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Microstructural analysis and compressive strength evaluation of interlocking concrete paving blocks incorporating crumb rubber

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ABSTRACT: Imaging Analysis Techniques (IATs) have become instrumental in civil engineering materials research, providing critical insights into the microstructural characteristics of mixtures and enabling associations between these features, numerical parameters, and laboratory-derived mechanical performance data. However, using IATs specifically for Concrete Paving Blocks (CPBs), particularly when modified with crumb rubber (CR), remains underexplored. In this study, two numerical parameters derived from IATs – interlocking parameter (P_{INT}) and interlocking rate (I_R) – were investigated for their correlations with the estimated compressive strength ($f_{pk,est}$) of CPBs after a 28-day curing period. CPBs were prepared with CR at 5%, 10%, 15%, and 20% by mass, with a reference concrete mixture designed per American standards for no-slump concrete and a target $f_{pk,est}$ of 50 MPa. P_{INT} and I_R were calculated using custom Python-based software developed by the authors. Consistent with prior findings, increasing CR content resulted in a decrease in $f_{pk,est}$, a trend that was well-represented by linear and power regression models. Both I_R and P_{INT} showed potential for explaining the reductions in $f_{pk,est}$, with I_R demonstrating stronger predictive capabilities. Consequently, I_R proves to be a promising parameter for describing the microstructural characteristics of CPBs, whether containing CR or not, due to its consistently good correlations with both $f_{pk,est}$, and CR content.

Keywords: compressive strength; concrete paving blocks; crumb rubber; microstructural parameters; slump test.

Análise microestrutural e avaliação da resistência à compressão de blocos de concreto intertravados para pavimentação incorporando borracha triturada

RESUMO: *As técnicas de análise de imagens (TAIs) tornaram-se instrumentais na pesquisa de materiais de engenharia civil, fornecendo insights críticos sobre as características microestruturais de misturas e permitindo associações entre* *essas características, parâmetros numéricos e dados de desempenho mecânico derivados de laboratório. No entanto, o uso de TAIs especificamente para blocos de concreto, particularmente quando modificados com borracha triturada, permanece pouco explorado. Neste estudo, dois parâmetros numéricos derivados de TAIs – parâmetro de intertravamento (P_{INT}) e taxa de intertravamento (I_R) – foram investigados para suas correlações com a resistência à compressão estimada ($f_{pk,est}$) dos blocos de concretos após um período de cura de 28 dias. Os blocos de concretos foram preparados com CR a 5%, 10%, 15% e 20% em massa, com uma mistura de concreto de referência projetada de acordo com os padrões americanos para concreto sem abatimento e um $f_{pk,est}$ alvo de 50 MPa. P_{INT} e I_R foram calculados usando software personalizado baseado em Python, desenvolvido pelos autores. Corroborando descobertas anteriores, o aumento do conteúdo de borracha triturada resultou em uma diminuição em $f_{pk,est}$, uma tendência que foi bem representada por modelos de regressão linear e de potência. Tanto I_R quanto P_{INT} mostraram potencial para explicar as reduções em $f_{pk,est}$, com I_R demonstrando capacidades preditivas mais fortes. Consequentemente, I_R prova ser um parâmetro promissor para descrever as características microestruturais de blocos de concretos, contendo borracha triturada ou não, devido às suas correlações consistentemente boas com $f_{pk,est}$ e conteúdo de borracha triturada.*

Palavras-chave: *blocos de pavimentação de concreto; borracha triturada; parâmetros microestruturais; resistência à compressão; teste de abatimento.*

1 Introduction

Interlocking Concrete Paving Blocks (CPBs), commonly known as pavers, represent an advancement of rectangular paving stones first introduced in Germany at the end of the nineteenth century and extensively used until the 1950s. In the United States, the initial CPB production facility was established in New Jersey in 1969, marking the beginning of multisided paver manufacturing. Brazil adopted CPBs during the 1960s, following similar trends in countries such as South Africa and Argentina (Jewell, 1982). Significant CPB applications in Brazil include urban development projects, such as the construction of light and heavy traffic roads in Rio de Janeiro, where over one million square meters of pavers were utilized, and the renovation of two major avenues in Fortaleza – Beira-Mar and Desembargador Moreira – each requiring more than seventy thousand square meters of CPBs (Cruz, 2003; Silva *et al*., 2023a, 2023b).

The versatility of Portland cement concrete allows CPBs to incorporate various types of waste materials, such as recycled aggregates (Rahman *et al*., 2020; Silva *et al*., 2023b; Wang; Chin; Xia, 2019), marble waste (Yeo *et al*., 2021), and foundry sand (Patil; Sathe, 2021). Crumb rubber (CR) is another waste material discussed in recent literature (Mohamad *et al*., 2022; Yeo *et al*., 2021). In Brazil alone, approximately 450,000 tons of tires are discarded annually (Moreno, 2022), making the exploration of viable applications for this waste an important research area. Previous laboratory studies generally indicate that replacing a portion of fine aggregates in CPBs with CR tends to reduce compressive strength (Adeboje *et al*., 2021; Ling, 2011, 2012; Ling; Nor; Kim, 2010; Rethinavelsamy; Chidambarathanu, 2016; Silva *et al*., 2015; Wang; Chin; Xia, 2019). For this reason, the literature typically recommends CR contents ranging from approximately 1%-6% (Adeboje *et al*., 2021; Wang; Chin; Xia, 2019; Yeo *et al*., 2021) to as much as 10%-20%

by volume (Ling, 2012; Ling; Nor; Kim, 2010; Meng; Ling; Mo, 2018; Rethinavelsamy; Chidambarathanu, 2016; Silva *et al*., 2015).

In the Brazilian standards for CPBs (ABNT, 1987, 2013) there is a minimum characteristic compressive strength ($f_{pk,est}$) of 35 MPa required for the use of pavers on streets or highways with light traffic levels. In the case of heavy traffic levels, the $f_{pk,est}$ value should be no lower than 50 MPa. Few national publications have reached $f_{pk,est}$ values of 50 MPa or closer for CPBs with alternative materials, e. g., CR (Silva *et al*., 2015), recycled sand from crushed polyethylene terephthalate (Pedroso, 2023) and marble powder (Carvalho *et al*., 2023). One of the issues regarding the preparation of CPBs with CR is the fact that the rubber particles create micropores in the concrete matrix (Silva *et al*., 2015; Yeo *et al*., 2021). However, the choice for a proper amount of rubber makes it possible to increase the compressive strength, rather than decreasing it. In such a case, this proper rubber content is enough to be evenly distributed throughout the concrete, thereby leading to an even distribution of the load in the CPB and increasing its compressive strength. In a microscopic scale, this phenomenon can be explained by the rubber particles filling in the voids between the aggregates under loading and bonding well with the cement matrix (Ling, 2012; Silva *et al*., 2015).

Brazilian standards for CPBs (ABNT, 1987, 2013) specify a minimum characteristic compressive strength ($f_{pk,est}$) of 35 MPa for pavers intended for light-traffic streets and highways, with a requirement of at least 50 MPa for heavy-traffic applications. Few Brazilian studies have achieved $f_{pk,est}$ values around or above 50 MPa for CPBs made with alternative materials such as CR (Silva *et al*., 2015), recycled sand from crushed polyethylene terephthalate (Pedroso, 2023), and marble powder (Carvalho *et al*., 2023). One challenge when producing CPBs with CR is that rubber particles can create microvoids in the concrete matrix (Silva *et al*., 2015; Yeo *et al*., 2021). However, selecting an optimal CR content can improve compressive strength by distributing rubber particles uniformly, enhancing load distribution, and reducing voids in the matrix. At the microscopic level, this effect may be due to the rubber particles filling gaps between aggregates under loading, thereby improving bonding with the cement matrix (Ling, 2012; Silva *et al*., 2015).

Thus, incorporating CR does not necessarily reduce compressive strength. Moreover, Imaging Analysis Techniques (IATs) provide valuable insights into the role of rubber particles in influencing the mechanical properties of CPB. Various IATs are employed to analyze materials, including concrete, such as computed tomography, neutron radiography, high-resolution cameras, X-rays, and line-scan cameras. Since the 1990s, these techniques have been extensively applied to asphalt mixtures (Bessa; Branco; Soares, 2012; Masad *et al*., 1999; Sefidmazgi; Tashman; Bahia, 2012; You; Adhikari; Kutay, 2009; Yue; Bekking; Morin, 1995) to correlate microstructural data with mechanical performance metrics, including the flow number (Sefidmazgi; Tashman; Bahia, 2012) and dynamic modulus (You; Adhikari; Kutay, 2009).

However, studies that directly compare CPB mechanical properties, particularly compressive strength, with IAT data remain scarce. Some researchers have utilized IATs to detect cracks, measure water absorption, analyze Poisson's ratio, and investigate microstructures, which can be correlated with compressive strength (Cho *et al*., 2024; Kim *et al*., 2021; Salák; Khmurovska; Štemberk, 2021). Other studies have focused primarily on porosity (Zhang *et al*., 2018), ultrasonic pulse velocity, and other non-destructive testing methods (Rathan; Sunitha, 2022; Rethinavelsamy; Chidambarathanu, 2016). Consequently, further research is needed to explore the relationship between IAT-derived parameters and the mechanical properties of CPB.

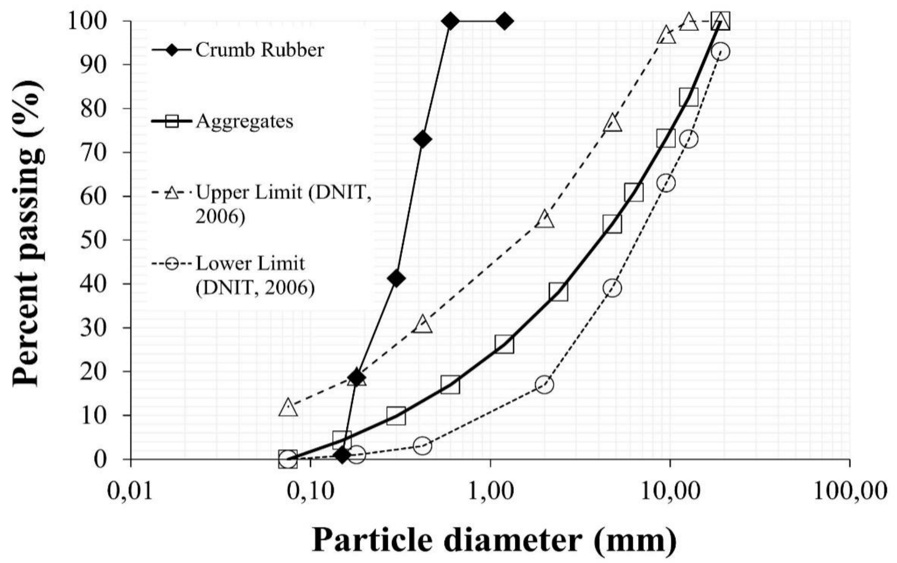
Accordingly, this study aims to: (a) propose a microstructural parameter based on IAT-derived data; (b) analyze the relationship between CR content and the 28-day compressive strength of CPBs; and (c) assess potential correlations between this microstructural parameter and compressive strength.

The structure of this paper is as follows: Section 2 provides details on the concrete mix designs, quantities, and design guidelines, as well as descriptions of laboratory tests and statistical analyses. Section 3 presents the primary findings on compressive strength and workability, alongside trendlines correlating CR content with compressive strength. Moreover, this section provides statistical analyses that focus on CR particle effects on CPB mechanical properties. Section 4 summarizes the main conclusions and offers recommendations for future research.

2 Experimental design

Aggregates of rhyolite sourced from the Guaricana quarry, situated in São José dos Pinhais, Paraná, Brazil, were selected for this study. The aggregates possess a Los Angeles abrasion index of 8.1% (DNER, 1998), a shape index of 1.3% (DER-PR, 1996), and a sand equivalency of 66% (DNER, 1997). The granulometric curve meets the Band "C" specifications defined by the National Department of Transport Infrastructure (DNIT, 2006). Figure 1 displays the final granulometric curve for the aggregates alongside the curve for the crumb rubber (CR) particles.

Figure 1 ▶ Granulometric curves of the aggregates and the crumb rubber particles. *Source: research data*



The Alfred particle packing model was employed in this study to enhance aggregate interlock and thereby improve the compressive strength of the reference concrete, designated as *C0*. Proper optimization of particle packing reduces voids in the granular skeleton, leading to decreased cement consumption; however, this packing efficiency is influenced by the characteristics of the aggregates (Londero *et al*., 2017; Moini *et al*., 2015; Sohail *et al*., 2018). Research indicates that this model delivers superior results to other packing models, optimizing aggregate interlock, minimizing voids, and reducing Portland cement consumption (Campos *et al*., 2022; Londero; Klein; Mazer, 2021). The anticipated outcome is that increased packing density will decrease concrete porosity and improve strength. Equation 1 describes the calculation of the cumulative percentage finer than a specific particle diameter (P_{per}),

$$P_{per} = 100 \times \left(\frac{D^q - D_s^q}{D_L^q - D_s^q} \right) \tag{1}$$

where D is particle diameter (in mm), q is a distribution coefficient (set at 0.37 to maximize density), D_s is the smallest particle diameter (in mm) and D_L is the largest particle diameter (in mm).

Four CR contents – 5%, 10%, 15%, and 20% by mass – were selected based on recommendations from existing literature and the observation that a 20% substitution results in a resistance loss exceeding 80%. These mixtures were designated *C5*, *C10*, *C15*, and *C20*, respectively. The partial replacement of aggregate mass with CR is extensively documented in the literature (Silva *et al.*, 2015; Sukontasukkul; Chaikaew, 2006; Wang; Chin; Xia, 2019). In this study, CR particles, sourced from recycled truck tires, replaced a portion of the fine aggregate fraction in the concrete, a substitution approach commonly adopted in similar investigations (Meng; Ling; Mo, 2018; Mohamad *et al.*, 2022; Yeo *et al.*, 2021).

The target compressive strength ($f_{pk,est}$) for the reference concrete *C0* was set at 50 MPa, and the American Concrete Institute method for no-slump concretes (ACI, 2002) was applied. High early strength Portland cement (CP V-ARI) was used due to its high purity, facilitating the early demolding of concrete block pavers (CPBs) and enabling large-scale production, if required. To address the low water-cement ratio (*w/c*) of 0.45, a superplasticizer additive at 0.25% by mass was included in all mixtures to achieve adequate workability during sample preparation.

For control purposes, cylindrical samples (10 cm diameter and 20 cm height) were cast according to NBR 5738 standards (ABNT, 2003). The reference concrete (*C0*) mix proportions were set at 1:2.358:2.095:0.455, respectively, for Portland cement, fine aggregate, coarse aggregate, and water. Table 1 summarizes the material quantities used in all concrete mixes, including *C0*, to produce approximately 59 kg of concrete per batch. The concrete mixes were manually prepared in a small-scale mixer in the Civil Engineering laboratories at the Federal University of Technology – Paraná (UTFPR), Curitiba campus, and were vibrated on a vibratory table to ensure homogeneity in the CPB molds. Figure 2 shows images of surfaces of Type I CPBs (ABNT, 2013) after demolding.

Table 1 ▼
Dosages of the reference concrete *C0* and mixes with crumb rubber particles.
Source: research data

ID	Crumb rubber content (% by mass)	Quantitative of materials per concrete dosage (kg)					
		Superplasticizer	Water	Portland cement	Crumb rubber	Coarse aggregate	Fine aggregate
C0	–	0.025	4.55	10.00	–	20.95	23.58
C5	5.0	0.025	4.55	10.00	0.8	20.95	22.77
C10	10.0	0.025	4.55	10.00	1.6	20.95	21.98
C15	15.0	0.025	4.55	10.00	2.4	20.95	21.18
C20	20.0	0.025	4.55	10.00	3.2	20.95	20.38

Figure 2 ▶
Surfaces of the pavers with (a) 10% of crumb rubber by mass and (b) 20% of crumb rubber by mass.
Source: authors' archive


(a) (b)

2.1 Compressive strength tests and consistency of the mixtures

The current Brazilian standard for CPBs (ABNT, 2013) outlines a protocol for compressive strength testing. Samples, cured for 28 days in a controlled environment at a temperature of 22 °C and relative humidity above 80%, with dimensions of 10 cm in width, 20 cm in length, and 8 cm in height, were initially immersed in a water bath at 23 ± 5 °C for a minimum of 24 hours. Subsequently, these saturated samples were tested using a DL30000N device with a maximum load capacity of 30 kN, at ambient temperature. The load application rate was set to 550 ± 200 kPa/s, as specified by the standards. To ensure uniform load distribution, auxiliary plates were placed on the top and bottom of each sample. The corresponding failure load (F) was then recorded.

An adequate number of replicates was prepared for each mixture type, and statistical analysis of individual results was conducted to determine the characteristic strength value, denoted as $f_{pk,est}$. It is noteworthy that abrasion testing is not required for CPB approval for paving in Brazil, so this test was omitted from the experimental procedures. In addition, a one-factor Analysis of Variance (ANOVA) was applied (Ikpa *et al.*, 2021; Ståhle; Wold, 1989) to detect any statistically significant differences in $f_{pk,est}$ values with varying CR content.

The consistency of each concrete mixture was evaluated using the slump test, per NM 67 standard (ABNT, 2020), with a single replicate tested for each concrete type. Target slump values vary among sources, for instance, approximately 10 mm (Irmawaty; Noor; Muhaimin, 2020) and between 30 mm and 60 mm (Amin *et al.*, 2022). Typically, Portland cement concretes intended for paving applications have slump targets below 50 mm (Fanijo *et al.*, 2023).

2.2 Microstructural analysis and parameter correlations

After the curing process, a CPB sample from each CR content category was vertically sawed at its midpoint. A Python-based software program, developed by the authors, was applied to the scanned cross-sections of each CPB to calculate the interlocking parameter (PINT), following methodologies outlined in the literature (Polaczyk *et al.*, 2023). Aggregate particles (APs) were automatically identified and delineated with red borders, while contact points between particles were counted to determine the PINT value. CR particles were excluded from this analysis, as only APs were considered. Due to software limitations, APs smaller than 4.76 mm (those passing through a #4 sieve) were omitted from PINT calculations for CR contents

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of 15% and 20%. However, these smaller particles contribute to granular packing and reduce concrete porosity. Figure 3 provides a representative image showing APs outlined in red within the concrete matrix of a CPB without CR.

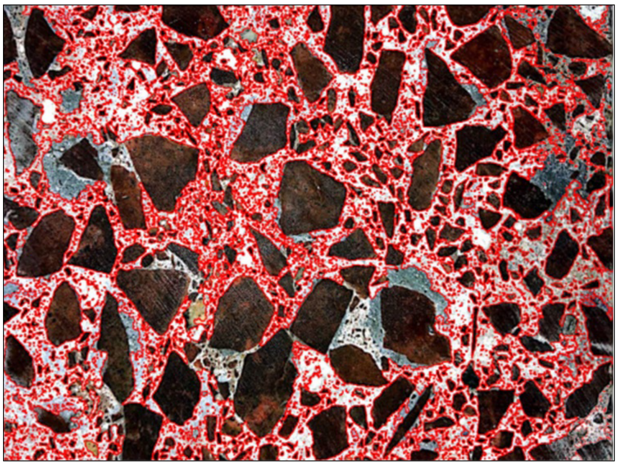

Figure 3 ► Transversal section of a paver reference concrete without crumb rubber, showing aggregate particles surrounded by red lines. *Source: authors' archive*

Direct correlations between P_{INT} and $f_{pk,est}$ values were investigated. Preliminary analysis using recycled aggregate concretes suggested that correlating these two parameters could be justified, which prompted the use of a similar methodology for CR-based concretes.

For relationships between CR content and compressive strength, logarithmic and power trendlines are generally suggested in the literature (Bompa; Elghazouli, 2019; Lim *et al*., 2020; Ling, 2011). Linear relationships are commonly proposed for slump and CR content correlations (Thakur *et al*., 2020). This study determined the trendline types that most accurately and effectively fit the data, exploring logarithmic, linear, and power models. It should be noted that identifying a trendline does not imply causation; it only illustrates the material's response pattern relative to the independent variable (in this study, CR content) and the dependent variable ($f_{pk,est}$). Furthermore, outliers may occasionally be excluded from the analysis, as in some previous studies (Bompa; Elghazouli, 2019).

3 Results and discussion

Figure 4 illustrates an example of the slump test performed on one of the concretes modified with 5% of CR. It is observed that the slump value remained consistent at approximately 80 mm across all concrete formulations, irrespective of the CR content. This result aligns with the Brazilian standards for concretes intended for paving applications, which recommend slump values around 70 mm (DNIT, 2005). The literature presents varied perspectives on the influence of CR addition on the workability of fresh concrete. While some studies (Amin *et al*., 2022; Irmawaty; Noor; Muhaimin, 2020; Soni; Mathur, 2020) report reduced slump values with increasing CR content, others (Awan *et al*., 2021; Thakur *et al*., 2020) highlight increases in slump at higher CR levels. The behavior of fresh concrete observed in this study aligns with the findings of Bignozzi and Sandrolini (2006), who reported negligible variations in slump for concretes with CR contents up to 34%. Thus, a standardized response of concrete slump behavior following CR addition remains undefined.

Figure 4 ▶
Example of a slump test with the corresponding result (80 mm).
Source: authors' archive

3.1 Compressive strength data

Table 2 presents the characteristic compressive strength values ($f_{pk,est}$) of the studied concretes, along with their respective statistical parameters: coefficient of variation (CV) and standard deviation (s). It is observed that $f_{pk,est}$ progressively decreases as the CR content increases. Furthermore, this reduction in compressive strength exceeds 86% for the highest CR contents (15% and 20%). Generally, none of the concrete mixtures incorporating CR particles are suitable for paving applications, as their $f_{pk,est}$ values fall below 35 MPa – the minimum compressive strength required for pavements subjected to light traffic loads (ABNT, 2013).

Table 2 ▼
Characteristic compressive strength results ($f_{pk,est}$) and corresponding statistical parameters.
Source: research data

Dosage ID	Crumb rubber content (% by mass)	$f_{pk,est}$ (MPa)	Coefficient of variation (%)	Standard deviation (MPa)
C0	0.0	49.34	1.31	0.65
C5	5.0	33.60	5.14	1.75
C10	10.0	13.43	8.24	1.13
C15	15.0	6.74	6.17	0.42
C20	20.0	6.27	15.99	1.05

These results align closely with previous studies, which also documented reductions in $f_{pk,est}$ values with increasing rubber content (Adeboje *et al.*, 2021; Awan *et al.*, 2021; Fauzan *et al.*, 2021; Irmawaty; Noor; Muhaimin, 2020; Ling, 2011, 2012; Ling; Nor; Kim, 2010; Rethinavelsamy; Chidambarathanu, 2016; Silva *et al.*, 2015; Soni; Mathur, 2020; Thakur *et al.*, 2020; Wang; Chin; Xia, 2019).

The progressive reduction in $f_{pk,est}$ with CR incorporation can be attributed to several factors, including the weak bonding between rubber particles and the cement paste, challenges encountered during the mixing process (particularly with *C20*), uneven stress distribution within the concrete matrix, the low specific gravity, and the rounded morphology of the CR particles. Furthermore, the high elasticity of CR particles may contribute to the formation of micro-cracks within the concrete matrix under compressive loads (Fauzan *et al*., 2021; Irmawaty; Noor; Muhaimin, 2020; Ling; Nor; Kim, 2010; Thakur *et al*., 2020).

The standard deviations and coefficients of variation observed are relatively low, indicating a homogeneous manufacturing process and consistent testing procedures, which result in minimal variability in the compressive strength of the specimens. Figure 5a illustrates that the relationship between $f_{pk,est}$, and CR content follows a linear trend. However, when data from the reference concrete is excluded, a power trendline better represents the relationship between these variables (Figure 5b). The reported R^2 values align with those found in the literature, ranging from 0.73 to 0.98 (Lim *et al*., 2020; Ling, 2011; Thakur *et al*., 2020).

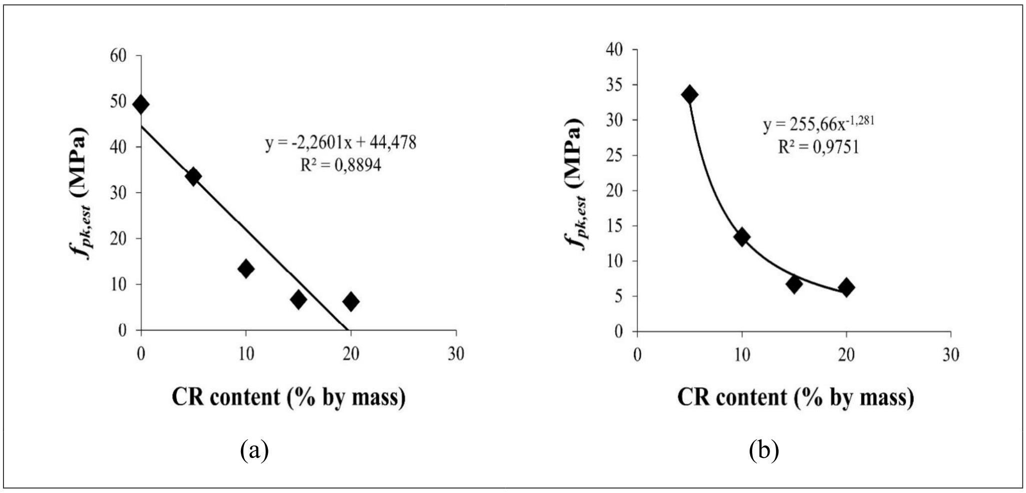

Figure 5 ► (a) Linear correlation and (b) power correlation between the characteristic compressive strength of the pavers ($f_{pk,est}$) and their corresponding crumb rubber (CR) contents.
Source: research data

Based on the results in Table 2, a statistical analysis was conducted using ANOVA and a comparison of means through the Tukey-Kramer test, with a significance level of 5%. The analysis revealed that the incorporation of CR into the concrete resulted in a reduction in compressive strength across all levels of addition. However, the mixture containing 5% CR shows potential as an alternative, provided adjustments are made to the mix design, as its compressive strength approaches 35 MPa.

3.2 Microstructural parameters and statistical analyses

Table 3 presents the P_{INT} values of all concrete dosages alongside their corresponding interlocking rates (I_R), which is defined as the ratio of P_{INT} to the total number of aggregate particles. Figure 6 provides an example of surrounded particles in the cross-sectional view of a CPB specimen containing 10% crumb rubber (CR). As anticipated, P_{INT} values decrease with higher CR contents, particularly at 15% and 20%, due to the increased presence of rubber particles compared to conventional aggregates. This trend is also observed in I_R values, as the number of potential contact points among aggregate particles declines with the addition of more CR. The reduction in aggregate-aggregate interlock at higher CR levels, coupled with factors inherent to the CR particles themselves and the orientation of the aggregates during specimen preparation, appears to be a significant determinant of the mechanical performance of these pavers. This observation aligns with prior studies on aggregate interlock behavior dating back to the 1990s (Masad *et al*., 1999; Polaczyk *et al*., 2023; Sefidmazgi; Tashman; Bahia, 2012).

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Table 3 ▶ Interlocking parameters (P_{INT}) and corresponding interlocking rates (I_R) of the pavers. *Source: research data*

Dosage ID	Crumb rubber content (% by mass)	P_{INT} value	Number of aggregate particles	I_R value (%)
C0	0.0	224	567	39.50
C5	5.0	360	946	38.05
C10	10.0	139	596	23.32
C15	15.0	67	312	21.47
C20	20.0	71	392	18.11

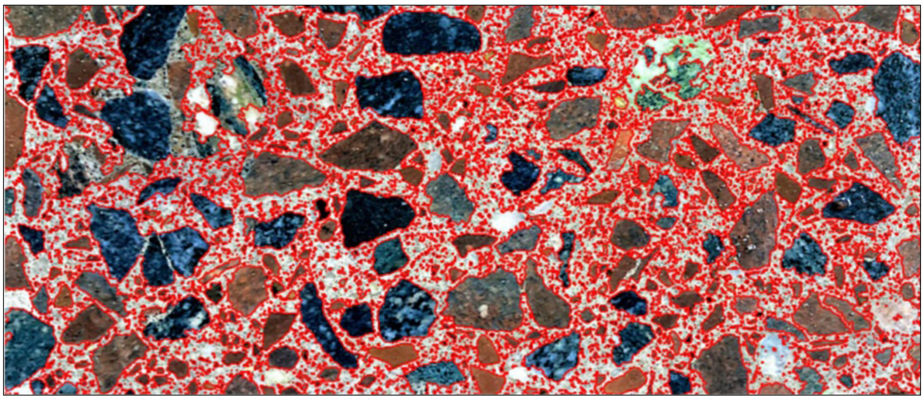

Figure 6 ▶ Cross-section of a paver with 10% crumb rubber, highlighting aggregate particles. *Source: authors' archive*

Figure 7 illustrates the linear correlations between CR content and the microstructural parameters P_{INT} and I_R. These correlations, with R^2 values around 0.6, are reasonable, with I_R showing a slightly stronger correlation than P_{INT}. Previous research suggests that combined parameters yield stronger correlations with laboratory data than individual metrics alone (Sefidmazgi; Tashman; Bahia, 2012), a finding supported here by the I_R parameter. Additionally, Polaczyk *et al.* (2023) investigated a similar parameter involving the ratio of interlocked particles to the total particle count. The findings of this study indicate that CPB performance may be better understood through composite parameters that incorporate microstructural criteria, such as the number of contact points among aggregate particles and the counting of conventional aggregates.

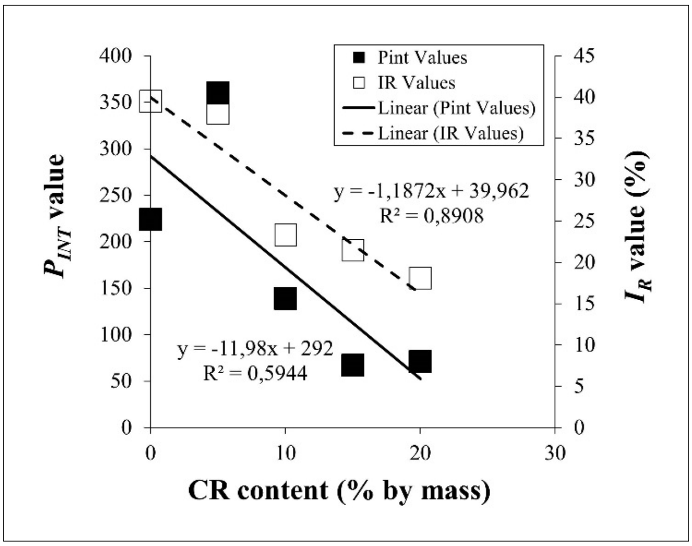

Figure 7 ▶ Linear correlations between Crumb Rubber (CR) contents and interlocking parameters (P_{INT}) and interlocking rates (I_R). *Source: research data*

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Figure 8 illustrates the power correlations between non-zero CR content and the parameters P_{INT} and I_R, yielding excellent R^2 values, consistent with previously reported values (Sefidmazgi; Tashman; Bahia, 2012). If plotted on a log-log scale, both trendlines would approximate linear relationships; however, such visualization is omitted here for brevity. As observed, I_R values appear to explain the decrease in CPB compressive strength with CR addition more effectively than P_{INT}, although distinctions between I_R and P_{INT} are less clear under power correlations. In general, either parameter provides valuable insights into the microstructural characteristics of CPBs, as illustrated in Figures 9a and 9b, which show that both P_{INT} and I_R values primarily increase with higher CPB compressive strength.

Figure 8 ▶
Power correlations among non-zero Crumb Rubber (CR) contents of the pavers and interlocking parameters (P_{INT}) and interlocking rates (I_R).
Source: research data

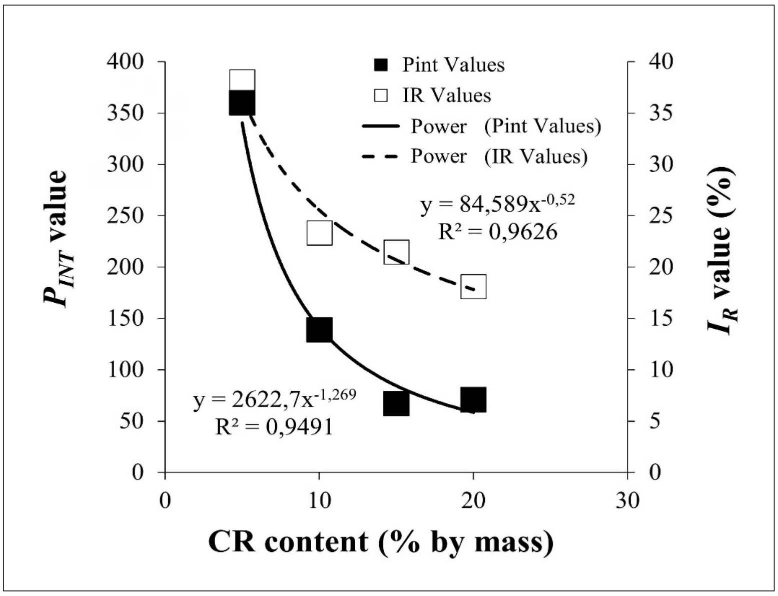

Figure 9 ▶
Linear (a) and power (b) correlations between compressive strength and interlocking parameters (P_{INT}) and interlocking rates (I_R).
Source: research data

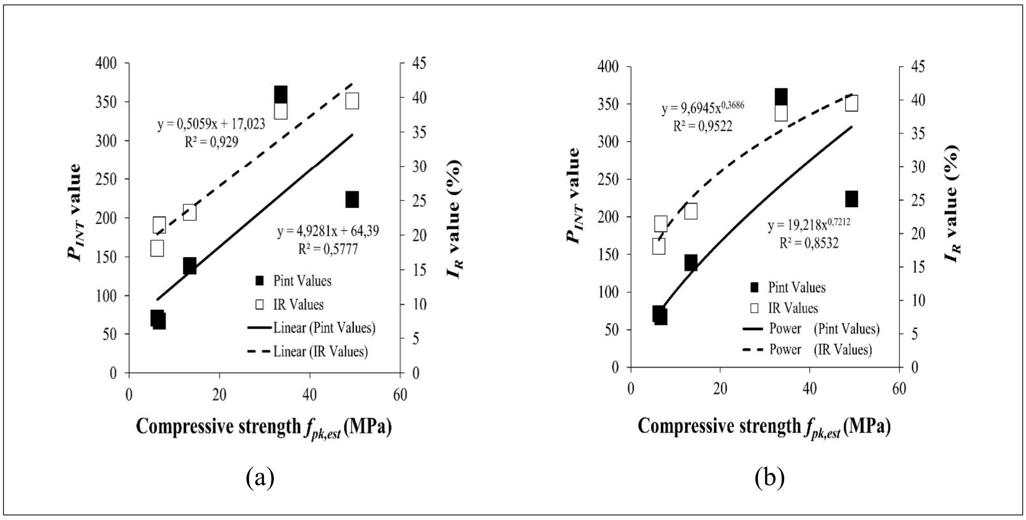

Table 4 presents the results of a one-factor ANOVA (Analysis of Variance) conducted on the compressive strength values ($f_{pk,est}$) as a function of CR content, with a 5% significance level. The p-value, approximately five times higher than 5%, suggests that the inclusion of CR particles plays a significant role in the compressive strength behavior of CPBs.

Table 4 ▶
One-factor ANOVA for characteristic compressive strength ($f_{pk,est}$) of pavers.
Source: research data

Source of variation	SQ	Degrees of freedom	MQ	Analysis of the null hypothesis (H_0)		
				F value	p-value	Critical F value
Between groups	370.11	1	370.11	1.7526	0.222	5.3176
Within groups	1689.37	8	211.17			

4 Conclusions

The following conclusions are drawn based on the data and analyses in this study:

- The incorporation of Crumb Rubber (CR) particles into the Portland cement concrete matrix for Concrete Paving Blocks (CPBs) results in a decrease in compressive strength ($f_{pk,est}$). These reductions can be well-described through linear and power regression trendlines. The literature attributes these declines to specific CR particle characteristics (e.g., rounded shapes) and factors related to aggregate interlock and bonding with cement paste;
- No variations were observed in the slump test results for the concretes containing CR particles, likely due to the low water-cement ratios and a consistent percentage of superplasticizer additives across the concrete formulations;
- The contact points between conventional aggregates, referred to as aggregate interlock (P_{INT}) in this study, serve as a valuable parameter for interpreting the microstructural characteristics of CPBs, both with and without CR in the composition. Correlations among P_{INT}, CR content, and $f_{pk,est}$ demonstrate a reasonable association.
- The combined parameter of P_{INT} relative to the total number of aggregate particles – designated here as interlocking rate (I_R) – significantly enhances the description of CPBs' microstructural features with and without CR. Correlations between I_R, $f_{pk,est}$, and CR content were consistently strong across cases.
- Both P_{INT} and I_R parameters offer useful insights into the extent of aggregate interlock within the concrete matrix, providing a basis for estimating CPBs' mechanical properties.

Future studies on this topic may consider: (a) assessing the technical feasibility of I_R and P_{INT} parameters for other concrete modifiers, such as construction and demolition waste; (b) adjusting concrete dosages to identify possible CR contents that could achieve the minimum compressive strength of 35 MPa for CPBs; and (c) conducting comparative analyses between I_R and P_{INT} findings and field/laboratory pavement section data.

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Declaration of competing interests

The authors declare no conflicts of interest.

Author contributions

DOMINGOS, M. D. I.; MAZER, W.: data analysis and/or interpretation; critical and intellectual contribution to the final manuscript revision. **GOMES, A. O.:** study/research design; data analysis and/or interpretation. **GOMES, R. O.:** study/research design. All authors contributed to the writing, discussion, review, and approval of the final version of the paper.

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