.; Amran, Y.H.M.; Aslani, F.; Alabduljabbar, H. Properties and utilizations of waste tire rubber in concrete: A review. *Constr. Build. Mater.* **2019**, *224*, 711–731. [[CrossRef](#)]
28. Nor, H.; Lim, S.K.; Ling, T.C. Using recycled waste tyres in concrete paving blocks. *Proc. Ice Waste Resour. Manag.* **2010**, *163*, 37–45. [[CrossRef](#)]
29. Chu, S.; Poon, C.S.; Lam, C.; Li, L. Effect of natural and recycled aggregate packing on properties of concrete blocks. *Constr. Build. Mater.* **2021**, *278*, 122247. [[CrossRef](#)]
30. Syed, H.; Nerella, R.; Madduru, S.R.C. Role of coconut coir fiber in concrete. *Mater. Today Proc.* **2020**, *27*, 1104–1110. [[CrossRef](#)]
31. Ali, M.; Liu, A.; Sou, H.; Chouh, N. Mechanical and dynamic properties of coconut fibre reinforced concrete. *Constr. Build. Mater.* **2012**, *30*, 814–825. [[CrossRef](#)]
32. Kochova, K.; Gauvin, F.; Schollbach, K.; Brouwers, H. Using alternative waste coir fibres as a reinforcement in cement-fibre composites. *Constr. Build. Mater.* **2019**, *231*, 117121. [[CrossRef](#)]
33. Navya, G.; Roa, J.V. Experimental Investigation on Properties Concrete Paver Block with the Inclusion of Natural Fibers. *J. Eng. Res. Appl.* **2014**, *4*, 34–38.
34. Amaral, L.F.; de Carvalho, J.P.R.G.; da Silva, B.M.; Delaqua, G.C.G.; Monteiro, S.N.; Vieira, C.M.F. Development of ceramic paver with ornamental rock waste. *J. Mater. Res. Technol.* **2019**, *8*, 599–608. [[CrossRef](#)]
35. *SLS 107:2008 Part 1*; Specification for Ordinary Portland Cement. Sri Lanka Standards Institute: Colombo, Sri Lanka, 2008.
36. Sri Lankan Standards. Concrete Paving Blocks—Requirements. Available online: [http://www.slsi.lk/index.php?option=com\\_content&view=featured&Itemid=101&lang=en](http://www.slsi.lk/index.php?option=com_content&view=featured&Itemid=101&lang=en) (accessed on 7 December 2021).
37. *BS EN 1338:2003*; British Standards. Concrete Paving Blocks—Requirements and Test Methods. British Standards Institution: London, UK, 2003. Available online: <https://www.thenbs.com/PublicationIndex/documents/details?Pub=BSI&DocID=263759> (accessed on 6 December 2021).
38. C15 Committee. *Specification for Solid Concrete Interlocking Paving Units*; ASTM International: West Conshohocken, PA, USA, 2013. [[CrossRef](#)]
39. *SLS 1425 Part 1*; Specification for Concrete Paving Blocks: Part 1: Requirements. Sri Lanka Standards Institute: Colombo, Sri Lanka, 2011.
40. *SLS 1425 Part 2*; Specification for Concrete Paving Blocks: Part 2: Requirements. Sri Lanka Standards Institute: Colombo, Sri Lanka, 2011.
41. Ling, T.-C.; Nor, H.; Hainin, M.R.; Chik, A.A. Laboratory performance of crumb rubber concrete block pavement. *Int. J. Pavement Eng.* **2009**, *10*, 361–374. [[CrossRef](#)]
42. Nataraja, M.C.; Das, L. A Study on the Strength Properties of Paver Blocks Made from Unconventional Materials. *J. Mech. Civ. Eng.* **2014**, *4*, 1–5. Available online: <https://www.semanticscholar.org/paper/A-study-on-the-strength-properties-of-paver-blocks-Nataraja-Das/073ff4a991a9dfe933ae713a5c59eb3e6df53b56> (accessed on 10 November 2021).
43. Purwanto, P.; Priastiwi, Y.A. Testing of Concrete Paving Blocks the BS EN 1338:2003 British and European Standard Code. *Teknik* **2008**, *29*, 80–84. [[CrossRef](#)]
44. Singh, M. Coal bottom ash. In *Waste and Supplementary Cementitious Materials in Concrete*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 3–50. [[CrossRef](#)]
45. Sukontasukkul, P.; Chaikaew, C. Concrete Pedestrian Block Containing Crumb Rubber from Recycled Tires. *Sci. Technol. Asia* **2005**, *10*, 1–8.
46. Aslantas, O. *A Study on Abrasion Resistance of Concrete Paving Blocks*; Natural and Applied Sciences of Middle East Technical University: Ankara, Turkey, 2004.
47. Haktanir, T.; Ari, K. Indirect Determination of Splitting strength and abrasion resistance of concrete paving blocks as a function of dry bulk specific gravity and ultrasonic pulse velocity. *Mater. Constr.* **2005**, *55*, 5–12. [[CrossRef](#)]
48. Mavroulidou, M.; Figueiredo, J. Discarded Tyre Rubber as Concrete Aggregate: A Possible Outlet for Used Tyres. In Proceedings of the 2013 International Conference on Current Trends in Engineering and Technology (ICCTET), Coimbatore, India, 3 July 2010; Volume 12, pp. 359–367.
49. Hussain, I.; Ali, B.; Rashid, M.U.; Amir, M.T.; Riaz, S.; Ali, A. Engineering properties of factory manufactured paving blocks utilizing steel slag as cement replacement. *Case Stud. Constr. Mater.* **2021**, *15*, e00755. [[CrossRef](#)]
50. Djamaluddin, A.R.; Caronge, M.A.; Tjaronge, M.; Lando, A.T.; Irmawaty, R. Evaluation of sustainable concrete paving blocks incorporating processed waste tea ash. *Case Stud. Constr. Mater.* **2019**, *12*, e00325. [[CrossRef](#)]
51. Liu, Y.; Zhuge, Y.; Chow, C.W.; Keegan, A.; Li, D.; Pham, P.N.; Huang, J.; Siddique, R. Utilization of drinking water treatment sludge in concrete paving blocks: Microstructural analysis, durability and leaching properties. *J. Environ. Manag.* **2020**, *262*, 110352. [[CrossRef](#)]

52. Evangelista, B.L.; Rosado, L.P.; Penteadó, C. Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute. *J. Clean. Prod.* **2018**, *178*, 176–185. [[CrossRef](#)]
53. de Rosso, L.T.; de Melo, J.V.S. Impact of incorporating recycled glass on the photocatalytic capacity of paving concrete blocks. *Constr. Build. Mater.* **2020**, *259*, 119778. [[CrossRef](#)]
54. Soni, R.; Mathur, D. An Experimental Study on Using of Commercialized Crumb Rubber in Interlocking Concrete Paver Block. *Int. J. Recent Res. Rev.* **2020**, *13*, 25–29.
55. Aboelkheir, M.G.; Thomas, S.; de Souza, F.G.; Filho, R.D.T.; Celestino, R.; Filho, S.T.; de Carvalho, F.V.; Maranhão, F.D.S.; Pereira, E.D.; da Costa, V.C.; et al. Influence of UV-modified GTR on the properties of interlocking concrete paving units. *J. Mol. Struct.* **2021**, *1234*, 130110. [[CrossRef](#)]
56. Ling, T.-C. Effects of compaction method and rubber content on the properties of concrete paving blocks. *Constr. Build. Mater.* **2012**, *28*, 164–175. [[CrossRef](#)]