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The behavior of permeable paving properties using different materials in their compositions: a review of the literature

Amanda Rafaely Monte do Prado
Master's student in Civil Engineering, UPE, Brasil.
armp@poli.br

Amaury Gouveia Pessoa Neto
Master's student in Civil Engineering, UPE, Brasil.
agpn@poli.br

Débora Vieira Muniz
Master's student in Civil Engineering, UPE, Brasil.
dvm@poli.br

Simone Rosa da Silva
Professor Phd, UPE, Brasil.
yesonerosa@poli.br

Emilia Rahnemay Kohlman Rabbani
Professor Phd, UPE, Brasil.
emilia.rabbani@upe.br

ABSTRACT

This systematic review addresses the behavior of the properties of permeable pavements with different materials in their compositions, with the objective of raising the state of the art of this area of study in a worldwide scenario. For this, the largest possible number of papers available was listed, according to the eligibility and quality criteria, detected in the Engineering Village, Scopus and Science Direct databases. After reading the titles and abstracts of all identified papers, 28 were chosen associated with the theme, of which 15 were included for the review. This result made it possible to demonstrate that the compensatory technique of permeable pavement is used in several parts of the world, presenting satisfactory results. Several studies presented in this work aimed to replace or even introduce other types of materials in the composition of permeable pavements, seeking to achieve better results in their properties, especially in mechanical and hydraulic.

KEYWORDS: Eligibility. Mechanical and Hydraulic Properties. Compensatory Technique.

1 INTRODUCTION

From the middle of the 20th century, the evolution of urbanization occurred in Brazil in an intense way, where, driven by the improvements generated by industrialization, there was a demographic explosion caused by the process of migration of people from the countryside towards the city (ALVES et al., 2018; SILVA et al., 2019; LIMA et al., 2021 However, this phenomenon has been happening in many Brazilian cities in an accelerated and disorderly way, with no proper supervision by public management, causing social, economic, cultural, and environmental problems that directly interfere in the daily lives of the population (ROCHA and SCHULER, 2016; SANTOS et al., 2017; SILVA JUNIOR et al., 2020).

According to these adversities, the disordered urbanization causes considerable alterations in the natural hydrologic cycle due to deforestation, degradation of natural areas, modification of the natural topography of the terrain, increased soil sealing, among other interventions, causing the expansion of surface runoff and the flow of watercourses and the decrease of infiltration of precipitated water and evapotranspiration (SANTOS et al., 2018; BEGA; RIBEIRO; LIMA, 2019; FONSECA NETO et al., 2020). Thus, according to Silva Júnior and Silva (2016), the impacts caused by these changes, especially floods and urban flooding, lead to a reduction in the quality of life of the population.

Aiming to control the amount of surface runoff water, as well as reduce the downstream impacts of the watercourse, compensatory techniques are considered environmentally appropriate urban solutions for the management of rainwater in urbanized areas (LINO et al., 2019). Permeable pavements, green roofs, individual micro reservoirs, infiltration wells, detention basins, infiltration trenches, vegetated ditches and rain gardens are some examples of the best known compensatory techniques, some already provided for in specific legislation (REIS; ILHA, 2019; RODRIGUES; SANTINI JUNIOR, 2021; RODRIGUEZ; TEIXEIRA, 2021).

Among these techniques, permeable pavements are one of the most widely used sustainable urban drainage solutions, with the objective of reducing water and environmental impacts. (ELIZONDO-MARTINEZ et al., 2020). Among its advantages, there is the reduction of

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urban runoff, with a lower peak of rainwater; groundwater recharge; pollution mitigation; improvement in safety when driving on rainy days, with greater resistance to skidding; noise reduction; and floor cooling (CHU; TANG; FWA, 2018; MA et al, 2020).

The adoption of this solution is essential for the construction of the so-called "sponge cities", that is, those that have a good response in adapting to environmental changes. With better management of the volume generated during rainfall, flooding scenarios would be avoided or mitigated. Also, by allowing water infiltration and consequent groundwater recharge, water shortages and heat islands could be minimized. (ZHU; HUANG; YANG, 2018).

Commonly, concrete and asphalt are the most used elements in its design, especially the first, which has advantages in construction operations compared to the second. In addition, it also reduces environmental impacts related to temperature (ELIZONDO-MARTINEZ et al., 2020). Permeable concrete, or even porous concrete, is defined as that "without fines", which allows infiltration of rainwater (GANESH et al, 2018), in line with the concept of permeable pavement.

However, the use of the materials mentioned also has environmental consequences. For asphalt pavements, there is a need for hazardous waste management, as well as greenhouse gas emissions during raw material processing. Concrete pavements, on the other hand, there are also greenhouse gas emissions associated with the high energy required during the manufacture of Portland cement (ELIZONDO-MARTINEZ et al., 2020).

Given the context, the development of studies aimed at the partial or total replacement of any of these two elements in the design of permeable pavements, as well as the addition of new materials and their influence on their properties are of fundamental importance.

2 OBJECTIVES

This research aims to gather information and data about the behavior of permeable pavements properties with different materials in their compositions.

3 METHODOLOGY

The methodology of this work consisted in the elaboration of a Systematic Literature Review (SLR), based on a research protocol, whose central question seeks to identify how the variation in the composition of permeable pavements affects their mechanical and hydraulic properties.

The bases selected were Engineering Village, Scopus and Science Direct. And the search strings used were constructed from search terms related to the chosen theme, with the following structure as a generic configuration: ("Pavement" AND "Drainage") AND ("Properties" OR "Mechanical Properties" OR "Mechanical Permeability") AND ("Materials" OR "Building Materials").

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The limitations for the selected studies were the English and/or Portuguese languages, in the areas of interest related to civil and environmental engineering and, finally, being published in journals, congresses or in book chapter format, in the last five years (2017 a 2021).

Based on the data obtained through the application of the search string in each database, quantitative and experimental studies were selected, as well as the inclusion and exclusion criteria, and then quality criteria, presented in Table 1.

Table 1 - Inclusion, exclusion and quality criteria

Inclusion Criteria	
CI1	The studies must have carried out experiments that analyze the behavior of the properties
CI2	The permeable pavements used in the studies must have different types of materials in their compositions.
Exclusion Criteria	
CE1	Will not be considered studies that do not perform experiments that analyze the behavior of properties.
CE2	They will not be considered pavements used in the studies, whose compositions do not present different materials from the "traditional".
CE3	Will not be considering studies whose search strings do not appear in the title, abstract or keywords.
Quality Criteria	
CQ1	Peer reviewed
CQ2	Detailed and understandable methodology.
CQ3	Results added value to the research area.
CQ4	Results evaluated impartially and clearly described.

Source: Elaborated by the authors

Subsequently, were applied the quality assessment forms (Table 2) and the eligibility of the studies and data extraction (Table 3).

Table 2 - Quality assessment form

Description of the quality criteria	Type of answer	Answer
Is the detailed methodology understandable?	Pick One List	(yes, No)
Do the results add value to the research area?	Pick One List	(yes, No)
Are the results clearly described?	Labeled Scale	Low level of clarity = 01 Medium level of clarity = 02 High level of clarity = 03

Source: Elaborated by the authors

Table 3 - Study eligibility and data extraction form

Description of eligibility criteria	Type of answer	Answer
Houve extração de dados?	Pick One List	(Yes, No)
Was there analysis of the properties of permeable pavements?	Pick One List	(Yes, No)
Were experiments conducted to evaluate properties?	Pick One List	(Yes, No)
Were different types of materials used in the composition of the permeable pavement?	Pick One List	(Yes, No)
Main properties addressed in the study?	Pick Many List	(Mechanical strength, permeability, porosity)

Source: Elaborated by the authors

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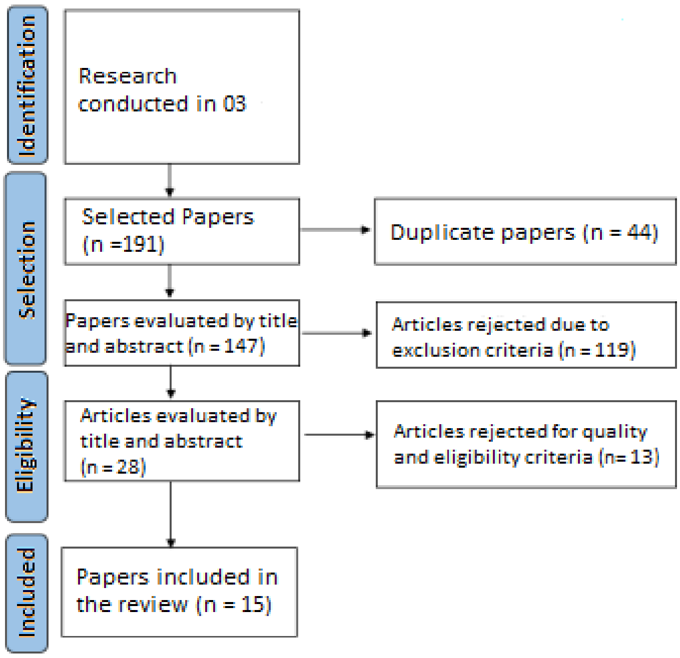
4 RESULTS

Using the methodology described, in the search performed in the 03 databases, 191 articles were initially found. In the selection phase, 44 duplicate articles were excluded and, by applying the selection criteria by reading the title and abstract, 119 articles were excludedThe 28 selected articles were evaluated by eligibility and quality criteria after full reading of the texts, which resulted in the exclusion of 13 articles, leaving a total of 15 articles included for this systematic review of the literature. Figure 1 presents the flowchart with the steps of identification, selection and eligibility that resulted in the articles that compose this research.

Figure 1 - Flowchart with the steps of the Systematic Literature Review



Source: Elaborated by the authors

Table 4 presents a summary of important information from the selected papers, namely: author, year, country, materials used in the composition of permeable sidewalk, and the main properties studied.

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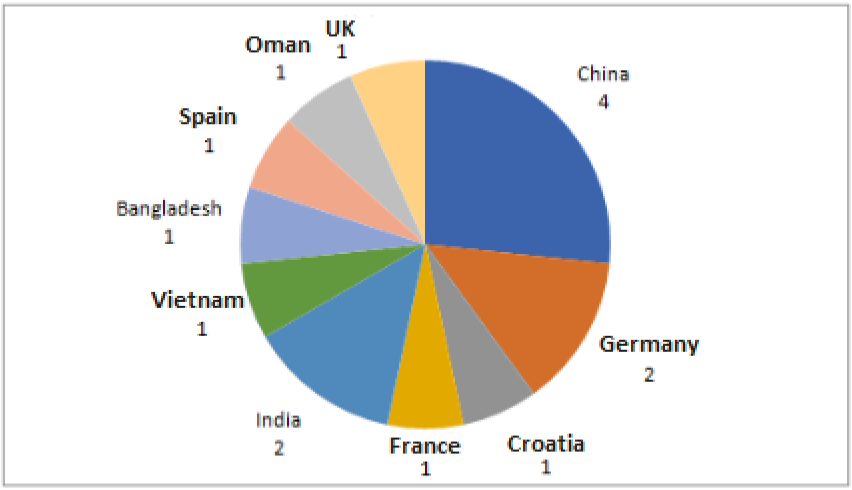
Table 4 - Summary table of selected articles

Authors	Year	Country	Materials used in permeable pavement	Main properties studied
Li et al.	2017	China	Reactive powder concrete composed of mineral mixtures and additives	Compressive strength, flexural strength, permeability, porosity
Nguyen et al.	2017	France	Partial replacement of natural aggregates by 03 types of crushed shells	Compressive strength, durability, porosity and permeability
Ganesh et al.	2018	India	Partial replacement with granulated blast furnace slag and the addition of cellulose fibers	Compressive strength, tensile strength, flexural strength and permeability
Grubeša et al.	2018	Croatia	Permeable concrete mixtures with 03 different types of aggregates (dolomite, diabase and steel slag from a landfill)	Compressive strength, flexural strength, porosity and permeability.
Yongtao et al.	2018	China	New drainage block with stone, sand, fly ash, cement and artificial holes	Compressive strength, flexural strength, split tensile strength and permeability
Heweidak e Amin	2019	UK	OASIS phenolic foam	Infiltration rate
Hu et al	2019	China	Addition of activated carbon	Mixture resistance and abrasion wear
Meddah et al.	2019	Oman	recycled aggregates from different sources (rubber, shell, shredded plastic, recycled concrete aggregate, etc.)	Porosity, resistance, density and permeability
Torzs et al.	2019	Germany	Polyurethane binders	Permeabilility
Torzs et al.	2019	Germany	Polyurethane binders	Porosity, mechanical resistance and permeability
Ahmed e Hoque	2020	Bangladesh	Partial replacement of cement by fly ash	Resistance to compression and permeability
Elizondo-Martinez et al.	2020	Spain	Metakaolin and mixture of geopolymers	Permeability, Indirect tensile strength
Ngo et al.	2020	Vietnam	Replacement of aggregate by autoclavable aerated concrete grãos and recycled aggregates	Permeability, compressive strength and water absorption
Rathan et al.	2021	India	Interlocked pavement blocks permeable with eco sand	Compressive strength, split tensile strength, and flexural strength
Xu et al.	2021	China	Limestone and basalt aggregates	Permeability, Flexural strength

Source: Elaborated by the authors

The systematic literature review gathered studies from 10 different countries, so that 60% of the studies were developed by Asian countries, with emphasis on 04 works in China, and the remaining 40% were developed in European countries (Figure 2).

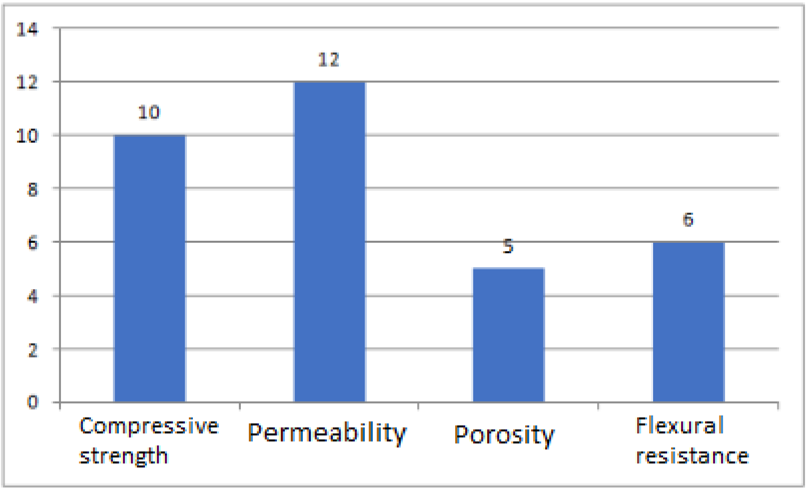
Figure 2 - Development countries of the selected studies



Source: Elaborated by the authors

Among the mechanical and hydraulic properties evaluated by the papers, compressive and flexural strengths, permeability, and porosity stand out, as presented in figure 3.

Figure 3 - Number of papers that addressed the main properties studied



Source: Elaborated by the authors

The systematic review of the literature proposes to present the results obtained by the evaluation of the properties of permeable pavements evaluated by the studies, as well as to discuss their main contributions.

Although permeable pavement is used in several countries with satisfactory results, some issues have not yet been resolved and are still being studied by researchers. Therefore, several studies seek to insert or replace materials in the composition of permeable pavements, seeking to achieve better results in their properties, especially in mechanical and hydraulic.

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Many of these problems, which have not yet been solved, are related to durability and long-term use behavior of pavements.

In this sense, Nguyen et al. (2017) used crushed seashells from the French west coast in partial replacement to natural aggregates in the development of a permeable concrete. After replacing 60% of the natural aggregates in permeable concrete with three types of crushed sea shells, the authors verified the effects on durability, comparing the results obtained in the freeze-thaw resistance tests, clogging test and leaching test of permeable concrete. with and without shells.

Whereas crushed shells are more fragile than natural aggregates, the permeable concretes made with the crushed shells presented a lower mechanical strength and a lower durability of freezing/thawing in relation to the permeable concretes without the shells. The experiment showed that some chemical characteristics of crushed shells may have more influence on durability than on the physical and mechanical properties of permeable concrete. It was also possible to compare the results according to the type of shell used.

The water permeability of permeable concrete with or without crushed shells varies between 2.2 and 3.4 mm. s, which compared to the recommended value of 1.0 mm. s, are high enough to be used for their use. Despite some unfavorable effects, the study showed an acceptable durability of permeable concrete with and without shells for application with low traffic load, evidencing the potential of the material and the need for further studies with field verifications.

In addition to durability, another difficulty is the conciliation between the properties of permeability and mechanical strength. In the search to determine the proportion of the mixture that produces the balance between compressive strength and permeability, Ahmed and Hoque (2020) provide an overview of permeable pavements through tests performed with different mixtures that allow the analysis of the behavior of the pavement.

For this study, a total of 14 mixtures were selected to be tested, including 42 standards cylindrical samples, with variation in aggregate proportion, aggregate size and water content. An addition of supplementary cementitious material was also carried out, a sustainable alternative to common Portland cement, by replacing 20% of the cement weight with fly ash.

As a result, changes in permeable concrete properties due to changes in the mix were reported and discussed. The analyses indicated that it was not possible to identify a precise recipe for the balance between compressive strength and permeability, considering also that the tests used do not provide a clear understanding of the behavior of permeable concrete. However, permeable pavements are an acceptable solution for low impact areas.

In contrast to this study, Yongtao et al. (2018) proposed a new type of drainage block prepared with artificial holes in order to solve the conflicts between resistance and permeability in paving products. The block has some advantages such as greater control of water permeability and the existence of a conical passage, where the top hole is smaller than the bottom hole, making it not easily blocked by pollutants on the road surface.

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The main raw materials for the preparation of new drainage blocks are: stone, sand, fly ash and cement. The samples were subjected to mechanical performance tests such as compressive and flexural strength, split tensile strength, and water permeability coefficient tests.

The results show that the new drainage brick design has the potential to solve the issue, due to the good results in the tests performed. In addition, considering that the holes are artificial, it is possible to make adjustments and prepare blocks with different performances to meet the various existing needs.

Also looking for solutions for the durability of pervious concrete pavements, Li et al. (2017) developed an innovative high strength permeable concrete pavement. For this, a reactive powder concrete was introduced as a matrix, in addition to building accessible pores. In this mixture, several materials were used as resources to achieve the objective, among them: Active silica, fly ash, expansion agents, superplasticizer additive, river sand, styrene-butadiene latex, silica sol and polypropylene fibers.

The experimental results showed that the compressive strength of 7 days reached 61.37 Mpa, associated with a permeability coefficient of 13.02 mm/s, which indicates a favorable performance for wide application. The optimum mix ratio has been determined to ensure high strength pervious concrete pavement performance. The results show that the optimized product has more than 70 MPa of compressive strength and about 10 MPa of flexural strength.

Following the trend of permeable blocks, Rathan et al. (2021) developed permeable interlocked pavement blocks and evaluated the influence of aggregate gradation and the percentage of fines on their mechanical, functional and structural performance. Twelve different permeable concrete mixtures were made with variable gradation of the aggregate and different percentage of fines. In the composition, the fine aggregates were replaced by 5% and 10% of the "eco sand", by-product of limestone, which has crystalline silica as the main by-product.

From the results of the tests and software used, it was observed that the compressive strength, split tensile strength, and flexural strength increase with the increase of the percentage of fines. The authors of the study cite that permeable interlocked pavement blocks can be an effective paving material for low volume roads, urban heat islands and pavements with drainage problems.

Some studies seek to minimize the use of cement in porous concrete pavements by adding alternative materials, due to the environmental impact on cement production. In this sense, Elizondo-Martinez et al. (2020) proposes a partial substitution of cement by different amounts of metakaolin and a mixture of geopolymers containing metakaolin and basalt powder. For the experimental mixtures, metakaolin was used to partially replace the cement in amounts of 5% and 10% of the cement weight.

After the analysis of mechanical and volumetric properties, it was possible to conclude that the substitution of 5% of cement by metakaolin increases both the indirect tensile strength and permeability, but a substitution of 10% of cement by metakaolin reduces

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both properties. Geopolymer mixtures, on the other hand, can achieve significantly higher permeability than traditional porous concrete, but this decreases their indirect tensile strength.

Considering the promising results, some adjustments in the mixtures can achieve results of increased mechanical properties without negatively affecting the porosity, making these materials a potential solution against traditional porous cement concrete.

The substitution of cement also occurred in the study developed by Ganesh et al. (2018), who studied the mechanical properties and permeability of permeable concrete, considering the partial replacement of 30% of the cement by granulated slag of blast furnace and the addition of cellulose fibers, including the combination of both materials.

The properties such as compressive strength, tensile strength, flexural strength and permeability were evaluated through tests. The results indicated an increase in compressive strength, tensile strength, flexural strength and decreased permeability in permeable concrete mixtures with the addition of selected materials, when compared to permeable concrete without modifications.

The commonly used porous asphalt is composed of bitumen-based binder materials. In the study developed by Torzs et al. (2019), a polyurethane (PU)-based binder material was selected to form a flexible and porous pavement layer, but also increases capable of increasing resistance. Two compositions of porous pavement materials with polyurethane were investigated, with differences only in terms of particle size distribution of aggregates and maximum grain diameters. The aggregates employed were a fine diabase gravel and a limestone filler.

The study sought to provide an insight into pore space from CT scans of both floors. Mechanical and hydraulic properties were also determined in laboratory experiments. The images obtained and the reconstructed volumes presented provided ideas about the bounding effect of the polyurethane binder, which are in the scope of future investigations, where the effects of clogging on hydraulic properties will be analyzed.

Another paper developed by Torzs et al. (2019) sought to investigate the hydraulic properties of pavement structures coated with polyurethane. In addition to the experiments performed, the performance of hydraulic models to describe the water retention behavior and hydraulic conductivity were studied.

The results showed that the water retention behavior and the corresponding air intake values of the pavement connected to the polyurethane were very low. However, the investigated properties can influence the hydraulic performance and drainage behavior of a real road structure.

Hu et al. (2019) studied the feasibility of using activated carbon in porous asphalt mixture and the effects of the material on optimal asphalt content, on properties and filtration characteristics through laboratory tests. The porous asphalt concrete was prepared with asphalt binder modified with styrene-butadiene-styrene, crushed basalt aggregate, limestone filling and activated carbon.

The results of the abrasion loss and binder drainage tests showed that activated carbon increases the optimal asphalt content of the porous asphalt mixture. The strength of permeable asphalt pavement is affected by the softening effect of high asphalt content and the stiffness effect of activated carbon. In addition, it can improve the bonding characteristics between asphalt binder and aggregate, contributing to better moisture stability of the mixture.

Ngo et al. (2020) investigated the properties of permeable concretes prepared from recycled aggregates and industrial by-products, such as autoclaved aerated concrete grains. The effects of using construction and demolition waste on the void ratio, permeability, compressive strength, water absorption, evaporation test and surface temperature reduction test were evaluated.

The results indicated that increasing the grain content of autoclaved aerated concrete decreases the strength of permeable concrete, but gradually improves the water retention properties of the pavement.

The study by Meddah et al. (2019) also used permeable concrete mixtures containing different recycled materials, in addition to a control mixture, for testing mechanical and hydraulic properties. The main objective of the research was to evaluate the effect of the use of various types and recycled aggregates as a partial replacement of the natural aggregate. Two types of materials were used (natural and recycled aggregates collected from different sources) in a total of 7 mixtures designed with a variety of natural and recycled granular fractions.

The results showed that the type, size and combinations of recycled aggregates strongly affected the fresh and hardened properties of permeable concrete including density, strength and porosity. It was also found that the classification, size and content of aggregates (natural or recycled) govern the mechanical and hydraulic properties of permeable concrete. The use of various recycled aggregates and waste to produce evidenced the potential to transform permeable Portland cement concrete into a green material using a drainage system.

In the study conducted by Grubeša et al. (2018) six permeable concrete mixtures were made with three different types of aggregate (dolomite, diabase and steel slag from a Croatian landfill near the city of Sisak) considering two different fractions for aggregates (4-8 mm and 8-16 mm). After 28 days submerged in a water tank, the properties of the hardened permeable concrete were evaluated, including compressive strength, flexural strength, density, porosity and permeability.

The study concluded that, from a hydrological point of view, the ideal aggregate is diabase, which allows water to pass smoothly. Regarding the mechanical properties, none of the mixtures met the European criteria for surface layers of pavements. For future studies, the authors noted that coarser aggregate fraction may result in improvements in hydraulic and mechanical properties of permeable concrete.

Heweidak and Amin (2019) added a layer of a material with highly porous cells called OASIS® phenolic foam to the permeable sidewalk. The study analyzed the effects of the presence of the material on the hydraulic properties of the permeable pavement, on the infiltration rate, on the water storage capacity and on the postponement of peak water flow during rainfall of different intensities.

The pavement consisted of a 250 mm sub-base, a 50 mm base, 100 mm paving layers without geotextile layer and thickness of 15 mm, 25 mm and 35 mm of OASIS material. It was observed that the material significantly increased the attenuation of the peak flow by water absorption and that 35 mm thickness of the OASIS 2 layer could absorb approximately a whole rain event of 100 mm /h.

In some European countries, it has become popular to use double-layer permeable sidewalks, which have a thin top layer with better road performance and a thick sub-layer that ensures the best drainage capacity.

In the article developed by Xu et al (2021), the feasibility of applying limestone as an aggregate in the drainage sublayer of a double-layer permeable asphalt pavement was studied. Based on the results, the laboratory properties related to the field performance of the limestone mixture can meet the requirements of the specifications.

Compared with the mixture that used basalt, the water permeability of the mixture with limestone is relatively low. From the point of view of flexural strength, the results of the mixture with limestone were lower than the basalt mixture, however the flexural stiffness of the limestone mixture was lower.

5 CONCLUSION

This systematic review of the literature allowed to present the performances of the properties of permeable pavements considered by the selected studies, as well as to discuss their main contributions in world societies.

The quantity of papers found in the databases for the restrictions performed was quite significant, and the search returned a total of 191 articles. These data reveal a growing interest in the subject, probably caused by the growing concern with environmental issues.

In the specific search for articles that deal with how the variation of the composition of permeable pavements affect their mechanical and hydraulic properties, through eligibility and quality criteria, a total of 15 studies were selected for this work.

This review made it possible to demonstrate that although the compensatory technique of permeable pavement is used in several parts of the world presenting satisfactory results, some dilemmas still need to be evaluated by researchers. This review made it possible to demonstrate that although the compensatory technique of permeable pavement is used in several parts of the world presenting satisfactory results, some dilemmas still need to be evaluated by researchers.

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