buildings

Review

Meta-Analysis of the Performance of Pervious Concrete with Cement and Aggregate Replacements

Faiz Habib Anwar [1], Hilal El-Hassan [1,*], Mohamed Hamouda [1], Gilbert Hinge [1] and Kim Hung Mo [2]

[1] Department of Civil and Environmental Engineering, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates; 202090162@uaeu.ac.ae (F.H.A.); m.hamouda@uaeu.ac.ae (M.H.); ghinge@uaeu.ac.ae (G.H.)
[2] Department of Civil Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia; khmo@um.edu.my
* Correspondence: helhassan@uaeu.ac.ae

Abstract: In recent years, pervious concrete (PC) has gained much attention as one of the strategies for low-impact development (LID) in pavements due to its structural, economic, and road-user benefits. This study sought to review and evaluate changes in the mechanical, hydraulic, and durability performance of PC produced with cement and aggregate replacements. A meta-analysis was conducted to elucidate the feasible range of the replacement percentage and the number of materials that could be used to replace cement and aggregates; single or binary replacements were considered. Results indicated that cement-replacing materials, industrial wastes (IWA), and recycled aggregates (RA) met the minimum requirement for the mechanical, hydraulic, and durability properties of PC. The use of a single cement replacement material provided PC with better performance than when cement was replaced with two or more materials or when cement alone was used. Industrial waste was found to be a better replacement to aggregates than RA. The combined replacement of cement and aggregates with IWA and other cement-replacing materials was the most effective method for improving the mechanical, hydraulic, and durability performance of PC. Replacements of up to 40% was considered viable for cement replacement, while up to 50% replacement was considered practical for aggregate and combined replacement. PC incorporating different cement-replacing materials exhibited equivalent or improved mechanical properties and maintained hydraulic performance compared to cement-based PC. Nonetheless, limited studies are available on the durability performance of PC made with cement and/or replacements. Thus, the durability of PC coupled with the applicability of replacement materials acquired from different locations need to be evaluated to address the viability of producing more durable PC with the use of replacements.

Keywords: pervious concrete; cement replacement; aggregate replacement; recycled aggregate; industrial waste materials; mechanical; hydraulic; durability

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1. Introduction

Concrete is the most widely utilized construction material globally [1]. It is a mixture of coarse and fine aggregates, cement, water, and other additives. Aggregates are primarily obtained from non-renewable natural resources, and thus aggregate extraction is considered to be a source of environmental burden. High demands for natural aggregates (NA) have led to the scarcity of their sources and prompted the search for more sustainable alternatives [2]. Meanwhile, cement production significantly contributes to global greenhouse gas (GHG) emissions [2]. Its production results in the liberation of harmful GHG into the atmosphere, leading to air pollution [3]. Studies have shown that the ordinary Portland cement (OPC) industry produces approximately 7% of the world's CO_2 emissions, with about 74% of the CO_2 being emitted during concrete production [4]. It has been reported that the manufacture of 1 ton of OPC consumes 1.6 ton0s of raw materials and about 6.5 million British thermal units (BTUs) of energy while emitting 1 ton of CO_2 [5]. Thus, there is a need to reduce cement consumption in concrete by replacing it with more sustainable binders with lower energy and carbon footprints. The release of poisonous gases and the energy consumption during cement production coupled with the harmful storage of industrial wastes are some environmental factors that encourage the use of alternative binding materials instead of cement [6,7]. The most suitable replacements for cement and aggregates are typically industrial wastes. Not only do they reduce the consumption of cement and aggregates in the production of concrete, but they are also beneficially recycled rather than stockpiled or landfilled. Indeed, the landfilling of industrial wastes raises concerns about environmental pollution and human wellbeing [8]. In addition, the cost implications of replacing cement in concrete is another crucial factor to be considered in the adoption of this concept [9]. The excessive utilization of these natural resources leads to an unstable environment and the eventual scarcity of NA [10]. Furthermore, environmental problems associated with RA and industrial waste disposal pose a hazard to the environment [11]. As such, different materials have been investigated as substitutes for NA in order to tackle these problems.

The emission of GHG is responsible for global climate change and the subsequent heatwaves and storms [8]. Owing to rapid urbanization, about 3% of the world's surface is imperviously paved, thus preventing water and air passage [12]. Such an increase in impervious surfaces has led to a decrease in groundwater recharge from precipitation events and an increased tendency of non-skid-resistant surfaces with low friction to promote surface runoff [12]. Flooding has become more frequent because of climate change-induced storms and impervious pavements [13,14]. An engineered solution is thus required to prevent flooding and efficiently manage stormwater. Pervious concrete (PC) is an open-graded pavement material that consists of coarse and little or no fine materials [12,15], and whose permeable network of voids offers a sustainable solution to the challenges of stormwater management and flood control.

PC pavement is characterized by a pore structure composed of a high volume of interconnected and capillary pores, typically with a total void content ranging from 15 to 30%, with pore sizes in the range of 2–8 mm [16] and water permeability of about 2–6 mm/s [15]. PC has been considered as one of the strategies for low-impact development (LID) in pavements due to its structural, economic, and road-user benefits [17]. It is recognized by the United States Environmental Protection Agency (EPA) as a best management practice for stormwater control [18]. It can mitigate the effect of Urban Heat Islands (UHI), where impervious pavement acts as heat storage during the day and releases heat to the atmosphere at night [16]. Furthermore, PC pavement improves skid resistance by increasing the friction on the road pavement as water drains off. It also reduces transportation-related noise as the sound produced by the interaction between the vehicle tire and the pavement is absorbed by the interconnected pores [17]. In addition, its use can aid in the removal of harmful contaminants such as heavy metals from the stormwater, which would lead to the recharge of aquifers with water of better quality [19]. PC pavements exhibit a 22% lower carbon footprint as compared to conventional impervious counterparts made with cement and well-graded NA [4]. However, similar to regular concrete, the sustainability of PC can be further improved by partially or completely replacing cement and natural aggregates with more environment-friendly alternatives.

Various materials such as mineral admixtures, artificial aggregates, and eco-friendly binders, among others, have been utilized to develop sustainable PC with satisfactory performance and properties [9,20]. Some studies have focused on partially replacing cement with industrial wastes, i.e., supplementary cementitious materials (SCM) [6]. Other studies have completely replaced cement with alkali-activated inorganic binders in single, binary, or ternary geopolymers [21]. Similarly, artificial and recycled aggregates (RA) have also been investigated in the partial and complete replacement of NA in PC [6]. However, to realize the full potential of these two approaches, the combined replacement of cement and aggregates was also investigated to produce a PC with mechanical and hydraulic performance similar to that of a control mix made with cement and NA [21]. To improve the durability performance of PC, especially abrasion resistance and freeze–thaw resistance, several measures were taken, including the replacement of cement with cementitious materials or the addition of macrofibers [22]. In recent work, the combination of fly ash (FA)-based geopolymer PC with 100% RA exhibited higher mechanical properties and a more cohesive nature than OPC- and NA-based PC [5].

The replacement of cement and aggregates in PC with more sustainable alternatives has gained global attention over the last few years. Thus, a review of PC produced while replacing cement and aggregates is needed to guide future sustainable material applications. Accordingly, for the first time, this work aims to conduct a review of the state-of-the-art literature and a meta-data analysis of the impact of cement and/or aggregate replacement on the performance of the produced PC. The present study seeks to examine the materials used for cement and aggregate replacement in PC and review the properties that were measured to evaluate the mechanical, hydraulic, and durability performance of the produced PC (with and without replacement). A meta-analysis is conducted to deduce the feasible range of the replacement percentage for cement and aggregates in PC, either as single or combined replacements, and the number of materials used, considering single or binary replacements. The ability to replace cement and aggregates without compromising the mechanical and hydraulic properties is also investigated. The findings are meant to provide collective information on PC produced with cement and aggregate replacements and to help outline the lessons learnt and the way forward in using various alternative materials in PC pavement applications.

2. Review Methodology

The literature survey followed a systematic approach to search for relevant articles that evaluated the performance of PC with cement and aggregate replacements, as shown in Figure 1. Search strings were chosen to include the most significant number of the articles of interest. All search expressions had a string of “pervious concrete” and “cement replacement” and “aggregate replacement” and “mechanical properties” or “porosity,” or “permeability,” or “abrasion OR resistance.” Peer-reviewed journal articles accessible through the Web of Science and Scopus databases, including the search expressions mentioned above, were targeted for this study. Data were extracted and processed from each article to provide essential information for the analysis, including the material used to replace the cement and aggregates, replacement percentage, and the mechanical, hydraulic, and durability properties of the PC. It should be noted that the most and least evaluated criteria were the mechanical and durability performance, respectively, owing to the respective ease and difficulty in evaluating the associated properties. Additionally, none of the articles investigating aggregate replacement considered durability as a performance measure, suggesting the need for more research in this specific field.

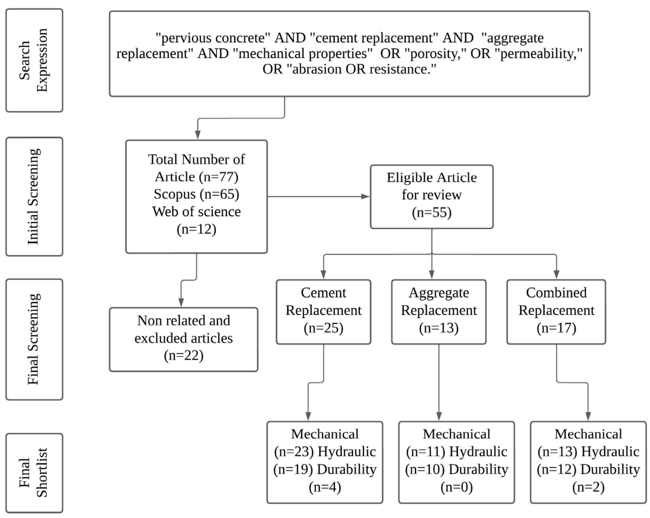

Figure 1. Flowchart of the methodology for selecting and screening the articles (n = number of articles).

3. Statistical Analysis

A fixed-effect meta-analysis (FEMA) statistical approach was employed in this study. It is a quantitative approach designed to establish a relationship between dependent and independent variables based on different parameters under consideration [23]. FEMA was used because the changes in the performance of PC are based on the variation of a single factor at a given time. In this study, only the properties that had been examined in more than five relevant articles were considered in the meta-analysis. The statistical parameter considered is the effect size, which differentiates between the dependent and independent variables [23,24]. A positive effect size signifies that the cement and aggregate replacement mixes perform better than the control mixes and vice versa. The dependent variables are the replacement mixes, while the independent variables are the control mixes. The factors considered are the mechanical, hydraulic, and durability properties. The steps followed for the meta-analysis are as follows:

1. Calculate the pooled standard deviation (S_p), also known as pooled *d*, using Equation (1).

$$S_p = \sqrt{\frac{(Nr - 1)s_r^2 + (Nc - 1)s_c^2}{Nr + Nc - 2}} \quad (1)$$

2. Calculate the Effect size (E) following Equation (2).

$$E = \frac{Mr - Mc}{Sp} \quad (2)$$

3. Find the Variance (ð) using Equation (3).

$$ð = \frac{1}{Nr} + \frac{1}{Nc} + \frac{E}{2(Nr + Nc)} \quad (3)$$

4. Determine the value of corrected J by multiplying Equations (2) and (3) to obtain the modified Effect sizes and Variance, respectively, as per Equation (4).

$$J = 1 + \frac{3}{4(Nr + Nc - 2) - 1} \quad (4)$$

5. The value of the modified Variance (ؠ) is inversed and multiplied by the modified Effect sizes (€) to obtain the fixed pooled d using Equation (5).

$$G = \frac{ؠ}{€} \quad (5)$$

6. The fixed effect (F.E.) is then calculated at the upper and lower 95% confidence interval, as per Equation (6).

$$\text{F.E.} = G \pm 1.96 \times \sqrt{ð} \quad (6)$$

where Nr = number of data points based on the cement replacement; Nc = number of data points based on control mixes; Sr = standard deviation based on the cement replacement; Sc = standard deviation based on control mixes; Sp = Pooled standard deviation; Mr = mean for data based on the cement replacement; Mc = mean for data based on control mixes; G = inverse of the product of effect size (E) and corrected J.

4. Geographical Distribution and Trend of Publications

Since its emergence, PC has gained worldwide acceptance, with studies being conducted across the globe. Of the various countries investigating PC, China and the USA have the highest number of relevant PC publications. In Asia, China and India conducted most of the PC studies, with at least 15 publications each. Iran has the highest number of studies in the Middle East, followed by Turkey, Egypt, United Arab Emirates, and the Kingdom of Saudi Arabia. About 10 studies on PC were carried out in Australia. Limited contribution to the literature was noted from South American, European, and African countries, with three or fewer publications being associated with each continent. However, new studies affiliated with these countries have been published in recent times, indicating a growing interest in the topic of PC across the globe. Nevertheless, there is a need for more studies from European and non-western countries. Furthermore, it is worth noting that all these studies were conducted using the locally available materials at the location of the study. Future work entails investigating the performance of PC made with the same materials but acquired from different locations to address the universal applicability of such research.

5. Results and Discussion

5.1. Evaluated Properties of Pervious Concrete

The performance of PC is assessed by its engineering properties, including its mechanical, hydraulic, and durability properties. Generally, the parameters used for mechanical performance evaluation are compressive, tensile, and flexural strengths at ages of up to 28 days. The hydraulic performance of concrete is its capacity to allow the passage of water and air to a certain degree without undermining its mechanical and durability performance [17]. Permeability and porosity are the main parameters used in evaluating the hydraulic performance of concrete [15]. Furthermore, the durability of concrete is its ability to resist long-term weathering, chemical attacks, and abrasion while maintaining mechanical and hydraulic properties. The different durability properties relevant to PC include, but are not limited to, skid resistance, sound absorption capacity, clogging potential, freeze–thaw resistance, and abrasion resistance.

Figure 2 shows the number of articles that considered the three categories for evaluating the performance of PC, i.e., mechanical, hydraulic, and durability. Of the various properties, 16 have been examined in PC manufactured with cement and aggregate replacements. In the first category, the mechanical properties comprise compressive strength, unit weight/density, flexural strength, tensile strength, and elastic modulus. At least 35 of the reviewed articles examined these properties, except for the elastic modulus. The most evaluated property was compressive strength, owing to its ease of testing and use as an indication of the general quality of the PC. This also emphasizes the abundance of research conducted to investigate the mechanical performance of PC while highlighting the need for more studies on the elastic modulus.

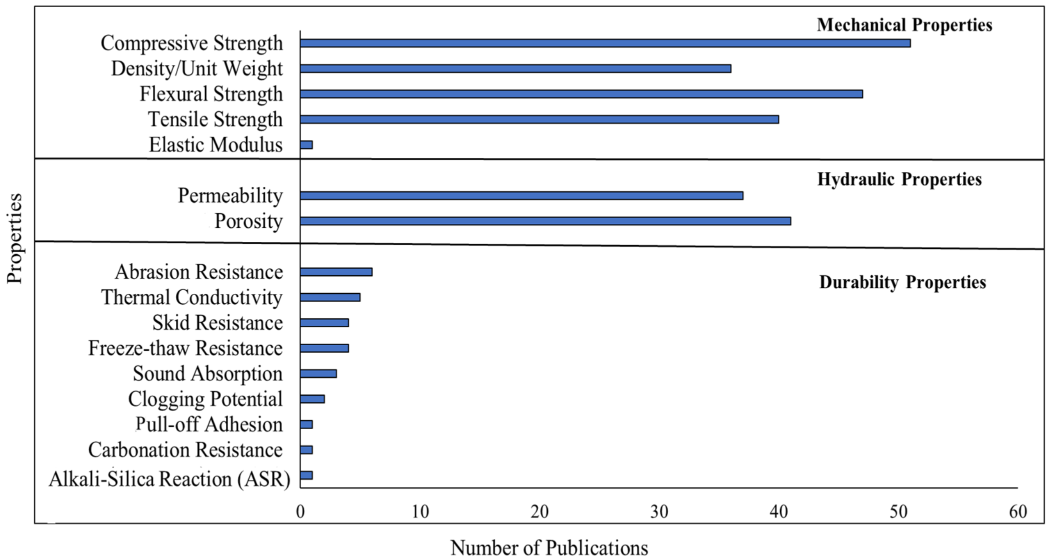

Figure 2. Number of studies conducted on the examination of various PC properties.

In the second category, the hydraulic properties encompass permeability and porosity. These were assessed by 37 and 41 of the reviewed articles, representing 67 and 75% of the total relevant studies, respectively. Indeed, the direct relationship between porosity and permeability justifies the comparable number of articles examining each property. The importance of such properties in PC also explains the high percentage of articles that have evaluated them.

The third category on the durability properties includes abrasion resistance, thermal conductivity, freeze–thaw resistance, sound absorption, clogging potential, pull-off resistance, carbonation resistance, and alkali–silica reaction. Only 11% of the relevant studies assessed the durability properties of the produced PC, with the focus mainly being on evaluating the abrasion resistance. This focus on abrasion resistance was probably due to the interest in assessing the extent of raveling on the surface of the PC [10,18,25,26]. Less interest was paid towards the remaining durability properties. In conclusion, most studies on PC made with cement and/or aggregate replacements focused on compressive strength for mechanical performance evaluation, coupled with permeability and porosity in order to evaluate hydraulic performance. Nevertheless, more work is needed to assess the durability performance of PC in order to ensure its reliability and long-term endurance for stakeholders and to promote its adoption by the pavement industry.

5.2. Cement Replacement in Pervious Concrete

5.2.1. Alternative Materials

Figure 3 shows the materials that have been investigated to replace cement in PC production. These include fly ash (FA), silica fume (SF), palm oil fuel ash (POFA), slag cement (SG), sugarcane bagasse ash (SCBA), palm jaggery (PR), pumice (PU), biochar (BC), coal ash (CA), latex (LX), crumb rubber (CR), butadiene latex (BL), rubber fiber (RF), nano clay (NC), rice husk ash (RHA), metakaolin (MK), nanoparticles (NP), and fibers (FB). Among these materials, both FA and SF appeared in 15% of the reviewed articles as a replacement for cement. This finding is primarily due to their global abundance, availability, and pozzolanic behavior when incorporated into the concrete mixture [21,27]. While FA is an amorphous industrial by-product of coal power plants with a surface area of 0.6–0.7 m^2/g, SF is a non-crystalline by-product of silicon, comprising amorphous silicon dioxide with a surface area of 15–25 m^2/g [18]. PC mixes incorporating FA as a partial replacement for cement, in binary or ternary form, exhibited comparable and superior properties to counterparts made with OPC as the sole binder [28]. An increase of about 59% in compressive strength was observed in the PC with 15% FA and 2% MK as compared to the PC with OPC. Meanwhile, comparable hydraulic performance was reported [27]. A 29% improvement in strength was reported in PC mixes with FA at C/A of (0.20–0.24), signifying the potential utilization of FA in PC without compromising performance [29]. Alternatively, reduced mechanical strengths coupled with enhanced hydraulic properties were noted for PC with FA, which were due to the porous nature of the aggregates used [30]. Moreover, most of the PC produced with an FA (single or binary) geopolymeric binder achieved satisfactory mechanical properties. This is evident in FA geopolymer concretes, where improved strength was observed at later ages compared to OPC-based PC [5,31]. Additionally, PC with SF showed higher compressive and flexural strengths than OPC-based PC as well as an improved removal efficiency of heavy metals without undermining permeability and abrasion resistance. A 29% increase in strength coupled with a 9% increase in hydraulic performance was observed in the PC with SF. Furthermore, heavy metal concentrations in the PC with SF were reduced, including Cu, Pb, and Zn, with respective reductions of 56%, 67%, and 93% compared to the PC with OPC [18,19,21]. The inclusion of SF in PC also improved the strength without any significant change in the hydraulic properties [32].

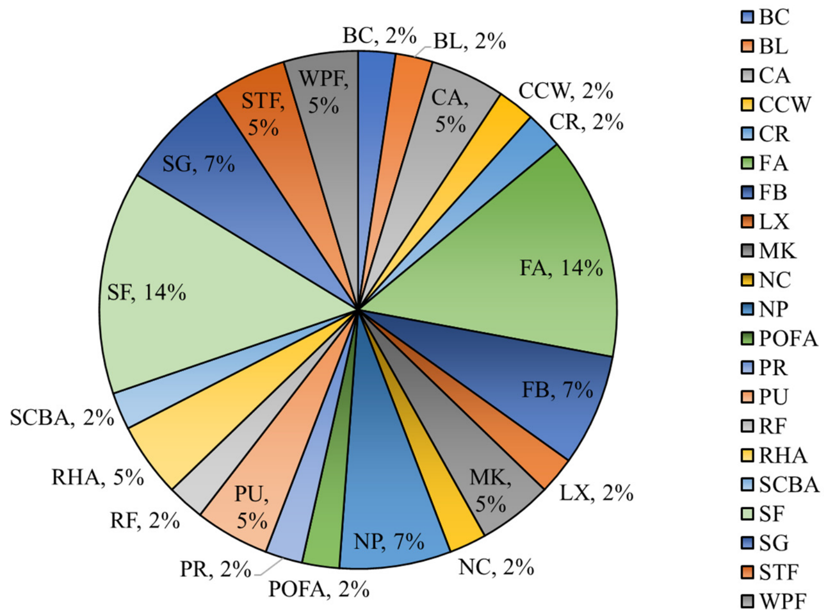

Figure 3. Distribution of materials used as a replacement for cement in the literature.

Fibers (FB), including RF, STF, WPF, and LX, have also been incorporated into the PC mix design to improve its mechanical properties. Nearly 8% of the reviewed papers investigated the use of fibers in PC as a replacement for cement. Experimental findings reported superior compressive, tensile, and flexural strengths but inferior workability than the plain, non-reinforced counterparts [10,33–35]. Similarly, NP was used in PC to improve its mechanical properties through the filling effect of the particles and good abrasion resistance, as noted in several studies [36,37]. The remaining materials had been employed in limited studies to replace cement in PC. Their main aim was to improve/maintain the mechanical and hydraulic properties of PC regardless of the replacement [9,18]. More details are given on this subject in later sections. The viable cement replacements with other materials were selected to satisfy the minimum strength and permeability requirements of PC as per international standards and regulations [38]. In summary, the practicable replacements for the investigated SCMs were found to be 20% for FA, 10% for SF, 10% for RHA, 10% for MK, 6.5% for BC, 10% for CCW, 0.05% for PR, 25% for PU, and 20% for POFA [8,20,21,25,29,34,39]. While utilizing SCBA provided inferior mechanical performance—producing PC with a compressive strength of 5.2 MPa [40]—the replacement of cement with FA, SF, and RHA in PC led to superior properties, where PC reached respective strengths of 18.5, 23.8, and 43.5 MPa [4,18,36]. However, reduced hydraulic performance was observed in PC with FA and SG, with obtained permeability values of 0.58 and 0.51 mm/s, possibly due to the high fineness of these SCMs [9]. The limited replacement of cement by PR and BC was recommended, as the performance deteriorated with high replacement percentages (>20%) [20,39].

Studies have explored the replacement of cement with a single replacement material in order to produce PC with superior strength coupled with adequate hydraulic performance as compared to OPC-based PC. A single replacement of FA, SF, and BC improved strength and durability, with no significant influence on the hydraulic performance [17,29,39,40]. While a 5.5% cement replacement by SF improved workability, strength, and durability at a fixed void ratio of 20%, a further increase resulted in inferior workability, strength, and durability [18]. Conversely, reduced strengths coupled with improved hydraulic performance were observed in PR and POFA replacements [8,20]. Furthermore, binary replacements were explored based on material combination and replacement percentage. SF and BL produced PC with improved strength and durability, while CR and polypropylene fibers had a negative effect on the strength [17]. The binary replacement of SF with MK, PU with NC, SF with NC, RHA with CCW, and FA with MK yielded PC with improved strength and durability and with adequate permeability, owing to the micro-filling ability and pozzolanic reactivity of such materials [10,21,25,27,35]. Contrarily, the binary replacement of FA with SG and CA with RHA produced PC with inferior strength and durability due to the excessive presence of fillers and limited pozzolanic activity [4,9]. Fibers, including STF, WPF, and MF, slightly influenced the performance of PC [10,35]. Sintering temperature, NH concentration, aggregate gradation, and cement–aggregate ratio greatly influenced the PC performance with cement replacement [4,29,36,41,42]. Geopolymer PC produced with SG and MK improved the strength with adequate hydraulic performance [43]. Higher strengths were achieved in PC made with AASC and EAFS, achieving a compressive strength of about 35 MPa [44]. The feasibility of slag-based geopolymer concrete with RM was also explored based on strength and heavy metal absorption. It was deduced that RM has the ability to adsorb heavy metals without compromising the strength [45]. Out of the SCM used in PC, FA and SF were mostly used due to their abundance and pozzolanic behavior.

Based on the obtained results, it can be noted that the majority of the SCMs can be utilized in PC production, as the values exceeded the minimum acceptable requirements stated by various transportation authorities [38]. While this is sufficient for its adoption by the industry, it is worth noting that PC mixes incorporating SF, FA, and RHA were superior to counterparts made with OPC only. Similarly, higher strengths coupled with adequate hydraulic performance were reported in geopolymer PC, with AASC exhibiting superior performance, followed by SG and FA. Nevertheless, the combined replacement of cement with fibers and SCMs are seen to produce PC with improved performance. It is clear that partial (single and binary) and complete (geopolymer) replacement have the potential to produce PC with improved mechanical, hydraulic, and durability performance.

5.2.2. Performance Evaluation

Table 1 summarizes the type of replacement material, percentage of replacement, and effect size of PC performance. The results show that PC with partial and complete cement replacement generally has comparable mechanical properties compared to OPC-based PC. With 14 of the 21 effect sizes for bulk density being positive, it can be noted that the bulk density of PC made with cement replacement is dependent on the replacement material and percentage. PC made with partial cement replacement by SF, BL, NC, FA, MK, STF, and MF and with complete replacement by SG had a higher bulk density than counterparts made with cement only. It seems that these materials densified the matrix and reduced the porosity, as evidenced by their respective positive and negative bulk density and porosity effect sizes.

Table 1. Effect size for PC performance based on cement replacement.

Ref.	Type	Percentage Replacement	Mechanical Properties				Hydraulic Properties		Durability Properties
			Bulk Density	Compressive Strength	Tensile Strength	Flexural Strength	Porosity	Permeability	Abrasion Resistance
[4]	CA+RHA	15% + 15%	*	−0.6	-	-	0.1	−0.1	-
[8]	POFA	10, 20, 30, 40%	−1.3	−1.8	−1.8	-	1.7	1.8	1.5
[9]	FA+SG	15% + 25%	-	−1.1	−14	−19	12.8	2.5	-
[10]	SF+NC (2% STF)	10% + 1%	-	14	-	4.9	−8.2	−3.7	-
	SF+NC	10% + 2%	-	25.2	-	23.1	−8.1	−10.5	-
	SF+NC	10% + 3%	-	49.8	-	10.4	−4.3	−8.2	-
	SF+NC (2%WPF)	10% + 1%	6.5	1.2	1.8	2.1	−1.4	−1.7	-
	SF+NC	10% + 2%	4.9	2.0	1.5	2.3	−1.7	−1.2	-
	SF+NC	10% + 3%	5.9	2.2	2.6	1.7	−1.6	−1.5	-
[17]	SF	5, 10%	3.0	4.4	1.5	2.3	−3.5	−3.5	−9.0
	BL	10, 20%	6.0	1.9	1.0	1.2	−6.7	−2.6	−21.0
	RF	1.5, 3%	−3.0	−1.3	−3.0	−3.0	3.4	9.0	-
	CR	5, 10%	−3.0	−2.5	−4.3	−3.4	2.0	5.0	-

Table 1. *Cont.*

Ref.	Type	Percentage Replacement	Mechanical Properties				Hydraulic Properties		Durability Properties
			Bulk Density	Compressive Strength	Tensile Strength	Flexural Strength	Porosity	Permeability	Abrasion Resistance
[18]	SF	5, 10, 15, 20, 25%	−1.6	−1.6	−0.9	-	1.8	-	-
[20]	PR	0.05, 0.1%	-	−1.1	−1.7	−1.1	−2.1	1.0	-
[21]	SF+MK+LX	5% + 5% + 5%	-	1.4	0.4	2.0	-	−2.2	-
[25]	RHA+CCW	5, 10, 15% 20%	-	0.0	-	-	-	−0.8	−0.6
[27]	FA FA+MK	15% 15% + 2%	0.8 0.3	1.3 0.9	- -	- -	−0.8 0.5	- -	- -
[28]	SG SG+RM SG+RM	100% 100% + 5% 100% + (5, 10)	- 0.5 1.8	−0.5 1.0 0.8	- 0.9 1.1	- 0.9 1.1	1.4 −0.6 −0.8	0.2 0.6 −1.0	- −0.9 −0.8
[31]	SG	100%	-	−0.2	-	-	0.5	1.2	-
[35]	PU + 2% STF PU + 2% MF PU + 2% WPF PU PU+NC	10, 25, 50% 10, 25, 50% 10, 25, 50% 10, 25, 50% 10% + 1, 2, 3%	1.5 17.4 −1.4 0.2 2.4	0.4 5.8 −0.5 0.5 −1.3	0.3 0.3 −2.1 −0.1 0.0	- - - - -	2.8 5.9 2.8 −0.4 2.0	5.7 8.7 4.2 24.8 5.9	- - - - -
[36]	FA	10, 20, 30, 40, 50%	-	3.1	0.5	-	-	-	-
[37]	FA	20%	-	0.3	-	-	-	−1.3	-
[39]	BC	0.65, 3.2, 6.5, 9.5% 13.5%	-	0.4	0.2	-	−0.3	−0.5	-
[40]	SCBA	5, 10, 15, 20, 25%	-	0.5	−0.1	1.8	0.8	0.7	-
[41]	PM	1 and 5%	-	−0.6	0.1	-	−6.5	-	-
[42]	FA (10 M) FA (15 M)	100% 100%	−2.2 1.3	2.8 1.7	5.7 2.2	- -	3.7 −200	−1.1 3.3	−8.3 −2.9
[43]	SG	100%	−5.0	1.9	-	-	0.2	0.4	-

* Data not available.

Furthermore, PC incorporating different SCMs and fibers, including FA, SF, BC, STF, WPF, and SCBA, yielded 24, 16, and 12 positive effect sizes out of 36, 25, and 16 effect sizes for compressive, tensile, and flexural strengths, respectively, indicating a general improvement in mechanical performance with cement replacement. This is mainly due to the pozzolanic reactivity of the replaced materials, which enhanced the properties of the PC [10,17,21,25,27,35,36,39,43,44]. However, the replacement of cement with other SCMs such as PR and POFA resulted in negative effect sizes, indicating inferior strengths with cement replacement. This may be due to the lower pozzolanic reactivity of these materials coupled with higher replacement percentages, inducing a filling effect with less binder.

Alternatively, out of the 32 and 31 respective effect sizes for porosity and permeability, 16 positive effect sizes were obtained for each hydraulic property in PC made with POFA, RF, CR, SG, PR, PU, and SCBA [8,45]. It seems that the finer particle size of the replacement materials and the higher degree of reaction in PC with cement replacement may have densified the concrete skeleton and reduced the hydraulic properties [46,47].

Furthermore, PC made with cement was generally more abrasion resistant than that made with partial or complete cement replacement, as 7 of the 8 effect sizes were negative. This inferior performance may be due to the cohesive nature of OPC particles compared to those of industrial wastes and replacement materials [48]. However, very limited studies have investigated this property. In conclusion, FA, SF, BC, STF, WPF, and SCBA produced PC with improved mechanical properties. The hydraulic performance was enhanced upon replacing cement with POFA, RF, CR, SG, PU, and SCBA. However, inferior durability performance was recorded for PC with cement replacement even though the mechanical properties had improved. Thus, there is a need for more studies to improve the durability properties of PC.

The results of Table 1 are further analyzed with fixed pooled *d* values, as shown in Figure 4. With reference to the vertical zero dashed line, a positive pooled *d* value (solid black box) signifies better performance for mixes with cement replacement and vice versa. Overall, it can be observed that the mechanical performance improved with cement replacement. Despite the significant variations in the strength results, with the fixed pooled *d* ranging from −6 to +2, all fixed pooled *d* values for strength were positive, confirming that the mechanical properties generally improved upon cement replacement. Meanwhile, the hydraulic performance was not as significantly affected. The pooled *d* values fell approximately at the vertical reference line, signifying that cement replacement had a limited impact on the hydraulic properties. Conversely, the durability properties, i.e., abrasion resistance, had a negative pooled *d* value of nearly −0.6 (range −11.5 to −0.2), indicating an inferior performance of mixes with cement replacement compared to those made with cement only. This can be attributed to the limited analyzed data obtained from the six durability studies identified in Figure 2. Unexpectedly, while the strengths of these PC mixes increased upon cement replacement, the abrasion resistance decreased, possibly due to the less cohesive nature of such industrial waste particles as compared to that of the OPC [49]. In conclusion, it can be observed that the replacement of cement generally improved the mechanical properties of PC without any significant change in hydraulic properties as compared to OPC-based PC. The analysis of the durability results is inconclusive due to insufficient data in this area.

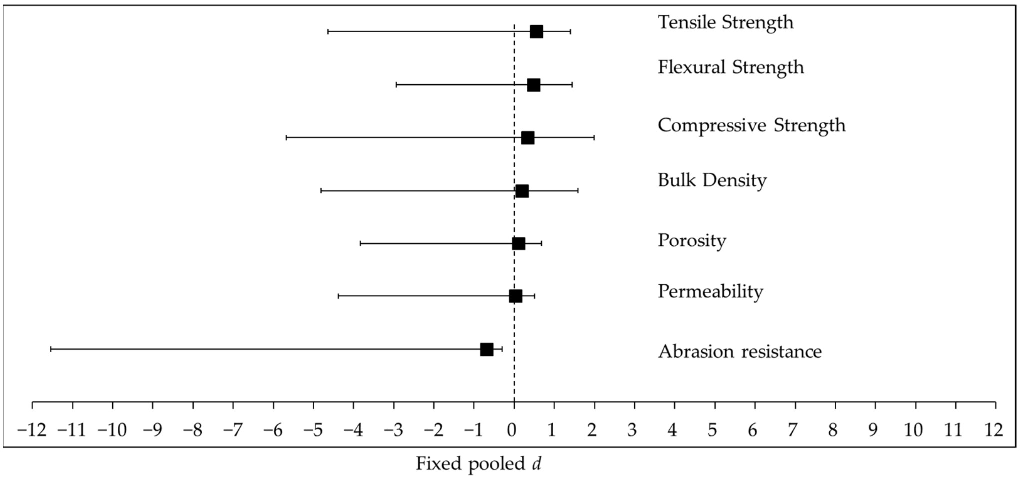

Figure 4. Overall performance of PC with different cement replacements based on fixed effect.

The effect of cement replacement percentage was also evaluated. Studies were conducted with partial and complete replacements of cement. Figure 5 presents the replacement percentages of cement in the reviewed articles. Partial replacement proportions are categorized as 1–10%, 11–20%, 21–30%, 31–40%, 41–50%, and 51–99%. Complete replacement is designated as 100%, while the control mix has 100% OPC and 0% replacement. Considering each proportion separately, mean values were obtained by dividing all the values of a specific property by the total frequency from all the reviewed studies. The results show that the compressive strengths are not negatively affected by cement replacement, as most mean values were similar to or higher than that of the control. Indeed, the highest mean values were for PC mixes, with 21–30% of the cement replaced with an SCM. Nevertheless, it should be noted that 100% cement replacement was possible without compromising the compressive strength. Moreover, the tensile and flexural strength patterns were similar to that of compressive strength, except that the highest improvement in these properties was when 41–50% and 1–10% of cement was replaced, respectively.

Nevertheless, it should be noted that none of the investigated studies tested the tensile and flexural strengths of PC made with more than 50% cement replacement. Accordingly, future work is required to evaluate the mechanical properties of such PC mixes.

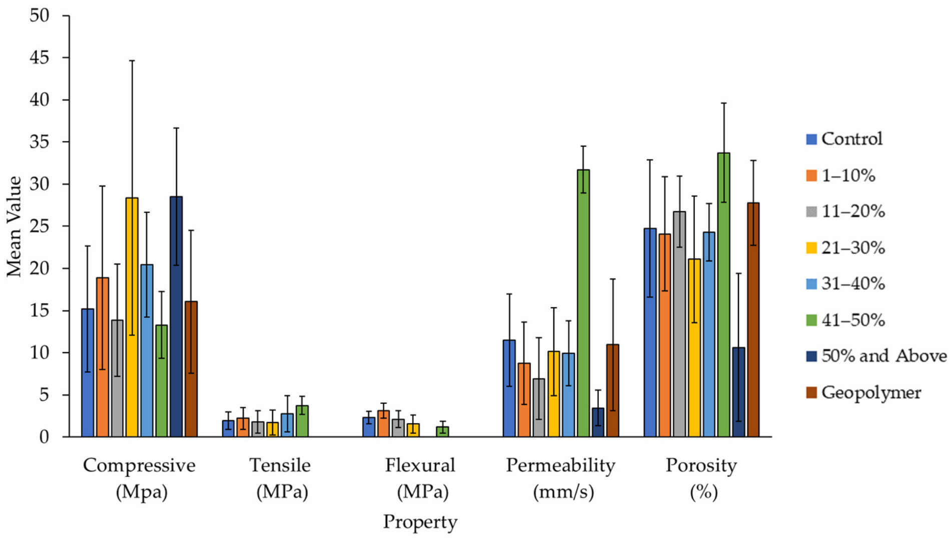

Figure 5. Mechanical and durability properties as a function of the cement replacement percentage.

Furthermore, the mean value of the permeability and porosity generally decreased with cement replacement, except for mixes replacing 41–50% and 100% of the cement, as seen in Figure 5. A higher mean value of 41–50% resulted from having fibers incorporated into the mixes, thereby producing more pore spaces at the fiber–binder interface [35]. To conclude, the viable partial cement replacement percentage that maintains the mechanical, hydraulic, and durability properties of PC is within the range of 1–40% while observing the acceptable replacement materials. Meanwhile, complete replacement (100%) of cement by FA or SG in geopolymer PC could also result in comparable performance.

The studies were also grouped based on the number of SCMs used in cement replacement, showing the distribution of data. Figure 6a–e show the variation in compressive strength, tensile strength, flexural strength, permeability, and porosity as a function of the number of materials used to replace cement in PC, i.e., zero (cement only), one, and two or more. The respective compressive strength medians of these three types of mixes were 13.7, 16.9, and 14.4 MPa, while those for tensile strength were 2.1, 1.7, and 2.1 MPa. In addition, the flexural strength medians were 1.8, 3.1, and 1.4 MPa, respectively. It can be observed that all the median lines for the strengths lie approximately at the center of the box, except for flexural strength, signifying that the values are normally distributed. Similarly, median lines within the boxplots indicate little difference in performance between the PC mixes across different studies. The respective interquartile for compressive strength of the three types of mixes (0, 1, and 2 replacement materials) were 7–20, 9–24, and 10–21 MPa, and those for tensile strength were 1.4–2.3, 1.0–2.1, and 1.5–3.0 MPa, while the flexural strength medians were 1.1–2.5, 2.8–3.3, and 1.2–3.1 MPa, respectively. The ranges show that the values were less dispersed for the 50% middle interquartile, indicating that PC with and without cement replacement exhibit similar mechanical performance regardless of the type and number of replacement materials used. This validates the potential replacement of cement in PC without undermining the mechanical properties. Similarly, the respective extreme whisker values, signifying the maximum and minimum, were 4–54, 5–28, and 7–45 MPa for compressive strength, 0.4–3.7, 0.3–3.7, and 1.0–3.3 MPa for tensile strength, and 0.9–4.6, 2.6–3.5, and 1.0–5.5 MPa for flexural strength. These values explain the performance disparities and indicate that PC made with cement or at least two replacement materials, in contrast to counterparts incorporating one replacement material, attained higher compressive strength while having higher divergence in the results. To conclude, the replacement of cement by other materials can maintain the performance of PC. However, the porous nature of PC seems to limit the enhancement potential of such materials but could offer a reduction in the carbon footprint of PC.

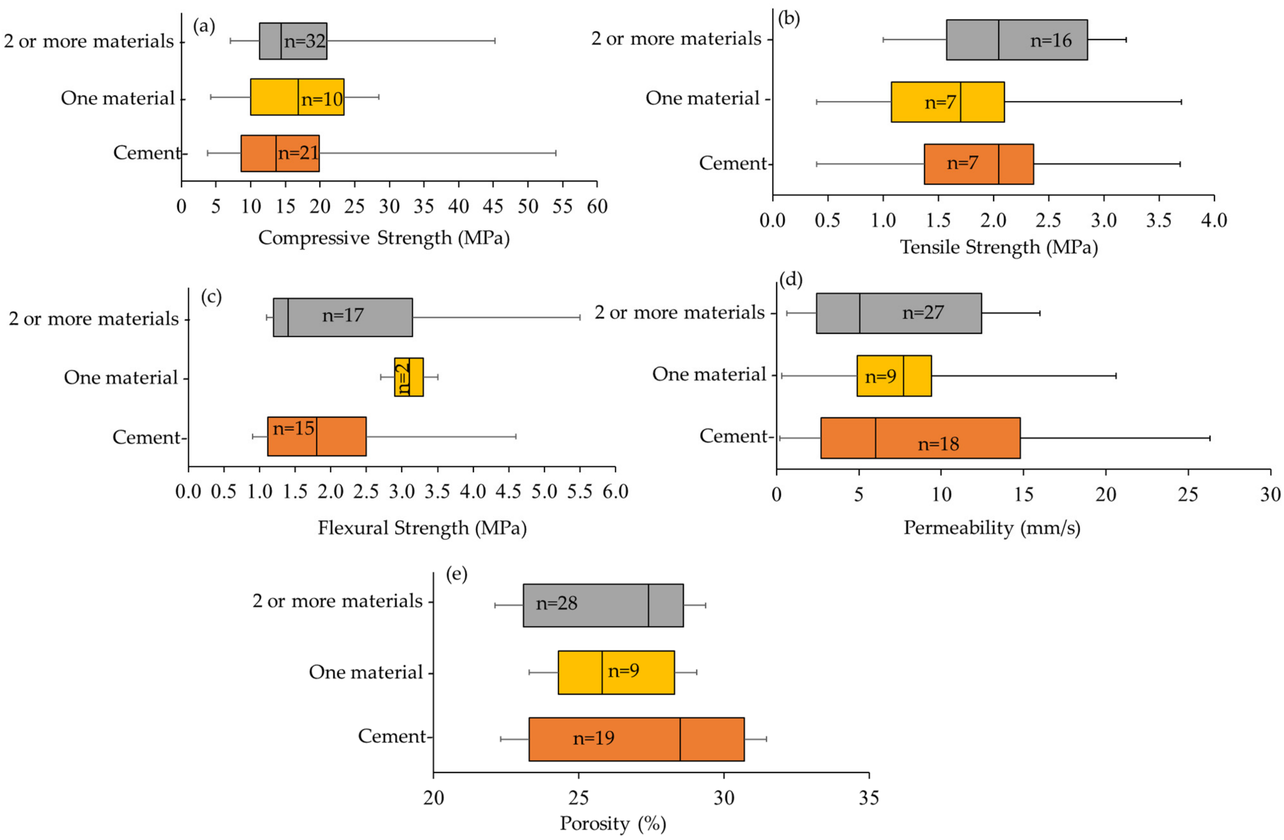

Figure 6. Variation in (**a**) Compressive strength, (**b**) Tensile strength, (**c**) Flexural strength, (**d**) Permeability, and (**e**) Porosity based on number of SCMs (n = number of publications).

In the case of hydraulic properties, the medians for the permeability of PC mixes made with cement only, one replacement material, and two or more replacement materials were approximately 6.0, 7.7, and 5.1 mm/s, respectively. The corresponding medians for porosity were 28.5, 25.8, and 27.4%, respectively. Despite the change in properties due to cement replacement, these values remain within the minimum acceptable requirement for hydraulic performance based on international standards and regulations [38]. The variability in hydraulic performance was likewise noted; the respective interquartile ranges of the types of mixes made with 0, 1, and 2 replacement materials were 2.7–14.8, 4.9–9.4, and 2.4–12.5 mm/s for permeability and 23.3–30.7, 24.3–28.3, and 23.1–28.6% for porosity. These ranges show more dispersed values, indicating dissimilarities in the hydraulic performance between the three types of mixes regardless of the number of replacement materials used. However, among the three types of mixes, those incorporating one replacement material had the lowest variability in the results. Similarly, the maximum and minimum whisker values were 0.1–27, 0.15–22, and 0.2–17 mm/s for permeability and 22.5–33, 23–27, and 22–28% for porosity, indicating the potentiality of exhibiting adequate hydraulic performance in PC with and without replacement. To conclude, the hydraulic properties of PC could be maintained upon the replacement of cement by one or more materials. The variability in the results of PC is generally improved upon cement replacement.

5.3. Aggregate Replacement in Pervious Concrete

5.3.1. Alternative Materials

Figure 7 shows the materials used to replace aggregates in PC production. These include recycled aggregates (RA), pumice (PU), waste glass (WG), steel slag (SS), copper slag (CS), electric arc furnace slag (EAFS), and polyethylene terephthalate bottles (RAP). RA has been investigated as an aggregate replacement in 40% of the reviewed articles. As the global human population increases, the demand for new infrastructure has augmented alongside the ongoing demolition of old structures [32]. The produced construction and demolition waste (CDW) have been stockpiled and landfilled, causing environmental pollution. With limited land space and an ever-increasing amount of CDW, it has become necessary to dispose of CDW properly. This explains the high number of publications investigating the use of RA as a replacement for NA. Nevertheless, the replacement of NA by RA in concrete decreased the mechanical properties due to its low density and high porosity, coupled with the weak transition zone between RA and cement paste [33,50–55]. Indeed, RA has adverse effects on most concrete strengths except impact resistance [56]. Furthermore, industrial wastes, including PU, WG, SS, CR, CS, EAFS, and RAP, have received significant attention in recent years; research has focused on means of recycling these industrial by-products rather than wastefully disposing of them [35]. When NA is replaced by an industrial waste aggregate (IWA), the resulting PC exhibits adequate compressive and flexural strength and hydraulic performance. Additionally, by using these waste materials, PC with good wear resistance can be achieved [26,44,46,57,58].

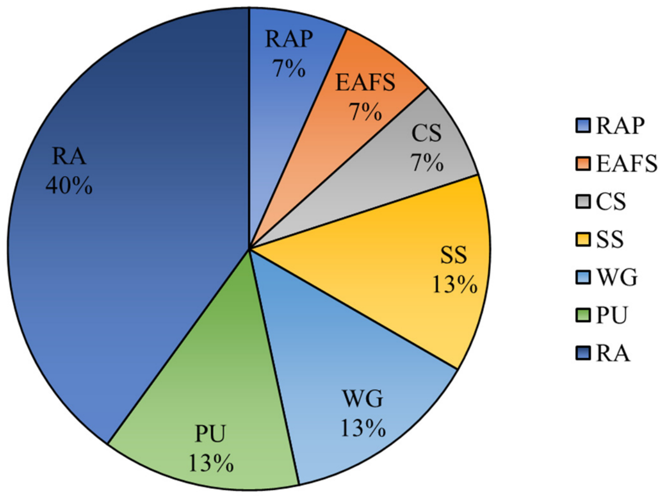

Figure 7. Distribution of materials used as a replacement for aggregates in the literature.

Despite the negative impact of using 100% RA on the properties of PC, the achieved strength can satisfy the minimum requirement stated by various transportation authorities. A study conducted by Toghroli et al. revealed that PC produced with 100% RA had a compressive strength of 10.5 MPa, which was 275% higher than the minimum required for PC [10]. Similarly, another study showed that PC compressive and flexural strengths of up to 27.6 and 3.8 MPa were reported with adequate hydraulic performance [5]. The higher strength in the latter study may be due to the nature and composition of the RA. The size of the RA also influenced the strength of the PC. A study showed that 100% RA that was 19 mm in size produced a 3.0 MPa PC, while a mix incorporating 100% RA 9.5 mm in size had a strength of 4.1 MPa. An opposite trend was observed in hydraulic properties, where 19 mm RA had better performance [17,22,50].

Compared to NA-based PC, 100% SS incorporation resulted in similar hydraulic performance, improved mechanical performance, superior carbonation resistance, and better abrasion resistance [26]. Meanwhile, mixes made with 50% AP experienced reduced strengths, low abrasion resistance, and improved hydraulic performance owing to AP's high porous nature [46]. The potential use of WG was also explored, where the obtained permeability and compressive strength of PC incorporating WG were within the minimum requirements of the Japanese Standard Association (JSA) standard, JIS A 5371. Furthermore, 60% CS replacement in PC increased the compressive, tensile, and flexural strengths by 31, 19, and 18% as compared to PC exclusively made with OPC [58]. Based on these results, it can be deduced that the performance of PC incorporating RA depends on the size and nature of the RA and the composition of the mix. Furthermore, 100% RA replacement can be viable in PC depending on its purpose and application. Similarly, IWA, including SS, WG, and CS, were found to be promising aggregate replacement materials in PC at 50 and 100% replacement levels, but for specific applications [59,60]. Nevertheless, between the two replacement materials, it seems that PC incorporating RA had inferior performance when compared to that made with IWA owing to the porous and weak nature of RA.

5.3.2. Performance Evaluation

Table 2 shows the type of replacement material for NA, the percentage of replacement, and the effect sizes for PC performance based on aggregate replacement. The mechanical performance of PC was generally inferior upon replacing NA with other aggregates such as RA. Out of the 11 effect sizes for bulk density, seven negative values were obtained, signifying a tendency for replaced aggregates to produce lighter-weight PC. This general decrease in bulk density may be attributed to the lower unit weight of the replaced aggregates as compared to that of NA [35,56,57]. Furthermore, out of the 14 and 10 effect sizes for compressive and flexural strengths, respectively, 8 and 6 negative effect sizes were obtained, signifying the inferior performance of PC with replaced aggregates. This is due to impurities, the porous nature of the replacement aggregates, and the weaker interfacial bond between the binding matrix and the aggregates [50,55]. While RA replacement gave conflicting results, replacement with EAFS, SS, and CS improved the mechanical properties. Such enhancement is due to the stronger nature of these slag-based aggregates compared to NA, alongside the improved bond with the binding matrix because of their angular and irregular shape [44,58,59].

Table 2. Effect size for PC performance based on aggregate replacement.

Reference	Type	Percentage Replacement	Mechanical Properties				Hydraulic Properties		Durability
			Bulk Density	Compressive Strength	Tensile Strength	Flexural Strength	Porosity	Permeability	Abrasion Resistance
[17]	RA	50% 100%	−2.8 −1.8	−2.0 −0.5	−250.0 0.0	−3.0 −3.8	3.0 3.0	3.0 2.0	−10.0 −9.4
[22]	RA	25, 50, 75, 100%	−2.2	−1.6	-	−2.2	2.6	2.7	-
[26]	SS	25, 50, 75, 100%	2.2	1.9	0.0	1.0	2.3	1.8	-
[32]	RAP	10, 20, 50, 100%	−1.3	−2.3	-	−1.7	1.0	-	-
[35]	RA	10, 25, 50, 100%	−1.6	−1.3	-	−2.7	1.6	2.3	-
[44]	EAFS	100%	2.5	0.5	-	-	0.6	0.6	-
[46]	PU	10, 20, 30, 40, 50%	−2.4	−1.4	1.4	−1.0	0.9	0.8	-
[57]	WG	25, 50, 75, 100%	−1.9	−1.8	-	-	−1.3	1.9	-
[58]	CS	20, 40, 50, 60, 80, 100%	2.6	1.9	2.5	4.4	4.4	1.3	-
[59]	RA	10%	-	1.5	2.8	-	−5.9	−42.4	-
[60]	RA	25, 50, 75, 100%	-	−3.7	-	−4.9	-	0.0	-
[61]	RA	100%	2.9	0.3	-	0.3	−0.6	−0.6	-
[62]	RA	8%	-	14.6	-	-	−7.4	−10.0	-

Alternatively, improved hydraulic performance was observed in PC with replaced aggregates as compared to NA-PC. Out of the 13 effect sizes for porosity and permeability, 9 and 10 positive effect sizes were obtained, respectively, indicating a general improvement in this performance with aggregate replacement. The replaced aggregates are more porous than NA, thus producing a more porous and permeable PC [50,52,55]. However, such an increase in hydraulic performance was not necessarily associated with a decrease in mechanical properties. In fact, this was the case for PC mixes with aggregates replaced by SS, EAFS, and CS, and occasionally by RA. Meanwhile, only one study examined the impact of NA replacement by RA on the durability properties. Despite having a negative effect size, the results are inconclusive due to insufficient data.

The results in Table 2 are further analyzed in Figure 8 using fixed-effect pooled *d* values. It can be observed that there is no significant change in mechanical and hydraulic performance with aggregate replacement, except for tensile strength, which was improved. Indeed, the *d* values (black box) ranged between −1 and +1.5. The durability properties were not included in the analysis due to limited available data. Conclusively, despite the negative effect of aggregate replacements in PC, especially RA, the mechanical performance of PC with aggregate replacement appeared to be similar to that of NA-based PC, with an improvement in hydraulic performance.

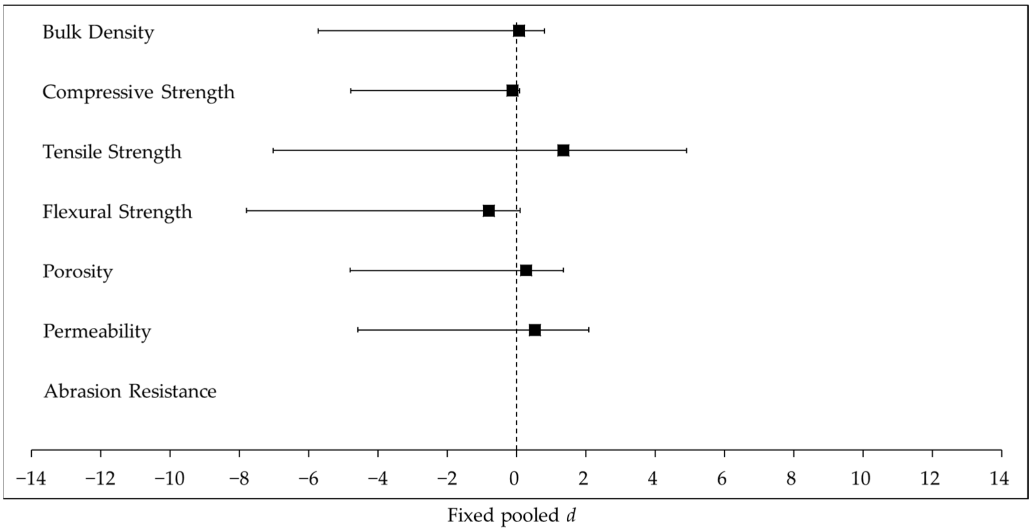

Figure 8. Overall performance of PC with different aggregate replacements based on fixed effect.

Variation in the performance of PC based on aggregate replacement was further analyzed with box and whisker plots, as shown in Figure 9. The aggregates considered were NA, IWA, and RA (including recycled coarse and fine aggregates). Correspondingly, the medians of NA-based PC, IWA-based PC, and RA-based PC for compressive strength were approximately 13.1, 20.3, and 10.1 MPa. The respective medians for tensile strength were 1.4, 2.8, and 0.8 MPa, while those for flexural strength were 2.5, 3.6, and 1.9 MPa, respectively. The results show that incorporating IWA can positively impact the mechanical performance of PC. In contrast, a 23% average reduction in performance was observed when RA replaced NA in PC mixes. Meanwhile, respective interquartile for the compressive strength of NA-PC, IWA-PC, and RA-PC were 11–17, 16–22, and 5–14 MPa, while for tensile strength these were 1.25–2.25, 2.2–2.95, and 0.7–1.2 MPa, and for flexural strength these were 2.1–3.1, 2.7–3.9, and 1.8–2.0 MPa, respectively. Among the three PC mixes, IWA-based PC had a similar interquartile range as that of NA-based PC. This may be due to the limited variations in the types and chemical compositions found in these wastes [63]. Conversely, RA-based PC had the highest dispersion in results due to the inert variation of these aggregates, as they are produced from CDW acquired from concretes having different properties. Extreme whisker values were obtained for the types of mixes as 5–49, 6–39, and 3–17 MPa for compressive strength, 1.1–3.1, 1.6–3.0, and 0.6–1.6 MPa for tensile strength, and 1.8–4.1, 1.6–4.3, and 1.15–2.1 MPa for flexural strength. Based on these results, the mechanical performance of PC with aggregate replacement exhibits skewed distribution, which indicates more dispersed performance, signifying a difference in performance based on the type of replacement used.

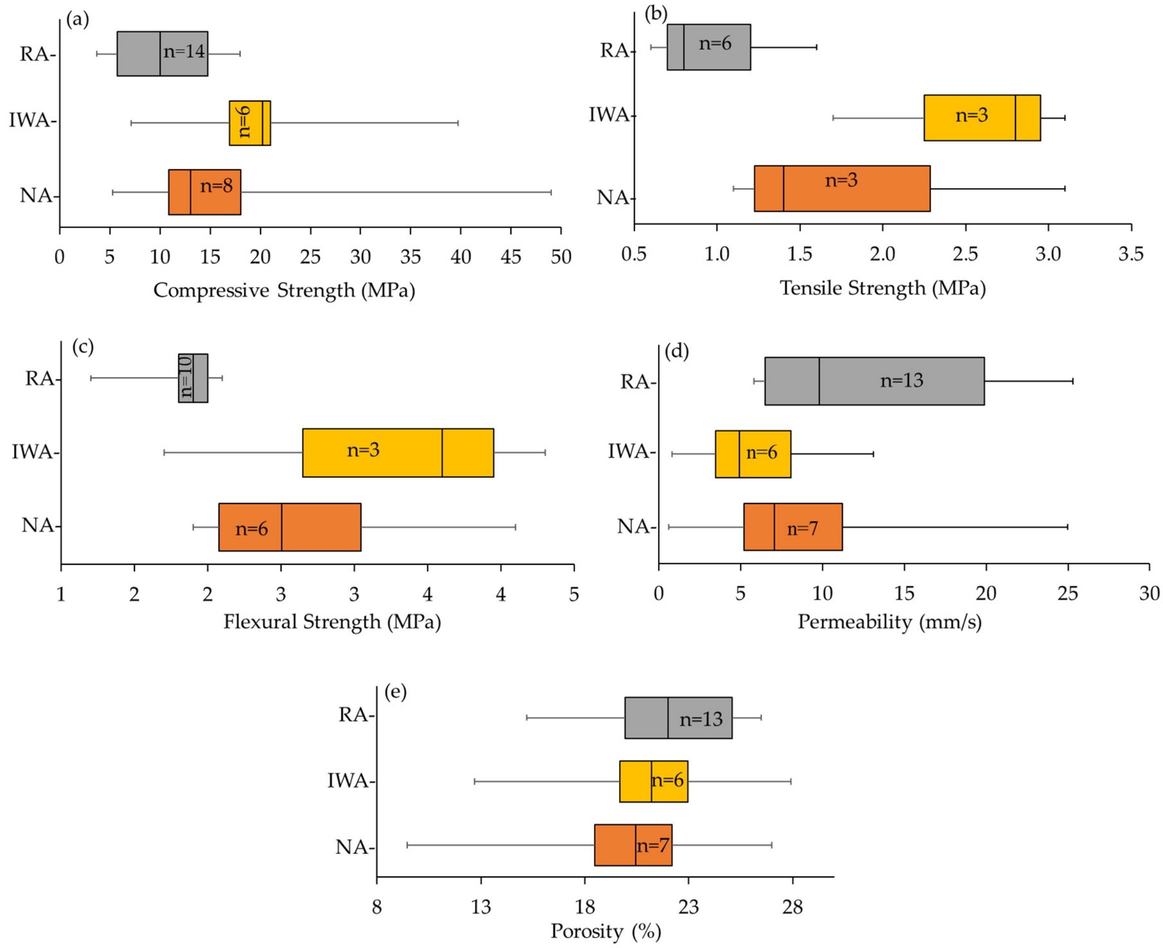

Figure 9. Variation in (**a**) Compressive strength, (**b**) Tensile strength, (**c**) Flexural strength, (**d**) Permeability, and (**e**) Porosity based on aggregate type (n = number of publications).

Considering the hydraulic performance, the respective permeability medians of PC mixes made with NA, IWA, and RA were 7.0, 4.9, and 9.8 mm/s. Meanwhile, the respective medians for porosity were 20.4, 21.2, and 22.0%. Despite the changes due to aggregate replacement, these values remain within the minimum acceptable requirement for hydraulic performance [38]. Thus, it can be stated that replacing NA with IWA and RA generally increased the total pore volume of PC, as evidenced by the higher porosity values, but the connectivity of these pores, i.e., permeability, only increased upon RA replacement, possibly due to the porous nature of these aggregates. The variability in permeability was noted with respective interquartile ranges of 5.2–11.2, 3.5–8.1, and 6.5–19.9 mm/s for NA-, IWA-, and RA-based PC and 18.5–22.2, 19.7–23.0, and 20.0–25.1% for the porosity of the corresponding types of mixes. Apparently, the dispersion in the results of hydraulic properties decreased with IWA replacement and increased upon RA replacement, owing to the extent of variability in these aggregates. Similarly, the respective extreme whisker values, signifying the maximum and minimum, were 1–25, 1–13, and 6.5–25.5 mm/s for permeability and 10–27, 12.5–28, and 15–25% for porosity. Based on these whisker values, it is clear that the replacement of NA by other aggregates has limited or no negative impact on the hydraulic performance.

In conclusion, IWA seems to be a better replacement for NA than RA with respect to the mechanical performance of PC, thus reducing the amount of landfill sites from industry practices. Although RA exhibits inferior performance compared to NA, it can still be used in PC production as it can produce PC with adequate mechanical and hydraulic performance, which could be used in low-traffic pavement applications. Nevertheless, with conflicting results for RA-based PC, more research is needed in the future to confirm their effect on the mechanical and hydraulic performance of PC mixes. Moreover, further studies are required to evaluate the durability properties of PC made with different types of aggregates.

Figure 10 shows the different aggregate replacement ratios in PC. While 0% served as a control mix with 100% OPC, partial replacement proportions were 1–10%, 11–20%, 21–30%, 31–40%, 41–50%, and 51–99%, and complete replacement was 100%. For each proportion, the mean values were obtained by dividing the values corresponding to a specific property by the frequency of assessing this property. The compressive, tensile, and flexural strengths were generally unaffected, with slight fluctuations, by the replacement of NA at all percentages. Furthermore, the permeability seemed to increase with aggregate replacement up to 50%, while a decrease was recorded beyond 50%, signifying that the connected porosity was greatly affected by the larger pore spaces. Conclusively, replacement ranges of 1–100% and 1–50% are considered to be viable for superior mechanical and hydraulic performance, respectively.

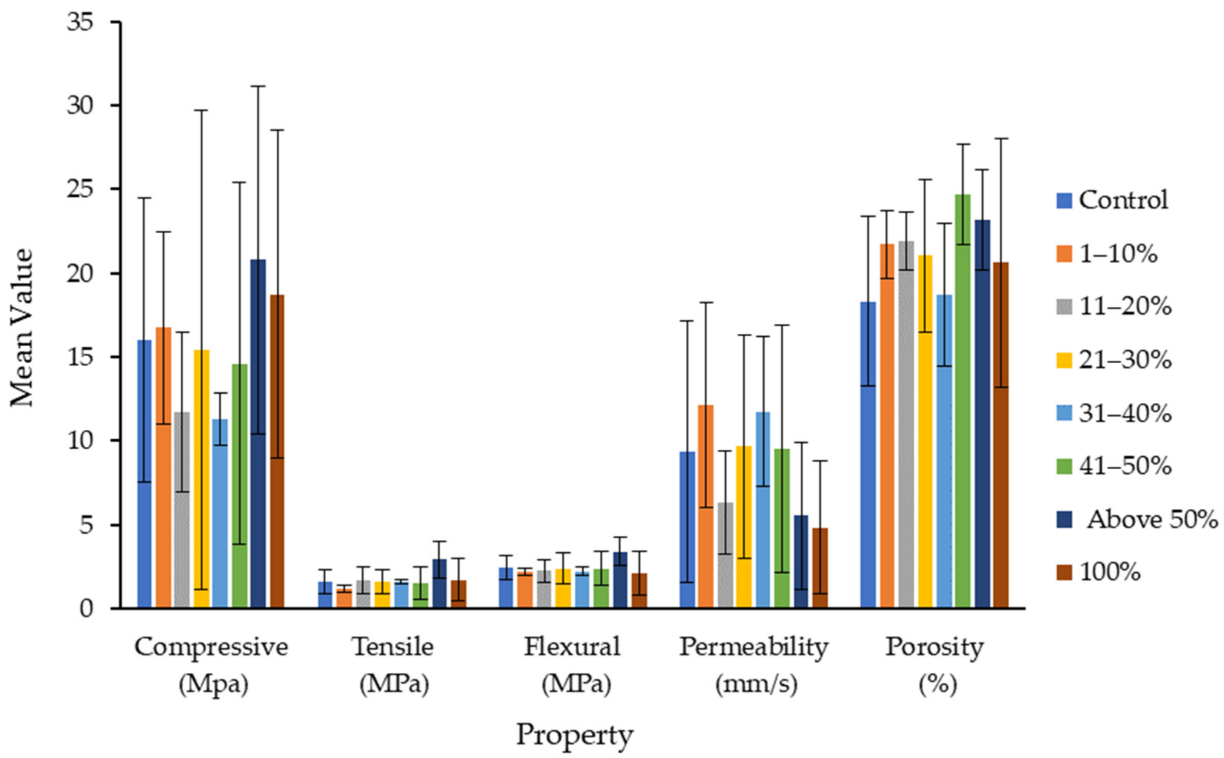

Figure 10. Mechanical and durability properties as a function of the aggregate replacement percentage.

5.4. Combined Replacement of Cement and Aggregates in Pervious Concrete

To capitalize on the promising effect of individual cement and aggregate replacement in PC, the effect of the combined replacement on PC performance was also evaluated. For instance, replacing cement with FA improved mechanical properties, while replacing NA with acidic pumice improved hydraulic performance [35,46]. Thus, combining two materials to replace cement and aggregates may produce PC with improved strength and hydraulic performance [64,65]. Table 3 summarizes the materials used to replace cement and aggregates with the designated replacement percentage.

Table 3. Effect size for PC performance based on combined replacement.

Ref.	Cement Replacement (Percentage)	Aggregate Replacement (Percentage)	Mechanical				Hydraulic		Durability
			Density	Compressive Strength	Tensile Strength	Flexural Strength	Porosity	Permeability	Abrasion Resistance
[3]	SG (100%)	PN (5, 10, 15%)	-	−2.0	−2.6	-	-	-	-
	SG (100%)	PN (3, 6, 12%)	-	0.2	0.8	-	-	-	-
[4]	FA (10%)	SD (8%)	-	−0.3	-	−0.1	-	0.0	-
	SF (5 and 10%)	RA (50%)	−5.0	50.0	3.3	10	3.0	1.9	−3.9
	CR (5 and 10%)	RA (50%)	−3.0	100	6.2	2.2	3.0	1.2	−11
	BL (10 and 20%)	RA (50%)	11.0	2.9	2.0	10	−7.0	−1.5	−3.4
[17]	RF (1.5 and 3%)	RA (50%)	4.0	2.3	2.0	2.5	−4.0	−500	−9.0
	SF (5 and 10%)	RA (100%)	5.0	1.6	500	5.0	−2.3	−200	−4.1
	CR (5 and 10%)	RA (100%)	5.0	−1.3	−1.9	−2.7	−3.0	−3.0	−27
	BL (10 and 20%)	RA (100%)	3.0	−1.0	1.0	−1.0	−3.5	−1.5	−13.8
	RF (1.5 and 3%)	RA (100%)	4.0	5.0	2.0	3.3	−3.0	−5.0	−3.2
[18]	SF (10%)	RA (25, 50, 75, 100%)	−0.8	−1.3	-	−1.7	2.1	2.5	-
[35]	PU (10, 25, 50%)	RA (25, 50, 75, 100%)	−1.7	−1.6	-	−1.3	2.1	2.5	-
	PU (10%), NC (1, 2, 3%)	RA (25,50,75,100%)	−1.6	−3.2	-	−1.0	1.5	2.0	-
[44]	AAS (100%)	EAFS (100%)	−2.5	2.8	-	-	1.0	0.9	-
[54]	SF (30%)	RA (25, 50, 75, 100%)	−2.1	−1.7	-	-	2.1	1.5	-
	SF (30%)	WGC (25, 50, 75, 100%)	−1.8	−2.8	-	-	1.6	2.7	-
[63]	GBFS (8%), FA (4%), SF (4%)	SS (100%)	−1.1	−0.5	-	-	0.9	0.7	-
[64]	FA (10%)	RA (25, 50, 75, 100%)	-	−4.7	-	−4.5	-	0.8	-

Effect sizes for PC performance based on the combined replacement of cement and aggregates are shown in Table 3. The mechanical properties of PC with combined replacement was generally comparable to NA-cement-based PC. Six of the 15 effect sizes for bulk density were positive values. A similar trend was observed in other mechanical properties, where 8 of the 19 effect sizes for compressive strength were positive, which signifies a comparable performance to that of the NA-cement-based control. In fact, the negative effect sizes were those incorporating up to 100% RA. These findings were further validated by 13 effect sizes for flexural strength, out of which six positive effect sizes were obtained. Conversely, PC became less durable with cement and aggregate replacement owing to the inferior properties of IWA and RA in comparison to NA [30,56,61,63,64,66]. To limit the reduction in performance, an RA replacement limited to 50% [10,35] or the addition of fibers was recommended [55]. Alternatively, the hydraulic performance of PC improved with combined replacement. Out of 15 and 17 effect sizes for porosity and permeability, six negative effect sizes were obtained for each. However, such behavior was not necessarily associated with increased mechanical properties, especially in PC mixes incorporating CR, BL, and RF. Furthermore, the combined replacement of SF and RA exhibited improved mechanical and hydraulic performance [17] as compared to individual replacements of SF and RA, which exhibited inferior mechanical performance coupled with adequate hydraulic performance [18,35]. Thus, it is possible to obtain improved performance from the combined replacement of materials that produced inferior performance individually [30,53,67–73].

The values in Table 3 were analyzed using fixed pooled d values, as shown in Figure 11. The combined replacement of cement and aggregates followed a similar trend to that of aggregate replacement. It seems that aggregate replacement has a more apparent impact on mechanical and hydraulic performance than cement replacement. This is attributed to the weak properties and porous nature of RA. Furthermore, the durability performance followed a similar trend to that of PC mixes with cement replacement, with an absence of sufficient data on aggregate replacement. Nevertheless, it is worth noting that all properties were insignificantly affected by the combined replacement. In conclusion, RA can be effectively utilized in combined replacement with other materials such as SF and SG, producing PC with improved mechanical and hydraulic performance. While similar properties were obtained with and without combined replacement, the performance of PC with combined replacement was more influenced by aggregate replacement than cement replacement.

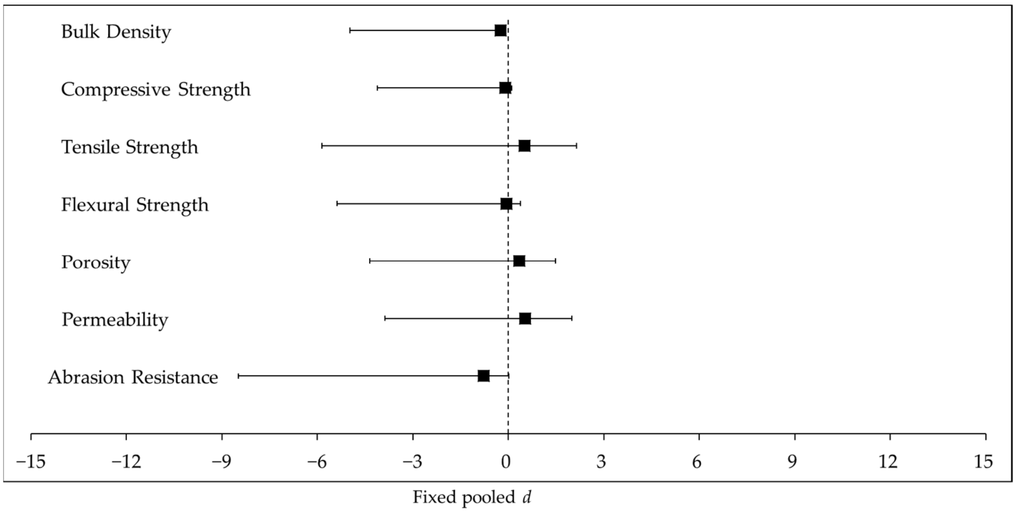

Figure 11. Overall performance of combined replacements based on fixed effect.

The combined replacement of cement and aggregates was analyzed using box and whisker plots to deduce the most practical combination of cement and aggregate replacements. The considered modes were OPC+NA, SCM+IWA, and SCM+RA, where SCM represents the cement replacement material. Figure 12a shows the influence of combined replacements on PC performance based on compressive strength. The respective medians of these three types of mixes for compressive strength were 9.9, 19.7, and 9.3 MPa. This shows that the combined replacement of SCM and IWA can positively affect the mechanical properties of PC, while incorporating SCM and RA in PC has a limited impact. Additionally, the interquartile ranges of SCM+IWA-PC and SCM+RA-PC were 14.3–26.9 MPa and 5.1–17.9 MPa, respectively, while that of the control PC was 6.0–23.0 MPa. The maximum and minimum whisker values were 4–39, 7–34, and 3.5–27 MPa for OPC+NA, SCM+IWA, and SCM+RA, respectively, signifying a reduction in the variability of the compressive strength with aggregate and cement replacement.

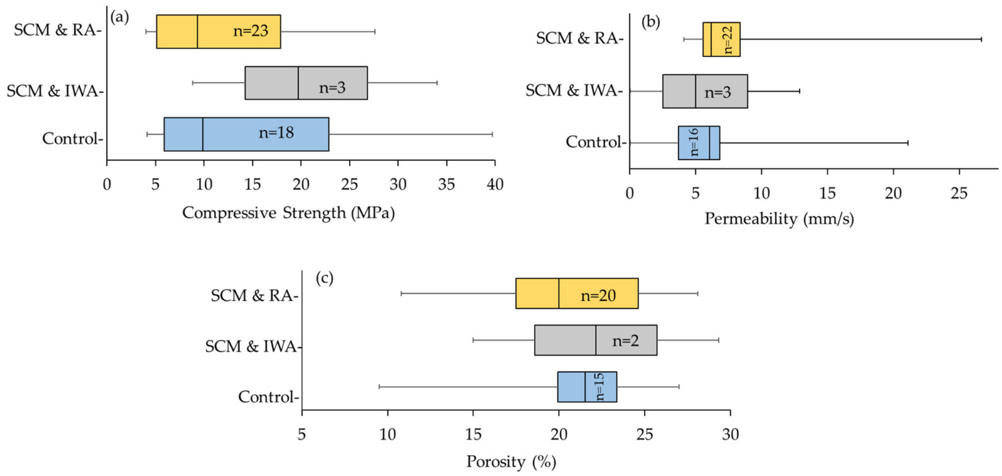

Figure 12. Variation in (**a**) Compressive strength, (**b**) Permeability, and (**c**) Porosity based on combined replacement (n = number of publications).

Furthermore, the hydraulic performance of PC with the combined replacement of cement and aggregate was also assessed, as shown in Figure 12b,c. The medians for the permeability of PC mixes made with OPC+NA, SCM+IWA, and SCM+RA were 6.1, 5.0, and 6.2 mm/s, respectively, while their respective porosity medians were 21.5, 22.2, and 20.0%. From these values, similar hydraulic performance can be observed for all modes of replacements. Nevertheless, the minimum permeability was observed for SCM+IWA-PC, which may be due to its more compact structure, leading to high mechanical performance. The variability in outcomes for PC mixes made with OPC+NA, SCM+IWA, and SCM+RA was noted with respective interquartile ranges of 3.7–6.8, 2.5–9.0, and 5.6–8.4 mm/s and 19.9–23.4, 18.6–25.7, 17.5–24.6% for permeability and porosity. Similarly, respective whisker values for permeability and porosity were 0–21, 0–13, and 3.5–27 mm/s and 9.5–27.5, 14.5–29, and 10.5–28%. Based on the boxplot results, similar hydraulic performance of PC with and without combined replacement was observed. Thus, there is potential in producing PC with the combined replacement of cement and aggregates while exhibiting adequate hydraulic performance. In conclusion, viable mechanical and hydraulic performance was observed for SCM+IWA-PC. Meanwhile, the SCM+RA-PC mix had comparable properties to the control PC mix, rendering it a promising mix for future applications.

6. Conclusions, Lessons Learnt, and Way Forward

This work reviewed the impact of replacing cement and aggregates with different materials on the mechanical, hydraulic, and durability properties of produced PC. A meta-analysis considering the changes in compressive strength, tensile strength, flexural strength, porosity, permeability, and abrasion resistance was employed to elucidate the feasible range of the replacement percentage and the number of materials used to replace cement and the aggregates. Based on these, the following conclusions can be drawn:

- Most studies on PC made with cement and aggregate replacement focused on density and compressive, tensile, and flexural strengths for mechanical performance evaluation. Permeability and porosity were examined to characterize hydraulic performance. The least evaluated criterion was the durability performance, for which abrasion resistance was the most tested property. Additionally, most of the relevant studies were conducted in Asia (China and India) and the USA.
- The mechanical properties were generally maintained or improved with single or binary cement replacement. Of the various materials used to replace cement, FA and SF were the most commonly investigated materials. While the replacement percentage was limited to 30% to maintain adequate performance, it was also possible to produce 100% cement-free geopolymer PC using FA or SG, with comparable properties to the cement-based counterpart.
- The hydraulic performance of PC was generally maintained with single or binary cement replacement. However, improvement was recorded upon the incorporation of POFA, RF, CR, SG, PU, and SCBA. Based on the analysis, the recommended partial replacement limit in hydration-based PC was up to 40%. However, complete replacement (100%) in geopolymer PC could provide comparable results to those of the cement-based control. While limited studies examined the durability performance, i.e., abrasion resistance, of PC with cement replacement, it was found that partially replacing cement had a detrimental effect.
- The most common material used for aggregate replacement was RA, while the most widely used IWA were PU, WG, SS, CR, CS, EAFS, and RAP. RA replacement gave conflicting strength results, but it increased permeability and porosity. Conversely, the replacement of NA with EAFS, SS, and CS improved the mechanical properties of PC. Nevertheless, their incorporation into PC negatively impacted hydraulic performance. In fact, the replacement percentage was recommended to be limited to 50% in order to maintain adequate mechanical and hydraulic properties.
- RA-based PC had the highest dispersion in strength results due to the inert variation of these aggregates, while IWA-based PC had a variability similar to that of OPC-based

PC. Moreover, the dispersion in the results of hydraulic properties decreased with IWA replacement and increased with RA replacement. Between the two alternatives, IWA served as a better replacement for NA than RA. However, RA-based PC still exhibited adequate properties for use in low-traffic pavement applications.

- The mechanical and hydraulic properties of PC made with cement and aggregate replacement (combined) were generally comparable to or better than the NA-cement-based control counterparts. In fact, it was possible to improve the performance of PC upon the combined replacement of cement and aggregates; on the other hand, inferior PC performance was noted for mixes with the individual replacement of cement or the aggregates. In addition, the combined replacement of NA and cement reduced the dispersion and variability of the results.

Based on these conclusions, it is envisioned that future investigations on PC with aggregate or cement replacement should incorporate the following recommendations:

- Ensure the universal applicability of the findings, investigated PC mixes should be made with the same materials but acquired from different locations;
- Include the modulus of elasticity of PC made with cement and/or aggregate replacement as an important mechanical property;
- Assess the durability performance of PC made with aggregate replacement;
- Investigate the effect of binary, ternary, and quaternary replacement of cement on the performance of PC, especially with replacement percentages above 50%, by cement mass;
- Evaluate various methods for improving the durability performance of PC with cement and aggregate replacement materials.

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References

1. Gagg, C.R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail. Anal.* **2014**, *40*, 114–140. [CrossRef]
2. Gupta, S.; Mohapatra, B.N.; Bansal, M. A review on development of Portland limestone cement: A step towards low carbon economy for Indian cement industry. *Curr. Res. Green Sustain. Chem.* **2020**, *3*, 100019. [CrossRef]
3. Ganesh, A.C.; Deepak, N.; Deepak, V.; Ajay, S.; Pandian, A. Utilization of PET bottles and plastic granules in geopolymer concrete. *Mater. Today Proc.* **2021**, *42*, 444–449. [CrossRef]
4. Lo, F.-C.; Lee, M.-G.; Lo, S.-L. Effect of coal ash and rice husk ash partial replacement in ordinary Portland cement on pervious concrete. *Constr. Build. Mater.* **2021**, *286*, 122947. [CrossRef]
5. Rahman, S.S.; Khattak, M.J. Roller compacted geopolymer concrete using recycled concrete aggregate. *Constr. Build. Mater.* **2021**, *283*, 122624. [CrossRef]
6. El-Hassan, H.; Kiamehr, P. Pervious concrete pavement incorporating GGBS to alleviate pavement runoff and improve urban sustainability. *Road Mater. Pavement Des.* **2018**, *19*, 167–181. [CrossRef]

7. Bosoaga, A.; Masek, O.; Oakey, J.E. CO_2 Captute Technologies in Cement Industry. *Energy Procedia* **2009**, *1*, 133–140. [CrossRef]
8. Khankhaje, E.; Rafieizonooz, M.; Salim, M.R.; Khan, R.; Mirza, J.; Siong, H.C. Salmiati Sustainable clean pervious concrete pavement production incorporating palm oil fuel ash as cement replacement. *J. Clean. Prod.* **2018**, *172*, 1476–1485. [CrossRef]
9. Chen, X.; Wang, H.; Najm, H.; Venkiteela, G.; Hencken, J. Evaluating engineering properties and environmental impact of pervious concrete with fly ash and slag. *J. Clean. Prod.* **2019**, *237*, 117714. [CrossRef]
10. Toghroli, A.; Mehrabi, P.; Shariati, M.; Trung, N.T.; Jahandari, S.; Rasekh, H. Evaluating the use of recycled concrete aggregate and pozzolanic additives in fiber-reinforced pervious concrete with industrial and recycled fibers. *Constr. Build. Mater.* **2020**, *252*, 118997. [CrossRef]
11. Farouq, M.M.; Lawan, U.F.; Garba, N.; Anwar, F.H.; Baba, Z.B.; Labbo, M.S.; Aliyu, D.S. Implementation of Environmental Management System in Construction Industry: A Review. *IOSR J. Mech. Civ. Eng.* **2017**, *14*, 33–38.
12. Elizondo-Martínez, E.-J.; Andres-Valeri, V.-C.; Jato-Espino, D.; Rodriguez-Hernandez, J. Review of porous concrete as multifunctional and sustainable pavement. *J. Build. Eng.* **2020**, *27*, 100967. [CrossRef]
13. Lo, W.; Huang, C.-T.; Wu, M.-H.; Doong, D.-J.; Tseng, L.-H.; Chen, C.-H.; Chen, Y.-J. Evaluation of Flood Mitigation Effectiveness of Nature-Based Solutions Potential Cases with an Assessment Model for Flood Mitigation. *Water* **2021**, *13*, 3451. [CrossRef]
14. Raeesi, R.; Soltani, A.; King, R.; Disfani, M.D. Mechanical Performance of Tire-Derived Aggregate Permeable Pavements Under Live Traffic Loads. In *Advances in Transportation Geotechnics IV*; Springer: Cham, Switzerland, 2021; Volume 164, pp. 515–528.
15. Zhong, R.; Leng, Z.; Poon, C. Research and application of pervious concrete as a sustainable pavement material: A state-of-the-art and state-of-the-practice review. *Constr. Build. Mater.* **2018**, *183*, 544–553. [CrossRef]
16. Chandrappa, A.K.; Biligiri, K.P. Pervious concrete as a sustainable pavement material—Research findings and future prospects: A state-of-the-art review. *Constr. Build. Mater.* **2016**, *111*, 262–274. [CrossRef]
17. Aliabdo, A.A.; Abd Elmoaty, A.E.M.; Fawzy, A.M. Experimental investigation on permeability indices and strength of modified pervious concrete with recycled concrete aggregate. *Constr. Build. Mater.* **2018**, *193*, 105–127. [CrossRef]
18. Adil, G.; Kevern, J.T.; Mann, D. Influence of silica fume on mechanical and durability of pervious concrete. *Constr. Build. Mater.* **2020**, *247*, 118453. [CrossRef]
19. Rahman, K.; Barua, S.; Anwar, M.S.; Hasan, M.Z.; Islam, S. Removal of Heavy Metals from Stormwater Using Porous Concrete Pavement. *J. Mod. Mater.* **2020**, *7*, 37–44. [CrossRef]
20. Elango, K.S.; Vivek, D.; Prakash, G.K.; Paranidharan, M.J.; Pradeep, S.; Prabhukesavaraj, M. Strength and permeability studies on PPC binder pervious concrete using palm jaggery as an admixture. *Mater. Today Proc.* **2021**, *37*, 2329–2333. [CrossRef]
21. Bilal, H.; Chen, T.; Ren, M.; Gao, X.; Su, A. Influence of silica fume, metakaolin & SBR latex on strength and durability performance of pervious concrete. *Constr. Build. Mater.* **2021**, *275*, 122124.
22. Yang, J.; Jiang, G. Experimental study on properties of pervious concretepavement materials. *Cem. Concr. Res.* **2003**, *33*, 381–386. [CrossRef]
23. Borenstein, M.; Hedges, L.; Higgins, J.; Rothstein, H.R. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res. Synth. Methods* **2010**, *2*, 97–111. [CrossRef] [PubMed]
24. Anwar, F.H.; El-Hassan, H.; Hamouda, M.A. A meta-analysis on the performance of pervious concrete with partial cement replacement by supplementary cementitious materials. In Proceedings of the ZEMCH 2021, Dubai, United Arab Emirates, 26–28 October 2021.
25. Adamu, M.; Ayeni, K.O.; Haruna, S.I.; Ibrahim Mansour, Y.E.-H.; Haruna, S. Durability performance of pervious concrete containing rice husk ash and calcium carbide: A response surface methodology approach. *Case Stud. Constr. Mater.* **2021**, *14*, e00547. [CrossRef]
26. Wang, S.; Zhang, G.; Wang, B.; Wu, M. Mechanical strengths and durability properties of pervious concretes with blended steel slag and natural aggregate. *J. Clean. Prod.* **2020**, *271*, 122590. [CrossRef]
27. Saboo, N.; Shivhare, S.; Kori, K.K.; Chandrappa, A.K. Effect of fly ash and metakaolin on pervious concrete properties. *Constr. Build. Mater.* **2019**, *223*, 322–328. [CrossRef]
28. Aoki, Y.; Sri Ravindrarajah, R.; Khabbaz, H. Properties of pervious concrete containing fly ash. *Road Mater. Pavement Des.* **2012**, *13*, 1–11. [CrossRef]
29. Wang, H.; Li, H.; Liang, X.; Zhou, H.; Xie, N.; Dai, Z. Investigation on the mechanical properties and environmental impacts of pervious concrete containing fly ash based on the cement-aggregate ratio. *Constr. Build. Mater.* **2019**, *202*, 387–395. [CrossRef]
30. Opiso, E.M.; Supremo, R.P.; Perodes, J.R. Effects of coal fly ash and fine sawdust on the performance of pervious concrete. *Heliyon* **2019**, *5*, e02783. [CrossRef]
31. Jo, M.; Soto, L.; Arocho, M.; St John, J.; Hwang, S. Optimum mix design of fly ash geopolymer paste and its use in pervious concrete for removal of fecal coliforms and phosphorus in water. *Constr. Build. Mater.* **2015**, *93*, 1097–1104. [CrossRef]
32. Mohammed, B.S.; Liew, M.S.; Alaloul, W.S.; Khed, V.C.; Hoong, C.Y.; Adamu, M. Properties of nano-silica modified pervious concrete. *Case Stud. Constr. Mater.* **2018**, *8*, 409–422. [CrossRef]
33. El-Hassan, H.; Elkholy, S. Enhancing the performance of Alkali-Activated Slag-Fly ash blended concrete through hybrid steel fiber reinforcement. *Constr. Build. Mater.* **2021**, *311*, 125313. [CrossRef]
34. Hesami, S.; Ahmadi, S.; Nematzadeh, M. Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement. *Constr. Build. Mater.* **2014**, *53*, 680–691. [CrossRef]

35. Mehrabi, P.; Shariati, M.; Kabirifar, K.; Jarrah, M.; Rasekh, H.; Trung, N.T.; Shariati, A.; Jahandari, S. Effect of pumice powder and nano-clay on the strength and permeability of fiber-reinforced pervious concrete incorporating recycled concrete aggregate. *Constr. Build. Mater.* **2021**, *287*, 122652. [CrossRef]
36. Carmichael, M.J.; Arulraj, G.P.; Meyyappan, P.L. Effect of partial replacement of cement with nano fly ash on permeable concrete: A strength study. *Mater. Today Proc.* **2021**, *43*, 2109–2116. [CrossRef]
37. López-Carrasquillo, V.; Hwang, S. Comparative assessment of pervious concrete mixtures containing fly ash and nanomaterials for compressive strength, physical durability, permeability, water quality performance and production cost. *Constr. Build. Mater.* **2017**, *139*, 148–158. [CrossRef]
38. ACI Committee 522. *522R-10: Report on Pervious Concrete*; ACI 522R-10; American Concrete Institute: Farmington Hills, MI, USA, March 2010.
39. Qin, Y.; Pang, X.; Tan, K.; Bao, T. Evaluation of pervious concrete performance with pulverized biochar as cement replacement. *Cem. Concr. Compos.* **2021**, *119*, 104022. [CrossRef]
40. Muthukumar, S.; Saravanan, A.J.; Raman, A.; Sundaram, M.S.; Angamuthu, S.S. Investigation on the mechanical properties of eco-friendly pervious concrete. *Mater. Today Proc.* **2021**, *46*, 4909–4914. [CrossRef]
41. Giustozzi, F. Polymer-modified pervious concrete for durable and sustainable transportation infrastructures. *Constr. Build. Mater.* **2016**, *111*, 502–512. [CrossRef]
42. Zaetang, Y.; Wongsa, A.; Sata, V.; Chindaprasirt, P. Use of coal ash as geopolymer binder and coarse aggregate in pervious concrete. *Constr. Build. Mater.* **2015**, *96*, 289–295. [CrossRef]
43. Sun, Z.; Lin, X.; Vollpracht, A. Pervious concrete made of alkali activated slag and geopolymers. *Constr. Build. Mater.* **2018**, *189*, 797–803. [CrossRef]
44. Chang, J.J.; Yeih, W.; Chung, T.J.; Huang, R. Properties of pervious concrete made with electric arc furnace slag and alkali-activated slag cement. *Constr. Build. Mater.* **2016**, *109*, 34–40. [CrossRef]
45. Chen, X.; Guo, Y.; Ding, S.; Zhang, H.; Xia, F.; Wang, J.; Zhou, M. Utilization of red mud in geopolymer-based pervious concrete with function of adsorption of heavy metal ions. *J. Clean. Prod.* **2019**, *207*, 789–800. [CrossRef]
46. Öz, H.Ö. Properties of pervious concretes partially incorporating acidic pumice as coarse aggregate. *Constr. Build. Mater.* **2018**, *166*, 601–609. [CrossRef]
47. Huang, J.; Zhang, Y.; Sun, Y.; Ren, J.; Zhao, Z.; Zhang, J. Evaluation of pore size distribution and permeability reduction behavior in pervious concrete. *Constr. Build. Mater.* **2021**, *290*, 123228. [CrossRef]
48. Sandoval, G.F.B.; GAlobardes, I.; Campos De Moura, A.; Toralles, B.M. Hydraulic behavior variation of pervious concrete due to clogging. *Case Stud. Constr. Mater.* **2020**, *13*, e00354. [CrossRef]
49. Pellenq, R.J.-M.; Van Damme, H. Why Does Concrete Set?: The Nature of Cohesion Forces in Hardened Cement-Based Materials. *Constr. Mater. Innov. Conserv.* **2004**, *29*, 319–323. [CrossRef]
50. El-Hassan, H.; Kianmeh, P.; Zouaoui, S. Properties of pervious concrete incorporating recycled concrete aggregates and slag. *Constr. Build. Mater.* **2019**, *212*, 164–175. [CrossRef]
51. Kachouh, N.; El-Maaddawy, T.; El-Hassan, H.; El-Ariss, B. Shear Behavior of Steel-Fiber-Reinforced Recycled Aggregate Concrete Deep Beams. *Buildings* **2021**, *11*, 423. [CrossRef]
52. El-Hassan, H.; Hussein, A.; Medljy, J.; El-Maaddawy, T. Performance of Steel Fiber-Reinforced Alkali-Activated Slag-Fly Ash Blended Concrete Incorporating Recycled Concrete Aggregates and Dune Sand. *Buildings* **2021**, *11*, 327. [CrossRef]
53. El-Hassan, H.; Medljy, J.; El-Maaddawy, T. Properties of Steel Fiber-Reinforced Alkali-Activated Slag Concrete Made with Recycled Concrete Aggregates and Dune Sand. *Sustainability* **2021**, *13*, 8017. [CrossRef]
54. Kachouh, N.; El-Hassan, H.; El-Maaddawy, T. Influence of steel fibers on the flexural performance of concrete incorporating recycled concrete aggregates and dune sand. *J. Sustain. Cem.-Based Mater.* **2021**, *10*, 165–192. [CrossRef]
55. Kachouh, N.; El-Hassan, H.; El-Maaddawy, T. Effect of steel fibers on the performance of concrete made with recycled concrete aggregates and dune sand. *Constr. Build. Mater.* **2019**, *213*, 348–359. [CrossRef]
56. Lu, J.-X.; Yan, X.; He, P.; Poon, C.S. Sustainable design of pervious concrete using waste glass and recycled concrete aggregate. *J. Clean. Prod.* **2019**, *234*, 1102–1112. [CrossRef]
57. Shen, P.; Zheng, H.; Liu, S.; Lu, J.-X.; Poon, C.S. Development of high-strength pervious concrete incorporated with high percentages of waste glass. *Cem. Concr. Compos.* **2020**, *114*, 103790. [CrossRef]
58. Lori, A.R.; Hassani, A.; Sedghi, R. Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. *Constr. Build. Mater.* **2019**, *197*, 130–142. [CrossRef]
59. Chen, X.; Wang, G.; Dong, Q.; Zhao, X.; Wang, Y. Microscopic characterizations of pervious concrete using recycled Steel Slag Aggregate. *J. Clean. Prod.* **2020**, *254*, 120149. [CrossRef]
60. Zhang, G.; Wang, S.; Wang, B.; Zhao, Y.; Kang, M.; Wang, P. Properties of pervious concrete with steel slag as aggregates and different mineral admixtures as binders. *Constr. Build. Mater.* **2020**, *257*, 119543. [CrossRef]
61. Bittencourt, S.V.; da Magalhães, S.; da Nóbrega Tavares, M.E. Mechanical behavior and water infiltration of pervious concrete incorporating recycled asphalt pavement aggregate. *Case Stud. Constr. Mater.* **2021**, *14*, e00473. [CrossRef]
62. Shang, H.; Sun, Z. PAHs (naphthalene) removal from stormwater runoff by organoclay amended pervious concrete. *Constr. Build. Mater.* **2019**, *200*, 170–180. [CrossRef]

63. Ibrahim, H.A.; Goh, Y.; Ann Ng, Z.; Yap, S.P.; Mo, K.H.; Yuen, C.W.; Abutaha, F. Hydraulic and strength characteristics of pervious concrete containing a high volume of construction and demolition waste as aggregates. *Constr. Build. Mater.* **2020**, *252*, 119251. [CrossRef]
64. Akkaya, A.; Çağatay, İ.H. Experimental investigation of the use of pervious concrete on high volume roads. *Constr. Build. Mater.* **2021**, *279*, 122430. [CrossRef]
65. Shen, W.; Liu, Y.; Wu, M.; Zhang, D.; Du, X.; Zhao, D.; Xu, G.; Zhang, B.; Xiong, X. Ecological carbonated steel slag pervious concrete prepared as a key material of sponge city. *J. Clean. Prod.* **2020**, *256*, 120244. [CrossRef]
66. AlShareedah, O.; Nassiri, S. Pervious concrete mixture optimization, physical, and mechanical properties and pavement design: A review. *J. Clean. Prod.* **2021**, *288*, 125095. [CrossRef]
67. Vieira, G.L.; Schiavon, J.Z.; Borges, P.M.; da Silva, S.R.; de Oliveira Andrade, J.J. Influence of recycled aggregate replacement and fly ash content in performance of pervious concrete mixtures. *J. Clean. Prod.* **2020**, *271*, 122665. [CrossRef]
68. Lang, L.; Duan, H.; Chen, B. Properties of pervious concrete made from steel slag and magnesium phosphate cement. *Constr. Build. Mater.* **2019**, *209*, 94–104. [CrossRef]
69. Chaitanya, M.; Ramakrishna, G. Enhancing the mechanical properties of pervious recycled aggregate concrete using silicafumes. *Mater. Today Proc.* **2021**, *46*, 634–637. [CrossRef]
70. Yang, L.; Kou, S.; Song, X.; Lu, M.; Wang, Q. Analysis of properties of pervious concrete prepared with difference paste-coated recycled aggregate. *Constr. Build. Mater.* **2021**, *269*, 121244. [CrossRef]
71. Singh, A.; Sampath, P.V.; Biligiri, K.P. A review of sustainable pervious concrete systems: Emphasis on clogging, material characterization, and environmental aspects. *Constr. Build. Mater.* **2020**, *261*, 120491. [CrossRef]
72. Huang, J.; Luo, Z.; Khan, M.B.E. Impact of aggregate type and size and mineral admixtures on the properties of pervious concrete: An experimental investigation. *Constr. Build. Mater.* **2020**, *265*, 120759. [CrossRef]
73. Tan, K.; Qin, Y.; Du, T.; Li, L.; Zhang, L.; Wang, J. Biochar from waste biomass as hygroscopic filler for pervious concrete to improve evaporative cooling performance. *Constr. Build. Mater.* **2021**, *281*, 123078. [CrossRef]