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REVIEW OF POROUS CONCRETE AS MULTIFUNCTIONAL AND SUSTAINABLE PAVEMENT

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ABSTRACT

Porous Concrete (PC) pavements have been gaining a lot of attention in recent years because of the many advantages they can provide, especially in urban areas because they are easy to lay and capable of mitigating the problems caused by conventional roads. For this reason, PC pavements have been recognized as one of the best solutions to reduce water and air environmental impacts, as well as to increase driver safety. Nevertheless, their use is still limited, since there are not enough studies addressing them comprehensively, mainly because of the lack of awareness about all their potential benefits. Therefore, this paper reviews the main properties that PC mixtures can provide for designing multifunctional and sustainable pavements. To this end, the investigations undertaken during the last decade (2009-2018) in this topic were analyzed in detail, identifying the regions where they are being most widely studied, analyzing and predicting their future potential developments. Results revealed that mechanical and hydraulic capacity are the two main properties studied in PC pavements. In addition, a predicted growth for 2019-2030 of 2.51% (4.29 PC publications per year) is expected.

KEYWORDS
Porous concrete pavement; sustainability; heat island mitigation; photocatalysis; skid resistance; sound absorption.

1 INTRODUCTION

As urban areas grow in population terms, and sprawl in size, the development of paved roads tends to be a crucial issue, since it is a key factor in the progress of the economy of cities. Paved roads make the movement of people and goods between different locations more efficient, saving time and money, as well as increasing safety and comfort when driving. On the contrary, environmental problems are starting to arise because of the impermeable area covered by roads around the world, since about 3% of the total surface of the planet is already paved [1]. This obstructs natural processes like the hydrological cycle by causing runoff and water pollution [2], while increasing temperature in urban areas due to the solar absorption favored by pavements [1]. In addition, the use of motor vehicles is also increasing, to the extent that there are around 132 vehicles per 1,000 persons in the world [3]. In the end, this massive presence of vehicles generates gas emissions into the air.

Many alternatives have been developed in the last years to mitigate these environmental problems, especially in relation to water treatment. In this context, the concept of Sustainable Urban Drainage Systems (SUDS) emerged to deal with stormwater management, one of the major challenges in urban areas. Permeable pavements are the most widely used type of SUDS due to their completeness and ease of laying in urban areas, providing an alternative to mitigate the problems caused by conventional road development. Different types of surface materials are commonly used in permeable pavement systems, including grass, pavers or porous materials such as asphalt and concrete. In particular, PC has been recognized as one of the best solutions to reduce both water and air environmental impacts due to its multifunctional nature [2]. PC is a special type of concrete used in pavement technology, composed of a granular skeleton coated with a cementitious material as a binder. It is designed to maintain a high air void content (AV), normally around 15-30% [4–6], which results in permeability rates between 1.0-47.7 mm/sec [4–6]. In turn, this enables the capture of rainwater and its subsequent infiltration into the ground [7].

Although the ultimate purpose of PC pavements is to infiltrate stormwater into the underlying subsoil, especially for aquifer recharge purposes [8], these systems can also provide other benefits. Some of the most relevant ones are related to the mitigation of the Urban Heat Island effect through the reflection of solar radiation [9], sound reduction by absorbing noise generated because of the interaction between tires and pavement [10] or enhanced road safety due to increased skid resistance provided by their high air void content [11]. As a result, they are highlighted as one of the best stormwater management practices by the United States Environmental Protection Agency (EPA) [12]. PC pavements are mainly used for construction in parking lots, minor roads and sidewalks because of their low strength, related to the air voids.

Based on these considerations, the aim of this investigation is to review the main uses and properties that make PC pavements multifunctional, including hydraulic, mechanical, safety (skid resistance) and environmental (sound absorption, temperature regulation and air quality improvement) characteristics. To this end, an extensive review of the PC pavement-related research conducted over the last 10 years has been undertaken, identifying the main trends and lines of research that will be developed in the future within this field.

2 LITERATURE REVIEW

This section compiles the main studies done on PC pavements in the last ten years, which addressed 13 properties as shown in Table 1. These characteristics were further arranged according to broader aspects representing the main perspectives from which PC pavements can be analyzed, including hydraulic, mechanical, safety and environmental ones.

Table 1. Number of publications found in the literature arranged according to the properties of porous concrete pavements

Areas identified	Properties	Number of studies (2009-2018)
Environment	Pollutant Removal	20
	Photocatalysis	5
	Urban Heat Island Mitigation	12
	Noise Reduction	18
Hydraulics	Infiltration	93
	Clogging	19
	Porosity	9
	Skid Resistance	19
Safety	Freeze Thaw	9
	Stiffness	5
Mechanical	Compression Strength	49
	Indirect Tensile Strength	13
	Flexural Strength	19
	Fatigue	1
Computer modeling	Prediction	3

These studies were provided by the Scopus database after employing the following search combinations from 2009 to 2018:

(porous AND concrete AND pavement) AND (permeability) / (porous AND concrete AND pavement) AND (compression AND strength) / (porous AND concrete AND pavement) AND (indirect AND tensile AND strength) / (porous AND concrete AND pavement) AND (flexural AND strength)/ (porous AND concrete AND pavement) AND (sound AND absorption) OR (noise AND mitigation) / (porous AND concrete AND pavement) AND (skid AND resistance) / (porous AND concrete AND pavement) AND (heat AND island AND mitigation) / (porous AND concrete AND pavement) AND (photocatalysis) / (pervious AND concrete AND pavement) AND (permeability) / (pervious AND concrete AND pavement) AND (compression AND strength) / (pervious AND concrete AND pavement) AND (indirect AND tensile AND strength) / (pervious AND concrete AND pavement) AND (flexural AND strength)/ (pervious AND concrete AND pavement) AND (sound AND absorption) OR (noise AND mitigation) / (pervious AND concrete AND pavement) AND (skid AND resistance) / (pervious AND concrete AND pavement) AND (heat AND island AND mitigation) / (pervious AND concrete AND pavement) AND (photocatalysis)

A total of 719 publications were found, of which only 171 corresponded to PC pavements. In addition, many publications considered certain combinations of the properties studied. For instance, some papers focused on hydraulic and mechanical issues, whilst others jointly addressed permeability and skid resistance. Overall, the number of times that the properties under considered were found in the publications was 294.

Six of these properties were considered of special interest due to their relevance in making these systems multifunctional, as specified in Figure 5. Hydraulic properties refer to the capability of PC pavements to infiltrate water to the ground or store it for future uses. Mechanical properties can be divided into compressive, indirect tensile and flexural strength, focusing on the ability of the pavements to withstand traffic loads without failing. The large proportion of voids in PC pavements facilitates the reduction of the noise generated by their interaction with tires through acoustic absorption, while increasing skid resistance because of the rapid stormwater filtration capacity and pronounced macrotexture of their surface layer. Finally, with the use of certain additives, PC pavements can remove pollutants from vehicle emissions, as well as reflect solar energy to cool urbanized areas.

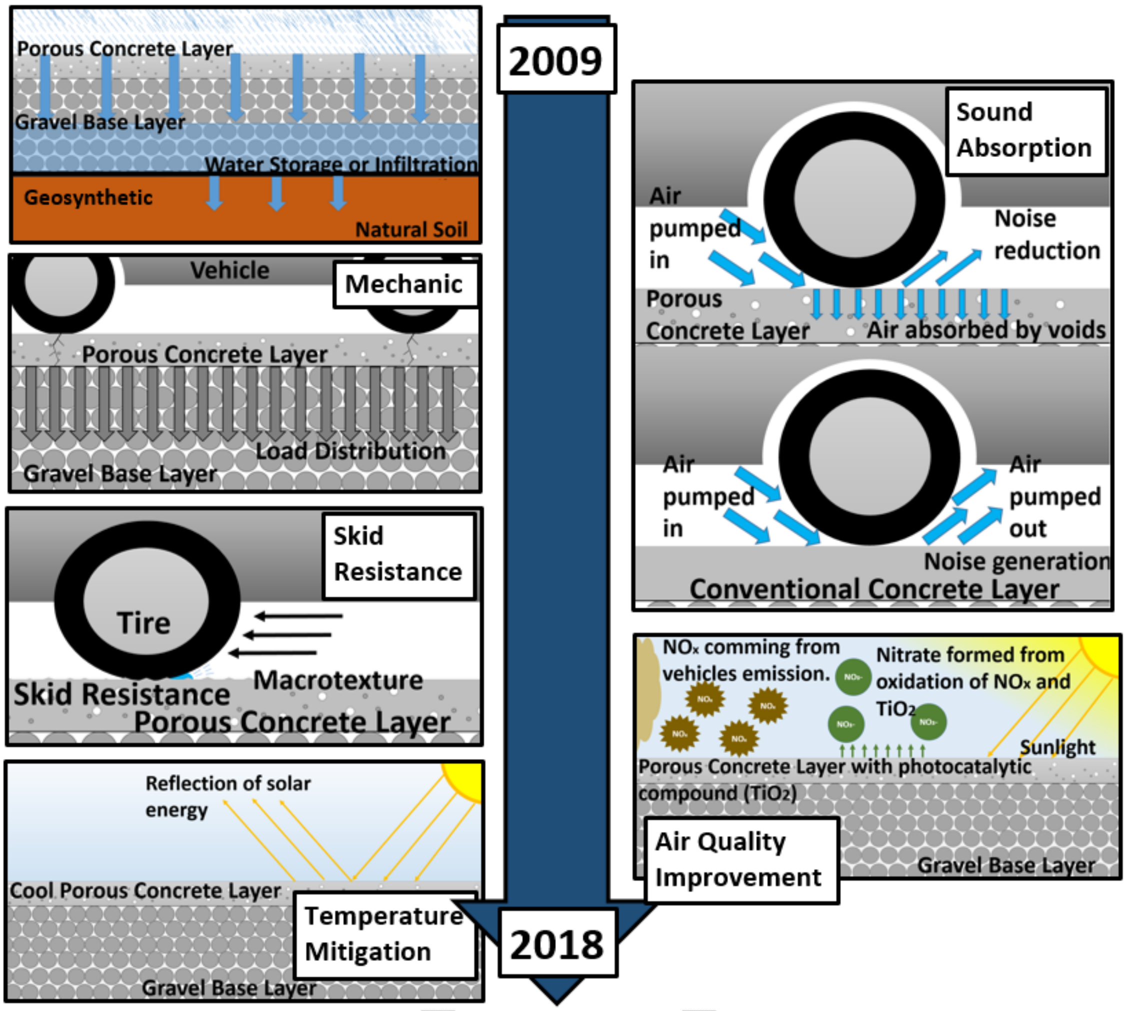


Figure 1. Scheme of the main aspects considered in the review of porous concrete pavements

PC mixtures have different components: coarse and fine aggregates, cementitious materials, water and admixtures [7,13]. The characteristics, size and gradation of the aggregates, as well as the cement and water dosages, cement paste content and admixtures used are factors influencing the properties of the resulting PC mixtures, leading to variations in their mechanical and volumetric behavior [14–16]. Table 2 shows the average proportions of the materials used in PC mixtures according to the literature reviewed [4–6,17]

Table 2. Average dosage for the main components used in porous concrete mixtures

Component	Minimum	Maximum	Average
Cementitious materials (kg/m^3)	150.00	560.00	341.37
Aggregates (kg/m^3)	565.00	2035.20	1507.73
Water to cement ratio	0.20	0.42	0.30
Aggregate to cement ratio	1.26	12.00	4.76
Fine to coarse aggregate ratio	0.00	0.17 (if used)	0.02 (if used)

2.1 HYDRAULIC PERFORMANCE

PC pavements must provide the necessary permeability for managing rainfall events that occur during their operational life, during which the whole percentage of total voids is not really interconnected [18]. Hence, although some authors obtained air void contents around 40% and even higher [19,20], the amount of interconnected air voids has been found to hardly surpass 30% [21,22]. This is mainly due to the compaction level used to build the pavement [23,24] (researchers mainly use the Proctor hammer, varying casting layers and blows), as well as to the utilization of more than one aggregate size in the mixture [25]. On the contrary, other researchers have obtained air voids as low as 10% due to the addition of certain additives (superplasticizers and fibers) and a rodding compaction method, leading to permeability rates of 0.70 mm/s [26].

Different methods have been used to measure the permeability of porous mixture surfaces directly, such as single-ring and double-ring infiltrometers [27,28], rainfall simulators [29,30] and permeameters [28,31]. The literature reviewed showed values ranging from 0.30 mm/s [32] to 47.7 mm/s, depending on the characteristics of the mixtures. The latter value corresponds to 31.8% air voids, a product of a cement paste design of 15% and aggregate size of 4.8-9.5 mm [33]. However, the highest air void ratio found was 42%, resulting in a permeability of 17.4 mm/s [25]. Moreover, the intrinsic porosity of PC mixtures depends mainly on the compaction energy applied, such that the higher the compaction energy, the lower the air void content.

2.2 MECHANICAL PERFORMANCE

PC pavements also have to meet specific mechanical requirements depending on their on-site application. Compressive strength is the most frequently employed mechanical parameter considered in the design of concrete pavement structures [34–38]. Since PC mixtures are rigid, they resist vertical stresses directly, so cracking occurs after their load-bearing capacity is surpassed. Then, the crack patterns are propagated throughout the porous structure forming little bridges. Therefore, PC tends to fail through these numerous weak bridges formed between the aggregates, making its ultimate behavior different from conventional mixtures [22]. The repeated application of vertical loads can also cause fatigue damage in PC mixtures [39], producing their failure.

The literature reviewed showed that PC mixtures can reach values of compressive strength over 40.0 MPa [22,35,40], tensile strength between 1.5-3.0 MPa [4–6] and flexural strength above 4.0 MPa [21,41,42]. However, these data vary depending on the test methods, compaction, materials, curing time and mixture designs used by each author. The literature reviewed demonstrated higher mechanical values when both curing time and the compaction force were increased [6]. For example, some researchers obtained around 19% higher flexural strength when curing time was increased from 7 to 28 days [41]. The same behavior was presented in compression and tensile strength, incrementing around 9% and 17% respectively, in the same curing time [43].

In the search for optimum designs, the highest value of compressive strength found in the literature was 65.80 MPa, compacted in 3 layers using slight vibration and three blows per layer with a Proctor hammer, at 28 days of curing. This led to a mixture with 19.8% air voids, an aggregate size of 1.19 mm, a w/c ratio of 0.22 and a combination of cement, silica fume, silica powder and water reducers [40]. In terms of flexural strength, some researchers obtained values around 4.40 MPa using 10% by weight of binder of nano black rice husk ash, at a 28-day curing time, employing the Proctor hammer at two layers for compaction. This value increased about 10% when curing was extended to 90 days [41]. Other authors achieved high values of tensile strength (3.09 MPa) using a Proctor hammer at three layers and 10 blows per layer for compaction. This design corresponded to an air void content of 18.90% (permeability of 5.3 mm/s), using a single aggregate size of 6.35 mm and a w/c of 0.33 [44].

2.3 SKID RESISTANCE

Skid resistance (SR) is a parameter mainly dependent on surface texture [45]. According to the Permanent International Association of Road Congresses, road surface texture patterns are classified as microtexture (< 0.5 mm), macrotexture (0.5 mm – 50 mm), megatexture (50 mm – 500 mm) and roughness (0.5 m – 50 m)[46]. The friction occurring between tires and pavements allows drivers to steer, brake, accelerate and stay on the road [47]. Three main pavement conditions that affect SR can be identified on a pavement: dry, wet and iced [48,49]. Microtexture mainly controls SR at low speeds, while macrotexture affects it at high speeds [45,50]. Macrotexture depth is a measurement of surface roughness under dry conditions [50].

SR can be measured on PC through the British Pendulum Test (BPT), producing a low-speed sliding contact of about 10 km/h between a standard rubber slider and the pavement surface. This is the most common test used for measuring SR according to the microtexture of pavements. The result is expressed in terms of a British Pendulum Number (BPN), such that the device allows readings to be taken from 0 to 100 [51] (the higher the value, the better the SR of the pavement [48,49]). Laboratory studies noted that the BPN of PC decreased about 13% (for both dry and wet conditions) as the area of contact between the rubber slider and the surface was reduced [52]. Therefore, it is important to perform the test with the same area of contact in all the samples evaluated to obtain a valid comparison. Moreover, trying to avoid big gaps in the surface layer to prevent the lost of friction.

Some authors studied the addition of sand in different percentages (0, 5 and 10 %), thus varying the w/c ratio. For instance, a value of BPN of 74 was recorded for dry conditions using a w/c of 0.27 in the mixture with 5% and 10% of sand [53]. Other authors demonstrated the differences between diverse PC pavement surface conditions by obtaining BPN values of 96.0, 74.5 and 29.0 for dry, wet and iced roads, respectively [49]. Nevertheless, the highest BPN values observed were almost 100 on a dry newly built pavement with a w/c of 0.32 and 23.5% air voids, based on employing ordinary Portland cement and a nominal maximum aggregate size of 6.30 mm [48].

2.4 SOUND ABSORPTION

The presence of a large volume of interconnected pores makes PC highly effective in acoustic absorption. This can be achieved because the large proportion of voids in PC pavements alters the generation of noise by minimizing the air pumping between the tire and the road surface. The acoustic behavior the aggregates provide, depends on the void percentage they have, their pore shape and size, as well as on their distribution in the mix [54]. However, the tendency of pores to be clogged by particulate substances and sediments can decrease both the permeability and the sound absorption capacity of pavements [46].

The absorption coefficient (AC) is one of the most widely used approaches to measure the sound absorption capacity of materials. Hence, an AC of 1.00 refers to a perfectly absorbing material, while a value of AC of 0.00 indicates that the material is completely reflective. Common values of AC for conventional concrete range between 0.03 and

0.05, a figure that increases to 0.10-1.00 in the case of PC [55]. This coefficient also depends on the frequency of the sound waves caused by the tire-pavement interaction. Some studies found that the most significant sound frequency range associated with this interaction is between 630 and 2000 Hz [10], the range 800-1200 Hz being the most unpleasant for the human ear [55]. Table 3 represents the values of AC obtained with PC by some authors for several materials between the frequencies considered annoying for the human ear.

Table 3. Absorption coefficients found in the literature for PC made with several materials

Reference	Aggregate type	Size (mm)	Absorption coefficient (AC)*	Maximum AC
[56]	Aluminous aggregate (ALAG) (synthetic calcium aluminate combined with bauxite and limestone)	0.60- >1.18	0.13-0.70	0.99 at 2750 Hz
[54]	Arlite and vermiculite	0.50- >4.00	0.20-0.91	0.96 at 1160 Hz
[57]	Gravel	2.40-4.80	0.01-0.87	0.95 at 250 Hz
	Electric arc furnace slag (EAFS)	2.40-4.80	0.02-0.88	0.95 at 156 Hz
[13]	Crushed limestone, recycled concrete and coal bottom ash aggregates.	4.75-9.00	0.20-0.40	1.00 at 500 Hz
[17]	Oil palm kernel shell and cockleshell	4.75-6.30	0.05-0.80	0.80 at 1700 Hz
[58]	Diamond ground	-	0.35-0.65	0.85 at 1700 Hz

***AC is unpleasant in a range of 800-1200 Hz**

2.5 TEMPERATURE MITIGATION

Pavement temperature periodically changes with the influence of solar radiation, air temperature and wind. It is also impacted by the properties of the materials forming the pavement themselves, especially their colors, since dark colors tend to increase temperature, and viceversa [59]. Therefore, the temperature of pavements varies even in the same environmental conditions [60], contributing to causing the Urban Heat Island (UHI) effect [61]. The UHI effect is defined as the increase in temperature in urban areas favored by the presence of construction materials with high solar radiation absorption capacity, as well as by industrial activities and vehicle emissions (greenhouse effect) [61]. The combination of these factors can increase temperatures around 10ºC in dense urban areas [62]. PC pavements are considered cool pavements because of their high reflection capacity (albedo), which helps mitigate the UHI effect. In addition to the water infiltration capacity that helps to avoid puddles on the surface, decreasing temperature and cooling cities [63].

The albedo coefficient is an indicator ranging from 0 to 1 that measures the reflecting power of a surface, such that the higher this coefficient, the higher solar reflectivity of the material [59]. Many investigations have attempted to evaluate the albedo of different pavements, especially conventional concrete, reaching values around 0.50, depending on the location and treatments employed (paints, admixtures, etc.) [64,65]. The literature reviewed revealed that conventional concrete can reach higher values of albedo than PC, as a result of the lower presence of voids in the mixture. The highest albedo found in the literature for PC pavements was 0.29, corresponding to a mixture with 17% of air voids, white cement and a nominal maximum aggregate size of 9.5 mm [63]. However, these values are still higher than those corresponding to asphalt mixtures, since some authors pointed out they can reach values of albedo from 0.10 to 0.18 [62].

PC pavements and conventional concrete pavements exhibit similar thermal behavior. The difference resides in the evaporative cooling after a rain event, PC pavements having lower temperatures on their surface during daytime and nighttime [66–68]. Moreover, the use of certain admixtures in PC, such as bottom ash and peat moss, has been found to provide surface temperature reductions of about 0.1 ºC in relation to asphalt mixtures [68].

2.6 AIR QUALITY IMPROVEMENT

PC pavements containing photocatalysts have the potential to remove pollutants from the air and curb contamination in urban areas [69,70]. Similar to the photosynthesis in plants, photocatalytic compounds can be used to trap and absorb organic and inorganic particles in the air, removing harmful pollutants such as nitrogen oxides (NO_X) [71] or polycyclic aromatic hydrocarbons that can be found in stormwater [69], among others [71,72]. Some studies have also addressed the photocatalytic degradation of NO_X, obtaining promising results [70].

Titanium dioxide (TiO_2) is one of the most investigated photocatalytic semiconductors incorporated into building materials [69,72,73]. This is due to its low cost, fast reaction under ambient operating conditions (room temperature, atmospheric pressure) and lack of need for chemical reactants. TiO_2 can decompose gaseous pollutants in the presence of sunlight, so its application to pavements can help remove emission pollutants close to the source, i.e. near the vehicles that drive on them. Rough surface and high porosity PC pavements retain more TiO_2 particles due to their higher specific surface area, contributing to a better photocatalytic effect for air purification during sunny days [69,71]. In fact, some laboratory results demonstrated an increment in the NO_X removal efficiency of PC pavements of about 3.60% per 25.0 mm of depth in the photocatalytic layer in the PC structure [74]. In particular, the best results were achieved when combining 75.0 mm depth and 31% air voids [74,75].

There are some commercially-available photocatalytic coatings, mainly used in conventional concrete pavements. Some researchers attempted to test three of them: stucco, white paint and clear paint. The application of stucco to roadside concrete yielded favorable results (81% NO_X removal) in comparison with clear paint (52% NO_X removal) and white paint (40% NO_X removal), which reached almost the same value as uncoated pavements (38%) [72]. Although these results refer to conventional concrete surfaces, PC pavements are assumed to better retain photocatalytic compounds because of their higher proportion of voids. However, PC pavements can lose part of this capacity with time because they are more likely to suffer traffic wear [72].

Photocatalytic coating is not widely used in PC pavements due to their high porosity, which is why some authors have investigated the application of innovative methods for incorporating TiO_2 into these mixtures. One of them consists of mixing water and TiO_2 uniformly and then brushing it onto the surface of PC. This approach leads to reducing large amounts of NO (97.14%), toluene (91.98%) and Tri-methyl-benzene (TMB) (96.34%) [71]. However, this coating was found to be very weak, to such an extent that it could wash off with water. Another method, known as the cement-water slurry, consists of a thin slurry layer with low cement concentration and TiO_2. This process enables NO, toluene and TMB levels to be reduced by 96.94%, 78.82% and 97.26%, respectively; however, it led to a decrease in infiltration of 51.50% [71].

Driveway protectors are another coating system used in PC pavements with satisfactory results, achieving 97.92% removal of NO. They consist of a transparent liquid, formed by mixing siliconate water-based concrete sealers with TiO_2. The removal efficiency of toluene and TMB was 61.65% and 93.87%, respectively. Again, its application involved a reduction in infiltration of 30.49% [71]. Other authors tried using a new method consisting of a spray application of TiO_2. They used it in three stages, so the TiO_2 layer thickness varied progressively. This approach led to a reduction in NO concentration of only 47.6% [73]. Some studies have developed photocatalytic additives, which are inserted into the mortar directly. The results revealed they required high amounts of water to ensure the fluency of the mix [76]. Photocatalytic Cement is an innovative method developed by some private companies across Europe aimed at facilitating the photocatalytic properties of PC mixtures. Nevertheless, this technique achieves poorer results than those based on coatings or additives [77].

3 DISCUSSION

The following section summarizes the results obtained from the extensive literature review carried out, analyzing the publications compiled according to the country and year (2009-2018) in which they were published, as well as the PC pavement characteristics considered.

3.1 OVERVIEW

Six aspects making PC pavements multifunctional were found to be of interest in the last decade: permeability, mechanical performance (compressive, flexural and indirect tensile strength), skid resistance, noise reduction, UHI mitigation and photocatalysis. The 171 scientific publications found since 2009 in the Scopus database are shown in Figure 2, where their distribution over the years is shown in terms of the properties they addressed. The hydraulic performance of PC pavements emerged as the most widely studied factor, followed by their compressive strength.

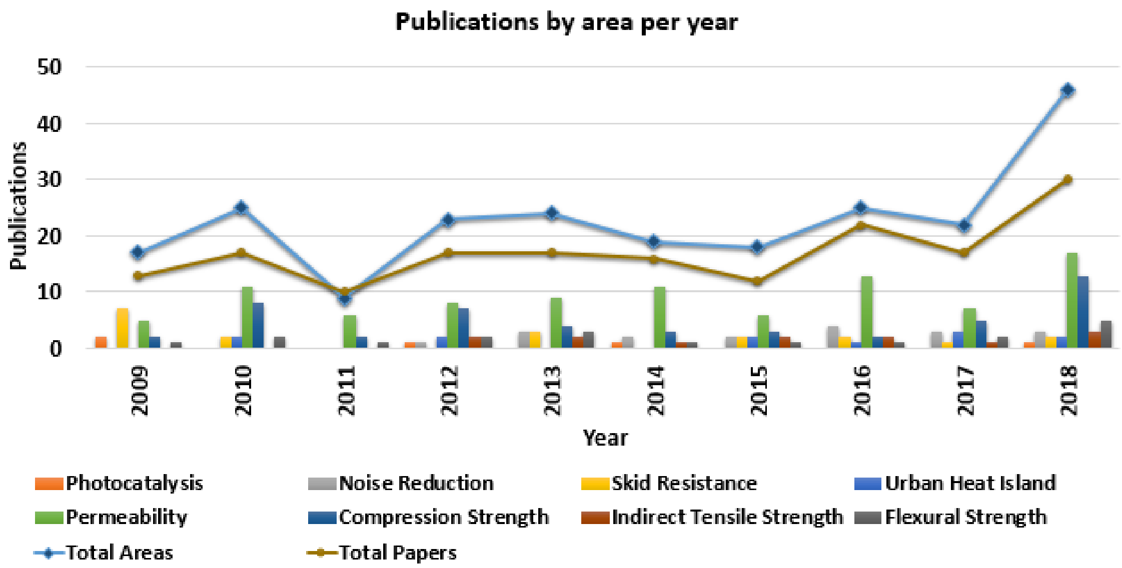


Figure 2. Temporal distribution of the number of publications reviewed in relation to the main properties of porous concrete pavements

Specifically, of the 171 papers found in Scopus, 41% corresponded to hydraulic performance studies of PC pavements, followed by 36% investigations concerning their mechanical properties, as seen in Figure 3. In turn, 61% of the contributions related to this aspect corresponded to compressive strength, whilst flexural and indirect tensile strength corresponded to 23% and 16% of the papers focused on this aspect, respectively. Up to 37 papers studied the relation between these two characteristics, trying to obtain the greatest infiltration without affecting the compressive strength of the pavements negatively by using different kinds of additives, aggregates and water-to-cement ratios. In other words, around 85% of the publications studying the mechanical capacity of PC pavements related it with permeability, always prioritizing the latter.

Moreover, there is still a lack of research oriented to the environmental and safety properties, as highlighted in Figure 3. Only 2% of the publications corresponded to photocatalysis and 5% to UHI mitigation. Nevertheless, these properties are considered crucial because of the impact that uncontrolled traffic and impermeable surfaces are causing on the environment in almost every country. PC mixtures outperform impermeable pavements in terms of skid resistance and noise reduction because of their high air void content. However, only 8% of the articles corresponded to skid resistance, whose frequency of publication has decreased about 50% since 2009 (Figure 2). The research conducted on noise reduction has been scarce but almost constant since 2013, amounting to 8% of the total publications found.

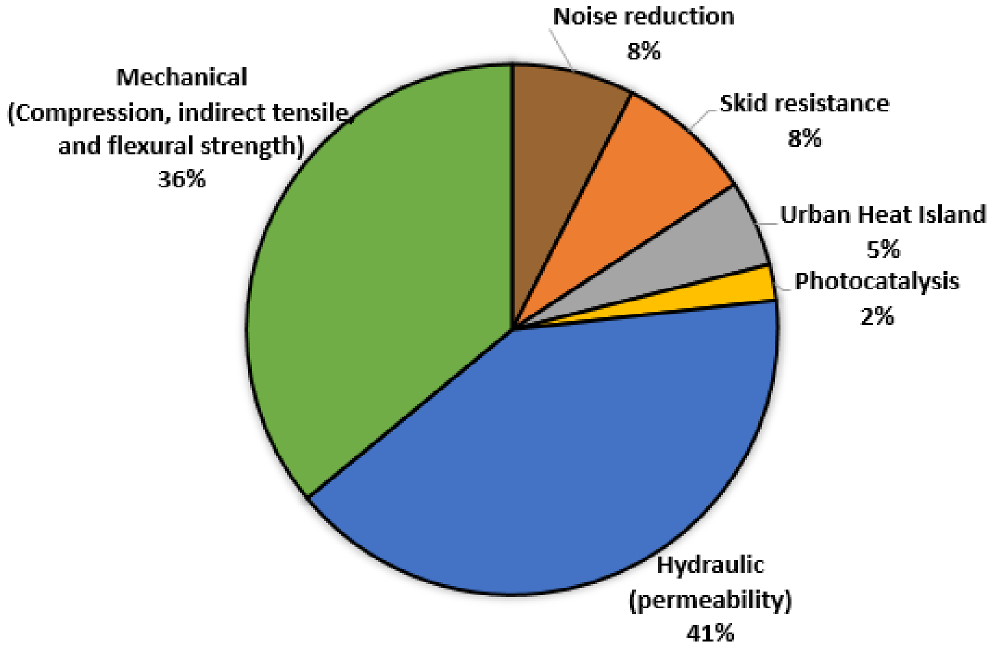


Figure 3. Breakdown of the properties of porous concrete pavements studied in the last decade

Figure 4 shows the top ten regions investigating PC pavements and the area they tend to address the most; the United States (USA) and China concentrate most of the publications related to this topic and include all the properties under study. However, China tends to study these properties in a more distributed form, while the USA mainly focuses on permeability. This might be associated with the huge environmental problems that China has been facing during the last years, which has oriented the concerns of this country to issues like the UHI effect. No UHI mitigation-related research could be found in the last decade in Europe, which was the third most important region with regard to PC pavements. In fact, almost 70% of the investigations developed in this continent focused on infiltration, with half of them carried out in Spain. The remaining 30% of PC-related studies carried out in Europe were found to be equally distributed across the rest of the properties under evaluation.

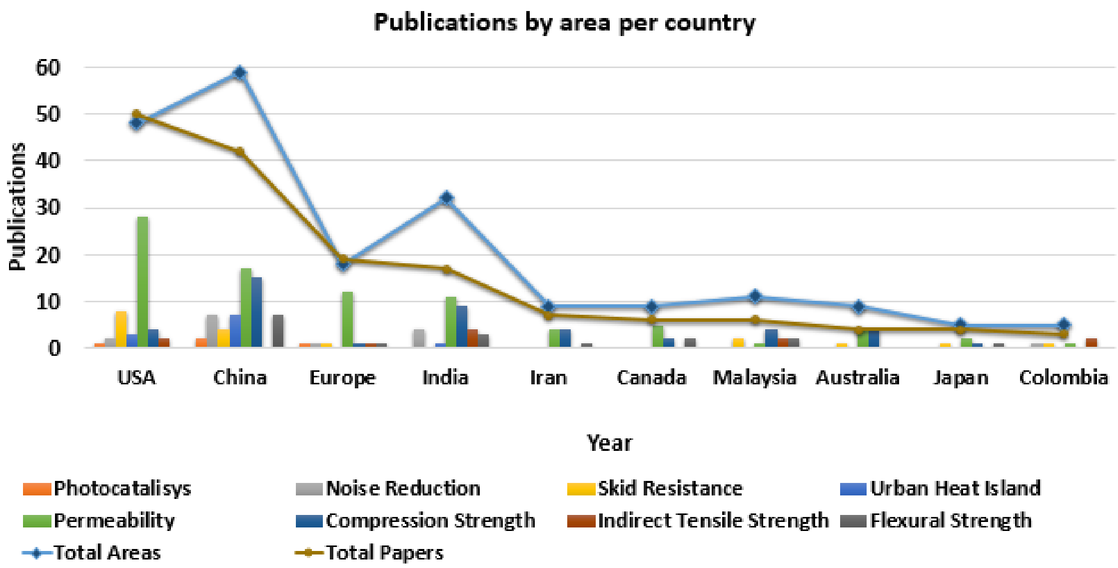
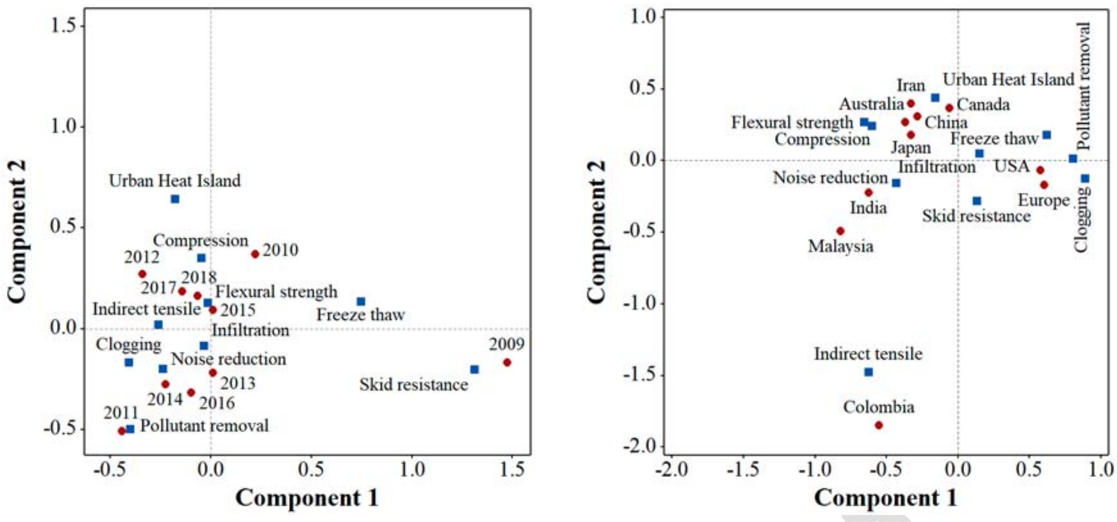


Figure 4. Spatial distribution of the number of publications reviewed in relation to the main properties of porous concrete pavements

3.2 STATISTICAL ANALYSIS

To get insight into the results described above, the spatiotemporal distribution of the publications on PC pavements compiled over the last ten years was further evaluated through statistical tests. First, a simple correspondence analysis was conducted to explore the relationships between the main PC pavement-related characteristics and both the region and year in which they were published. Figure 5 depicts the symmetric plots representing the interactions between both pairs of factors, which were introduced as a contingency table.



(a) (b)

Figure 5. Interaction between pavement characteristics and (a) Year (b) Region

The interpretation of these plots depends on the distance and angle from rows (year and region) and columns (PC properties) to the origin [0, 0]. Hence, the farther a row and a column label are from the origin and the narrower the angle they form with respect to it, the higher the association with each other. Indeed, those column labels situated closer to the origin are likely to be similar to the rows, either years or regions. In this sense, infiltration emerged as the closest variable to the origin in Figure 5(a) and (b), confirming that this is the most widely addressed PC-related aspect regardless of both time and space.

On the contrary, pairs of elements such as [2009, Skid resistance], [2011, Pollutant removal], [Colombia, Indirect tensile] or [Europe, Clogging] were found to be strongly associated. The relationship between the first two cases was attributed to the increasing importance of the additional benefits provided by PC pavements, such as Urban Heat Island effect or noise reduction, in comparison with traditional hydraulic and mechanical aspects. The association between indirect tensile and Colombia might lie in the origins of the common standard to test this property [78], which was originally conceived in Brazil and might have had a greater impact on Latin America. Finally, the lifestyle in Europe, which concentrates most of the countries with the highest number of vehicles per capita [79], favors the existence of clogging issues and the interest in studying this phenomenon.

To further explore the evolution of the publications reviewed with time, the results were divided into two groups according to the two frameworks set by the United Nations to monitor sustainable development: The Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs). The former applied between 2000 and 2015, whilst the latter are their successors and will remain in force until 2030. Therefore, each item reviewed was allocated to either the MDGs or SDGs group, depending on whether they were published before or after 2015.

Next was the application of inferential statistics to determine the existence or absence of significant differences between these groups, both separately (per PC variable) and as a whole. Since the implementation of pairwise comparisons depends on the distribution of datasets, their normality was previously verified using the Shapiro-Wilk test. Table 4 lists the p-values obtained for each dataset, where only four cases were normally distributed for both MDGs and SDGs (skid resistance, Urban Heat Island, indirect tensile and freeze thaw), according to a significance level of 0.05 [80].

In accordance with the results yielded by the Shapiro-Wilk test, pairwise comparisons were conducted by applying either the Student's t (normal) or the Mann-Whitney U (non-normal) tests. Table 4 collects the p-values associated with these tests, which highlighted that noise reduction was the only aspect undergoing a significant increase in the number of publications during the SDGs' period (p-value < 0.05). No other topic was studied significantly more in detail in recent years, despite the growing importance allocated in the SDGs to a variety of issues related to the characteristics considered. This might be due to the high carbon footprint associated with the cement forming PC pavements, which penalizes them from the perspective of sustainability and Climate Change mitigation.

Table 4. Normality and pairwise comparison tests conducted to evaluate the number of publications about porous concrete pavements during the periods of Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs)

Variable	Normality (Shapiro-Wilk test)		Pairwise comparison	
	p-value (MDGs)	p-value (SDGs)	Test	p-value
Pollutant removal	0.925	0.382	Student's t	0.604
Clogging	0.597	0.382	Student's t	0.500
Noise reduction	0.128	0.904	Student's t	0.019
Skid resistance	0.076	0.017	Mann-Whitney U	0.831
Urban Heat Island	0.006	0.904	Mann-Whitney U	0.110
Infiltration	0.540	0.657	Student's t	0.450
Compressive	0.210	0.251	Student's t	0.629
Indirect tensile	0.047	0.904	Mann-Whitney U	0.136
Flexural strength	0.107	0.139	Student's t	0.602
Freeze thaw	0.047	0.904	Mann-Whitney U	0.831
All	0.283	0.686	Student's t	0.282

Although without being statistically significant, there was an average rise in the number of publications over time. Hence, a trend analysis was carried out to model the results stemming from the review and make forecasts for the remaining period covered by the SDGs (2019-2030). Three types of model were tested for this purpose: linear, exponential and quadratic. The goodness-of-fit between observed and predicted values was measured using Spearman's rho coefficient [81], due to its suitability for dealing with ordinal data.

Figure 6 summarizes the results derived from the trend analysis, which suggested that the linear model was inappropriate to fit the observed data due to its low and non-significant Spearman's rho (p-value > 0.05). Instead, both the exponential and quadratic functions achieved identically strong and significant correlations with the observations compiled between 2009 and 2018. However, the projections associated with both models differed substantially. Those corresponding to the quadratic function would result in about 200 publications by 2030, which is a rather unrealistic value. The exponential function pictured a more likely scenario, yielding consistent fits with the trend observed during the last years. In fact, the average growth predicted for 2019-2030 was 4.29 publications per year, a slightly higher figure than that observed between 2009 and 2018 (3.60). Still, the potential interest in investigating PC pavements hereafter will depend on the societal concerns of future generations. Based on the increasing growth of megacities concentrating most of the world population, China and India might lead the way in terms of PC-related research as a solution to ensure the sustainability of megacities.

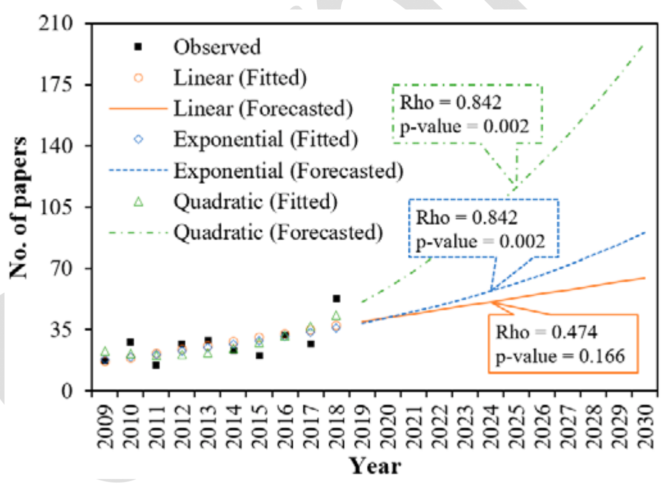


Figure 6. Evolution and forecast of the number of publications released regarding porous concrete pavements using linear, exponential and quadratic functions

4 CONCLUSIONS

Despite many years of relevance, research and implementation of PC pavements has been increasing in recent times, including the evaluation of new characteristics to mitigate climate and environmental problems societies are dealing with nowadays. Under this premise, this paper identified and reviewed the properties studied in PC pavements and the research conducted to assess them around the world in the last decade. To this end, 171 publications devoted to the analysis of up to 10 different aspects to which PC pavements can contribute were compiled and revised in detail. Although the breakdown of this literature review according to the location where the studies were conducted revealed that PC pavements have been studied worldwide during the past ten years, most of the research focused on these systems was concentrated in the United States (U.S.) and Asia, especially China and India.

The literature reviewed pointed out that it is possible to design high-performance PC mixtures for specific applications. Nevertheless, further research is needed in order to optimize the design of the mixtures to accomplish the integration of environmental and safety characteristics with the hydraulic and mechanical requirements of PC pavements, since several of these aspects are in conflict with each other. In this sense, it is noticeable that there are still not enough contributions and confidence to use these systems in roads, despite the environmental and safety advantages they can provide. In fact, apart from their widely known hydraulic and mechanical characteristics, these supplementary benefits are still unexplored in many countries around the world, as suggested by the concentration of the research on PC pavements in developed countries.

This highlighted the need to keep investigating and disseminating the features of PC pavements as multifunctional systems in urban areas, especially in overpopulated cities that are facing big environmental issues like air pollution, UHI effect and high temperatures, as well as flooding and water pollution. According to the number of publications during the period of analysis, future forecasts indicate an increasing trend in the investigation of PC pavements for the coming years, which is consistent with the rising degree of resilience that will be required by cities in a context of forthcoming Climate Change and urban sprawl.

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REFERENCES

[1] K.C. Sinha, D. Bullock, C.T. Hendrickson, H.S. Levinson, R.W. Lyles, A.E. Radwan, Z. Li, Development of Transportation Engineering Research, Education, and Practice in a Changing Civil Engineering World., J. Transp. Eng. 128 (2002) 301. doi:10.1061/(ASCE)0733-947X(2002)128:4(301).

[2] J. Rodriguez-Hernandez, A.H. Fernández-Barrera, V.C.A. Andrés-Valeri, A. Vega-Zamanillo, D. Castro-Fresno, Relationship between Urban Runoff Pollutant and Catchment Characteristics, J. Irrig. Drain. Eng. 139 (2013) 833–840. doi:10.1061/(ASCE)IR.1943-4774.0000617.

[3] Intelligent Energy Europe, Current diffusion of cars, Energy Sav. Sustain. Transp. (2011).

[4] M. Rangelov, S. Nassiri, L. Haselbach, K. Englund, Using carbon fiber composites for reinforcing pervious concrete, Constr. Build. Mater. 126 (2016) 875–885. doi:10.1016/j.conbuildmat.2016.06.035.

[5] N.A. Brake, H. Allahdadi, F. Adam, Flexural strength and fracture size effects of pervious concrete, Constr. Build. Mater. 113 (2016) 536–543. doi:10.1016/j.conbuildmat.2016.03.045.

[6] F. Giustozzi, Polymer-modified pervious concrete for durable and sustainable transportation infrastructures, Constr. Build. Mater. 111 (2016) 502–512. doi:10.1016/j.conbuildmat.2016.02.136.

[7] P.D. Tennis, M.L. Leming, D.J. Akers, Pervious Concrete Pavements, 2004. http://myscmap.sc.gov/marine/NERR/pdf/PerviousConcrete_pavements.pdf.

[8] C. Lian, Y. Zhuge, Optimum mix design of enhanced permeable concrete - An experimental investigation, Constr. Build. Mater. 24 (2010) 2664–2671. doi:10.1016/j.conbuildmat.2010.04.057.

[9] A. Fini, P. Frangi, J. Mori, D. Donzelli, F. Ferrini, Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements, Environ. Res. 156 (2017) 443–454. doi:10.1016/j.envres.2017.03.032.

[10] L. Chu, T.F. Fwa, K.H. Tan, Evaluation of wearing course mix designs on sound absorption improvement of porous asphalt pavement, Constr. Build. Mater. 141 (2017) 402–409. doi:10.1016/j.conbuildmat.2017.03.027.

[11] J. Nicholls, Review of UK porous asphalt trials., Crowthorne, Berkshire, 1997.

[12] A. Bonicelli, F. Giustozzi, M. Crispino, M. Borsa, Evaluating the effect of reinforcing fibres on pervious concrete volumetric and mechanical properties according to different compaction energies, Eur. J. Environ. Civ. Eng. 19 (2015) 184–198. doi:10.1080/19648189.2014.939308.

[13] C. Ngohpok, V. Sata, T. Satiennam, P. Klungboonkrong, P. Chindaprasirt, Mechanical properties, thermal conductivity, and sound absorption of pervious concrete containing recycled concrete and bottom ash aggregates, KSCE J. Civ. Eng. 00 (2017) 1–8. doi:10.1007/s12205-017-0144-6.

[14] J. Sansalone, X. Kuang, V. Ranieri, Permeable Pavement as a Hydraulic and

Filtration Interface for Urban Drainage, J. Irrig. Drain. Eng. 134 (2008) 666–674. doi:10.1061/(ASCE)0733-9437(2008)134:5(666).

[15] W. Martin, B. Putman, A. Neptune, Influence of Aggregate Graduation on Clogging Characteristics of Porous Asphalt Mixtures., J. Mater. Civ. Eng. 26 (2014) 04014026.

[16] A. Álvarez, A. Martin, C. Estakhri, Internal Structure of compacted permeable friction course mixtures., Constr. Build. Mater. 24 (2010) 1027–1035.

[17] E. Khankhaje, M.R. Salim, J. Mirza, Salmiati, M.W. Hussin, R. Khan, M. Rafieizonooz, Properties of quiet pervious concrete containing oil palm kernel shell and cockleshell, Appl. Acoust. 122 (2017) 113–120. doi:10.1016/j.apacoust.2017.02.014.

[18] P.J. Vardanega, State of the Art: Permeability of Asphalt Concrete, J. Mater. Civ. Eng. 26 (2014) 54–64. doi:10.1061/(ASCE)MT.1943-5533.0000748.

[19] P.J. Ramadhansyah, M.Y. Mohd Ibrahim, H. Mohd Rosli, M.. Naqiuddin, M.. Wan Ibrahim, Porous Concrete Pavement Containing Nano-silica: Pre-Review, 911 (2014) 454–458.

[20] H.T. Ghashghaei, A. Hassani, Investigating the Relationship between Porosity and Permeability Coefficient for Pervious Concrete Pavement by Statistical Modelling, Mater. Sci. Appl. 7 (2016) 101–107. doi:10.4236/msa.2016.72010.

[21] W. Shen, L. Shan, T. Zhang, H. Ma, Z. Cai, H. Shi, Investigation on polymer-rubber aggregate modified porous concrete, Constr. Build. Mater. 38 (2013) 667–674. doi:10.1016/j.conbuildmat.2012.09.006.

[22] A.S. Agar-Ozbek, J. Weerheijm, E. Schlangen, K. Van Breugel, Investigating porous concrete with improved strength: Testing at different scales, Constr. Build. Mater. 41 (2013) 480–490. doi:10.1016/j.conbuildmat.2012.12.040.

[23] L.K. Crouch, J. Pitt, R. Hewitt, Aggregate Effects on Pervious Portland Cement Concrete Static Modulus of Elasticity, J. Mater. Civ. Eng. 19 (2007) 561–568. doi:10.1061/(ASCE)0899-1561(2007)19:7(561).

[24] M.S. Sumanasooriya, O. Deo, N. Neithalath, Particle packing-based material design methodology for pervious concretes, ACI Mater. J. 109 (2012) 205–214. doi:10.14359/51683707.

[25] A. Ibrahim, E. Mahmoud, M. Yamin, V.C. Patibandla, Experimental study on Portland cement pervious concrete mechanical and hydrological properties, Constr. Build. Mater. 50 (2014) 524–529. doi:10.1016/j.conbuildmat.2013.09.022.

[26] H. Wu, B. Huang, X. Shu, Q. Dong, Laboratory Evaluation of Abrasion Resistance of Portland Cement Pervious Concrete, J. Mater. Civ. Eng. 5 (2011) 697–702. doi:10.1061/(ASCE)MT.

[27] M. Dougherty, M. Hein, B. Martina, B. Ferguson, Quik Surface Infiltration Test to Assess Mainte4nance Needs on Small Pervious Concrete Sites., J. Irrig. Drain. Eng. 137 (2011) 553–563.

[28] H. Li, M. Kayhanian, J. Harvey, Comparative field permeability measurement of

permeable pavements using ASTM C1701 and NCAT permeameter methods., J. Environ. Manage. 118 (2013) 144–152.

[29] J. Rodríguez-Hernández, V. Andrés-Valeri, A. Ascorbe-Salcedo, D. Castro-Fresno, Laboratory study on the stormwater retention and runoff attenuation capacity of four permeable pavements., J. Environ. Eng. 142 (2016) 04015068.

[30] V. Andrés-Valeri, M. Marchioni, L. Sañudo-Fontaneda, F. Giustozzi, G. Becciu, Laboratory assessment of the infiltration capacity reduction in clogged porous mixture surfaces., Sustain. 8 (2016) 751.

[31] V. Ranieri, P. Colonna, J. Sansalone, A. Sciddurlo, Measurement of Hydraulic Conductivity in Porous Mixes, Transp. Res. Rec. J. Transp. Res. Board. 2295 (2012) 1–10. doi:10.3141/2295-01.

[32] J. Yang, G. Jiang, Experimental study on properties of pervious concrete pavement materials, Cem. Concr. Res. 33 (2003) 381–386. doi:10.1016/S0008-8846(02)00966-3.

[33] Y. Zaetang, A. Wongsa, V. Sata, P. Chindaprasirt, Use of lightweight aggregates in pervious concrete, Constr. Build. Mater. 48 (2013) 585–591. doi:10.1016/j.conbuildmat.2013.07.077.

[34] J. Li, Y. Zhang, G. Liu, X. Peng, Preparation and performance evaluation of an innovative pervious concrete pavement, Constr. Build. Mater. 138 (2017) 479–485. doi:10.1016/j.conbuildmat.2017.01.137.

[35] G. Xu, W. Shen, X. Huo, Z. Yang, J. Wang, W. Zhang, X. Ji, Investigation on the properties of porous concrete as road base material, Constr. Build. Mater. 158 (2018) 141–148. doi:10.1016/j.conbuildmat.2017.09.151.

[36] E. Khankhaje, M.R. Salim, J. Mirza, M.W. Hussin, M. Rafieizonooz, Properties of sustainable lightweight pervious concrete containing oil palm kernel shell as coarse aggregate, Constr. Build. Mater. 126 (2016) 1054–1065. doi:10.1016/j.conbuildmat.2016.09.010.

[37] H. Wang, H. Li, X. Liang, H. Zhou, N. Xie, Z. Dai, Investigation on the mechanical properties and environmental impacts of pervious concrete containing fly ash based on the cement-aggregate ratio, Constr. Build. Mater. 202 (2019) 387–395. doi:10.1016/j.conbuildmat.2019.01.044.

[38] B. Debnath, P.P. Sarkar, Permeability prediction and pore structure feature of pervious concrete using brick as aggregate, Constr. Build. Mater. 213 (2019) 643–651. doi:10.1016/j.conbuildmat.2019.04.099.

[39] Y. Chen, K. Wang, X. Wang, W. Zhou, Strength, fracture and fatigue of pervious concrete, Constr. Build. Mater. 42 (2013) 97–104. doi:10.1016/j.conbuildmat.2013.01.006.

[40] R. Zhong, K. Wille, Compression response of normal and high strength pervious concrete, Constr. Build. Mater. 109 (2016) 177–187. doi:10.1016/j.conbuildmat.2016.01.051.

[41] R.P. Jaya, A. Mohamad Idris, M.Y. Mohd Ibrahim, M.R. Hainin, H. Yaacob, N.A. Hassan, W.I. Mohd Haziman, S. Ekarizan, Flexural strength properties of porous concrete pavement incorporating nano black rice husk ash, IOP Conf. Ser.

Mater. Sci. Eng. 527 (2019). doi:10.1088/1757-899X/527/1/012044.

[42] O. AlShareedah, S. Nassiri, J.D. Dolan, Pervious concrete under flexural fatigue loading: Performance evaluation and model development, Constr. Build. Mater. 207 (2019) 17–27. doi:10.1016/j.conbuildmat.2019.02.111.

[43] O. AlShareedah, S. Nassiri, Z. Chen, K. Englund, H. Li, O. Fakron, Field performance evaluation of pervious concrete pavement reinforced with novel discrete reinforcement, Case Stud. Constr. Mater. 10 (2019) e00231. doi:10.1016/j.cscm.2019.e00231.

[44] A. Torres, J. Hu, A. Ramos, The effect of the cementitious paste thickness on the performance of pervious concrete, Constr. Build. Mater. 95 (2015) 850–859. doi:10.1016/j.conbuildmat.2015.07.187.

[45] K. Jafari, V. Toufigh, Interface between Tire and Pavement, 29 (2009) 1–10. doi:10.1061/(ASCE)MT.1943-5533.0001963.

[46] A.S. Gandage, V. Vinayaka-Ram, M. Panwar, M. Shah, R. Singhvi, Study on reduction of pavement noise using porous concrete, (2016) 12–21.

[47] E. Eriskin, S. Karahancer, S. Terzi, M. Saltan, Examination of the Effect of Superhydrophobic Coated Pavement under Wet Conditions, Procedia Eng. 187 (2017) 532–537. doi:10.1016/j.proeng.2017.04.411.

[48] E. Khankhaje, M. Rafieizonooz, M.R. Salim, R. Khan, J. Mirza, H.C. Siong, Salmiati, Sustainable clean pervious concrete pavement production incorporating palm oil fuel ash as cement replacement, J. Clean. Prod. 172 (2018) 1476–1485. doi:10.1016/j.jclepro.2017.10.159.

[49] A.M. AMDE, S. ROGGE, Development of High Quality Pervious Concrete Specifications for Maryland Conditions, (2013) 111.

[50] Y. Chen, K. Wang, W. Zhou, Evaluation of surface textures and skid resistance of pervious concrete pavement, J. Cent. South Univ. 20 (2013) 520–527. doi:10.1007/s11771-013-1514-y.

[51] NLT-175/98, Resistance to sliding coefficient with the TRRL pendulum., (1998).

[52] T.F. Fwa, Y.S. Choo, Y. Liu, Effect of Aggregate Spacing on Skid Resistance of Asphalt Pavement, J. Transp. Eng. 129 (2003) 420–426. doi:10.1061/(ASCE)0733-947X(2003)129:4(420).

[53] A. Bonicelli, F. Giustozzi, M. Crispino, Experimental study on the effects of fine sand addition on differentially compacted pervious concrete, Constr. Build. Mater. 91 (2015) 102–110. doi:10.1016/j.conbuildmat.2015.05.012.

[54] J. Carbajo, T.V. Esquerdo-Lloret, J. Ramis, A.V. Nadal-Gisbert, F.D. Denia, Acoustic properties of porous concrete made from arlite and vermiculite lightweight aggregates, Mater. Construcción. 65 (2015) 1–11.

[55] American Concrete Institute ACI Committee 522, 522R-06: Pervious Concrete, (2006) 25.

[56] K. V. Horoshenkov, D.C. Hughes, A. Cwirzen, The sound speed and attenuation in loose and consolidated granular formulations of high alumina cements, Appl. Acoust. 64 (2003) 197–212. doi:10.1016/S0003-682X(02)00069-5.

[57] J.J. Chang, W. Yeih, T.J. Chung, R. Huang, Properties of pervious concrete made with electric arc furnace slag and alkali-activated slag cement, Constr. Build. Mater. 109 (2016) 34–40. doi:10.1016/j.conbuildmat.2016.01.049.

[58] B.I. Izevbekhai, Effect of Diamond Grinding on Pervious Concrete, Congr. Tech. Adv. 2017 Cold Reg. Eng. - Proc. 17th Int. Conf. Cold Reg. Eng. Present. 1st Congr. Tech. Adv. (2017) 25–36.

[59] H. Li, J.T. Harvey, T.J. Holland, M. Kayhanian, The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management, Environ. Res. Lett. 8 (2013). doi:10.1088/1748-9326/8/1/015023.

[60] L. Hu, Y. Li, X. Zou, S. Du, Z. Liu, H. Huang, Temperature Characteristics of Porous Portland Cement Concrete during the Hot Summer Session, Adv. Mater. Sci. Eng. 2017 (2017). doi:10.1155/2017/2058034.

[61] R.M. Rehan, Cool city as a sustainable example of heat island management case study of the coolest city in the world, HBRC J. 12 (2016) 191–204. doi:10.1016/j.hbrcj.2014.10.002.

[62] P. Coseo, L. Larsen, Cooling the Heat Island in Compact Urban Environments: The Effectiveness of Chicago's Green Alley Program, Procedia Eng. 118 (2015) 691–710. doi:10.1016/j.proeng.2015.08.504.

[63] H. Li, J. Harvey, Z. Ge, Experimental investigation on evaporation rate for enhancing evaporative cooling effect of permeable pavement materials, Constr. Build. Mater. 65 (2014) 367–375. doi:10.1016/j.conbuildmat.2014.05.004.

[64] T. Karlessi, M. Santamouris, K. Apostolakis, A. Synnefa, I. Livada, Development and testing of thermochromic coatings for buildings and urban structures, Sol. Energy. 83 (2009) 538–551. doi:10.1016/j.solener.2008.10.005.

[65] Y. Qin, A review on the development of cool pavements to mitigate urban heat island effect, Renew. Sustain. Energy Rev. 52 (2015) 445–459. doi:10.1016/j.rser.2015.07.177.

[66] M. Santamouris, Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments, Renew. Sustain. Energy Rev. 26 (2013) 224–240. doi:10.1016/j.rser.2013.05.047.

[67] L. Haselbach, M. Boyer, J. Kevern, V. Schaefer, Cyclic Heat Island Impacts on Traditional Versus Pervious Concrete Pavement Systems, Transp. Res. Rec. J. Transp. Res. Board. 2240 (2011) 107–115. doi:10.3141/2240-14.

[68] J.T. Kevern, L. Haselbach, V.R. Schaefer, Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems, Second Int. Conf. Countermeas. to Urban Heat Islands. 7 (2009) 1–9.

[69] M.R. Hasan, M.F.M. Zain, R. Hamid, A.B.M.A. Kaish, S. Nahar, A Comprehensive Study on Sustainable Photocatalytic Pervious Concrete for Storm Water Pollution Mitigation: A Review, Mater. Today Proc. 4 (2017) 9773–9776. doi:10.1016/j.matpr.2017.06.265.

[70] M.M. Ballari, M. Hunger, G. Hüsken, H.J.H. Brouwers, Modelling and experimental study of the NOx photocatalytic degradation employing concrete

pavement with titanium dioxide, Catal. Today. 151 (2010) 71–76. doi:10.1016/j.cattod.2010.03.042.

[71] S. Shen, M. Burton, B. Jobson, L. Haselbach, Pervious concrete with titanium dioxide as a photocatalyst compound for a greener urban road environment, Constr. Build. Mater. 35 (2012) 874–883. doi:10.1016/j.conbuildmat.2012.04.097.

[72] C.J. Cros, A.L. Terpeluk, L.E. Burris, N.E. Crain, R.L. Corsi, M.C.G. Juenger, Effect of weathering and traffic exposure on removal of nitrogen oxides by photocatalytic coatings on roadside concrete structures, Mater. Struct. Constr. 48 (2015) 3159–3171. doi:10.1617/s11527-014-0388-2.

[73] D. Osborn, M. Hassan, S. Asadi, J.R. White, Durability Quantification of TiO2 Surface Coating on Concrete and Asphalt Pavements, J. Mater. Civ. Eng. 26 (2014) 331–337. doi:10.1061/(ASCE)MT.1943-5533.0000816.

[74] S. Asadi, M. Hassan, J. Kevern, T. Rupnow, Development of Photocatalytic Pervious Concrete Pavement for Air and Storm Water Improvements, Transp. Res. Rec. J. Transp. Res. Board. 2290 (2012) 161–167. doi:10.3141/2290-21.

[75] M. Hassan, S. Asadi, J.T. Kevern, T. Rupnow, Nitrogen Oxide Reduction and Nitrate Measurements on TiO2 Photocatalytic Pervious Concrete Pavement, in: Constr. Res. Congr., 2012: pp. 1920–1930.

[76] M. Pérez-Nicolás, Í. Navarro-Blasco, J.M. Fernández, J.I. Álvarez, The Effect of TiO2 Doped Photocatalytic Nano-Additives on the Hydration and Microstructure of Portland and High Alumina Cements, Nanomaterials. 7 (2017) 329. doi:10.3390/nano7100329.

[77] M. Faraldos, Guía Práctica de la Fotocatálisis Aplicada a Infraestructuras Urbanas, (2012) 1–77. http://www.eptisa.com/descargas/articulos/conama2012_guia_practica.pdf.

[78] G. Hondros, The evaluation of Poisson's ratio and the modulus of materials of a low tensile resistance by the Brazilian (indirect tensile) test with a particular reference to concrete, Aust. J. Appl. Sci. (1959) 243–268.

[79] The World Bank, World Bank Data: Motor vehicles (per 1,000 people), (2014). http://data.worldbank.org/indicator/IS.VEH.NVEH.P3 (accessed September 2, 2014).

[80] R.A. Fisher, Statistical Methods for Research Workers, Kots, S., Johnson, N.L. (Eds.), Break. Stat. Methodol. Distrib. Springer, New York. (1992) 66–70. doi:http://doi.org/10.1007/978-1-4612-4380-9_6.

[81] J.H. Zar, Significance testing of the spearman rank correlation coefficient, J. Am. Stat. Assoc. 67 (1972) 578–580. doi:10.1080/01621459.1972.10481251.