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Review

Influence of Different Types of Wastes on Mechanical and Durability Properties of Interlocking Concrete Block Paving (ICBP): A Review

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Abstract: This paper examines the compressive, flexural and tensile strength, ultrasonic pulse velocity, unit weight, water absorption, freeze-thawing, thermal and abrasion resistance, and microstructural properties of Interlocking Concrete Block Paving (ICBP) containing major industrial and agricultural wastes along with an assessment of their environmental effects, with a specific focus on recent work. The color, shape, and patterns of the blocks, their advantages, and their relationship with sustainability are discussed in this study. In addition, a limited number of studies that investigated the use of other byproducts are presented. Based on a review of the existing studies in the literature, recommendations are made for future studies. It has been determined that up to 30% inclusion of waste evaluated in ICBP provides optimal performance in terms of the evaluated properties. Moreover, as ICBP provides opportunities for low-energy concrete block production, the environmental burden and total cost of concrete and concrete block pavements can be reduced. Considering these benefits, studies performed on this subject seem promising. However, one of the missing points in ICBP is that the surface layer is not homogeneous due to the presence of various material types due to the coating design and analysis method. Therefore, modified slab analysis, layered elastic analysis, and finite element analysis can be used to analyze ICBP in detail.

Keywords: interlocking concrete block pavement; engineering properties; by-products; sustainability

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1. Introduction

One of the greatest demands of human society is the transport system, supported by important transport infrastructure assets for socio-economic development. However, more energy-efficient and sustainable transport infrastructure assets are needed as integral parts of a sustainable society. Effective street design is a good measure for viable improvement. Recently, the reduction of ecological weights has brought into question the imperative reassessment of fundamental natural aspects in road construction, construction design, and development. Every competing industry (cement and asphalt) is in an attempt to find solutions that are environmentally friendly and increasingly economical. However, in road construction, environmental conditions and road use capacity, such as raw materials used in conversion initiation, production, maintenance processes, support, reuse, and dismantling, must be taken into consideration throughout the entire life cycle [1]. For example, in the work of Al-Hasan et al. [2], recycled aggregate and partial polymer substitution were used together to improve the quality and performance of the road. The presence of polymers in roads has the advantage of being more durable by increasing the load that the road can withstand. As a result of this project, it was easily recognized that adding 15% polymer to road construction could lead to increased strength and performance. The use of recycled aggregates and polymers in this way has contributed to both ensuring sustainability by being considered an environmentally friendly technique, and to reducing costs. The cost-effectiveness of the conservation processes selected in the study of Zulu et al. [3] was examined with a Life Cycle Cost and Assessment (LCA) technique over a 30-year analysis period to quantify embodied energy and carbon emissions. These processes can be applied separately or in combination during the preventive maintenance of road pavements. Unlike these studies, state-of-the-art engineered landfills are equipped with nearly impermeable litter and cover systems, gas collection systems, and groundwater monitoring systems to minimize leachate infiltration and transport of gases released into the atmosphere. Alternative cover systems should meet regulatory requirements to minimize inflation. Various alternative cover systems have been developed, such as evapotranspiration covers, anisotropic covers, capillary barriers, and engineered turf covers that use natural processes to control the infiltration of rainwater into the waste. One of the key advantages of alternative cover systems is the reduction in construction and maintenance costs associated with conventional cover systems, as well as the reduction of damage from physical and biological processes that can lead to increased swelling. However, each of these cover systems has put certain limitations on their applicability in dynamic climatic regions. Furthermore, cover systems remain in development and need to be validated by extensive field-testing programs in order to validate laboratory findings and results. For example, in the study of Zheng et al. [4], it is stated that evaporation, transpiration, and wetting-drying cycles should be taken into account when evaluating the long-term performance of cover systems with water-repellent soils. It is stated in the study that the durability of induced water repellency is another factor that affects the long-term performance of coating systems, and further investigation of the long-term degradation of the coating is necessary. In addition to all these studies, developments related to smart and composite materials have increased their speed and become a popular research topic. It has been found that such materials as those mentioned above can undergo large reversible deformations against mechanical loading and produce high mechanical forces. Studies have shown that SMA fiber and panel geometry play an important role in the buckling and post-buckling responses of the structure. For instance, Huang et al. [5] developed a size-dependent model to provide a comprehensive analysis of static stability in bi-curved micro panels resting on an elastic foundation. In the study, the double-curved panel is made of advanced composites reinforced with carbon-based materials. The results show that CNT-reinforced composite curved shells exhibit a stiffening response under buckling. It has been noted that variation of the weight fraction of CNTs can significantly alter the static stability properties of composite curved size-dependent shells reinforced with CNTs. In a similar study performed by Bousahla et al. [6], the buckling and vibration behavior of a composite beam equipped with single-walled carbon nanotubes (SW-CNT) resting on an elastic foundation was investigated. Bourada et al. [7] presented a dynamic and stability analysis of a simple supported SWCNT-reinforced concrete beam on an elastic foundation using integrated first-order shear-deformation beam theory. The frequency responses of a sandwich disc with a lactic core (honeycomb), two middle layers containing SMA fiber, and two outer layers (multiscale hybrid nanocomposite (MHC)) are discussed in the review by Al-Furjan et al. [8]. Along with these studies, the recent application of CNTs in asphalt modification for road pavement indicates that more efforts have been made in this area. In the study of Eisa et al. [9], three different percentages of carbon nanotubes (CNTs) (0.1%, 0.5%, and 1% by mass of asphalt cement) were used to modify conventional asphalt cement (60/70). Marshall stability tests, low temperature cracking tests, indirect tensile tests, and wheel tracking tests were performed to evaluate the mechanical performance of the modified hot asphalt mix. The results of the present study confirmed the positive effect of CNTs in increasing the rutting and crack resistance of asphalt mixtures. The results showed that modifying asphalt cement with CNTs reduces its penetration and increases its kinematic viscosity and softening point. However, that study had limitations due to restrictions on measurement possibilities and available data. In a similar study by Ismael et al. [10], cost analysis results determined 1.5% of CNT mixed with 40/50 bitumen as the economic feasibility threshold, and it was emphasized that using a higher dosage or softer bitumen could eliminate its applicability. Despite all these developments, bitumen cannot maintain its original shape, which causes permanent deformation under high-temperature pavement deterioration under traffic loads; at low temperatures, the bitumen loses its elasticity and starts to crack due to the rigid structure formed. These phenomena reveal that unmodified bitumen is unable to withstand the increase in traffic volume and load and that the pavement's ability to withstand wide temperature ranges throughout its service life is limited. However, it is always a challenge to choose the most suitable modifying agent for asphalt to ensure rutting resistance and flexibility. In addition, due to the high unit cost of the concrete road and the asphalt road, the production of bitumen is becoming more difficult every day. Moreover, despite published studies on bitumen modified with nano-additives, current information on how nano-additives affect the overall performance and overall cost of the asphalt mix remains in development. Noticing the various flaws in these paths, researchers have turned to other options. Here, the idea bringing road construction technologies to the present in accordance with the current era has been put forward. As a result, a concept called "Interlocking Concrete Block Paving" (ICBP) has been introduced. This concept is based on the theme of "Stone Paving" which dates back a thousand years ago in the world. The modern version of ICBP was produced as a replacement for burnt bricks in the late 1940s. ICBP was introduced as an alternative to brick paving and became identified as a durable paving material. In addition, it is known that ICBP that complies with 4R policies (reclaim, recycle, reuse, and reduce) has high reuse potential. Although it had a place for designers with its aesthetic outlook in the early days, over time its superior aspects compared to other techniques have emerged. Consequently, ICBP has seen far-reaching used for commercial, municipal and industrial applications from the 1960s until today [11].

ICBP has pros and cons. While it is able to handle heavy loads and abrasive traffic even if the subfloor is weak, being reusable throughout its 20-year design life, requiring almost no maintenance, being resistance to the environment, and reducing the damage caused by fuel and oil spillage, its performance is low in humidity and low-speed applications. The fact that the unit cost of an ICBP surface paving is 50% less than the unit cost of Portland cement is important in terms of economic savings. Although the initial cost of ICBP is high, it is balanced with low maintenance costs in LCA. In addition, the disadvantages can turn into advantages when conditions such as the quality of the material, availability, cost of the material, and traffic conditions are known [12].

The advantages and disadvantages of ICBP against other known parquet types are presented below [13];

- While the initial cost of ICBP is high compared to both concrete blocks and asphalt pavement, the final cost is low.
- ICBP has superior toughness and strength compared to concrete blocks. These blocks help mechanize the combined load-bearing mechanisms that combine the hinge formation at joints and the bending of blocks.
- Compared to asphalt pavement, ICBP has a faster construction time and relatively easy maintenance and rehabilitation.
- Available in different sizes, shapes, and flooring patterns to provide horizontal and vertical locking. The joint sand provides the joints between adjacent blocks, while the bedding sand creates a smooth surface on which the blocks can placed at the same level, resulting in vertical and rotational locking. The performance of bedding and joint sand depends on a variety of factors, including layer thickness, grading, angularity, moisture, and mineralogy; the absence of any individual locking type results in a deficiency in the pavement system. Therefore, bedding and joint sand must have certain properties, such as a certain size and grade, to ensure maximum bonding.

- Thanks to increasing recycling technologies, the excess of different waste materials reduces the environmental burden and total cost of concrete and concrete block pavements, as it provides opportunities for the production of low-energy concrete blocks for ICBP.
- The pavement design and analysis method cannot be used directly on the surface layer because the surface layer is not homogeneous due to various material types. Therefore, it has been indicated that modified slab analysis, layered elastic analysis, and finite element analysis can be used to analyze ICBP.
- The ICBP system provides a more uniform response against wheel loads with flexural hardening, and allows block separation at the ultimate load.
- It is possible to develop related models by examining properties of ICBP such as joint width and traffic load.

2. Literature Review

Large amounts of industrial waste or byproducts accumulate each year in both developing countries and industrialized countries, leading to research on whether these byproducts can be incorporated into the concrete industry. Construction demolition wastes, most of which are mineral-based, can be used as recycled aggregate in concrete after passing through the separation, screening, and crushing stages. Apart from recycled aggregates, other construction wastes such as plastic, wood, and metal (less than mineral-based ones) can be used. In addition, it has recently become popular to use agricultural wastes in this sector, with research into their mechanical and physical properties and the obtained contributions ongoing. There are several studies on the recycling of various waste materials and their incorporation into ICBP production. In these studies, how the byproducts or wastes included in ICBP affect properties such as compressive and splitting tensile strength flexural strength, water absorption, porosity, freeze-thaw, abrasion resistance, and efflorescence state were surveyed and the results were interpreted. Koksal et al. [14] created a mixture design by using 10%, 20%, and 30% Bottom Ash (BA) replacement of cement to investigate the effects of recycling of BA in ICBP production. Research on the subject includes testing of many parameters, such as unit weight, absorption, compressive and splitting tensile strength, freeze-thaw, abrasion, and leaching tests on samples. The results of the study found that the use of up to 20% BA in ICBP improves its wear and freeze-thaw properties. Uygunoglu et al. [15] comprehensively examined the effect on splitting tensile strength, density, apparent porosity, water absorption by weight, abrasion resistance, alkali–silica reaction (ASR), and freeze-thaw resistance of Fly Ash (FA) (10–40%) amount and replacement of Crushed Sand Stone (CSS) aggregate with concrete wastes and Marble Waste (MW) in ICBP. In the study, it was stated that FA up to 10–20% had a significant effect on ICBP in terms of the aforementioned features. The study of Cerqueira et al. [16] consists of determining the effect on compressive strength by making partial replacement of 30% processed waste glass and sand in the production of ICBP. The compressive strength test results of the study have shown that the use of processed glass waste from water treatment at this ratio provides substantial outcomes. Koganti et al.'s [17] research came out of analyzing the strength properties and comparing the cost in ICBP with partial substitution of fine aggregate byproducts in various proportions (20, 30, 40%), such as Quarry Dust (QD), GP Glass Powder (GP), Coal Dust (CD), and Ceramic Dust (CrD). Considering the strength properties, it was concluded that it is ideal to replace QD, GP, CD, and CrD at the ratio of 20%. However, CD is not suitable as an alternative to be used for the replacement of fine aggregate because it reduces strength. Although QD appears to save costs when utilized up to 40%, it limited strength increase. Santos et al. [18] partially replaced FS (0, 5, 10, 15, and 20%) and ED as aggregates. Compressive strength, size measurement, and water absorption of ICBP were investigated in this study, and the results obtained were satisfactory in terms of mechanical and physical properties. Mokhtar et al. [19] discussed the suitability and advantages of PET (Polyethylene Terephthalate) as aggregates in ICBP. They searched the impact of concrete on strength and workability by using PET aggregates as a partial component at the ratios of 0–15% in the construction of ICBP. Even though the compressive strength and density resulting from the study indicated a decrease with the increase in the amount of PET, higher compressive strength results were obtained for a 5% ratio compared to the other ratios. It has been stated that many factors such as alignment of ICBP to conventional concrete blocks, easy installation, and resistance to slipping are also preferred. In the study carried out by Cong and Truong [20], various types of fibers (nylon fiber, steel fiber, coconut fibers, glass fibers, polypropylene fibers) and FA in different proportions were added as replacement to cement, and various properties of ICBP were investigated. The results showed that the tested compressive strengths and durability properties improved after 7, 14, and 28 days of curing.

Materials and Methods

Research articles published in Science Citation Indexed Journals were collected from 2005 to 2021 by searching Scopus and Web of Science for this literature review. The search parameters consist of "interlocking concrete paving block", "by-product", "agricultural waste", and the body of the article used in the title, mechanical properties (compressive strength, flexural strength, tensile strength, abrasion and skid resistance), durability (water absorption, freezing and thawing and thermal resistance), mix design, and other keywords. In the first search, an extensive collection of articles was gathered using these keywords. Then, the abstracts of the articles were screened for their relevance to the general theme of this review, which is the mechanical and durability-related properties of waste-added ICBP and its LCA impact.

Strength is an important criterion in the design of ICBP; bearing capacity and cross-sectional areas are determined according to this criterion, which is used as a universal size. In addition, the compressive strength is directly proportional to the bending and tensile strength, stiffness, and elastic behavior. In certain climatic conditions, the only concern for parquet blocks is durability; thus, factors such as freeze-thaw and thermal resistance should be examined in studies. Even if there is no heavy vehicle traffic on the pavement blocks, as they are used for transportation and landscaping purposes the abrasion resistance must be determined. For this reason, these parameters were mainly examined in the studies, and research was carried out on sulfate resistance and alkali–silica reaction (ASR). In addition to these parameters, energy, water, raw material use, and related environmental emissions have been determined for different wastes participating in ICBP, and savings have been realized by addressing transportation costs and other economic factors.

Although a few evaluation studies have been carried out on this subject, the types of waste that have entered the literature later are not included in these studies; thus, they are narrower than this study. LCA with several of these wastes are involved only in this study. In addition, within the scope of this study, the shape, color, and types of ICBP have been mentioned in the last section, and offers have been made to include different additives which were determined to be the most suitable and best mechanically.

In previous works, materials revived in this work, such as waste granite dust, bottom ash, and agricultural wastes, were not studied. In addition, certain characteristics such as aesthetic value and sustainability impact were not studied. Evaluation of the results of previous studies, pros and cons of the studies, and suggestions about what can be done in future studies have been made.

3. Properties of Typical Byproducts Used in ICBP

Concrete is among the most important materials for the construction industry. However, the inconceivable consumption of resources during its production, consumption of large amounts of energy, and environmental degradation caused by cement production have partially or completely led researchers to search for suitable alternatives [21]. In this context, solutions such as the inclusion of various wastes (byproducts) partially or completely in concrete have been sought, and experimental studies have been carried out for this purpose. Several of these wastes and their general characteristics are presented below.

3.1. Industrial Wastes

3.1.1. Fly Ash

Fly ash appears as a very fine-grained mineral additive obtained by burning pulverized coal. FA, which is physically amorphous and spherical, has a grain size between 1–150 µm and an average density of 2.4 g/cm^3. Chemically, it consists of high amounts of oxides such as SiO_2, Al_2O_3, and Fe_2O_3. FA can be used in the concrete industry by replacing cement or sand. During cement production, it can be utilized as an SCM by adding it to the clinker. Studies have observed an increase in the strength and durability parameters of concretes produced using FA thanks to its pozzolanic activity. In order to limit the negative effects of FA as cement replacement, it is recommended to use a replacement ratio of up to 25% [22–25].

3.1.2. Bottom Ash

BA, or Coal Bottom Ash (CBA), is a waste material from burning powdered coal in thermal power plants. It has a grain size distribution between 20 µm and 4 mm and shows pozzolanic binding properties. While the chemical properties of BA are similar to FA, they differ in terms of morphological properties. BA is not smoothly spherical, rather it is amorphous and glassy. BA is a sustainable material that can be utilized in concrete as both a Portland cement and an aggregate replacement. In research studies, the suitability of BA used in concrete in terms of both mechanical and durability performances has been examined and it has been shown that the use of 5–20% bottom ash in mortar, concrete, and geopolymers contributes positively to the mentioned properties as well as to the sustainability of the environment [26–33].

3.1.3. Marble Waste

MW and Waste Marble Powder (WMP) are binding materials with a physical grain size of 75–150 µm, a density of 2.7 g/cm^3, and a specific weight of 2.5–2.8 g/cm^3; chemically, they have high levels of CaO (30–65%), partial proportions of SiO_2 (1.4–23.5%), and small amounts of MgO, Al_2O_3, $Fe_2O_3SO_3$, K_2O, and other compounds. In experimental studies, adding MW or WMP up to a 20% replacement ratio in concrete, reduces CO_2 emissions, ozone layer puncture risk, and provides efficient usage of agricultural lands with energy and cost savings along with improved strength and durability properties. This can pave the way for environmental and economic improvements [34–42].

3.1.4. Granulated Blast-Furnace Slag

This is an industrial by-product obtained from iron production. The physically amorphous Granulated Blast Furnace Slag (GBFS) has a density between 2.88–2.94 g/cm^3. Chemically, it consists of CaO (29–50%), SiO_2 (30–40%), Al_2O_3 (7–18%), and a small amount of Fe_2O_3 and other compounds (MgO, MnO, S). Studies have recommended that utilizations up to 30% ratios (by volume or weight) in concrete using GBFS can improve strength and durability properties and limit adverse impacts [33,43–47].

3.1.5. Glass Powder

The specific gravity of amorphous GP is 2.45, and its density is 2.6 g/cm^3. It contains a high degree of silica and it is a construction material that shows binding when it is ground below 75 µm. It is partially composed of CaO and Na_2O compounds. In studies, slump values compared to cement increased thanks to the transparency, smooth surface texture, low water absorption, and specific surface of GP [48,49]. In studies with a reduced slump, a hyper-plasticizer should be added to avoid loss of workability and placement [50]. As a result of research on the effects of GP on hardened concrete, it has been shown that using 0–20% as a cement or aggregate substitute improves its mechanical and durability properties [50–53].

3.2. Agricultural Wastes

3.2.1. Rice Husk Ash

Rice Husk Ash (RHA) has been stated to be somewhat pozzolanic, as it contains silica, reacting with calcium to produce the extra calcium silicate hydrate (C-S-H) paste, which is the binder compound of concrete [54]. It is a highly SiO_2 (about 85%) binder material with a 3–6 µm particle size, a specific gravity of about 2 g/cm^3, and a surface area of 2–37 m^2/g [55]. Consequently, it has been shown that the usage of 10–30% RHA by weight rises the compressive, splitting tensile, and flexural strength [56,57] and the elastic modulus, although it reduces the workability of fresh concrete [42,58]. In addition, studies have demonstrated that it decreases water permeability, chloridation, carbonation, ASR expansion, thermal resistance [54,59], and drying shrinkage [58], as well as increasing sulfate and electrical resistance [55,58].

3.2.2. Coconut Shell

The specific gravity of Coconut Shell (CS) is 1.05–1.20, dry bulk density 650–660 kg/m^3, water absorption 2.12%, and fineness modulus 6.55 [60–62]. It is rich in SiO_2 (45.5%), Al_2O_3 (15.6%), and Fe_2O_3 (12.4%) components [63]. It is possible to produce structural lightweight concrete or mortar with CSA (Coconut Shell Ash). Research on this subject has indicated that adding it up to 20% ratios by weight in concrete exhibits better strength at later ages compared to concrete samples in addition to reducing the pore structure of the concrete and enhancing the durability of the concrete, although increasing water absorption and sorptivity [60–62,64,65].

3.2.3. Sugarcane Bagasse Ash

Sugarcane Bagasse Ash (SBA), with a particle size of 0.1–0.2 µm, has a specific gravity of 2.2 and a density of 575 kg/m^3, and contains high amounts of silica (62%) and alumina (31.5%). It has been reported that SBA, which is used as a substitute for cement or aggregate to obtain structural concrete, improves workability and strength [66] and durability [67] properties when used at up to 20% ratios; the optimum replacement ratio is 10% [21,68–75].

The physical and chemical properties of other agricultural wastes used in the referenced studies are provided in Table 1.

Table 1. Physical and chemical properties of different agricultural waste materials [18,76–80].

	Waste Material											
										Iron Ore		
	WGrD	**PWTA**	**POFA**	**ED**	**FS**	**BOS**	**ROSA**	**PG**	**BPD**	**Floatation Tailings**	**Fine Tailings from Magnetic Separation**	**Coarse Tailings from Magnetic Separation**
Physical Properties												
Specific Gravity	2.58	2.05	2.42	2.63	2.74	-	-	-	-	-	-	-
Fineness Modulus	1.78	-	-	1.41	1.63	-	-	-	-	-	-	-
Chemical Compound (%)	-	-	-	-	-	-	-	-	-	-	-	-
SiO_2	57.12	43.74	62.6	67.25	68.49	11.43	45.91	2.43	21.86	84.40	47.90	90.40
Al_2O_3	15.79	0.46	4.65	16.91	17.41	1.60	26.51	0.81	3.85	0.45	5.61	0.43
Fe_2O_3	8.45	1.3	8.12	3.48	2.62	28.24	5.23	0.36	2.57	15.10	42.40	8.38
CaO	-	49.82	5.70	0.54	0.76	41.29	6.88	37.30	53.40	0.07	0.13	0.06
SO_3	0.12	0.32	1.16	-	3.44	0.44	1.37	53.07	7.10	-	-	-
MgO	3.29	0.11	3.52	-	-	8.27	2.13	0.40	1.13	<0.1	<0.1	<0.1
K_2O	2.76	4.04	9.05	3.08	-	0.02	1.35	0.24	3.64	0.03	0.22	0.01
TiO_2	-	-	-	1.21	0.57	0.39	1.41	0.03	0.29	0.02	0.07	<0.1
P_2O5	-	0.92	-	-	-	1.48	0.98	0.02	0.08	-	-	-
MnO	-	-	-	-	-	4.35	0.08	<0.01	0.02	0.02	0.33	0.06
Na_2O	-	-	-	-	-	0.02	0.61	0.03	0.41	-	-	-
Fe	-	-	-	-	-	-	-	-	-	10.9	29.80	6.07
FeO	-	-	-	-	-	-	-	-	-	0.52	0.27	0.28
P	-	-	-	-	-	-	-	-	-	0.024	0.214	0.035
LOI	-	12.4	6.25	3.90	5.40	3.12	7.11	4.09	5.64	0.09	2.77	0.22

4. Effect of Waste Materials on the Fresh Properties of ICBP

Workability

Three studies on the addition of different wastes to ICBP are presented in Figure 1. In the study of Murugan et al., Waste Crumb Rubber (WCR) was included in ICBP [81]. The fineness of the WCR was 3.68 and the unit weight 1.56 g/cm^3. WCR contributed positively, as it required less water than river sand and had good workability with less water. In the study of Olofinnade et al. [82]., the workability of Waste Furnace Slag (WSF) added to ICBP was investigated. WSF has a very angular particle shape and rough surface texture, with specific gravity and modulus of fineness of 3.18 and 2.68, respectively. The results of the study showed that the slump increased. Djamaluddin et al. [79] investigated the effect of using 10, 20, 30, 40, and 60% Processed Waste Tea Ash (PWTA) (specific gravity: 2.05, max. size particle: 300 µm) from agricultural waste as a cement substitute on both fresh and hardened properties of ICBP. After adding water to the mixture to prevent the precipitation of fresh ICBP, the workability of the ICBP was marked by the relationship between w/b and PWTA. The results showed that the w/b ratio increased with the increase in PWTA content. This was attributed to the porous surfaces and high surface area of PWTA.

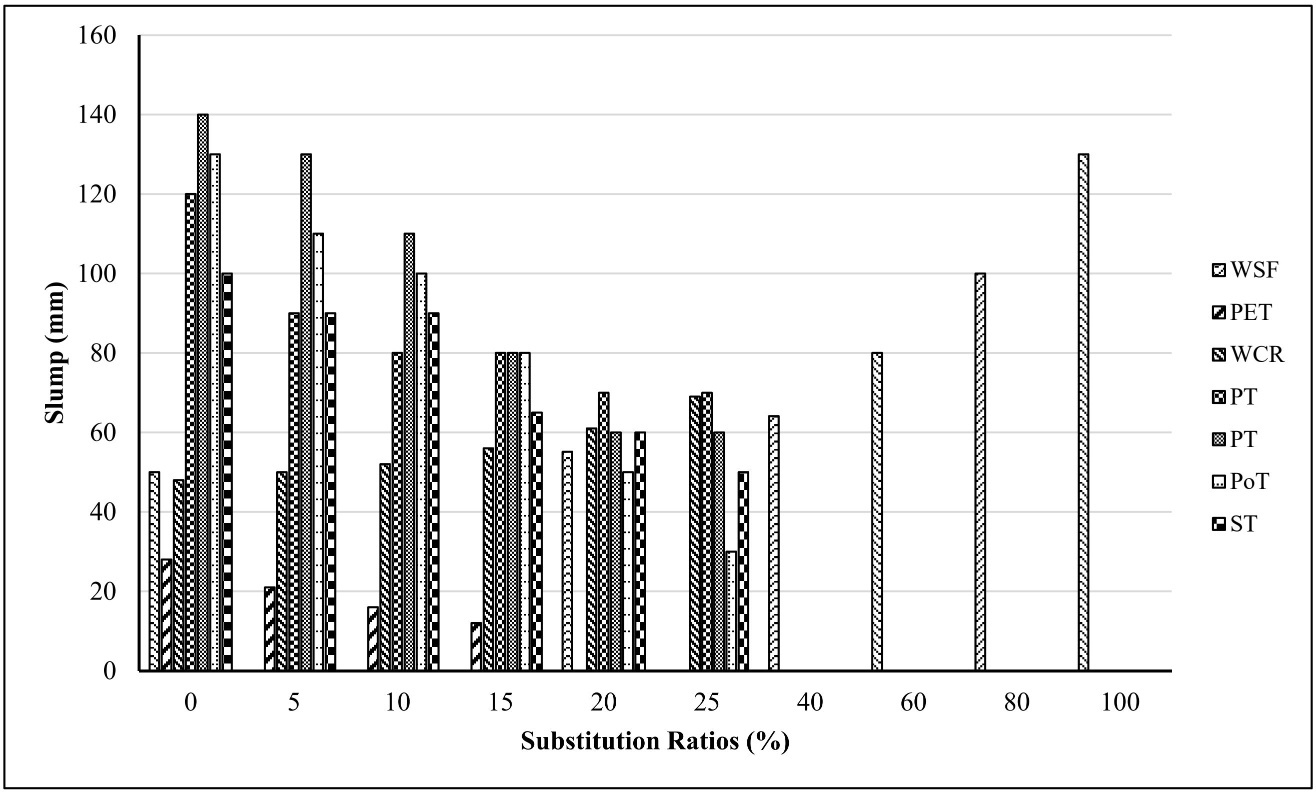


Figure 1. Slump test results of ICBP [19,81–83].

5. Effect of Waste Materials on the Hardened Properties of ICBP

5.1. Unit Weight

In Table 2, the range of the lowest and highest unit weight values obtained for the mixtures formed with the waste materials added to ICBP is given. The results obtained in the studies show that there is a general decrease in the unit weights due to the increase in the content of the waste. However, there are studies in which the unit weight increased depending on the waste addition. In Mashaly et al. [84]'s work, density values increased for up to 20% MW used in ICBP. Olofinnade et al. [82] found that the 28-day densities of ICBP increased with the rise in WSF (20–100%). They attributed this to the high bulk density and specific gravity of WSF compared to sand. The density values in the study vary between 2521–2362 kg/m^3. Similarly, the work of Agyeman et al. [85] revealed that the density increases in concrete blocks with low and high content PET added. Aggregate type and cement content, gradation, and compaction were highlighted as major factors that considerably affect the density of ICBP.

Table 2. Unit weight values of ICBPs using waste obtained from the previous studies.

Waste Material	Unit Weight (kg/m^3)	Ref.
FA-1	1750–2095	[15]
FA-2	2025–2345	
FA-3	2100–2350	
PET	1750–2250	[19]
WCR+SBA-1	1770–1800	[86]
WCR+SBA-2	1950–2075	
MW	2270–2370	[87]
	2320–2430	
PWTA	1900–2000	[79]
MW	2080–2170	[84]
FNS	2133–2880	[88]
BA	2140–2260	[14]

5.2. Compressive Strength

Tables 3 and 4 show the waste materials included in the ICBP, the percentage/percentages of replacement with the material replaced, the investigated mechanical properties, test times and their positive or negative effects on these mechanical properties, and the optimum range of additives obtained compiled from studies on the subject. The structure of wastes added to ICBP becomes denser than conventional blocks, indicating more C-S-H gel formation, resulting in increased strength. However, as seen in Table 3, strength losses increase when the amount of waste exceeds a certain value. Strength loss of mixes is due to the significant reduction of the potential C_2S and C_3S, caused by the addition of wastes, which is mainly responsible for strength. In addition to these tables, results obtained by other researchers concerning different wastes participating in ICBPs were as follows.

Ling and Poon [89] investigated the practicality of using recycled glass from discarded cathode ray tube (CRT) glass as fine aggregate in the generation of dry-mixed ICBP. Mixtures were made in two different types and compressive strength results of these mixtures were compared at 7, 28, 56 days. Compressive strength was determined according to ASTM C 349 using a universal testing machine with a maximum load capacity of 3000 kN. It was found that the compressive strength of C-PB (paving blocks with coarse aggregate) was slightly higher than that of PB (paving blocks without coarse aggregate) mixture for all glass contents. Agyeman et al. [85] manufactured composite parquet blocks by adding plastic in mixing ratios of 1:0.5:1 and 1:1:2 by weight or volume. Mostly, by using plastic waste replacement of cement the compressive strength of the samples increased at 7, 14, and 28 days. There was a significant rise for samples with high plastic content compared to both control and specimens with low plastic content. In the study of Hamid et al. [90], the strength and durability of the eco-friendly paving blocks obtained by not using waste materials such as tin and plastic, and QD replacement of fine and coarse aggregate were compared with the ICBP. Although the results do not provide satisfactory outcomes for eco-paving blocks, it should be considered that they can be used in ICBP in very small amounts. Similar results were attained in ICBP made using Recycled Coarse Aggregate (RCA) and crushed clay bricks in research carried out by Poon and Chan [91].

Table 3. Findings on the compressive strengths of ICBP's obtained using waste from the literature.

Ref.	Waste Material	Ratios (%)	Replacement	Days	Increment/Decrement	Mechanical Property
[19]	PET	0, 5, 10, 15	Fine Aggregate	28	Decrement	Compressive
[17]	QD	0, 20, 30, 40	Fine Aggregate	7, 14, 28	Increment	Compressive
	GP	0, 20, 30, 40			Up to 20% Increment	Compressive
	CrD	0, 20, 30, 40				
	CD	0, 20, 30, 40			Decrement	Compressive
[16]	GW	30	Sand	7		
[15]	FA	0, 10, 20, 30, 40	Crushed Sand Stone	28	Up to 10% Increment	Compressive
[78]	WGrD	0, 5, 10, 15, 20, 25, 30	Sand	3, 7, 28	Increment	Compressive
[82]	WSF	0, 20, 40, 60, 80, 100	Sand	7, 14, 28	Up to 40% Increment	Compressive
[87]	MW	0, 10, 20, 30, 40	Aggregate	3, 7, 28	Decrement	Compressive
[79]	PWTA	0, 10, 20, 30, 40, 60	Cement	7, 28	Decrement	Compressive
[92]	FA	0, 10, 20, 30, 40	Fine Aggregate	7, 28	Up to 10% Increment	Compressive
[81]	WCR	0, 5, 10, 15, 20, 25	Fine Aggregate	28	Decrement	Compressive
[93]	FA+GBFS	0, 10, 20, 30, 40, 50, 60	Cement	3, 7, 28, 90, 180	Decrement	Compressive
[84]	MW	0, 10, 20, 30, 40	Cement	3, 7, 28	Up to 20% Increment	Compressive
[94]	RHA	0, 5, 10, 15, 20	Cement	7, 28, 56	Up to 10–15% Increment	Compressive
[95]	Sinabung Ash	0, 5, 10, 15, 20, 25	Cement	Non-curing, 28	Up to 10–15% Increment	Compressive
	Lime	0, 5, 10, 15, 20, 25				
[88]	FNS	0, 10, 20	Lime Stone Aggregate	28	Decrement	Compressive
[89]	CRT-glass	0, 50, 100	Fine Aggregate	7, 28, 56	Decrement	Compressive
[14]	BA	0, 10, 20, 30	Cement	90	-	Compressive

Table 4. Findings from the literature on the flexural and tensile strengths of ICBPs obtained using·waste.

Ref.	Waste Material	Ratios (%)	Replacement	Days	Increment/Decrement	Mechanical Property
[78]	WGrD	0, 5, 10, 15, 20, 25, 30	Sand	3, 7, 28	Up to 25% Increment	Flexural
[79]	PWTA	0, 10, 20, 30, 40, 60	Cement	28	Decrement	Flexural
[92]	FA	0, 10, 20, 30, 40, 50	Fine Aggregate	7, 28	Up to 10–15% Increment	Flexural
[81]	WCR	0, 5, 10, 15, 20, 25	Fine Aggregate	28	Up to 10–15% Increment	Flexural
[93]	FA+GBFS	0, 10, 20, 30, 40, 50, 60	Cement	3, 7, 28, 90, 180	-	Flexural
[84]	MW	0, 10, 20, 30, 40	Cement	28	Up to 10–15% Increment	Flexural
[94]	RHA	0, 5, 10, 15, 20	Cement	28, 56	Up to 10–15% Increment	Flexural
[15]	FA	0, 10, 20, 30, 40	Crushed Sand Stone	28	Up to 10–15% Increment	Splitting
[78]	WGrD	0, 5, 10, 15, 20, 25, 30	Sand	3, 7, 28	Up to 25% Increment	Splitting
[82]	FS	0, 20, 40, 60, 80, 100	Sand	7, 28	Up to 25% Increment	Splitting
[87]	MW	0, 10, 20, 30, 40	Aggregate	3, 7, 28	Decrement	Splitting
[94]	RHA	0, 5, 10, 15, 20	Cement	28, 56	Up to 10% Increment	Splitting
[88]	FNS	0, 10, 20	Lime Stone Aggregate	28	Decrement	Splitting
[14]	BA	0, 10, 20, 30	Cement	90, 360	-	Splitting

5.3. Flexural Strength

The flexural strength of ICBPs increment with the addition of wastes can be seen in Table 4. The addition of the wastes increases the amount of paste and this helps strengthen the transition zone. The waste densifies by filling the micropores, thereby strengthening the bending characteristics of concrete. In the study of Murugan et al. [81], a flexural strength increase for up to 15% WCR participating in ICBP indicated a possible bridging of the rubber within the fracture zone, resulting in the arrest of fracture propagation. This is described as "strain hardening" in fiber-reinforced concrete under tension, where the tensile behavior has demonstrated the fiber bridging within propagating cracks. Ribeiro et al. [96] designed mixtures by adding bagasse fiber (1, 2, and 5%) and bagasse sand (5%) replacement of gravel and sand in the preparation of ICBP. According to the JIS A 5371, it is stated that flexural strength of ICBP can be used as pavement for pedestrians in light vehicle traffic if it is above or equal to 3 MPa, or in heavy vehicle traffic if it is equal to or more than 5 MPa. In this scope, control paving block samples and ones containing sugar residue material had their flexural strengths measured after 1, 3, 5, 7, 10, 14, and 28 days and interpreted in keeping with these limits. As a result of this work, flexural strength in all samples during the entire curing time made it possible to use ICBP for light vehicle traffic and flexural strengths acquired by using sugarcane residues material at the mentioned ratios on the 10th, 14th, and 28th day demonstrated that they are suitable for ICBP in heavy vehicle traffic.

5.4. Splitting Tensile Strength

Similar to the compressive strength, splitting tensile strength has commonly been enhanced up to similar ratios. Ganjian et al. [77] investigated the usability of byproducts and waste materials such as GBFS, By-Pass Powder (BPD), Run-Off Station (ROSA), Basic Oxygen Slag (BOS), Plaster Board Gypsum PG, BA, Recycled Crushed Glass (RCG), RCA, Recycled Bricks (RB), Steel Fibre (SF), and PVA-Fibre in ICBP. Control mixes were composed with GBFS and PVA-Fibre, while other mixtures by mentioned wastes in different proportions by weight. The conclusions applied in two phases signaled that decreasing the cement amount with GBFS is effective in reducing the amount of cement compared to ROSA, BOS, PG. In addition, it has been shown that ICBP prepared with OPC (7%) + GBFS (6.3%) + BPD (0.7%) meets the minimum 3.6 MPa splitting tensile strength with regards to the BS EN1338. In the study of Limbachiya et al. [97], splitting tensile strengths for ICBP with GBFS (25%) and SF (15%) added to cement in certain proportions showed better results than control concrete.

5.5. Water Absorption

Water absorption of concrete is related to its strength and durability against all kinds of chemical and physical effects that it may encounter throughout its service life. The water absorption of concrete depends on the total amount of voids and their connectivity in hardened concrete. It seems that water absorption values (presented in Table 5) increase for both industrial and agricultural wastes added to ICBPs. The increase in porosity and water absorption of ICPBs may be related to their densities. The study of Tene et al. [98] investigated the mechanical and physical effects of ballast (5–20%) added at different ratios to paving blocks made using Low-Density Polyethylene. The water absorption ability test of ICBP was carried out in accordance with EN BS 1338. According to the results, the water absorption of the blocks, at 0% and 5%, indicated almost no significant difference in the optimum sand to plastic ratio. In the study of Pennarasi et al. [99], a water absorption test was performed for CS added to control concrete, and the 28-day absorption of control concrete and CS blocks was found to be 3.112% and 2.23%, respectively.

Table 5. Water absorption values obtained from the literature for ICBPs using waste.

Waste Material	Days	Water Absorption (%)	Increase/Decrease	Ref.
FA-1	-	4.05–9.5	Increase	[15]
FA-2		8.5–16.5	Increase	
FA-3		3.8–6.1	Increase	
MW-1		5.0–6.0	Decrease	[87]
MW-2		3.75–5.25	Decrease	
PWTA	28	8.0–11.0	Increase	[79]
FA-1	-	3.0–4.5	Increase	[92]
FA-2		3.0–5.5	Increase	

Table 5. *Cont.*

Waste Material	Days	Water Absorption (%)	Increase/Decrease	Ref.
NCA+RCA RCA	28	3.5–5.6 3.5–9.86	Increase Increase	[100]
RHA-1 RHA-2 RHA-1 * RHA-2 *	7, 56	3.20–4.0 1.6–2.0 5.0–5.5 2.4–2.8	Increase Increase Increase Increase	[94]
Synthetic Zeolite Admixture-1 Synthetic Zeolite Admixture-1	7, 28	4.30–4.60 4.05–4.35	Decrease Decrease	[101]
FNS	28	4.9–5.6	Increase	[88]
BA-1 BA-2 BA-3	-	3.0–4.5 4.5–6.0 4.0–6.0	Increase Increase Increase	[14]
WGrD	-	3.97–5.05	Increase	[78]
BA FA+BA-1 FA+BA-2 FA+BA-3	28	6.0–9.5 3.05–7.5 5.25–6.0 2.0–2.9	Increase Increase Slightly Decrease Increase	[102]
WSF	7	4.2–6.2	Decrease	[82]
PT-1 PT-2 PoT ST	-	5.22–5.8 4.88–5.78 4.76–5.42 5.07–5.22	Increase Decrease Decrease Decrease	[83]
CH	-	8.18–9.18	Increase	[103]

*: The other mixes prepared with RHA.

5.6. Freeze-Thaw Resistance

Because the damage to concrete engendered by freezing and thawing (F-T) is caused by freezing and expansion of water in cement paste or the concrete aggregate pore system, the development of resistance against F-T lies primarily in the production of a quality concrete without pores. Uygunoglu et al. [15] attained this by separately evaluating tensile splitting strength in order to determine the effect of the amount of FA included in CSS, Concrete Wastes (CW), and MW-modified ICBP on F-T resistance. It was found that F-T durability decreases with the increase in FA content such that there is no remarkable effect for FA replacement of cement up to 40% ratios. Gencel et al. [87] revealed that F-T effects of concrete with included MW replacement of aggregate showed better results than reference samples. It was emphasized that samples containing marble are less affected by F-T because these specimens absorb less water. Another result related to this study is that F-T losses are lower in samples with high cement content. It received the lowest value for MW amount up to 20% according to the weight loss results obtained by Mashaly et al. [84]. Although weight loss increased after this ratio, it met BS EN 1338 except for 40% MS content. Sahu et al. [92] researched F-T effects on concrete tiles and parquet blocks substituted FA by replacing sand. Even though the inferences show that F-T losses increment as the ratio of FA increases, it has been observed that weight loss does not exceed 1% of initial weight, thus providing durability according to the IS 15658 standard (Figure 2). The strength losses for up to 30% ratios of BA added to ICBP were below the boundary with regards to the ASTM C 666 standard in the study by Koksal et al. [14].

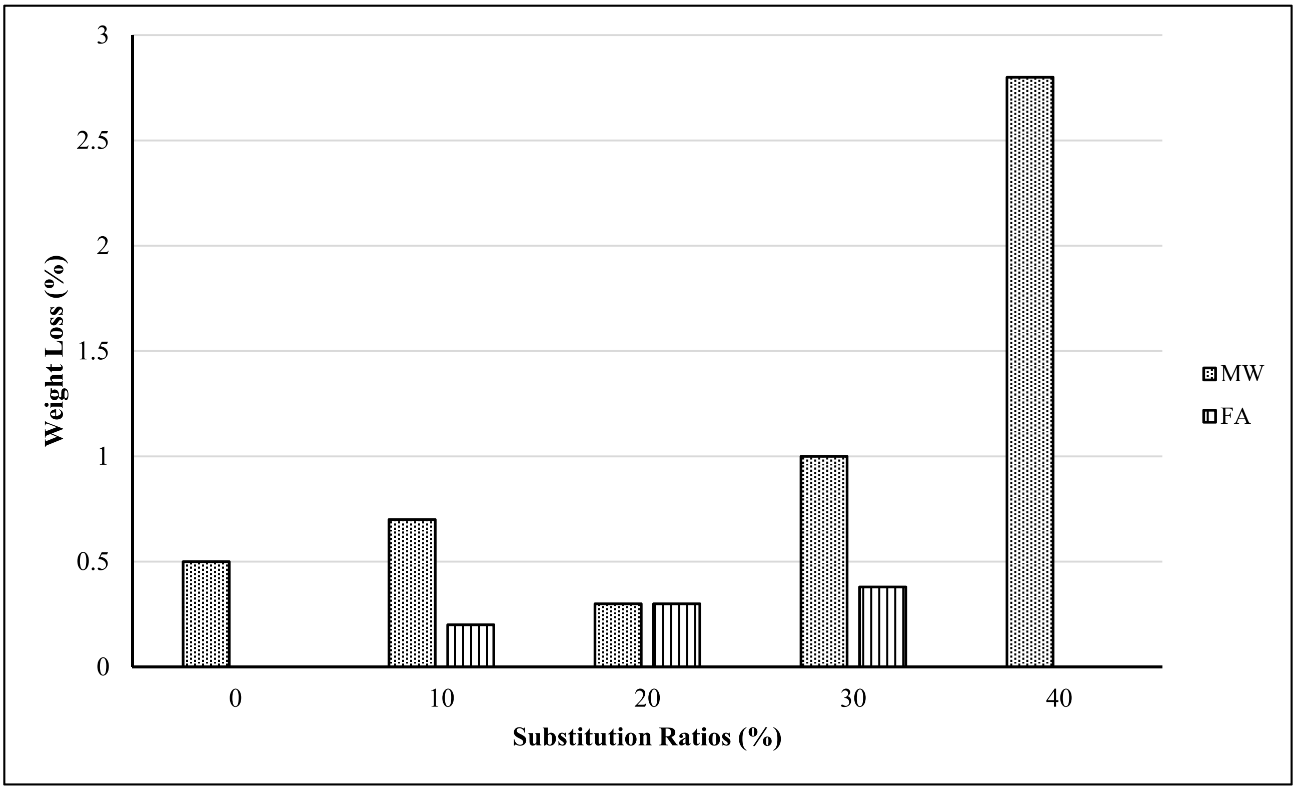


Figure 2. Weight loss after freeze and thaw in ICBP [84,92].

5.7. Abrasion Resistance

Abrasion resistance is the ability of concrete surfaces to not lose weight as a result of being exposed to the effect of friction in a moisture-free environment. Uygunoglu et al. [15] investigated the abrasion resistance test of prefabricated ICBP with FA integrated with CSS, CW, MW and reported the results obtained. With the increase in the amount of CW in ICBP, greater abrasion resistance was obtained compared to other wastes, and wear length was found to be lower. It is known that material transfer from sample surface occurs with a combination of normal load and shear forces and that it is very important to bond well-dispersed fine aggregates with cement as well as coarse aggregates. Gencel et al. [87] determined the abrasion resistance of ICBP with MW at 3, 7, and 28 days. The results demonstrated that curing age increment with the addition of MW increases the wear resistance of ICBP. Mashaly et al. [84] indicated that results on abrasion resistance increased with the use of up to 20% ratios of MW and declined for 30% and 40% ratios. A study by Dimitrioglou et al. [88] specified that wear resistance decreased moderately with the addition of Ferronickel Slag (FNS) to ICBP. This situation supports the fact that the abrasion resistance decreases as the strength of the concrete decreases. Similar results for BA substitution in ICBP were found [14] (Figure 3). It has been noticed that although the BA has a rough surface structure, it is not as hard as limestone aggregates in its porous structure, and therefore a compact form does not occur; similar results were observed in the study of Antoni et al. [102].

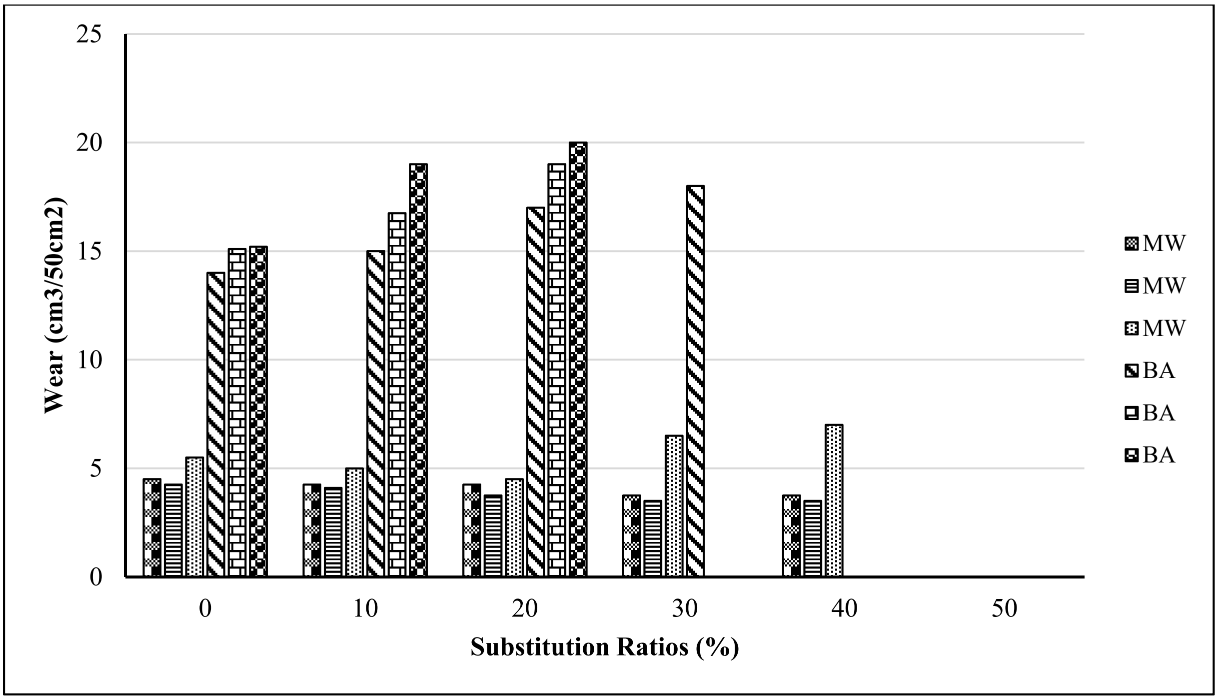


Figure 3. Abrasion resistance of ICBP [14,84,87].

6. Strength Verification/NDT

Ultrasonic Pulse Velocity

By determining the transition time of the ultrasound waves created between the receiver and the transmitter with the ultrasonic pulse velocity, data can be obtained to calculate the compressive strength, homogeneity, defect and crack information, and elasticity modulus of concrete. Mohamad et al. [104] researched the effects of petroleum products such as FO, K, and Engine Oil Waste (EOW) on ICBP of two different shapes as well as ultrasonic pulse velocities (UPV) for different soaking times (0, 30, 60, 90 days). The results were similar to the compressive strength results for all oil derivatives, and higher UPV was recorded at all ages for I letter shape ICBP. In the study of Arjun Siva Rathan and Sunitha [78], UPV results in pavement blocks with WGrP added were excellent in all samples on day 28. This increase in UPV was sighted up to the addition of 25% WGrP thanks to dense packaging. Gencel et al. [87] measured the UPV in the ICBP and noted that UPV decreased with the increase in the ratio, and that these results could be related to the decline in unit weight (Figure 4). In the study of Attri et al. [100], a decrease in UPV was determined by the increase in the change percentage ICPB of coarse or fine RCA.

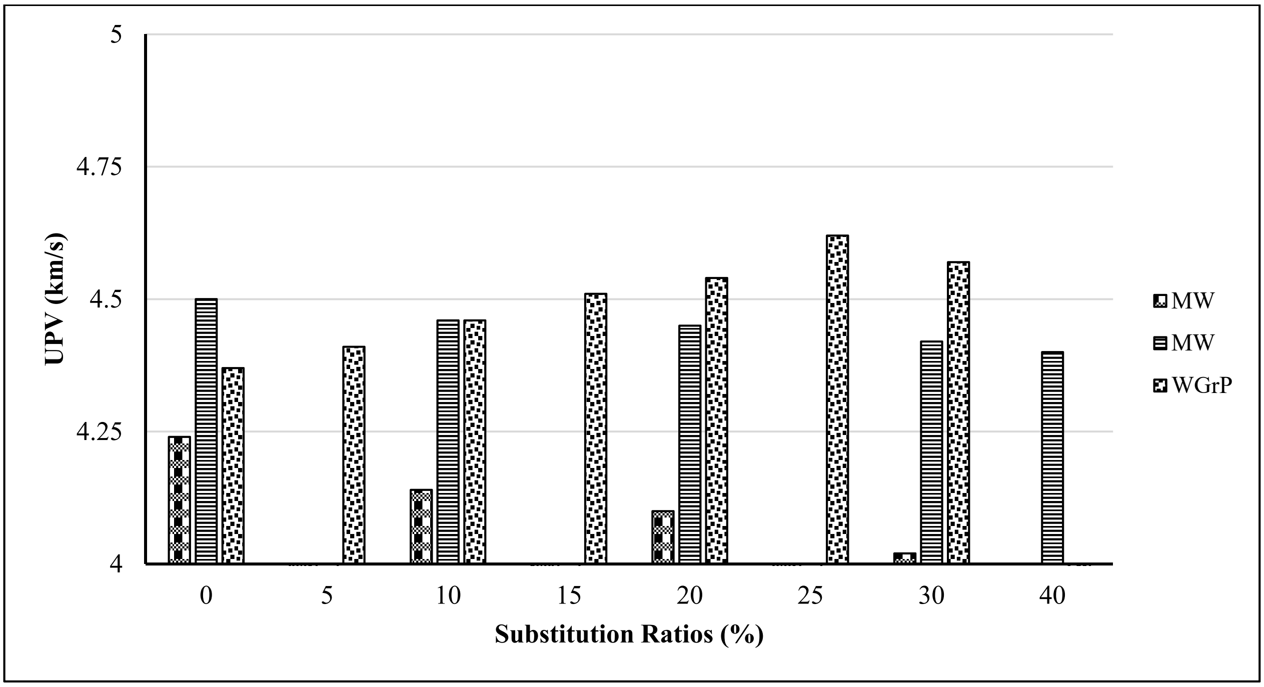


Figure 4. UPV results for ICBP [78,87].

7. Other Properties

7.1. Skid Resistance

In Arjun Siva Rathan's study [78], because the water absorption capacity of WGrD is higher it was noticed that the skid resistance was better in wet WGrD-added ICBP. In research by Alaskar et al. [80], the combination of PP fibers and POFA as partial cementing materials significantly increased the skid resistance of concrete samples under both wet and dry conditions. This higher skid resistance of POFA blends may be due to the strong bonding between the PP fibers and the hardened binder paste as a result of the pozzolanic effect of POFA, which reduces material losses in concrete samples and therefore increases the skid resistance.

7.2. Thermal Conductivity

Ribeiro et al. [96] concluded that the surface temperature of the blocks could be reduced by adding a certain amount of SBA to ICBP. However, it was stated that other factors such as density, wind effect, and ambient humidity should be investigated to clarify the whole mechanism. In the research conducted by Souza et al. [103], the lowest thermal conductivity and transmittance, and the highest thermal resistivity values were observed in blocks with 2.5, 5.0, and 7.5% SBA; however, for 10% SBA, thermal conductivity and transmittance increased even though higher porosity. This may be related to the connection between microcracks and pores in the matrix formed by the interlocking of particles, allowing a greater flow through the block. However, the thermal conductivity values for CH did not change. In another study by Dimitrioglou et al. [88], the thermal conductivity of the blocks decreased with increasing FNS substitution. It has been said that this reduction should be attributed to the nature of the aggregates used, as this can result in an approximately twofold reduction in the thermal conductivity of concrete mainly due to their degree of crystallization.

7.3. Sulphate Resistance

Subashi et al. [94] observed that sulfate resistance increased as the percentage of mass loss decreased with the increase of RHA level in ICBP; the reduced voids and pore structure obtained with RHA made the samples less permeable for sulfate ions to penetrate the concrete samples.

8. SEM Analysis

Microstructural image analysis results in the experimental study of Olofinnade et al. [82] revealed that mixtures containing 40% and 100% WSF contain more pores than reference mixtures. Undoubtedly, for mixtures containing 40% WSF pore size remained smaller than mixtures containing 100% WSF. In this case, it can be understood that with the increase of the amount of WSF in concrete the formation of a weak interfacial transition zone and decrease in strength was inevitable. Similarly, in the study of Djamaluddin et al. [79], SEM images observed in samples with 0% and 40% PWTA were found to be more porous than control samples. Again, when the pavement morphology in Koksal et al.'s [14] study was analyzed, the addition of BA caused a lean interface between aggregate and cement, resulting in losses in strength and wear resistance. According to the SEM images (Figure 5) analyzed in the study of Arjun Siva Rathan and Sunitha [78], samples including 25% WGrP had a more compact matrix structure than control samples.

Naturally, the rate of hydration and amounts of hydrated products are higher than control samples. However, the excessive voids in samples containing 30% WGrP weakened the mechanical properties due to the higher water absorption of WGrP. Similar results were seen in SEM analysis of samples with RHA added to two different ICBPs (M15 and M25) in Subashi De Silva and Priyamali's [94] study. The samples involving 5% and 10% RHA had a stronger interface bond than control concrete, and more C-S-H gel formation was observed in samples containing 10% RHA. However, with the further rise in RHA it was concluded from SEM that ettringite (long needle-type morphology) formation increases, thus weakening the matrix and reducing the strength.

In the study of Ling and Poon [89], a weak bond between glass aggregate and cement paste could be seen from SEM analysis, with the effect of increasing glass content. Dimitrioglou et al. [88] took electron micrographs of samples involving 10% and 20% FNS after 28 days of hydration. It was noticed that C-S-H gel formed a fibrous dense network. Eventually, it was highlighted that volume of hydration products in the aggregate paste enhanced the interface zone; thus, the cohesion between the cement matrix and FNS improved.

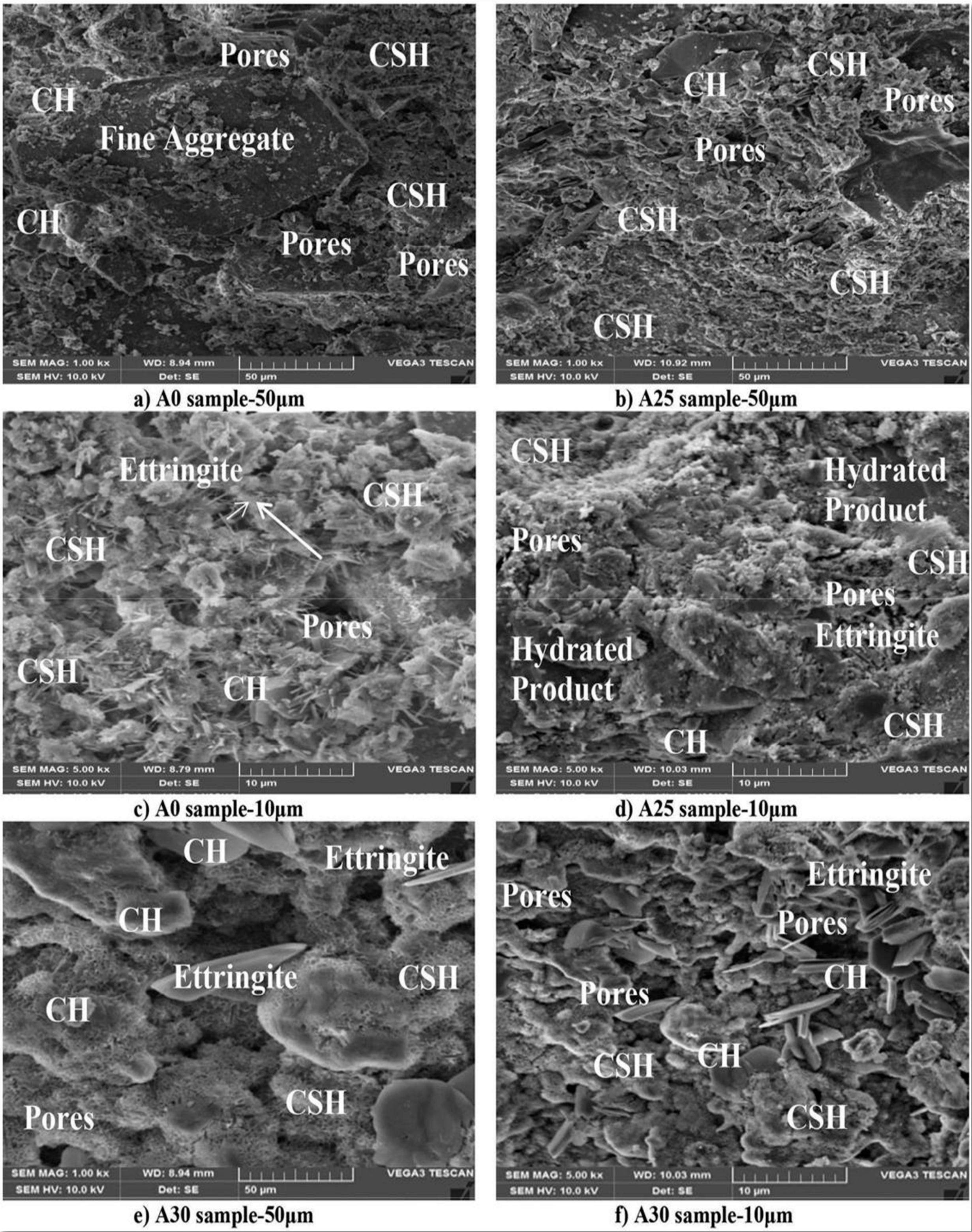


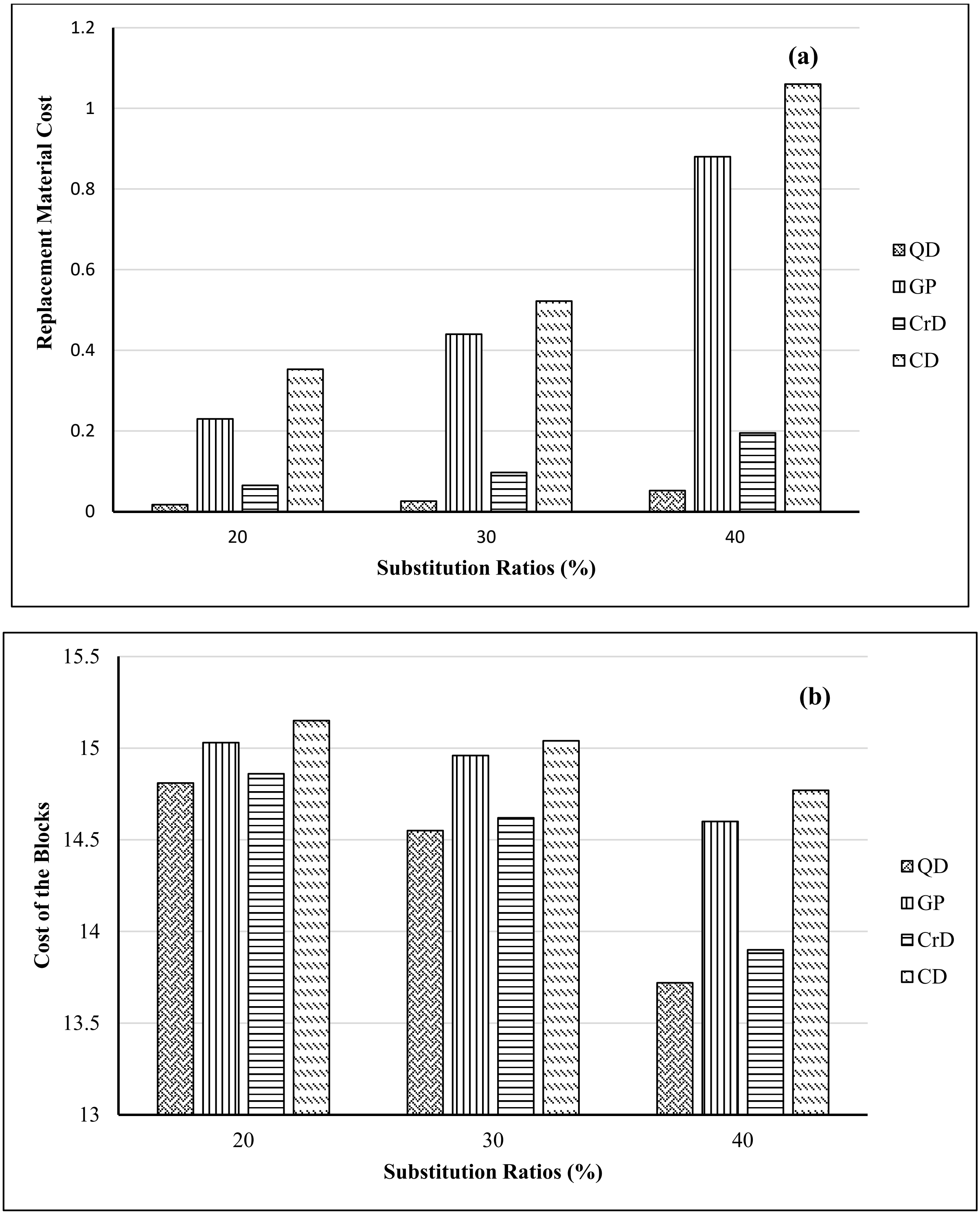
Figure 5. SEM image of A0 (0%), A25 (25%), and A30 (30%) samples at different magnifications [78].

9. Sustainability Impact

It is a fact that millions of people have started life in our age where environmental pollution, global warming, and natural resources are consumed extravagantly. Rapid developments in various sectors and the world trigger this depletion. The physical dimensions of the world, as on the survivor's island, are the most important parameters that determine how many people can live in what conditions. Considering variables such as climate change, fossil fuels, the fact that not every land is arable, and the amount of water, calculations can be made about how sustainable human civilization is. In this way, a more sustainable understanding model is adopted. This management philosophy provides a process that is fully integrated with waste reduction, social responsibility, the implementation of innovation through continuous learning and development, and the organization's goals and strategies. Effective control of a society's waste management policy in reducing waste, waste generation, recycling, reuse, and disposal is carried out with regular, comparable, valid, and representative data [105].

Incineration, which is one of the basic elements of solid waste processing, has an important advantage as it both reduces waste volumes and solves the problem of limited landfills. Glass (35%) and ash (25%) have the largest share in the composition of waste generated by the incineration of solid wastes. In particular, the disposal of ash, which is one of the main residues, in landfills, leakage of the pollutants during the process, and pollution of the groundwater are in question. Ash, glass, and partially or unburned organic materials obtained from the incineration of waste can be made good use of in the construction industry. The effects of the wastes mentioned in elements such as reinforced concrete, concrete mortar, and concrete pavement blocks in certain proportions have been evaluated for their strength and durability properties as well as in which proportions good results can be obtained by including them [106].

The work carried out by Evangelista et al. [107] consists of the LCA of ICBP produced with 50% Electric Arc Furnace Aggregate (EAFA) and examining the properties such as human health, climate change, ecosystem quality. The results of 50% EAFA added pavers reduced the total impact of cement by 42%, Natural Coarse Aggregate (NCA) by 3%, and for sand, dust stone, and electricity by 1%. However, in the study it was pointed out that there are important gaps in transportation distances and costs are related to the density of EAFA. Therefore, it was stated that a better economic analysis is necessary, and geographical, temporal, and technological conditions should be taken into consideration for future LCA studies. In the study of Djamaluddin et al. [79], CO_2 emissions per m^3 in ICBP involving PWTA and their costs were calculated. Gradual decrease was observed for these properties at each replacement ratio. Researchers have confirmed the usability of PWTA as a building material with a more sustainable and economical potential in ICBP. Cost analyses were made for GP, QR, CD, and CrD reinforced compared to normal ICBP in Koganti et al. [17]'s study. According to Figure 6, profit percentage remained significantly higher for QD and CrD than for other materials. Although it has a higher profit percentage, it was reported that for 40% QD, it cannot be used over 20% ratios when considering the strength. Analyses have signified that QD is the most economical waste product, and CD and GP are the costliest waste products compared to other recyclable materials in concrete.



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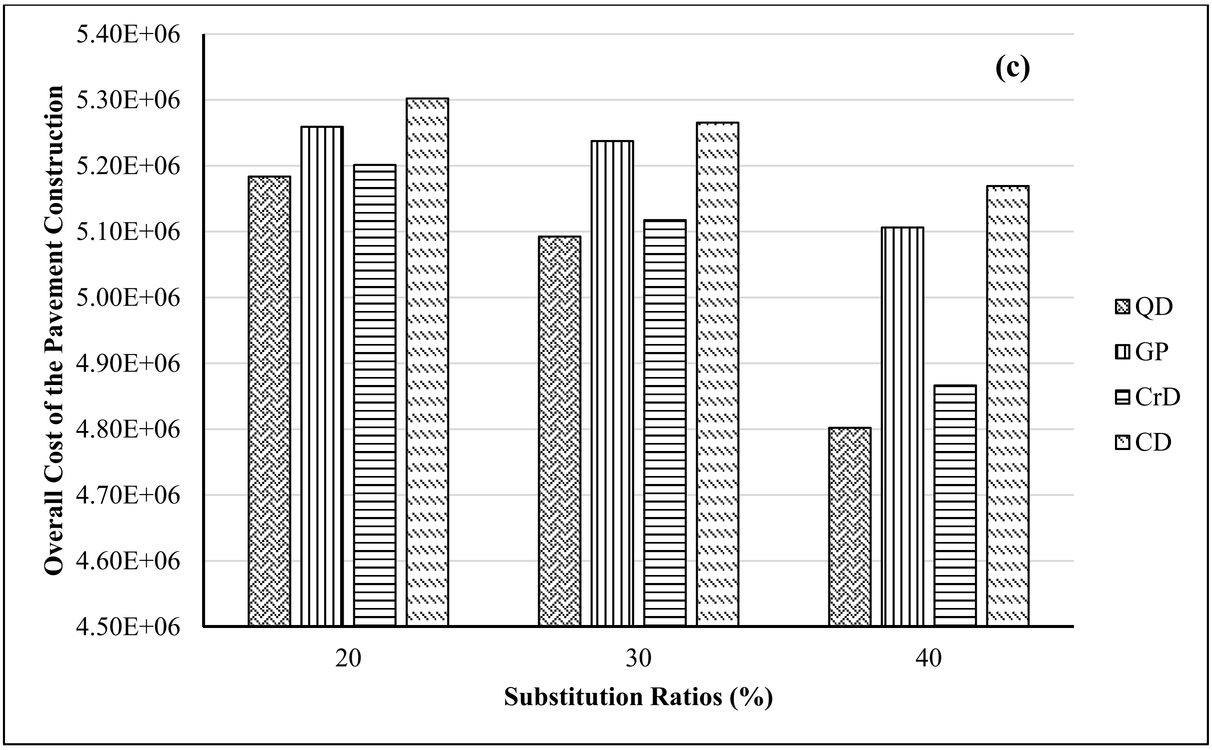

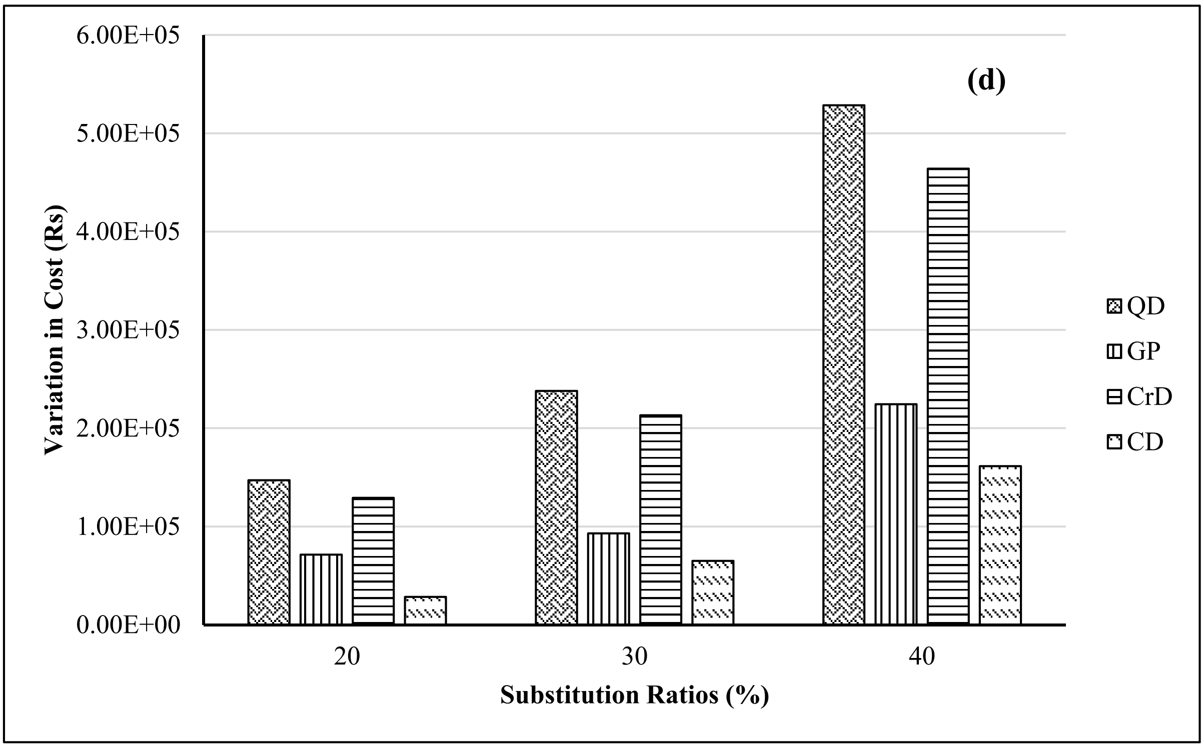

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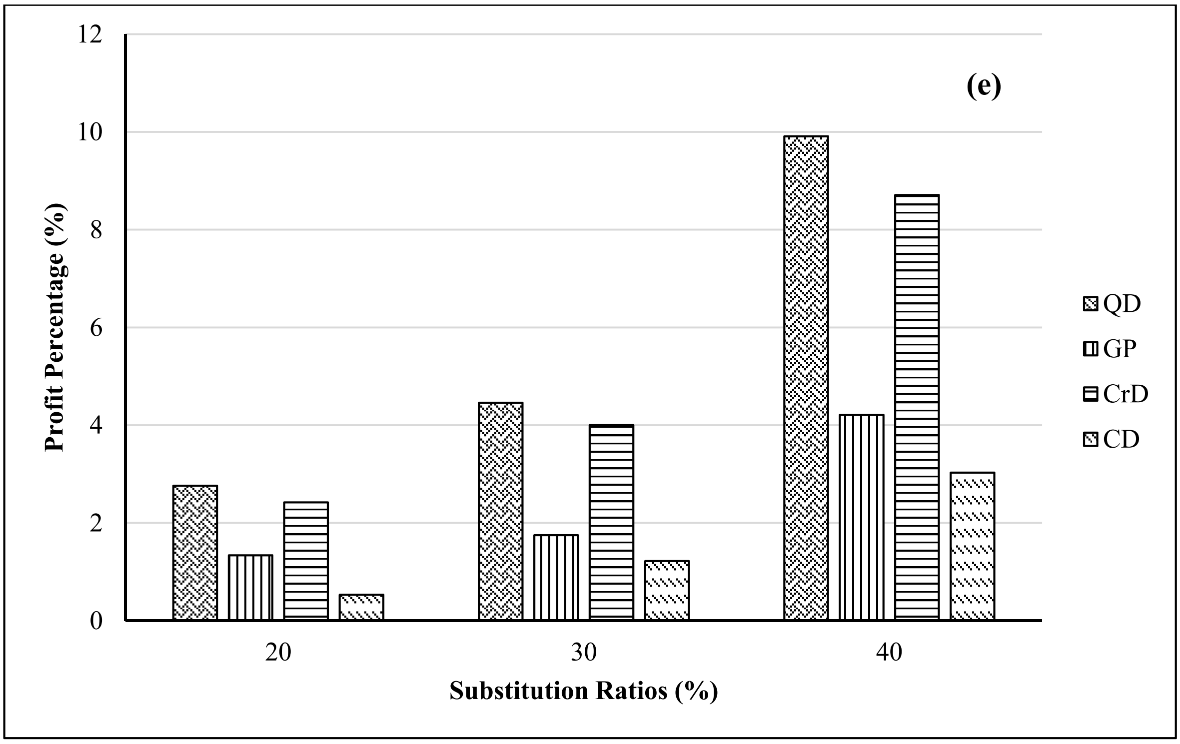

Figure 6. Materials cost (**a**), costs of the blocks (**b**), pavement construction (**c**), variation in costs (**d**), and profit percentages (**e**) of blocks for fine aggregate replacing with QD, GP, CrD, and CD [17].

10. Aesthetic Value

Considering the aesthetics of concrete blocks, shapes, colors, and patterns emerge as basic aesthetic elements. These elements must be combined with performance and economic criteria. Strength, shape, thickness (60-mm for pedestrian traffic, 80-mm for vehicular traffic, and 100-mm for some heavy industrial applications), and dimensional tolerance parameters should be taken into consideration during the design phase. Studies on the development of new paving blocks and increasing their diversity by manufacturers around the world, including in South Africa, continue. In South Africa, paving stones produced with aggregates and various cement from different places and using many pigments create a pleasant effect when laid over large areas (Figure 7). In this scope, it has been expressed that the introduction of colored blocks brings the visual effect created by the ICBP to another dimension. Looking at past and present experience and research, it can be understood that the ICBP industry is involved in producing a wide variety of block shapes. ICBP is divided into three different categories, Type I, Type II, and Type III, depending on the locking type. For example, the unit style in the Type I group allows geometric locking of all vertical or side faces between adjacent blocks, while the cobble style in the Type III group does not. Studies have concluded that features such as vertical and horizontal creep are Type I blocks that develop the best resistance, and they have revealed that Type II and Type III blocks can be preferred with aesthetic concerns. In addition, the results of traffic studies in Australia, South Africa, and the USA demonstrates that shaped blocks have a greater vertical surface area than rectangular or square blocks of the same order, showing better performance and less deformation [108–112].

Figure 7. Different colors and shapes of paver blocks [99].

As the load distribution in ICBP-lined roads is achieved by interlocking actions, it has been stated that the floor arrangement of ICBP functions as an important component in the spread of the load on ICBP lined roads. It was emphasized that laying down the most effective flooring model that can improve the interlocking action is very important [108,109]. In this context, tests and field observations on flooring patterns are important for the performance of ICBP. There are four main types of block flooring models used in industrial applications, herringbone tie, stretch tie, basket weave, and pile tie, of which the most suitable flooring type in terms of performance is the herringbone tie. In addition, one of the findings of researchers is that charcoal gray and tan brown provide the highest resistance to both horizontal and vertical deformation. In addition, 45° angle patterns are commonly used in block concrete slab applications. However, tiling patterns have been found to perform better when running in the direction of traffic or at a right angle. Studies on the increase in slab thickness have shown that a significant reduction in elastic deflection and stress is transmitted to the lower base. It has been emphasized that thicker blocks provide a higher friction area; thus, the load transfer will be higher. It has been determined that with increasing block size, less deviation is obtained in pavement, and when small blocks are used, the number of joints per unit coverage area is higher [11].

11. Conclusions

It is clear that if recycling and energy generation of waste materials used as SCM in ICBP are promoted, resource and environmental savings can be achieved and serious savings can be acquired for different industries. In addition, for storage management this situation is an effective and sustainable approach to reducing the pressure on landfills. Thanks to the different properties of various wastes, ICBP with high added value can be produced in accordance with the determined standards. The purpose of this review is to provide a better understanding of the structural performance, durability, and sustainability of ICBP containing SCM and to make certain inferences about its advantages and disadvantages. According to the literature studies on waste, the following conclusions can be reached:

- The inclusion of industrial wastes such as BA, FA, GP, which are widely used in concrete, mortar, and other construction materials, as well as agricultural wastes such as CSA, RHA, and SBA up to 20% [113,114] and up to 15% [103] for CH and PWTA, have yielded good results in ICBP. Although it is possible to use wastes such as GBFS, MW, WSF, and EAFA which have high strength and hardness in ICBP at ratios higher than 30%, it is recommended to use them at lower ratios to limit their negative effects on durability properties.
- For waste powders that are finer than the cement used in ICBP, slump values decrease due to the increase in surface area. In addition, while the mechanical properties for the waste aggregates and powders used are low in the early periods, they increase in the later stages. The reason for this is the acceleration of the pozzolanic impact reaction and the intensification of the interfacial transition zone at later ages.
- It was observed that the economic benefit of industrial wastes such as QD, GP, CrD, and CD increments with increasing addition ratios in ICBP. Results show the sequential form of reduction in parquet costs as QD > CrD > GP > CD. The results with the highest economic gain and the lowest economic change were obtained by adding 40% QD to ICBP. Similarly, in a different study on agricultural wastes it has been proven that both CO_2 emissions and block costs are significantly reduced by increasing the proportion of PWTA included in ICBP. In another study, it was determined that 50% EAFA in ICBP, one of the recycling materials, increases human health and ecosystem quality and reduces climate change.
- CH is a recently-studied material with a strong fiber structure used in prefabricated buildings. Research has shown that CH and SBA used in concrete blocks between 2.5% and 7.5% provides lower water absorption and better thermal properties. Thanks to this technology, which re-evaluates such materials in addition to their contribution to durability properties, a step can be taken towards the sustainable and circular world of the future.
- Many studies have been conducted on the utilization of PET and other plastic shards in the production of lightweight concrete, aggregate in asphalt concrete, synthetic aggregate or binder, and fiber-reinforced concrete. Studies have shown that the addition of plastic aggregate reduces workability, unit weight, and compressive and tensile strengths. Because the connection between cement paste and plastic aggregate is weak, the plastic aggregate strength is low. However, it has been argued that this is advantageous in applications that require a low modulus of elasticity. Considering these features mentioned in ICBP, positive results were obtained for the use of PET up to 5%.
- When the colors, shapes, patterns, and angles used in ICBP are examined in terms of aesthetics as well as in terms of performance and economics, within the scope of the subject it is concluded that Type I, Charcoal Gray, and Tan Brown are the most suitable, as are with 45° angles.

For future studies, strength and durability properties can be investigated by increasing the variety of waste added to ICBP. More specifically, the effects of CW [115], wastes from human activities, animal bones, and human hair on the petrographic properties of the concrete were investigated [116]. In future studies, mineralogic–petrographic properties in different industrial and agricultural wastes used in concrete/parquet blocks need to be examined. The properties of each byproduct to be used in studies and its effect on ICBP should be investigated in detail. Adding waste materials to ICBP can result in lighter pavers, thus increasing paving speed on projects. In addition, considering the research showing that these wastes have a significant contribution to sustainability, LCA should not be overlooked in studies such as environment, energy, transportation, and cost. Thus, such studies increase contributions to cleaner production and the sustainability of different industries. Most studies only include testing of a single-block element, and do not show block–base interactions. The flexural response of the loaded single block may lie opposite to the formation of the joint hinge, resulting in reduced stress at the joints. However, for continuous slab paving this mechanism is lacking, which further emphasizes the advantage of using block pavements for roadway loading. Moreover, a detailed laboratory evaluation is needed to identify factors influencing structural behavior.

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Nomenclature

BA	Bottom Ash
BOS	Basic Oxygen Slag
BPD	By-Pass Powder
CBA	Coal Bottom Ash
CD	Coal Dust
CH	Coffee Husk
GP	Glass Powder
CrD	Ceramic Dust
CS	Coconut Shell
CSA	Coconut Shell Ash
CSS	Crushed Sand Stone
EAFA	Electric Arc Furnace Aggregate
ED	Exhausted Dust
EOW	Engine Oil Waste
FA	Fly Ash
FO	Fuel Oil
FS	Foundry Sand
FNS	Ferronickel Slag
GBFS	Granulated Blast Furnace Slag
GP	Glass Powder
GW	Glass Waste
ICBP	Interlocking Concrete Block Paving

K	Kerosene
MW	Marble Waste
NCA	Natural Coarse Aggregate
PET	Polyethylene Terephthalate
PG	Plaster Board Gypsum
POFA	Palm Oil Fuel Ash
PoT	Porous Tile Waste
PT	Porcelain Tile Waste
PWTA	Processed Waste Tea Ash
QD	Quarry Dust
RB	Recycled Bricks
RCA	Recycled Coarse Aggregate
RCG	Recycled Crushed Glass
RHA	Rice Husk Ash
ROSA	Run-Off Station
SBA	Sugarcane Bagasse Ash
SF	Steel Fibre
ST	Stone Tile Waste
WCR	Waste Crumb Rubber
WGrD	Waste Granite Dust
WMP	Waste Marble Powder
WSF	Waste Furnace Slag

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