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Design Of Polyurethane Pervious Concrete And Weather Resistance

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Polyurethane pervious concrete has gained significant attention in urban pavement applications due to its rapid construction, wide color range, and improved comfort underfoot. This material offers a promising alternative for sustainable and aesthetically adaptable pavements. Research has focused on optimizing the aggregate-to-binder ratio to balance key properties such as compressive strength, surface porosity, and water permeability. Experimental results indicate that a 30:1 aggregate-to-binder ratio achieves the best compromise, providing approximately 5 MPa compressive strength and 11.45 mm/s permeability. While increasing aggregate content enhances surface porosity, most pores remain isolated, limiting permeability improvement. Thermal aging tests revealed an initial increase in strength due to polymerization, followed by a decline from oxidation. Red specimens exhibited higher resistance to heat degradation compared to green and yellow ones. UV exposure had a less significant effect, but red specimens again demonstrated superior durability. High-humidity conditions severely reduced compressive strength, with a 26% loss after fourteen days, highlighting vulnerability to water vapor. The study is limited to laboratory-scale testing, utilizing only iron oxide pigments, without field validation or evaluation of alternative pigments. Additionally, drainage system design and freeze-thaw performance were not assessed. Future research should focus on enhancing water vapor resistance through modified binder compositions or surface treatments, testing other pigments, evaluating freeze-thaw durability, and validating performance in real-world field conditions. These steps will provide a comprehensive understanding of polyurethane pervious concrete's durability, functionality, and practical applicability in urban infrastructure projects.

Keywords: Polyurethane pervious concrete; Aging resistance; Color; Water vapor damage; Thermal aging; Weather resistance; Permeable pavement; Drainage design; Infrared absorption

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1. Introduction

Due to climate change and hasty urbanization, the natural calamity of fast-growing urban floods has put a quintessential need for sustainable drainage methods in the modern city. Without impairing the use of the pavement, pervious concrete is one of the most innovative ideas for handling surface water. Unlike conventional concrete, pervious concrete permits water lateral movement through its interconnected pore structure for fast infiltration into subsoil, thus minimizing surface runoff and threats of waterlogging. Out of all the pervious concrete types, a polyurethane-based pervious concrete is gaining popularity because of its superior physical, mechanical, and environmental properties. The polymer concrete material is made up of coarse aggregates that are bonded by a polyurethane resin, which provides a flexible and strong matrix support under mechanical loading and at the same time maintains high porosity [1]. Polyurethane-based solutions are faster-curing in contrast to environmentally friendly cement-based pervious concrete or asphalt pervious concrete and are characterized by chemical resistance and pigment ability for aesthetic and functional applications in light traffic areas, pedestrian walkways, parks, and parking zones. Design and optimization of pervious materials require selecting the right materials and determining their proportions to obtain a suitable compromise between compressive strength, permeability, and durability. The aggregate-to-binder ratio is of principal importance to these properties [2]. An increased amount of aggregate could enhance the porosity and water permeability of the system, but if too much aggregate is used, the coating thickness of the binder lining the aggregate surfaces could be reduced, which might weaken the internal bonds responsible for structural strength. On the other side, too much binder may reduce the void ratio, which will consequently reduce permeability and the much-needed factor for stormwater infiltration; thus, a balanced formulation is crucial for the material's structural integrity and hydraulic performance [3]. Another factor that is just as essential for the real-world use of polyurethane pervious concrete is its ability to resist weathering. Road surface components are constantly exposed to very harsh environmental scenarios that normally consist of a combination of high temperatures, UV radiation, and fluctuating humidity. These impacts gradually wear down the physical characteristics of the binder through the process of aging, which is accompanied by embrittlement, adhesion, and strength losses. In the case of heating, it can sometimes enhance the strength of a polyurethane-based binder by further polymerization; however, the resulting oxidative degradation will tend to lower the duration of their performance significantly [4].

In addition, ultraviolet radiation, a major source of which is solar radiation, intensifies the breakdown of the organic parts of the binder. Incorporation of pigments in the concrete can delay or even prevent this degradation by modifying thermal and optical properties. This can mean pigments modify the amount of light absorbed and reflected, depending on whether the thermal build-up and aging go on at different rates. Color is no longer simply a matter of aesthetic choice; it may also be an important factor in determining the speed of degradation under UV exposure. Moisture accumulation is; hence, another environmental problem associated with poorly drained substrates. While the concrete itself allows for water to permeate, bad drainage, by which standing water accumulates on top of the concrete surface or entirely stays within disconnected pores, creates a humid environment [5]. This issue will cause the separation of the aggregate from the polyurethane binder over time, i.e., it will be similar to the damage that happens in asphalt materials due to moisture. Long periods of high humidity provide conditions for fast water vapor-induced degradation, which in turn causes reduction of compressive strength, binder softening, and structural performance degradation [6]. For the successful application of polyurethane pervious concrete in the field, not only will the material selection be of importance, but the design of the pavement system, including drainage in the sub-base, will also be important. If, however, the drainage design treatment below the pervious concrete layer is well done, then there will not be anything retained that can promote moisture induced damage [7].

Besides that, the performance tests are being conducted under artificially freeze-thaw cycles, mechanical fatigue, and a combination of environmental factors in order to understand the material behavior under various climatic conditions. Hence, in conclusion, polyurethane pervious concrete is a highly functional and versatile material that is usable for sustainable pavement and urban drainage. Combining imperviousness with sufficient strength and an aesthetically pleasing charging offers a very good case for using polyurethane pervious concrete in low-traffic areas, matching performance with aesthetic integration into the urban environment [8]. The triumph of weaving this tech into the fabric of daily life hinges on the complete grasp of how the material behaves, how long it lasts in the open air, and whether it is compatible with the existing construction. More research and field trials need to be continued to optimize formulations and enhance weather resistance and application options for the more modern infrastructure projects [9].

By and large, substantial research has been performed, where in one such study, polyurethane pervious concrete has demonstrated superior performance to asphalt pervious concrete. However, weather resistance is an important index to evaluate the application of pervious concrete with an organic binder [10]. The effect of different weather conditions needs to be further studied. Moreover, pervious concrete used in non-motorized and park roads often adopts some colors, but the effect of colors on aging is still unclear [11]. Therefore, the resistance to thermal and ultraviolet aging of polyurethane pervious concretes with red, yellow, and green colors was studied, and water vapor damage was analyzed to promote their application in this paper [12].

Wang et al. [13] examined the strength and performance characteristics of porous polyurethane composites to determine their viability for use in pavement systems. The changes of aggregate gradation and binder in the mixture were the main factors that the authors considered in their work. They did a series of tests to measure the impact of the factors on the performance of the samples. They measured the mechanical properties such as the compressive strength, the flexural strength, and the permeability. The research concluded that polyurethane as a binder is the best way to improve the adhesion of aggregates, thus increasing the strength of the composite in a mechanical way and without the reduction of porosity. The composites also have good water permeability and resistance to thermal aging and water damage. Wang et al. came to the conclusion that porous polyurethane composites can maintain a balance between load capacity and drainage efficiency, thus being suitable for use in permeable pavement systems.

Törzs et al. [14] conducted a study on the permeability behavior of polyurethane-bound permeable pavement materials under unsaturated flow conditions for laboratory experimentation to assess the integration of different polyurethane binder proportions on the permeability and water retention capacity of these materials. In line with prior expectations, it was disclosed that when the binder content was increased, both the permeability and porosity of the material were lowered, thus the material's ability to water infiltration and retention was decreased. The study also noted that for the empirical design of permeable pavements to be effective in stormwater management, the hydraulic performance under unsaturated flow conditions should be taken into account.

Wu et al. [15] assessed the application of waste plastics in asphalt pavements, focusing on their prospects for promoting high-temperature performance and maintaining environmental sustainability. They explored the various methods for plastic modification, compatibility of waste plastics with asphalt, and performance effects due to their inclusion, as well as issues related to potential microplastic pollution and emissions, and long-term durability. Eventually, the authors highlighted the need for standardization, life-cycle assessments, and field tests to demonstrate that the use of waste plastics was secure and feasible.

Xu et al. [16] described their research on determining the optimum compacting time for porous polyurethane mixtures through multiscale techniques, which included laboratory tests, microstructural analysis, and statistical approaches. This study tried to understand the underlying mechanism of strength evolution of these mixtures to improve the performance of pavements. Compaction observed at different times significantly altered the aforementioned two properties in the pavement. Defining the optimum compaction window saved the authors' effort toward constructing practical guidelines for improving construction quality and longevity of porous polyurethane pavements.

Xu et al. [17] assessed the applicability of couple-proportioning with municipal solid waste incineration. Bottom Ash (BA), besides cement, was used to make the pervious concrete. The main aim of the investigation was to find out if BA might be a feasible tool for promoting sustainability in the making of concrete. The research had a focus on the assessment of the physical and mechanical properties of the old concrete with different BA dosages. Their findings pointed out that the inclusion of BA had a singling-out influence on these properties: porosity, permeability, and compressive strength. A maximum BA content yielding a proper relationship between mechanical performance and permeability criteria was determined. Therefore, it was concluded that BA would have a proper application in pervious concrete mix designs in conjunction with the waste streams valorization and green construction.

Cong et al. [18] performed a laboratory evaluation comparing the performance of Porous Polyurethane Mixtures (PPMs) to Open-Graded Friction Course (OGFC) mixtures. The main goal of the research was to find out if PPMs can be used as a substitute for regular OGFC in the pavements. The study focused on these aspects: permeability, mechanical strength, and durability under the conditions of simulated traffic and the environment. Results evidenced the comparable or superior permeability and mechanical properties of PPMs concerning OGFC mixtures, whereas PPMs were also found to have considerably improved resistance to various common distresses, possibly making them an ideal choice for pavement performance and longevity improvement.

Chen et al. [19] conducted an experimental study to test the anti-icing and de-icing performance of polyurethane concrete as a road surface layer. The main focus of the study was whether ice can form or be easily removed from the pavement using polyurethane concrete. For characterizing the thermal properties, ice adhesion strength, and deicing efficiency, laboratory tests mimicking winter scenarios were conducted. The final report mentions that PU concrete has exhibited superior anti-icing properties in comparison to other standard pavement materials, which is attributed to its lower surface energy as well as better thermal insulation. Furthermore, it was efficient in deicing, thus necessitating less ice removal work. The authors also inferred that the use of polyurethane concrete on the road surface would thus significantly improve traffic safety, besides decreasing maintenance activity during the ice conditions.

Alvarado-Vicencio et al. [20] studied natural water infiltration rates within a newly developed permeable pavement material made using a polyurethane binding system. Scientists aimed to figure out how well this substance would help water to soak into the ground beneath the sustainable urban drainage systems. They carried out a series of experimental tests to check the permeability of the pavement in saturated conditions. The studies led to the achievement of very high values for saturated hydraulic conductivity, which means that polyurethane-bound permeable concrete would be a suitable medium to contain stormwater runoff and flooding in urban areas. Hence, this innovative pavement material can be a source of solution to urban water management problems.

With respect to the engineering capacity, transmissivity, and ecological friendliness of polyurethane open-graded cementitious material, there are substantial gaps in the understanding of which hinder the optimal application and subsequent use of the material. The majority of the pervious works have been done in controlled laboratory settings, which do not have the variability and, in some cases, extreme environmental exposure typical of actual field conditions. Consequently, the durability and the structural strength of polyurethane pervious concrete in real field applications are a matter of speculation. Daily ambient temperature variations and seasonal variations, constant exposure to ultraviolet radiation, continual presence of water, and freeze-thaw cycles can have important implications for the behavior of the polyurethane binder and the overall pavement system durability. However, there is a significant shortage of holistic studies that model or simulate these combined environmental stresses under extended exposure. Further, even though it is a common practice to use pigments either for functional or aesthetic reasons, there has been too little attention given to how different types and shades of pigments influence material aging behavior, particularly in terms of heat absorption and UV radiation degradation. Iron oxides have perviously received the majority of the attention in prior studies, yet other pigments used in commerce that can react differently to sun radiation and the ambient environmental conditions have never been thoroughly studied. This leaves a shortfall in critical knowledge in pigment system optimization, which is important in maximizing aesthetic value and prolonging material life. In addition, the internal pore structure of polyurethane pervious concrete, particularly the presence of large isolated or impermeable voids, presents a significant challenge in precisely predicting both actual permeability and frost resistance. Trapping of water in these isolated voids can lead to internal freeze damage and, hence, compromise both the strength and durability of the material under cold climate conditions. Despite this, there has been very little work that explicitly examines the size of this problem and recommends remedial actions, e.g., optimization of the pore structure or incorporation of binder additives that boost freeze-thaw durability. A significant lack in the existing literature concerns the design of sub-base drainage systems. It is the drainage below the concrete layer that is vital for the prevention of water accumulation, which is a major cause of the separation of the aggregate and binder. Unfortunately, this feature of the pavement material, which is very significant for its durability, has never been thoroughly investigated. There is a need for detailed studies to understand the interrelation of the concrete hydraulic performance with the layer structure. To put it briefly, the question of a complete model that includes environmental sustainability, economic feasibility, and life-cycle performance in addition to the mechanical aspects and permeability characteristics that have been researched separately remains to be answered. Such integrated analyses are very important to support material selection and pavement design based on the principles of sustainability, resilience, and economic efficiency.

One of the main ways this paper advanced the area of environmentally friendly road materials was through its in-depth study and practical use of polyurethane pervious concrete. Initially, a thorough and methodical assessment of the most important performance measures, for example, compressive strength, surface porosity, and water permeability for various aggregate-to-binder ratios, was carried out. An optimum ratio of 30, which gives a very expeditious balance to structural and hydraulic performance, was found after completing the entire investigation. The unique study also explored the impact of different colors in defining the aging performance behavior of polyurethane pervious concrete, considering combinations such as red, yellow, and green on thermal and ultraviolet degradation. It was possible to observe that color made a remarkable difference in aging resistance, with red giving the best performance in both ways. This has emphasized the color as having a dual-function use that is in both the functional aspect and aesthetic requirements. Thirdly, the study examined water damage vapor, which was a major factor in durability. Experimental evidence indicated there would be a considerable reduction in compressive strength under high humidity conditions, which implied the need for appropriate drainage designs at the substructure layer. In sum, the paper contributed unique insights regarding formulation, environmental durability, and practical application of polyurethane pervious, a brand-new material with advantageous guidance for selection of materials and pavement design, among other possible wider benefits of durability, permeability, and aesthetic flexibility for sustainable urban

Table 1. Comparative study of research gaps.

Authors	Research Area	Contribution	Identified Research Gaps
Wang et al. [13]	Porous polyurethane composites for pavement	Evaluated mechanical performance, water permeability, and environmental durability of polyurethane binders	Did not assess long-term durability under real environmental conditions or moisture-induced degradation
Törzs et al. [14]	Hydraulic behavior of polyurethane pavements	Investigated permeability under unsaturated flow conditions	Lacked integration with environmental and mechanical performance under variable field conditions
Wu et al. [15]	Waste plastic in asphalt	Studied the mechanical performance and sustainability of plastic-modified asphalt	Did not explore interaction with polyurethane systems or their durability in diverse climates
Xu et al. [16]	Compaction of porous polyurethane mixtures	Determined optimum compacting time through multi-scale tests	Did not connect compaction timing to aging or freeze-thaw performance
Xu et al. [17]	MSW bottom ash in pervious concrete	Examined the physical/mechanical effects of bottom ash integration	Lacked long-term field performance and freeze-thaw durability assessment
Cong et al. [18]	Polyurethane vs. OGFC mixtures	Compared the mechanical and permeability performance of polyurethane and OGFC	Limited data on thermal or UV aging and moisture vulnerability
Chen et al. [19]	Anti-icing/deicing of polyurethane pavements	Assessed performance under simulated winter scenarios	Did not consider combined environmental effects (UV, heat, humidity)
Alvarado-Vicencio [20]	Infiltration performance of polyurethane pavement	Measured saturated hydraulic conductivity	Lacked pore network analysis or degradation mechanisms under real weather conditions

infrastructure.

2. Materials and methods

2.1. Raw Materials and Mixing Ratio of the Pervious Concrete

PU binder is a two-component binder (A and B) that is produced by Jingjiang Hengye Cementing Agent Technology Co., LTD. A is the main component of PU binder, and is a white liquid. B is used as hardening agent and is a colorless liquid. The physical indexes of PU binder are shown in Table 2.

Aggregate is a single gradation crushed stone with a size range of 4.75 mm $\sim$ 9.5 mm. To reduce the influence of dust, it was cleaned and dried at 105°C. After 5 hours, the mass loss was less than 1% between 20 min . The bulk density is 2890 $\mathrm{kg/cm^3}$ and water adsorption ratio is 0.8%. The content of needle-like and flaky stones is less than 3%.

Three iron oxide powders with red, yellow and green were used as pigments.

The mixing ratio of pervious concrete was designed based on the target porosity (20%). The aggregate to PU binder ratio (wt) is about 30 and A to B ratio is 1.5 . The amount of pigment is 50% of PU binder which is provided by Jingjiang Hengye Cementing Agent Technology Co., LTD . After that, the aggregate to binder ratios were changed to 20, 25, 35, and 40 , as shown in Table 3.

2.2. Methods

(1) Compressive strength

Groups A and B were put in a mixer and mixed for 30 seconds. After that, the pigment was added for a uniform color, and the mixture was stirred. Finally, aggregate was added and stirred until the surface of the aggregates was all coated. The mixture was made into 100 mm × 100 mm × 100 mm samples. The samples were removed from the mold after 24 h and were still kept indoors at $20-25$°C (Fig. 1) to be used in all experiments. A load-bearing capacity test was done following the Chinese standard GB/T 50081. The number of samples was three.

(2) Surface porosity

Surface porosity is tested according to T/CSTM 00040-2019 (net basket method) and is used to analyze the connectivity of pores. The sample was dried to constant weight at 45°C in a vacuum oven and cooled to room temperature. The cooled sample was weighed (m_0) in a plastic net basket. Then, it was fully immersed in water until no air bubble appeared in the water. The sample was taken out of water and filtered with a net basket until no water drops remained. The filtered sample was again placed in water and weighed (m_1). The above program was repeated three

Table 2. Physical indexes of A and B in PU binder.

Setting time(min)	Hardness	Tensile strength (N/mm^2)	Tearing strength (N/mm^2)	Elongation (%)	Viscosity (23°C) (MPa · s)	Density (23°C) (g/mL)
30 ± 10	70 ± 5	≥ 25	≥ 90	≥ 15	A: 600 ± 250 B: 210 ± 40	A: 1.15 ± 0.05 B: 1.22 ± 0.2

Table 3. The initial mixing ratio of the pervious concrete.

Aggregate / Binder (wt)	Aggregate(g)	A(g)	B(g)	Pigment(g)
20	2400	72	48	60
25	3000	72	48	60
30	3600	72	48	60
35	4200	72	48	60
40	4800	72	48	60

Fig. 1. Samples.

times for every sample. The number of samples was three. Surface porosity can be obtained according to Eq. (1).

$$P = \left(1 - \frac{m_0 - m_1}{\rho V_0}\right) \times 100 \tag{1}$$

Where P is surface porosity, %; V_0 is bulk volume, cm^3; m_0 is dry mass, g; m_1 is saturated face dry mass, g; ρ is water density, 1.0 g/cm^3.

Eq. (1) only excludes the effect of some impermeable small pores, but some large unconnected pores will still affect the results.

(3) Water permeability

The water permeability coefficient was tested according to JC/T 2558-2020. The side of the sample was sealed with paraffin wax. The specimen was placed in water for 24 h and put into a device (Fig. 2). The valve of the water system was turned on and adjusted to keep a constant waterhead (about 150 mm). After the overflow outlet flow was steady, the change of water in the vessel was recorded during the 90s. The above program was repeated three times for every sample. The number of samples was three. The permeability coefficient was calculated according to Eq. (2).

$$K_t = \frac{QL}{AHt} \tag{2}$$

Where K_t is the permeability coefficient, mm/s; Q is water amount through sample during 90 s after the overflow outlet flow is steady, mm^3; L is the height of sample, mm; A is the base area of the sample, mm^2; H is the waterhead, mm; t is testing time (90), s.

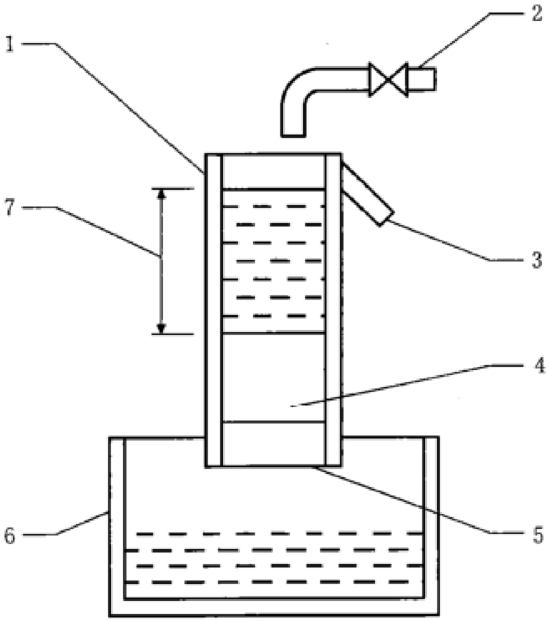

Fig. 2. Installation diagram. 1-Sealed device 2-Water supply system 3-Overflow port 4-Sample 5-Outlet 6-Vessel 7-Waterhead.

(4) Aging resistance

Aging resistance was evaluated by thermal aging and ultraviolet aging. (a)Thermal aging

Thermal aging was carried out in the KY-401A aging test chamber. To obtain an appropriate aging temperature, combined with the road surface temperature, a failure test at 2 MPa was conducted after heat treatment at 50°C − 90°C for 2 hours. Mass loss is shown in Table 4. The sample below 60°C remained intact, but some aggregates over 60°C were detached from the sample. In addition, the high-temperature properties of asphalt mixtures are often tested at 60°C. Therefore, the thermal aging temperature was set to 60°C.

To simulate the effect of day and night alternation (hot-cold cycle) on road properties, the sample was first heated at 60°C for 5 hours and then taken out and placed about 2 hours at room temperature. The 5h thermal aging time is selected because the temperature is higher from 11:00 AM to 4:00 PM in summer in Henan Province, China. The sample can be fully cooled to room temperature during two hours. The mentioned operation was repeated for 5, 10, 15, and 20 cycles. Compressive strength was measured to see the influence of thermal aging. The number of all color samples was three.

Table 4. Mass loss of samples after hot-cold cycle.

Temperature (°C)	50	55	60	65	70	80	90
Mass Loss (%)	0	0	0	0.1	0.6	5	8

(b) Ultraviolet aging

Ultraviolet aging was carried out using an XQ-876 UV aging equipment with two 15 W lamps. Irradiation wavelength was 360 nm , and experimental temperature was 25°C. The rotating rate of the sample tray was 9RPM/min. The aging time was set to 25 h, 50 h, 75 h, and 100h. Finally, compressive strength was tested. The number of all color samples was three. (5) Water vapor damage

The specimens were kept in a curing room with 98%RH and 20 ± 2°C. Load-bearing capacity was assessed following 7 and 14 days of exposure. The number of samples was three. The effect of water vapor was analyzed by comparing with the same age samples under the condition (20 − 25°C, 60 − 70%RH).

3. Results and discussions

3.1. Effect of aggregate to binder Ratio on the Properties of Pervious Concrete

3.1.1. Compressive strength

The compressive strength of the sample with different aggregate to binder ratios is shown in Fig. 3. An increase in the aggregate to binder ratio only is accompanied by a reduction in the strength of pervious concrete. It might be so that the main reason for this is that the increase in the ratio of aggregate and pavement binder results in less thickness of the polyurethane binder being coated on the surface of the gravel. As a result, the adhesion between gravels decreases, especially for samples with a high aggregate to binder ratio. When the aggregate to binder ratio is 30 , the strength is only reduced by 0.6 MPa , but a 40 aggregate to binder ratio causes a decline in the performance of about 26%. So, the aggregate to binder ratio should not be higher than 30.

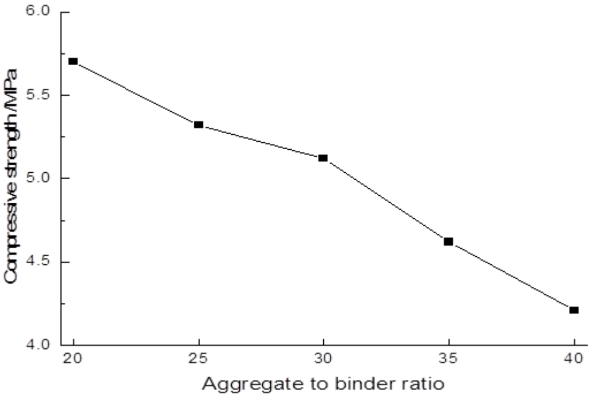

Fig. 3. Compressive strength of samples with different aggregate to binder ratios.

3.1.2. Surface porosity

The surface porosity of samples with various granular materials and a rising proportion is displayed in Fig. 4. The Surface porosity of all samples is higher than the target value (20%). As the aggregate to binder ratio is raised; the surface porosity is found to go up linearly from 28.5% to 37.3%. At a 30% aggregate to binder ratio, the surface porosity is 34.3%. Nevertheless, there are a few large unconnected pores in pervious concrete, and surface porosity will be greater than the connected porosity. Consequently, the permeability cannot be determined yet. In addition, the difference between m_0 and m_1 indicates that some small pores exist in which water will be retained, and the frost resistance of pervious concrete will be reduced.

3.1.3. Permeability

Permeability coefficients of samples with different aggregate to binder ratios are displayed in Fig. 5. As the aggregate to binder ratio increase, the permeability coefficient gradually increases from 10.95 mm/s to 11.97 mm/s, but the increase of the coefficient (about 9%) is far smaller than that of surface porosity (about 37%). This means that there are more unconnected pores in the sample. Even so, those values are more than the largest required value (8 mm/s).

When the aggregate to binder ratio is 30%, the permeability coefficient reaches 11.45 mm/s, which can ensure the rapid discharge of rainwater through Polyurethane pervious concrete.

Higher aggregate to binder ratio have reduced the mechanical strength of the material, while adequate permeability continues to be another very critical requirement, especially in water drainage situations or for materials that interact with the environment. Thus, choosing a particular aggregate-to-binder ratio is again important to sustain strength requirements along with functional performance [21]. The use of an excessive amount of binder may result in a reduction of pore connectivity and permeability, while an insufficient amount may reduce strength. By thorough consideration of the key indicators of performance, including surface porosity and permeability coefficient, as well as the production cost, it was determined that 30% aggregate-to-binder would be a reasonable compromise. This would develop enough mechanical strength while allowing the necessary permeability for practical applications.

A suitable aggregate-to-binder ratio should make sure that the concrete meets not only technical requirements but also lower cost [22]. Based on the above results, 30% of aggregate-to-binder ratio was selected in the following experiments.

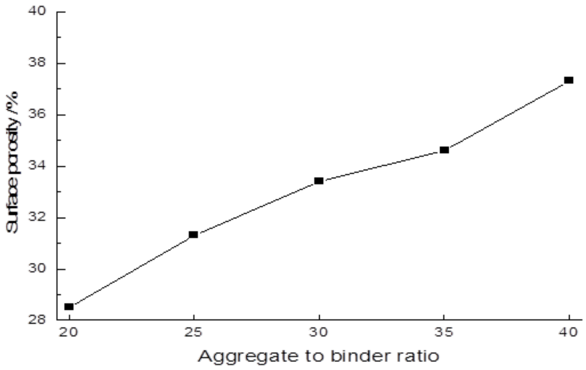

Fig. 4. Surface porosity of samples with different aggregate to binder ratios.

3.2. Aging Resistance of Pervious Concrete

3.2.1. Thermal aging

In indoor conditions, curing ages have almost no effect on the strength, as shown in Table 5. The strength of the samples at different ages was about 5 MPa after 25 h. However, the hotcold cycles have larger effects on the strength. In the initial 5 cycles, the strengths increase by about $1-1.5$MPa. With the increase in cycles, the strengths begin to decrease (Table 6). The strength of each sample is, after 20 cycles, lower than the initial strength in all cases, and the biggest difference is about 1 MPa . The above changes are related to the polymerization and oxidation reactions of the polyurethane binder in the heating process. In initial cycles, the polymerization is the main factor that accelerates the transformation of elasticity to viscosity and increases the bonding force of the polyurethane resin with granular material. In later cycles, oxidation is the main factor that decreases the bonding force of the polyurethane resin with aggregate. The rise in the degree of polymerization also leads to a diminishment of the deformation ability of the polyurethane resin. The temperature shifts cause the continuous expansion and contraction of the polyurethane binder, which eventually breaks its structure, and thus the adhesion force with the aggregate is decreased even more.

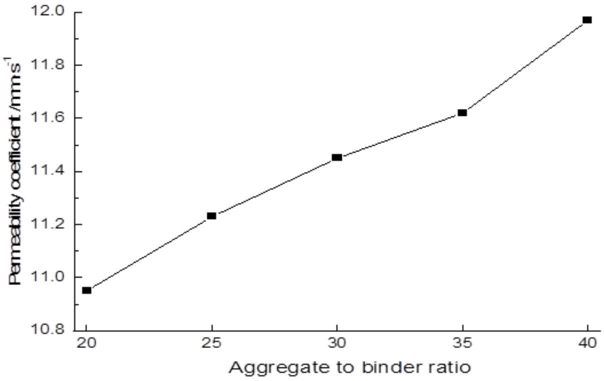

Fig. 5. Water permeability of samples with different aggregate to binder ratios.

Table 5. Development of compressive strength under indoor curing.

Ages /**h**	**25**	**50**	**75**	**100**
Compressive strength /MPa	5.12	5.06	5.11	5.02

In indoor conditions, the color of the sample also has little influence, and the largest difference is only 0.4 MPa (Table 6). However, after the hot-cold cycles, compressive strengths show obvious changes. In the initial five cycles, the strengths increase rapidly by 39% (red), 27.5% (green), and 38.8% (yellow). At 10 cycles, the red sample's strength is almost 11% lower, while the yellow and green samples' strengths are 20% and 26% lower, respectively. Compared with the initial strength, the red sample still has higher strength (22%), and the yellow only increases by 2%, while the green is reduced by 3.8%. At 15 cycles, the red strength is still 12% higher than the original one; the yellow and green samples show 11% and 15% strength losses, respectively. At 20 cycles, the red strength is close

Table 6. Effect of hot-cold cycle times on compressive strength of samples with different colors.

Cycles/times	Compressive strength/MPa			Strength loss/%		
	Red	Yellow	Green	Red	Yellow	Green
0	4.91	5.12	5.31	0	0	0
5	6.80	6.50	6.87	-38.8	-27.5	-29.6
10	6.00	5.20	5.10	-22.5	-2.0	3.8
15	5.59	4.53	4.50	-12.2	11.2	15.1
20	4.88	4.33	4.20	0.04	15.1	20.8

Note: '-' before data means that the strength increases.

to the initial one; the yellow and green samples have 15% and 21% strength losses, respectively. The above effects of color are related to the absorption of light. The heating in an electric furnace is equivalent to a process in which the sample is subjected to infrared radiation. Different colors have different absorption capacities for infrared light. The red sample has a worse absorption capacity than the green and yellow samples, which leads to slower polymerization and oxidation and reduces some negative effects of oxidation. So, the properties of the red sample have a slower change.

In general, the red sample has a strong resistance to heat aging, and pervious concrete roads should select red.

3.2.2. *Ultraviolet aging*

The consequence of ultraviolet light on the load-bearing capacity of differently colored samples is depicted in Table 7. The impact of ultraviolet light is less than that of infrared radiation. The strength rises during the first 75 hours, notably at 50 h , but it decreases to a level at 100 h which is still above that of the initial strength. Hong et al. [23] also found that ultraviolet illumination increased the tensile modulus of polyurethane binder.

Samples with different colors also show different changes. Red samples have a slower strength increase than the yellow and green samples. As such, in the case of 50 h illumination, the red sample strength growth rate is 4.3%, while for the yellow and green samples, these are 12.0% and 11.7% respectively. At 75 h, the red sample is increased only by 7.8%; however, the yellow and green are increased by 18.1% and 22.7% respectively. It is worth noting that the green and yellow show markedly more significant decreases (about 4% and 9%) at 100 h as compared to 75 h . Hence, red samples feature a stronger resistance to ultraviolet aging. Chen [24] also found that the red pigment can improve resistance to ultraviolet aging of wood fiber/PVC composites.

The above results of heat and ultraviolet aging indicate that red should be preferentially selected in the application of polyurethane pervious concrete.

3.3. Resistance to Water Vapor Damage of Pervious Concrete

Polyurethane pervious concrete has a strong permeability, and water can quickly enter the substructure of the road. However, if the water in the substructure cannot be quickly drained, polyurethane-coated concrete will be in a humid environment. The compressive strengths of samples in the condition of 98%RH are shown in Table 8.

When the samples were exposed to the humid environment, the strength decreased rapidly, and the strength losses at 7 d and 14 d were, respectively, 23.5% and 27.4%. This indicates that a humid environment reduces the interaction between the polyurethane binder and aggregate surfaces. This is similar to water damage to the asphalt mixture. In addition, water that is undrained in some pores, i.e., small pores, also has a negative effect. In general, polyurethanepaved concrete roads should pay attention to water damage and be equipped with an appropriate drainage design in the substructure.

4. Conclusions

The current study's investigation explored in depth the permeability, mechanical properties, and durability of polyurethane pervious concrete with respect to environmental degradation. Altering the aggregate-binder ratio, an optimal value of 30 yielded a compressive strength of about 5 MPa along with the water permeability coefficient of 11.45 mm/s. Moreover, the increase of aggregate content not only facilitated permeability and porosity but also decreased the coverage of the aggregates with the binder, thus leading to a decrease in the compressive strength, particularly at higher ratios. When talking about environmental resistance, the red samples had better performances than their yellow and green counterparts in both thermal and ultraviolet aging tests. These findings indicate that pigment selection has a dual function of providing visual appeal and long-term durability. But, the exposure to water vapor caused the strength to be significantly decreased; a large 26% loss was recorded after 14 days at 98% relative humidity. This makes the incorporation of efficient substructure

Table 7. Effect of ultraviolet illumination time on compressive strength.

Illumination time/h	Compressive strength / MPa			Strength growth rate /%		
	Red	Yellow	Green	Red	Yellow	Green
0	4.91	5.12	5.31	0	0	0
25	5.00	5.40	5.49	1.8	5.5	3.5
50	5.12	5.74	5.91	4.3	12.0	11.7
75	5.29	6.04	6.51	7.8	18.1	22.7
100	5.24	5.80	5.90	6.7	13.4	11.1

Table 8. Effect of water vapor on compressive strength.

Ages /**d**	**0**	**7**	**14**
Compressive strength /MPa	5.12	3.94	3.77
Strength loss /%	0	23	26

drainage systems imperative to reduce moisture-induced deterioration. To sum up, the research points to the potential of polyurethane pervious concrete to be used as an environmentally friendly pavement material, specifically in the case of lightly trafficked urban areas. The material demonstrates a very good balance of permeability, durability, and weathering resistance, with the performance being significantly promoted by the use of red pigmentation and the aggregate-to-binder ratios that were closely controlled. Subsequent research works may concentrate on confirming installation in the field, assessing the resistance to freeze-thaw cycles, and changing binder compositions to enhance water vapor tolerance, thus broadening the feasible application of the material under actual conditions.

Additionally, the study has not gone deep enough into testing of key attributes such as flexural strength, fatigue life, and environmental sensitivity. It showed sensitivity toward water vapor, leading to a reduction in strength in moist environments, emphasizing the need for reformulating the binder for improved resistance to moisture. In addition, despite achieving enhanced resistance due to the addition of red pigment, the base mechanisms are unclear.

Future research would need to verify results in real-world environments, determine long-term durability, and formulate improved versions with higher environmental resistance for broader applications in sustainable city planning.

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Author contributions

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nomenclature

Acronyms

ρ	Density of water (1.0 g/cm³)
$\boldsymbol{A}$	Base area of sample (mm²)
$\boldsymbol{K_t}$	Water permeability coefficient (mm/s)
$\boldsymbol{m_0}$	Penalty coefficient
$\boldsymbol{m_1}$	Saturated surface-dry mass of sample (g)
$\boldsymbol{m_2}$	Saturated surface-dry mass after filtration
H	Water head (mm)
L	Height of sample (mm)
P	Surface porosity (%)
Q	Water amount permeated during time t (mm³)
A	Polyurethane binder
B	Polyurethane binder component B (with -NCO groups)
CSTM	China Structural Testing and Measurement
HR	Relative Humidity
OGFC	Open-Graded Friction Course
PPMs	Performance of Porous Polyurethane Mixtures
PU	Megapascal (unit of pressure)
t	Time during permeability testing (s)
UV	Ultraviolet
V_0	Bulk volume of sample (cm³)

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